THE PRECISION SCREW IN SCIENTIFIC INSTRUMENTS OF THE 17th-19th CENTURIES:
WITH PARTICULAR REFERENCE TO ASTRONOMICAL, NAUTICAL AND SURVEYING INSTRUMENTS

RANDALL CHAPMAN BROOKS

March 1989

A thesis submitted as partial fulfillment of the degree of

Doctor of Philosophy

at the University of Leicester

Department of Astronomy

Statement

The accompanying thesis submitted for the degree of Doctor of Philosophy entitled:

The Precision Screw in Scientific Instruments of the 17th-19th Centuries: With Particular Reference to Astronomical, Nautical and Surveying Instruments

is based on work conducted by the author in the Department of Astronomy of the University of Leicester mainly during the period between January, 1986 and April, 1989.

All the work recorded in this thesis is original unless otherwise acknowledged in the text or by references.

None of the work has been submitted for another degree in this or any other University.

Signed: Date:

PAGE
MISSING
IN
ORIGINAL

We fail!
But screw your courage to the sticking place,
And we'll not fail.
Shakespeare. Macbeth.

Acknowledgements

In the preparation of such a work as this, many people are involved in a direct or indirect manner and without them, the research could not have been completed. I am indebted to each but particularly to: Dr. Allan Mills, who, as supervisor of the work, has provided his expertise in certain aspects of the work, made many suggestions and helpful comments on how to proceed and spent many hours with the tedious task of reading the manuscript and, my wife, Diane Brooks, who assisted in the bibliographic searching aspects of the research and carried out the final proof reading; her patience and sacrifices made while I have been working on this thesis can never be repaid.

The Inter-library Loan staff at University of Leicester have provided admirable service in hunting down the many difficult requests which I placed before them. Thanks are also due to the Astronomy Department technician, Ray McErlean, for making some of the required apparatus. Many museum curators have provided access to their collections, without which the majority of this research would not have been possible. Dr. Jon Darius, Rebecca Walker and Kevin Johnson of the Science Museum's Astronomy Dept. have had to endure the majority of my visits while the help provided by Dr. Paulo Brenni of the Istituto Salvemini, Florence during my visit there saved what would otherwise have been a wasted trip. Other curatorial staff members which provided assistance were: J.H. Andrews (Birmingham), Dr. James Bennett (Cambridge), Luke Brooke (Science Museum, Engineering), Dr. Anita McConnell (Science Museum, Surveying), Anne Marie de Narbonne (Observatoire de Paris), Sherri Steel (Newark Houses Museum, Leicester), Carole Stott and Dr. Rosalie Lopez (Royal Observatory, Greenwich), Martin Suggett (Liverpool), Dr. Gerrard Turner and John Simons (Oxford), Dr. Denys Vaughan (Science Museum, Time) and Jenny Wetton (Manchester).

The financial assistance of the Committee of Vice-Chancellors and Principals of the Universities of the United Kingdom in the form of an Overseas Research Award is acknowledged. Research grants from the Royal Society of London and from the Research Board of the University of Leicester permitted trips to Florence and Paris to study important instruments in the collections of the museums there. Encouragement and contributions to the cause by my father, Rev. Garland Brooks, my sister, Sheila Brooks and my brother, Dr. Garland Brooks made the work and life more tolerable.

THE PRECISION SCREW IN SCIENTIFIC INSTRUMENTS OF THE 17th-19th CENTURIES: WITH PARTICULAR REFERENCE TO ASTRONOMICAL, NAUTICAL AND SURVEYING INSTRUMENTS

ABSTRACT

The application and perfecting of the screw for scientific purposes has been studied for the period ca.1600-1900. An historical review of the means of producing screws--with special attention to precision screws--provides the basis for historical studies of the application of the screw to various types of micrometers and dividing engines. Developmental histories of micrometers--mainly astronomical--and dividing engines are also provided. Means of studying the profiles and accuracy of screws have been developed; the methods adopted employ techniques of period searching which are used for variable star studies. The Jurkevich-Swingler period searching technique (a modified Fourier transform method) has been used to study precision screws which may be fundamentally characterized as a periodic phenonena. Using the primary period of the screw thread (the pitch) an 'atlas' of screw profiles has been produced to determine the characteristics of the screws and to search for patterns in the profiles as a function of maker, period and use. The profiles and direct measurements of the micrometer screws have also provided estimates of the errors of the instruments. Summaries and graphical analysis of these data have permitted a search for relationships between some of the fundamental characteristics of various classes of screws. These studies have identified the most serious types of errors encountered in precision-screws. Estimates of the accuracy of the best machining capabilities and the accuracy of astronomical observations and scale dividing, etc. as a function of time are provided. These estimates are compared with contemporary estimates and modern estimates for other types of related mechanism.

Table of Contents

Statement ii
Signature Page iii
Acknowledgements iv
Abstract v
Table of Contents vi
List of Figures xi
List of Tables xv
Abbreviations and Conventions Employed xvi

CHAPTER 1: Philosophy and Objectives 1
1.1 Introduction 2
1.2 Approaches to the Study of the History of Science & Technology 2
1.2.1 Methods of Approach in this Thesis 4
1.3 Rationale and Objectives 5
1.4 Previous Research 7
1.4.1 Identifying Instrument Makers by Screw Thread Form 8
1.4.2 Studies of Screw Production 9
1.4.3 Studies of Instrumental Accuracy 10
CHAPTER 2: Historical Usage and Production of Screws 11
2.1 Terminology 11
2.1.1 The Handedness of Screws 11
2.1.2 The Screw Form 12
2.2 Technical Requirements for Various Types of Screws 12
2.3 Origins of the Screw 13
2.3.1 The Helix in Nature: 13
2.3.2 European Origins 14
2.3.2.1 Graeco-Roman times to the Middle Ages 14
2.3.2.2 The Renaissance to the Enlightenment 16
2.3.2.3 Application of screws in science 18
2.3.3 Chinese Origins 20
2.3.4 Inuit Origins 21
2.4 Methods of Screw and Nut Production 23
2.4.1 Hand Production Tools 23
2.4.1.1 Tempering of Cutting Tools 25
2.4.2 Techniques in the Early 18th Century 25
2.4.3 Early Lathes for Screw Cutting 28
2.4.4 18th/19th Century Methods of Screw Production 31
2.4.4.1 Maudslay's revolution in lathe design 32
2.4.4.2 Mechanization of screw making 33
2.5 Standardization of Screw Threads 35
2.5.1 The Royal Microscopical Society Thread 36
2.5.2 The Royal Astronomical Society Thread 36
2.5.3 The Photographic Society of Great Britain's Thread for Optics 37
2.6 Techniques Applicable to Create 'Precision' Screws 37
2.6.1 Thread Grinding Techniques 38
2.6.2 Description of Cutting Tools and Their Production 38
2.6.2.1 Diamonds for cutting screw threads 39
2.6.3 Methods of Generating Precision Screws 41
2.6.3.1 Ramsden's method for making precision screws 42
2.6.4 Early 19th Century Attempts at Making an Original Screw 43
2.6.4.1 Maudslay's screw experiments 44
2.6.4.2 Robinson's precision lead screw 46
2.6.4.3 Barton's precision screws 46
2.6.4.4 Allan's method 47
2.6.4.5 Ross' modification to Allan's method 47
2.6.4.6 Clement's procedures for generating original screws 48
2.6.4.7 Walsh's thread rolling method 48
2.6.4.8 Donkin's curved correction guide 49

2.6.4.9 Precision screws for dies 49
2.6.4.10 Rutherfurd's method of making a screw 50
2.6.4.11 Rogers' contributions 51
2.6.4.12 Brashear's observations 54
2.6.4.13 Rowland's perforated grinding nuts 54

Chapter 3: Development of Screw Micrometers **56**
3.1 Precursors to the Micrometer **56**
3.1.1 Introduction 56
3.1.2 Early Use of Screws on Scientific Instruments 57
3.2 17th Century Micrometers **59**
3.2.1 Brunn/Treschler Micrometer (1609/1619) 59
3.2.2 Heintz Circumferentor (1631) and Mögling Sundial (1621-7) 60
3.2.3 the Gascoigne (1639) and Townley (1667) Screw Micrometers 61
3.2.4 Hevelius Micrometer Devices (1644) 64
3.2.5 Ocular Micrometers 66
3.2.6 Auzout (1666) and the French developments 68
3.2.6.1 On calibration Errors 69
3.2.7 A Proliferation of Micrometers 72
3.2.8 Hooke's Scale Micrometer 73
3.3 18th Century Micrometers **76**
3.3.1 Early Filar Micrometers 76
3.3.2 Discovery of a Calibration Error 78
3.3.2.1 The parallax effect 78
3.3.2.1 Focal plane error 80
3.3.3 LaHire's Glass Grid Micrometer 81
3.3.4 Application to Scale Reading and Other Continental Micrometers 82
3.3.4.1 Louville's scale micrometers 83
3.3.4.2 Graham's scale micrometers 84
3.3.4.3 Marinoni's scale micrometers 85
3.3.4.4 Ramsden's scale micrometers 85
3.3.5 Heliometers 89
3.3.5.1 Bouguer's heliometer 89
3.3.5.2 The English contenders 90
3.3.6 Filar Micrometers of British Design 92
3.3.6.1 Bradley/Graham design and Bradley's observing techniques 92
3.3.6.2 Marinoni's filar micrometers 94
3.3.6.3 Brander's micrometers 95
3.3.6.4 Smeaton's astronomical micrometer 96
3.3.6.5 Ramsden's astronomical micrometers 98
3.3.6.6 Herschel's micrometers 100
3.3.7 Optical Micrometers 103
3.3.7.1 Brander's grid micrometers 103
3.3.7.2 Watt's optical micrometers 105
3.3.8 Miscellaneous Micrometers/Instruments Employing Micrometers 107
3.3.8.1 Micrometers on nautical instruments 107
3.3.8.2 Smeaton's pyrometer 107
3.4 19th Century Micrometers **109**
3.4.1 Astronomical Micrometers 109
3.4.1.1 Troughton's bifilar micrometer 110
3.4.1.2 Scale micrometers in the 19th century 112
3.4.1.3 Fraunhofer's position micrometer 113
3.4.1.4 Measuring Position Angles with Filar or Bifilar Micrometers 114
3.4.1.5 Micrometers for Measuring Large Separations 114
3.4.1.6 Warner & Swasey's Micrometers 117
3.4.1.7 Devices to to eliminate errors--Repsold's contributions 118
3.4.1.8 Repsold's "Impersonal Micrometer" 119
3.4.2 Heliometers 119
3.4.3 Dynameters 12(

3.4.3.1 Origins--Nairne and Jones 120
3.4.3.2 Ramsden's dynameter 121
3.4.3.3 Dollond's dynameter 122
3.4.3.4 Divided lens micrometer--Airy's 123
3.4.4 Other Micrometers 124
3.4.4.1 Fraunhofer's glass micrometers 124
3.4.4.2 Optical micrometers: 124
Cavallo's, Coventry's, Fraunhofer's and Baily's circular, Nobert's, Walker's and Wollaston's
3.5 Bench Micrometers and Comparitors 127
3.6 Micrometers used with Microscopes 129
3.7 Fabrication of Fiducial Wires 130

Chapter 4: DIVIDING AND RULING ENGINES 134
4.1 Mechanical Basis of Instrument Division and Ruling 134
4.1.1 Hooke's Scale Division Technique 134
4.1.2 Methods Employing Beam Compasses 136
4.2 Dividing Engines of the 18th Century 136
4.2.1 Hindley's Dividing Engine 138
4.2.1.1 Smeaton's Proposed Improvements 139
4.2.2 Brander's Dividing Engines 140
4.2.3 Chaulnes' Dividing Engines 142
4.2.4 Ramsden's Dividing Engines 147
4.2.5 Troughton's Circular Dividing Engine 150
4.2.5.1 Troughton's Original Dividing Technique 151
4.2.6 Other English Dividing Engines of the 18th Century 152
4.2.6.1 Watt's dividing apparatus 153
4.2.6.2 Harrison/Atherton patent 153
4.2.7 Other French Dividing Engines of the 18th Century 154
4.3 Dividing Engines of the 19th Century 155
4.3.1 Some Early but Insignificant Contributions 155
4.3.1.1 Hornblower's device 155
4.3.1.2 Cavendish's proposal for original dividing: 156
4.3.2 Allan's Technique of Making the Teeth on a Dividing Engine 156
4.3.3 Kater's Technique 157
4.3.4 Gambey's Dividing Engine 158
4.3.5 Donkin's Dividing Engine 159
4.3.6 The Dividing Engine and Dividing Method of Andrew Ross 159
4.3.7 Everest's Method 161
4.3.8 Some Errors Appear 162
4.3.9 Simm's Self-acting Dividing Engine 163
4.4 Discovery and Production of Spectral Gratings 164
4.4.1 Fraunhofer's Early Experiments 165
4.4.2 Barton's Contributions 166
4.4.3 Nobert's Dividing Expertise 168
4.4.4 Waterhouse Ruling Engine 171
4.4.5 Rutherfurd's, Rowland's and Other Contributions in the U.S. 171
4.4.6 Mallock's Ruling Engine 172
4.4.7 Hilger's 'Blythswood' Ruling Engine 173
4.4.8 Smith's ruling device 175
4.5 Note on Inlaying of Silver Scales 176
4.6 Summary 176

CHAPTER 5: Measurements of Screw Profiles, the Screws of Micrometers and Dividing Engines 178
5.1 Acquisition of Thread Samples 178
5.1.1 Choice of Samples--Rationale 180
5.1.2 Identification 181
5.1.3 Sample Preparation 181
5.1.4 Moulding and Casting Techniques 182
5.1.5 Casts 182

5.2 Shadowgraphs and Digitized Profiles 183
5.2.1 Preparation and Equipment 184
5.2.2 Exposure of the Shadowgraphs 185
5.2.3 Shadowgraph Measurements--Direct Measurement 186
5.2.4 Digitized Profiles and Digitizing Precision 187
5.2.4.1 Digitizing procedures 187
5.2.4.2 Production of digitized shadowgraphs 188
5.2.4.3 Plotting digitized profiles 188
5.2.5 Measuring the Digitized Profiles 189
5.2.5.1 Extracting instrumental errors 191
5.2.5.2 Correcting for the digitizing error 192
5.3 Micrometric Measurements 193
5.3.1 Types and Causes of Non-Uniformity in Micrometric Screws 193
5.3.1.1 Non-periodic errors 193
5.3.1.2 Periodic errors 196
5.3.2 Selection and Calibration of the Dial Indicator 198
5.3.3 Data Handling and Reduction 200

Chapter 6: Analysis of the Results 202
6.1 Introduction 202
6.2 Interpretation of the Digitized Profiles of Appendix B 207
6.3 Summary and Comparison of Results 209
6.4 Graphic Comparisons (data from the shadowgraphs) 220
6.4.1 Date vs. Pitch 220
6.4.2 Date vs. Diameter 221
6.4.3 Date vs. Flank Angle 222
6.4.4 Date vs. Error (% of Pitch) 223
6.4.5 Pitch vs. Error (% of Pitch) 224
6.4.6 Date vs. Error (mm) and Date vs. Log Error (mm) 225
6.4.7 Date vs. Aspect Ratio (A/R) and Pitch (mm) vs. Aspect Ratio (A/R) 226
6.4.8 Aspect Ratio (A/R) vs. Truncations (Tc & Tr) and Tc vs. Tr 227
6.4.9 Combined Precision Screw Results 228
6.5 Dial Indicator Results 229
6.6 Interpretation of the Jurkevich-Swingler Periodograms 230
6.6.1 Alias Frequencies 231
6.6.2 Periodograms Generated from the Dial Indicator Data 232
6.7 Periodograms as a Means of Studying Dividing Engine Ruling Techniques 233
6.7.1 Edward Troughton's Circular Dividing Engine (1793) 233
6.7.2 The Standard Meters of van Swinden and Aeneae (ca.1799) 234
6.7.3 Roger's Cornell Screw and van Woerd's Waltham Screw (1882) 235
6.7.4 Watts Circular Dividing Engine (1904) 235
6.8 Conclusions 236

Chapter 7: Significance of the Results 237
7.1 Some Problems Dependent on Precision Screws 237
7.1.1 Consequences of Bradley's Search for Stellar Parallax 238
7.1.2 Bird's Micrometers 238
7.1.3 Ramsden's Micrometers 239
7.1.4 Herschel's Micrometers 240
7.1.5 Troughton Micrometers and the Impact of Glass Making Technology 240
7.1.6 Fraunhofer's Göttingen Heliometer 242
7.1.7 Final Observations of finding the Parallax and Instrumental Errors 243
7.2 Placing These Research Results in Perspective with Final Observations 244

Bibliography 248

Appendix A: Results of Maddock's Research 279
Appendix B: Computer Programs
Jurk.for 282
LSQ.for 283
Profil1.for 287
Sample prompts requested by Profil1.exe 292
Calbrat.for 293
Appendix C: List of Dividing and Ruling Engines 295
Appendix D: List of U.K. Screw Patents to 1852 298
Appendix E: The Screw Profiles and Associated Graphs 302
Back Pocket: Relevant papers by the author and Appendix E overlays

List of Figures

Figure No.	Short Description	On or Facing Page
2.1.1	Definition of terms used in this thesis	12
2.3.1a/b	Hero's dioptra (reconstruction) and screw cutter	14
2.3.2	Piccolpasso's medieval chaser for making threads on pottery	14
2.3.3	Hunter's (1781) configurations for his differential screw	19
2.3.4	"Difference" Screws	20
2.4.1	Examples of taps, screw-boxes and screw-stocks	23
2.4.2	Illustration of a screw lathe with lead screw and cross slide	28
2.4.3	The screw lathe with lead screw illustrated by Mertz	28
2.4.4	Besson's treadle driven lathe with lead screw and cross-slide	29
2.4.5	Plumier's (1701) mandrel screw lathe for watch makers	29
2.4.6	Wetschgi's small screw 'lathe' (e. 18th c)	30
2.4.7	The screw lathe with colinear lead screw figured by 'IBN' (1753)	30
2.4.8	Healy's screw lathe (1804) with colinear lead screw	30
2.4.9a/b	Thiout's screw lathes illustrated in his 1741 work on clockmaking	31
2.4.10a/b	Two of Nartov's screw lathes	32
2.4.11	Samuel Varley's scheme (ca.1820) for copying master screws	33
2.4.12	A German instrument making lathe with thread followers	33
2.4.13	Maudslay's screw lathe with micrometer adjusted cross-slide	33
2.6.1	Kier's and Barton's Diamond points for screw cutting	39
2.6.2	Barton's 'Atometer' (1805) with differential screws	40
2.6.3	The fusee engine made by leLievre employing an inclined plane	41
2.6.4a	Ramsden's screw lathes for making his circular dividing engines	41
2.6.4b	Ramsden's screw lathes for making his circular dividing engines	42
2.6.5	Ramsden's screw lathe for making the screw of his linear dividing engine	42
2.6.6a	Maudslay's small screw lathe (ca.1800)	44
2.6.6b	Maudslay's side bar to correct errors of pitch of a lead screw	45
2.6.7	James Allan's screw originating machine (1816)	47
2.6.8	Clement's screw originating machine	48
2.6.9	Walsh's thread rolling technique for producing original screws	48
2.6.10	The lathe made for Rogers (1891)	53
2.6.11a	Four piece grinding nut employed by Rowland on his ruling engine	54
2.6.11b	Rowland's two-piece, free floating nut of cast iron	54
3.1.1	Heron's dioptra--reconstructed diagram	57
3.1.2	'Family tree' of micrometers of the 17th c	57
3.1.3	Two of Tycho instruments with screw adjustment mechanisms	58
3.2.1a	The Brunn/Treschler micrometer device of 1609/1619	59
3.2.1b	An example of Treschler's gun-sights with fine adjustment	59
3.2.2	The circumferentor of Heintz (1631)	60
3.2.3	Gascoigne's illustration of a telescope's optical path micrometer	62
3.2.4	Townley's micrometer as illustrated by Hooke (1667)	63
3.2.5	The components of Hevelius' micrometric devices	65
3.2.6	Auzout's (1666) micrometer	69
3.2.7/8/9	Cherubin's (1671), Petit's (1667) and Romer's micrometers (1672)	72
3.2.10a	Screw and index mechanism of Hooke's scale micrometer (1676)	73
3.2.10b	Application of the above mechanism to Hooke's zenith sector	73
3.2.11a/b	Flamsteed's 7ft quadrant (1676) with Tompion's fine mechanism	74
3.2.12	Sharp's mural arc (1689) made for Flamsteed	75
3.3.1a	Micrometers illustrated by Balthasar (1710)	77
3.3.1b	Micrometer (ca.1700) in the Science Museum, London	77
3.3.2a	Micrometer by Rowley (ca.1703)	77
3.3.2b	An unsigned micrometer at Christ Church, Oxford (ca.1700)	77
3.3.3/4	LeFevre's (1705) and Bion's micrometers (1709)	78
3.3.5a	LaHire's proportional compasses for micrometric observations	78
3.3.5b	LaHire's Calibration Card Pattern	79
3.3.6	Focal plane errors in filar micrometers	81
3.3.7	Rowley's sextant made for Trinity College (ca.1707)	82
3.3.8	Style of micrometer developed for quadrants by Louville	83

3.3.9	Klein's quadrant with micrometer employing gears (ca.1746)	84
3.3.10	Illustration of scales and micrometers on Graham and Bird quadrants	85
3.3.11	Marinoni's scale micrometer (ca.1740)	85
3.3.12a	Ramsden's large theodolite made for General Roy	86
3.3.12b	Ramsden's scale micrometer for Roy's baseline standard.	86
3.3.12c	Eyepiece micrometer of Roy's Geodetic theodolite	86
3.3.12d	Ramsden's scale micrometer from Roy's theodolite (1790)	86
3.3.12e	Troughton's scale micrometer	86
3.3.13	Cary's transit circle (1793) made for Wollaston	87
3.3.14	Ramsden's micrometer arrangement for Mudge's zenith sector	88
3.3.15	Illustrations of Bouguer's heliometer (1748)	89
3.3.16	Savery's heliometers as presented to the Royal Society	90
3.3.17	Two forms of heliometer made by Dollond	92
3.3.18	General form of filar micrometer made by Graham and Bird	93
3.3.19a	Marinoni's large micrometer	94
3.3.19b/c	Marinoni's small micrometer and position micrometer	95
3.3.20a	Brander's scale micrometers and filar micrometer (ca.1770)	96
3.3.21	Two views of Smeaton's micrometer (ca.1770)	97
3.3.22a	Ramsden's micrometers (1777) for a reflecting telescope	98
3.3.22b	Ramsden's micrometer (1777) with divided eye-lens	99
3.3.23	Ramsden's filar micrometer for an equatorial refractor	99
3.3.24	LeMonnier's filar micrometer for his transit telescope	99
3.3.25	Two of the micrometers used by Herschel	100
3.3.26a	Herschel's position angle micrometer (1781) and lamp micrometer	102
3.3.27	Patterns of grid lines used by Brander	104
3.3.28a/b/c	Brander's micrometer distance measurer, 'rangefinders' and level	104
3.3.29	Watt's fiducial pattern in his 'stadiometer'	105
3.3.30	Watt's prism micrometer	106
3.3.31a	Fouchy's octant (1723) with curved fiducial	107
3.3.31b	Ramsden's sextant (ca.1783) with screw micrometer	107
3.3.32	Smeaton's pyrometer (1753)	107
3.4.1a/b	Troughton's design for a bifilar micrometer and scale micrometer	110
3.4.2a/b	Biot's filar micrometer (1803) and micrometer of 1810	110
3.4.3a	Troughton's form of bearing surface for a micrometer screw	111
3.4.3b	Repsold's form of bearing surface for a micrometer screw	111
3.4.4a	Vogler's micrometer with double springs for backlash control	112
3.4.4b	Huneaus' micrometer with single coil spring for backlash control	112
3.4.5a	Fraunhofer's filar micrometer (ca.1820)	113
3.4.5b	The most advanced of Fraunhofer's micrometers	113
3.4.6	Clark's filar micrometer made for the Washburn Observatory	115
3.4.7	Grubb's 'Duplex' micrometer (ca.1870)	115
3.4.8	Burton/Grubb ghost micrometer (1880)	116
3.4.9a	Warner & Swasey's micrometer for the 40in Yerkes refractor	116
3.4.9b	Warner & Swasey filar/position angle micrometer (ca.1880-5)	117
3.4.9c	US Naval Observatory's position micrometer by Warner & Swasey	117
3.4.10a	Filar micrometer by Browning (ca. 1875)	118
3.4.10b	Repsold's Cape Observatory micrometer (ca.1878)	118
3.4.11a	Repsold's scale micrometer (mid-19th c)	119
3.4.11b	Cape Observatory's impersonal micrometer by Repsold	119
3.4.12a	Wellman's prism micrometer (1789)	120
3.4.12b	Dollond's divided object glass micrometer with vernier	120
3.4.13a	Fraunhofer's heliometer (ca.1825) made for the Göttingen Obs.	120
3.4.13b	Repsold's 7.5in heliometer made for the Oxford University Obs.	120
3.4.14	A Ramsden type dynameter made by Mathew Berge (ca.1800-20)	121
3.4.15	Thomas Jones' dynameter (ca.1820)	121
3.4.16	Dollond's dynameter design (ca.1820)	121
3.4.17	Airy's divided eye glass micrometer (ca.1840)	123
3.4.18	Fraunhofer's circular and 'net' micrometers (ca.1810)	123
3.4.19	Wollaston's 'wire' micrometer (1813)	123
3.5.1	Chaulnes' two-legged 'spherometer' (ca.1767)	127

3.5.2	Watt's bench micrometer which is in the Science Museum	127
3.5.3	Siemen's English/Metric micrometer (ca. 1880)	127
3.5.4	Burton's 'atometer' (1805)	128
3.5.5	A comparitor by Whitworth (1869)	128
3.5.6	A comparitor by the Hartford, CT. firm of Pratt & Whitney	128
3.5.7	A comparitor by Cooke of York (1894)	128
3.6.1	Gray's barometer with microscope micrometer (1698)	129
3.6.2	Römer's transit (1704) with the scale reading micrometers	129
3.6.3	Hertel's microscope with two-axis mechanical stage (ca.1720)	129
3.6.4	Martin's pocket and universal microscopes with micrometers	130
3.6.5	Brander's pocket microscope (ca.1760)	130
3.6.6a/b	Adam's Sr. 'Prince of Wales' microscope and 'George III' microscope	130
3.6.7	Chaulnes' microscope with micrometers	130
3.7.1	Position angle errors and Dawes' method of correction	133
4.1.1a/b	Hooke's 4 foot quadrant with screw limb (1674) and 10 foot quadrant	134
4.2.1	An 18th century fusee engine used by clockmakers	136
4.2.2	Hindley's worm with circular form	139
4.2.3	Errors in spacing of lines on 3 glass micrometers ruled by Brander	140
4.2.4	Brander's linear dividing apparatus and scribing apparatus	140
4.2.5	Two views of Brander's circular dividing engine	141
4.2.6	Duc de Chaulnes' circular dividing engine (1762)	142
4.2.7	Chaulnes' circular dividing engine designed in 1765	143
4.2.8	Chaulnes' linear dividing engine (1768)	144
4.2.9a	Chaulnes' circular dividing engine (1768)	144
4.2.9b	Illustration of the dividing technique employed	144
4.2.10	Detail of Chaulnes' microscope micrometer	145
4.2.11a/b	Ramsden's 1774-5 dividing engine (1777) and current condition	147
4.2.11c	Details of the mounting of the worm and engraver frame	147
4.2.12	Ramsden's linear dividing engine	148
4.2.13	John Troughton's (1778) circular dividing engine	150
4.2.14a	Edward Troughton's circular dividing engine (1793)	151
4.2.14b	Mountings for Troughton's micrometer microscopes	151
4.3.1	Cavendish's method of using micrometers in place of a beam compass	156
4.3.2	Henry Kater's method for detecting errors with the micrometers	157
4.3.3a/b	Andrew Ross' circular dividing engine (1830) and Cross-sectional view	160
4.3.4	Everest's method of copying a circular scale	162
4.3.5	Errors of the Armagh mural circle by Jones	163
4.3.6	Details of William Simms' automatic dividing engine (1843)	164
4.4.1	Ruling engine (1820-22, SML-34) for ruling Barton's buttons	166
4.4.2	Nobert's ruling engine on which he ruled gratings for Ångstrom	168
4.4.3/4	Waterhouse ruling engine and Rutherfurd's ruling engine	171
4.4.5	Mallock's ruling engine (1879/81) made by Munro	172
4.4.6a/b	Blythswood ruling engine made by Adam Hilger in 1888	173,174
4.4.7	Smith's (1898) simple apparatus for ruling lines on glass	175
4.5.1	Inlaying of silver scales	176
5.1.1	The form used to record information on the study samples	180
5.2.1	The screw thread projector made by Hartness (1920)	183
5.2.2a/b	Shadowgrams and profiles of the ILO zenith telescope micrometer	184
5.2.2c	Error curves for the ILO zenith telescope micrometer	184
5.2.3	Baty screw thread projector	185
5.2.4a	The shadowgram of the Barton ruling engine screw	185
5.2.4b	The effect of a misaligned thread	185
5.2.5	Form 03 used to record the measurements	186
5.2.6	Lines drawn to make the measurements of flank angles	186
5.2.7	Profiles resulting from repeated digitizing of a single thread	187
5.2.8	The digitized thread profile for Troughton's eyepiece micrometer	189
5.2.9	Measuring the parameters of the digitized profile	190
5.2.10	Comparison of results of pitch and flank angles of screw samples	191
5.2.11	Plot used to determine the correction for digitizing error	192
5.3.1	An experiment to test wrapping ruled paper around a screw blank	194
5.3.2	Errors due to worn micrometer screw thread	197

5.3.3	Capacitance comparitor test rig	199
5.3.4	Part of a calibration curve of the Mitutoya dial indicator	200
5.3.5	Calibration curves for the Mitutoya dial indicator	201
5.3.6a	Measurements of a scale micrometers from Langlois' 6ft sextant	201
5.3.6b	Same data fitted with a 3rd degree polynomial	201
5.3.6c/d	Data after subtracting the 2nd and 3rd degree polynomial	201
5.3.7	Flow chart showing the steps required to produce the error graphs	201
6.2.1a	Wear on a Ramsden filar micrometer screw	207
6.2.1b	Wear on the crest and root of an adjusting screw by Chaulnes	207
6.2.1c	Wear on the nut (above) and screw of an octant index clamp	207
6.2.2	Maudslay screws showing 'good' or well defined thread roots	208
6.2.3	Tool markings on a Ramsden (left) and Sisson leveling screws	208
6.2.4a	Broad trough on a Dollond micrometer screw (ca.1780)	208
6.2.4b	Fine pitched screw of Herschel micrometer (ca.1780)	208
6.2.4c	Bird scale micrometer screw (1772) of relatively course pitch	208
6.2.5	Effect of the curvature of dividing engine wheels	209
6.2.6a	Effect of a tapered thread on an eyepiece	209
6.2.6b	Poorly finished thread of a short filter mounting thread	209
6.4.1a/b	Date vs. Pitch(mm)	220
6.4.2a/b	Date vs. Diameter(mm)	221
6.4.3a/b	Date vs. Flank Angle(°)	222
6.4.4a/b	Date vs. Error (% of Pitch)	223
6.4.5a/b	Pitch(mm) vs. Error (% of Pitch)	224
6.4.6a/b	Date vs. Error(mm)	225
6.4.7a/b	Date vs. Log Error(mm)	225
6.4.8a/b	Date vs. Aspect Ratio (A/R)	226
6.4.9a/b	Pitch(mm) vs. Aspect Ratio	226
6.4.10a/b	A/R vs. Truncation (Tc & Tr)	227
6.4.11a/b	Tc vs. Tr	227
6.4.12	Combined results for Precision (micrometer) screws and Adjusting Focusing and Leveling screws	
6.4.12a	Diameter(mm) vs. Error (% of Pitch)	228
6.4.12b	Pitch(mm) vs. Log Error(mm)	228
6.4.12c	Date vs. Log Error(mm)	228
6.5.1	Results of the dial indicator measurements of micrometers	229
6.5.2	Comparison of the shadowgraph and dial indicator errors	229
6.5.3	Error(mm) vs. date for the scale and bench micrometers	229
6.6.1	Periodograms for a single period and for two periods	231
6.6.2	Periodograms for a filar micrometer screw by Heath & Wing	231
6.6.3	Same as 6.6.2 but for the nut	231
6.6.4	Periodogram for the Mitutoya dial indicator	232
6.6.5	Periodograms for 3 micrometer screws	232
6.7.1	Errors for Troughton's circular dividing engine (1793)	233
6.7.2	Smoothed (5 points grouped) for Troughton's circular dividing engine	233
6.7.3	Periodograms for Troughton's circular dividing engine	233
6.7.4a/b	Errors for the van Swinden and Aeneae standard meters	234
6.7.5a/b	Periodograms for the van Swinden and Aeneae standard meters	235
6.7.6a	Errors determined by Rogers (1884) for the Cornell screw	235
6.7.6b	Periodogram of the errors of the Cornell screw	235
6.7.6c	Errors determined by Rogers for van Woerd's screw	235
6.7.7a	Errors of a scale divided on Watts circular dividing engine	236
6.7.7b	Periodogram of the errors in the above circular scale	236
7.1.1	Chapman's estimate of scale accuracies for instruments	239
7.1.2	Errors of the Göttingen heliometer	242
7.1.3	Chapman's instrumental accuracy compared with current results	243
7.2.1	Improvement of efficiency of stationary steam power plants	244

List of Tables

Table No	Table Description	Page
3.1	Malvasia's solar observations	68
4.1	Hooke's 4ft quadrant	135
5.1	Museum codes	180
5.2	Thread generating experiment	195
6.1	List of instruments studied	202
6.2	Results of measurements of samples	
6.2a	Filar micrometers	210
6.2b	Scale micrometers	212
6.2c	Bench micrometers/comparitors	213
6.2d	Dividing engines	214
6.2e	Adjusting screws	215
6.2f	Leveling screws	216
6.2g	Focus screws	216
6.2h	Eyepieces	217
6.2i	Tubes	217
6.2j	Tools	218
6.2.k	Gauges	219
6.2l	Binding and miscellaneous screws	219
7.1	Bird's micrometers	239

Abbreviations and Conventions Employed

approx.	approximately
≈	approximately
c	century
ca.	circa
cm	centimeter
DI	dial indicator
ft	foot/feet
ID	inside diameter
in	inch
NA	not applicable or not available
NS; N/S	not signed
OD	outside diameter
s	second of time
SG	shadowgraph
"	second of arc
'	minute of arc
°	degree of arc or of temperature
&	used in the name of a firm, e.g. Troughton & Simms, to differentiate from a list. e.g. Troughton & Simms and Ramsden.
§	Section

CHAPTER 1

Philosophy and Objectives

1.1 Introduction:

The most common of all mechanical devices is the screw. Our civilization is held together by these simple contrivances; indeed much of our science--particularly physical science--has its foundations based on observations and theories which demanded the use of precision screws for the measurement of a wide variety of phenomena.[1] Although the screw appeared in antiquity, the use of the screw as a measuring device did not become a practical possibility before the 17th century. As the means of production of the screw thread improved, the variety and frequency of use increased to the point where most astronomical and nautical instruments of the 19th century relied upon a screw for their precision. This reliance may have been direct as in the case of micrometers for position measurement, or may have been indirect, as was the case for scales divided with dividing engines. Precision screws continue to be employed, of course, but with the advent of stepping motors, shaft encoders and similar products the future use of precision screws is limited. Indeed, the 'golden era of the screw age' may be nearing an end as the variety and versatility of glues increasingly impinges on the use of mechanical fasteners.

Before proceeding, the distinction between binding, adjusting and micrometric screws should be clearly made. Binding screws, the most common by far, are intended to mechanically hold two or more components rigidly together and thus must be able to withstand the stress from mechanical loading. Adjusting screws are intended to permit controlled motion and adjustment of the relation between components: smoothness of operation is the critical factor while mechanical loading is generally not of prime concern. Micrometric screws are adjusting screws with the added requirement of having accurate pitch, which will then allow position to be determined by the motion of the screw.

Parallel with and bearing on the advancement of screw technology, were developments in mathematics, mechanics, astronomy, geographic exploration, etc. Though the advancements of the 18th century were made by practical minded mechanics, mathematical and mechanical theory gradually guided the direction in the 19th century towards smaller, more efficient, but stronger screws to meet increasingly stringent

---

[1] In this thesis the term 'precision' should be interpreted as being 'accurate for the time' since what would have been a screw accurate enough for micrometric measurements in the 17th century might well not meet specifications for an ordinary machine screw today.

standards. Yet especially for the most precise screws, knowledge of optimum form and best metallurgical information could not replace a practical minded machinist given the job of producing a perfect inclined plane wrapped around a shaft. As a result, the advancement of the precision screw was erratic, and documentation of its improvement has been equally erratic and sparse. Fortunately, a large number of precision screws have survived in good condition and have served as the 'documentary' evidence on which the physical aspect of this research has been based.

The 18^{th} century impetus for improvements to the screw thread seems to have been largely linked with demand for better navigational methods. The Board of Longitude Act of 1714 encouraged a great many attempts to improve nautical instruments, and a link between advances in marine chronometer design and screw making will be proposed. Once the navigational problem was solved, a period of several decades saw the adoption of precision screws in a variety of applications and on a wide range of nautical and surveying instruments. The 19^{th} century demand for improvements came directly from business interests and were profit driven; the driving force of the 18^{th} century was indirectly profit driven in that, if the Board of Longitude connection can be substantiated the improvements were motivated by the need to help commercial, as well as naval, ships more safely cruise the oceans and by the most direct routes.

1.2 Approaches to the Study of the History of Science and Technology:

The study of history of technology was popular for a time in the 19^{th} century as evidenced by the works of John Farey, Samuel Smiles and Thomas Ewbank (Cardwell: 1968, p.112) but waned to a low level until the second half of the 20^{th} century. Rapid advances in technology seem to spur an interest in the roots of those advances in an attempt to make comparisons and draw parallels with the direction and stresses which result within society. Whatever the cause, we in the late 1980's are certainly in a period when interest has been aroused; the interest in the scientific instruments has never been greater.

John Olmsted criticized the studies of history of science carried out by scientists-turned-historians. In his view many failed to appreciate and to follow historical method described as using the essential tools, i.e. systematic bibliography, internal criticism by contemporaries of the original scientists, external criticism by the researcher, and historiography--which he defined as "the logical organization of historical data and writing of history" (Olmsted: 1949, p.213). However, it is becoming increasingly difficult to research the developments of science and its related technology, particularly of the 19^{th} and 20^{th} centuries, without specific training in these disciplines. The complexities of the subject matter require a sophisticated knowledge of the basic science. Thus one might suggest that classically-trained historians will have an increasingly difficult task dealing with science from the 19^{th} century as non-professional scientists became increasingly rare (I will not use the term amateur here, since in its proper sense, amateur refers to a lover of something and surely all professional scientists are amateurs). It is proposed that the tables have been turned since Olmsted's admonition--without a good fundamental knowledge of science and/or technology an historian may be at a distinct disadvantage in his ability to recognize important elements in the advancement of a scientific topic or the development of a technology. The scientist and engineer have the advantage as long as they are aware of Olmsted's prescription for good historical research and are prepared to follow his prescription. Hopefully, his four elements will be recognized in this work.

Also opposing Olmsted's contention, G. L'E. Turner in his 1972 Quekett Lecture, (1972: p.172), criticized historians of science thus:

> Some historians of science like to describe themselves as intellectual historians, seeing as their proper study the development of concepts in man's attempt to explain the material universe. I do not, of course, dispute the value of this study. What is unfortunate is the imbalance that I see in the history of science brought about through the failure to recognize the potential of the study of scientific instruments, which are, after all, ideas made brass. To take an example: the author of a recent book on the history of spectroscopy deliberately omits any consideration of the instruments concerned. This omission cripples the book because, particularly in this subject, the development of the concepts is so intimately connected with the instrumentation. Another case where the development of theory cannot be considered apart from the design, manufacture and use of instruments, is in the study of the 18^{th} century 'electricians', as they were called. Here the conceptual framework had to be teased out empirically from extensive experiments.

In a study of micrometers one cannot possibly do justice without a detailed and careful inspection of existing instruments to determine their accuracy since the obtainable accuracy at any period defined the scientific problems which could be tackled with success.

Cardwell (p.113) proposed that there were three approaches to the study of the history of technology: study and preservation of the objects (antiquarian approach), study of the economic impact of technology (economic history) and, a relatively new approach at that time, a combination of the two (industrial archaeology). In the study of the technology of science, it has been popular to study the writings and results of scientific experiments (what I might term the intellectual approach), but detailed 'hands on' study of the instrumentation itself has too often been placed in the background, i.e. the antiquarian approach has been neglected. This may reflect unfamiliarity and unease with technical devices on the part of historians of science; or perhaps it is the product of a 20^{th} century 'school' of history of science biased against or skeptical of the accuracy of such evidence. This is reminiscent of the manner in which Aristotelians' carried on their philosophical debates, an approach not broken down until the revolution created by the philosophy of science as expounded by Bacon and Galileo. Whatever the cause of the 'hands-off' approach to the study of scientific instruments it is a regrettable attitude, for a thorough knowledge of the design, application and limitations of instruments should lead to a better understanding of why science developed in particular directions and at particular times. Turner (1967 III: p.272) noted: "It may not generally be realized that our scientific and technical museums can be a source of new historical information. The collections can fill a much more important role than that of providing exemplars of particular types of instruments or apparatus associated with an eminent scientist....Historians have long used manuscripts as their raw material, and instruments are similar original documents and should be preserved and catalogued as such....I have in mind the plotting of magnetic declination against date from the study of sundials, and the transmission of astronomical knowledge through Europe from the study of astrolabes." Fortunately, a growing number of researchers are adopting methods to balance the old approaches. These include Chapman's 1976 study of scale dividing on astrolabes and quadrants, Mills on heliostats, King and Milburn on orreries, Cotter on sextants, McConnell on compass needles, Goodison on barometers, etc. (Darius: 1987, p.1).

1.2.1 Methods of Approach in This Thesis:

The aim of this thesis admits to study by Cardwell's first method. Although screws had an immense economic impact, this will not be considered. Suffice to say that the development of accurate lead screws for lathes and high-precision screws for dividing engines, were important factors launching Britain ahead of the competition in instrument making in the period ca.1765-1825, and in the tool making trade from ca.1800-50. The latter was, of course, an important factor in Britain's dominance of manufacturing throughout the 19th century. To Cardwell's three techniques, we may perhaps add a fourth--that of forensic technology, of which there have been a few previous examples. Although perhaps an extension of the antiquarian approach, it has some distinctiveness since it results in knowledge which cannot be gleaned from casual perusal of artifacts although it must rely upon the successful application of the antiquarian approach for preservation of examples of technology. The forensic technique applies modern technology to obtain information about the procedures used in the artifact's production. Allan Chapman's PhD thesis **Dividing the Circle** (1976) is an example of this method and another is that of dating instruments by metallurgical analysis. The present thesis carries the approach still further by the application of computers to carry out mathematical analysis which previously would have been impossible. A relative lack of documentary evidence must be countered by careful consideration of the remaining artifacts and successful application of forensic technology.

1.3 Rationale and Objectives:

Willem Hackman (1985, p.89) notes the two traditions in instrument development identified by the late Derek de Solla Price. These are: "firstly, describing the world by scientific models, and secondly, making and quantifying instrumental revelations." Examples of the former tradition are astrolabes, armillary spheres or orreries, and of the latter, the use of the telescope or microscope to describe natural phenomena beyond the range of human sight. However, a third tradition may be considered as having developed on the shirt tails of mathematical science--the deliberate design of an instrument to attempt observation of a theoretically predicted phenomenon. An example in this category would be the zenith telescope of Molyneaux and Bradley to observe stellar parallax in 1725. This particular example is highly relevant to this research as much of 18th century astronomy was devoted to the problem of precise measurement of planetary and stellar positions and instrumental developments can be directly linked with attempts to measure position. The parallax of a star due to the Earth's orbital motion waited three centuries for measurement and was of fundamental importance to conclusively prove Copernican theory. The eventual resolution (1838) was dependant on acquisition of precision micrometer screws, careful design of the equipment and meticulous attention to both the instrumental and observational errors.

This thesis is largely concerned with the study of screws used on scientific instruments and with the tools representative of the instrument maker's trade which would have been used for the production of such screws. Unfortunately, the amount of written material describing the manufacture of screws in general is very limited prior to the 19th century; material describing the process of making precision screws is even more limited until Ramsden's description of 1765. Contemporary illustrations permit some conclusions to be drawn and reveal an evolution of conceptual innovations, but may not accurately reflect the technical ability of the day. Thus the intention is to attempt to learn more from a close inspection of a variety of screw samples primarily taken from scientific instruments. Choice of scientific instruments has been deliberate since at any time in history, they represent the pinnacle of technical achievement. A knowledge of the highest precision obtainable at a specific period is more instructive in understanding technical advances than knowledge of normal everyday working tolerances. The form of the micrometer screws will be studied to learn about the shape of cutting tools. The form will also permit an assessment of the precision of the screw cutting--a factor in the history of technology which is currently lacking. Measurements of the motion of sample micrometers will also provide information on the accuracy obtainable from these devices and will provide a cross check on the precision of the screw cutting precision.

19th century advancements in screw production can best be ascribed to a desire to improve means and quantity of production during the Industrial Revolution. Whereas 18th century improvements emanated from workshops of instrument makers such as Hindley, Chaulnes and Ramsden, 19th century improvements came from manufacturers e.g. Maudslay, Whitworth, Sellers, Pratt and Whitney, and Hewitt. These gentlemen were also those most concerned with standardization of screws which required much higher tolerances for the tools and, in turn, their products. Whereas micrometer screws were the acme of screw production until ca.1765, the screws of dividing engines were the pinnacle until ca.1880. From that time, the screws manufactured to the highest precision were those employed to generate gratings for spectroscopy. But, as happens for any useful piece of technology, the methods to produce the highest precision of one generation becomes the technology of everyday production for the next.

Obviously a prime objective would be to attempt to identify makers of scientific instruments by the 'finger prints' they might have imparted to the screws they employed in assembly. Success in such a search would in turn permit dating instruments of unknown provenance, identify instruments which had later been repaired or even those which had been deliberately forged. Different avenues of study have been developed on a 'need to know' basis. For example, the promotion of standardized screws adversely affects the ability to identify makers and, to some extent, to date instruments yet a knowledge of the forms of standard screws would help identify repaired or forged instruments and also provide a means of assessing machining accuracy for the late 19th century. An ability to identify production techniques would assist in dating but in turn requires knowledge of the tools and methods of screw production.

Having had previous experience with the non-interchangeability of binding screws, even between holes on the same instrument, it seemed unlikely that a simple direct comparison of screw profiles would successfully identify a maker. A reasonable approach appeared to be to closely study screws made with greater care, e.g. precision screws used in micrometers. This in turn raised the question of the development of screw micrometers and how their precision is related to the precision of screw manufacture. Since there has been little previous research on any of these topics, the scope of this thesis has been broadened. Conclusions on whether instrument makers were subcontracting the making of screws, which was labour intensive and expensive might be answered; one may assume that apprentices produced most binding screws, but the date when screws were contracted out remains unanswered. There is evidence to prove makers were specializing in certain types of instruments by the mid-18th century and wholesaling these to be sold under another maker's name. It is hoped that the avenues followed will produce a homogeneous study which will relate the hand-in-hand advancement of screw production to the accuracy of screw measurement.

1.4 Previous Research:

A number of works published in this century have investigated the history of the screw as the primary theme. It seems to have been a topic of particular interest to the Germans, perhaps arising from their contributions to the discussion of the possible independent discovery of the screw by the Inuit (See § 2.3.4.3). The first publication to consider the early screw was Mötefindt's **Zur Geschicht der Schraube...** (1925) wherein he described a number of early artifacts and relics with screws mainly preserved in German museums. Zetter (1927) compiled a short summary of the development from the spiral and helix in nature through Greek and Roman applications including a suggestion that: "La plus ancienne application de la vis dont j'aie trouvé la trace date du x^{e} siècle avant Jésus-Christ : c'est un escalier tournant en spirale utilisé dans la construction du Temple de Salomon, à Jérusalem." He also suggested that the Phoenicians were responsible for the introduction of screw lifting technology. The source of this information is presumably the **Bible** but has not been accepted by later scholars who have continued to ascribe the European origins to Archimedes. One of the more interesting passages describes the spread of screw technology by the Arabs during the Crusades including the use by the mechanician and horologer Ridvan who used a form of tap thus predating those of Leonardo by some 2 centuries. A number of other interesting tid-bits are provided sans references making it difficult to corroborate Zetter's information. The major work on the history of the screw is Kellermann and Treuge's 1962 **Die Kulturgeschichte der Schraube.** It is a most interesting and important work since its perspective is outside the English-speaking sphere. Unfortunately, it has not been translated and its impact on the history of technology has been less than it deserves. To a degree, it is a compilation of the papers mentioned but also covers the use of the screw in Germany as well as aspects of standardization. It attacks the subject from an historical rather than from a technical perspective which limits its overlap with this thesis. The most useful section is that which deals with screws employed in scientific instruments and has provided a starting point for some aspects of this research. Battison's "Screw-Thread Cutting by the Master-Screw Method Since 1480" (1964) and Woodbury's **History of the Lathe to 1850** (1961) provide necessary background information on standard techniques during recent centuries. However, they have expended minimal space to discussion of special techniques for the fabrication of precision screws. The most important recent work--one not well known--which fills this void is that by Zagorskii (1960, English trs., 1982) which discusses screw lathes and other metal working machines from a Russian perspective. **An Outline of the History of Metal Cutting Machines to the Middle of the 19th Century** brought to light the inventions of Russians in the 18th century which particularly relate to lathes with lead screws. The discussion by Zagorskii on the dissemination of knowledge in the early 18th century is interesting and provides insights into the evolution and spread of pieces of technology.

1.4.1 Identifying Instrument Makers By Screw Thread Form:

There have been three previous studies of screws in scientific instruments but only one published paper has resulted. A.A. Mills and P.J. Turvey (1979) have published an analysis of the screw threads used on the reflecting telescope traditionally attributed to Sir Isaac Newton in the possession of the Royal Society. But this instrument now appears to be a later reproduction probably having been made in the shop of the London instrument makers Heath and Wing ca.1760. The mirror is very possibly that from the first of Newton's two reflecting telescopes while the iron screws (based on documentary evidence) may be from the second telescope shown before the Royal Society in 1670. The tube and base were probably reproductions fabricated while the components were in the possession of Heath and Wing, and prior to their presentation to the Royal Society in 1766.

The work on the screw threads on 'Newton's' telescope was part of a larger study carried out by Charles Maddock under the supervision of Mills at Leicester University. Unfortunately, Maddock died prior to the completion of the study, and except for a short progress report, the results were lost. The casts which remain can only be identified as having come from a particular museum with only a fraction identifiable with specific instruments (mainly quadrants in the Science Museum, London). Some of these have been employed in this study for remeasurement as have those for the 'Newton' telescope. Maddock's report includes results on leveling screws on 20 instruments: these have been included in Appendix A for comparison and to preserve the results which will otherwise be lost.

Two other studies of screw threads have been made in the last 30 years. In the mid-1950's, a study of microscope screw threads (apparently on Wilson screw barrel microscopes) was made at the Whipple Museum of the History of Science at Cambridge by the then director, Heywood. But again nothing was published and a single verbal report (G. L'E. Turner, private communication) suggested that the results were inconclusive in that the thread could not be used to identify makers. Attempts to locate a report on this research were unsuccessful. The current Director, Dr. J.A. Bennett, was unable to locate any reference to it and a former Director, D.J. Bryden, could not recall having seen or heard of the research.

The most recent attempt to study screw threads was made at the Smithsonian Institution by Debra Jean Warner. This work remains unpublished but in private communications (1987, 1988) Ms. Warner has reported a lack of success in identifying makers of nautical instruments (in particular, octants and sextants). She indicated rust and wear of the screws were complicating factors. The effects of wear were not very obvious in the samples processed during this study, and rusted samples were excluded (with one important exception) from the outset as being unsuitable. The number of rusted micrometer screws found and rejected was a remarkably small proportion of the number investigated, presumably because of the respect and care taken for preservation of precision screws by the original users and later by museum curators.

A current study of screws should be mentioned although it does not relate directly to this research. Eldon Worrall (Liverpool University and Merseyside Museum) is carrying out a study of screws employed on items reputably of Chinese manufacture of the late 18th and 19th centuries. He is attempting to determine whether screws can assist in attributing items to Chinese artisans or to European makers attempting to take advantage of the western demand for Chinese works--a strong force in the market place of the period. Worrall's work is part of his PhD research, but the study of screws is only a small aspect of the work. Discussions indicated that he has not adopted any advanced techniques that might be applied here. The same is true of Warner's approach.

1.4.2 Studies of Screw Production:

Methods and tools of screw production have been investigated in recent years, the most significant studies being those by F.N. Zagorskii (1960), Edwin Battison (1964) and Robert Woodbury (1972). Kellerman and Treuge (1962) discuss many aspects of the use of screws; of particular interest are the applications by German instrument makers of the 16th-18th centuries. Some of these will be discussed in the chapter on micrometers. Historians of technology are familiar with Woodbury's series of studies on machine tools and the combined studies published in 1972 serve as the first reference for any questions on tools and methods of production. Both Woodbury and Battison examine the production of binding screws and discuss early screw lathes. The latter hold considerable significance for late 18th century production of precision screws. F.N. Zagorskii in his **An Outline of the History of Metal Cutting Machines to the Middle of the 19th Century** (translated by E.A. Battison: 1982) covers much of the same territory as Woodbury but adds a very significant study of the contributions of his fellow Russian, N.A. Nartov. Nartov developed machines for screw cutting prior to his Western European colleagues: these included lead screws and cross feeds, and were large enough for production needs.

However, there is no modern work which specifically traces the production of precision screws from the earliest suggestion for their use as measuring devices. Both the modes of production and the accuracy achieved are interesting topics for consideration, and will be dealt with in this work. The impetus for many of the advances in precision screws in the 18th -19th centuries was the demand for precise spatial measurement by scientists and navigators; this replaced the impetus from artillery officers of the 16th

and early 17th centuries. Hence, the concentration on scientific instruments which has been adopted by this researcher.

1.4.3 Studies of Instrumental Accuracy:

A number of works, e.g. by Daumas (1963, 1972) and van Helden (1985), have peripherally discussed the precision screw but there has been no attempt to quantify the actual precision of such devices as astronomical micrometers by direct measurement of surviving examples. Van Helden has deduced the precision of astronomical observations made with micrometers by analysis of early observations and comparison with modern values (e.g. planetary diameters). Also related are: Thoren's (1973) study of Tycho Brahe's instruments; Allan Chapman's assessment of scale divisions of important 18th-19th century observatory quadrants (1976 II, 1983II) and astrolabes (1976 I, 1983 III); Goldstein's (1977) study of astrolabe divisions; Turner's (1967 II) investigation of the accuracy of microscope objectives; and Ward's (1961) review of time piece accuracy.[1] Important as Chapman's work on astronomical quadrants is, it answers only half the question since most quadrants of the 18th-19th century employed a scale micrometer to determine fractions of the divisions. In most instruments the potential error from the micrometer is of the same order as (or may even exceed that from) the scale divisions. Evidence of this will be developed and presented in due course.

---

1 See also Howse, 1975, p.181.

CHAPTER 2

Historical Usage and Production of Screws

2.1 Terminology:

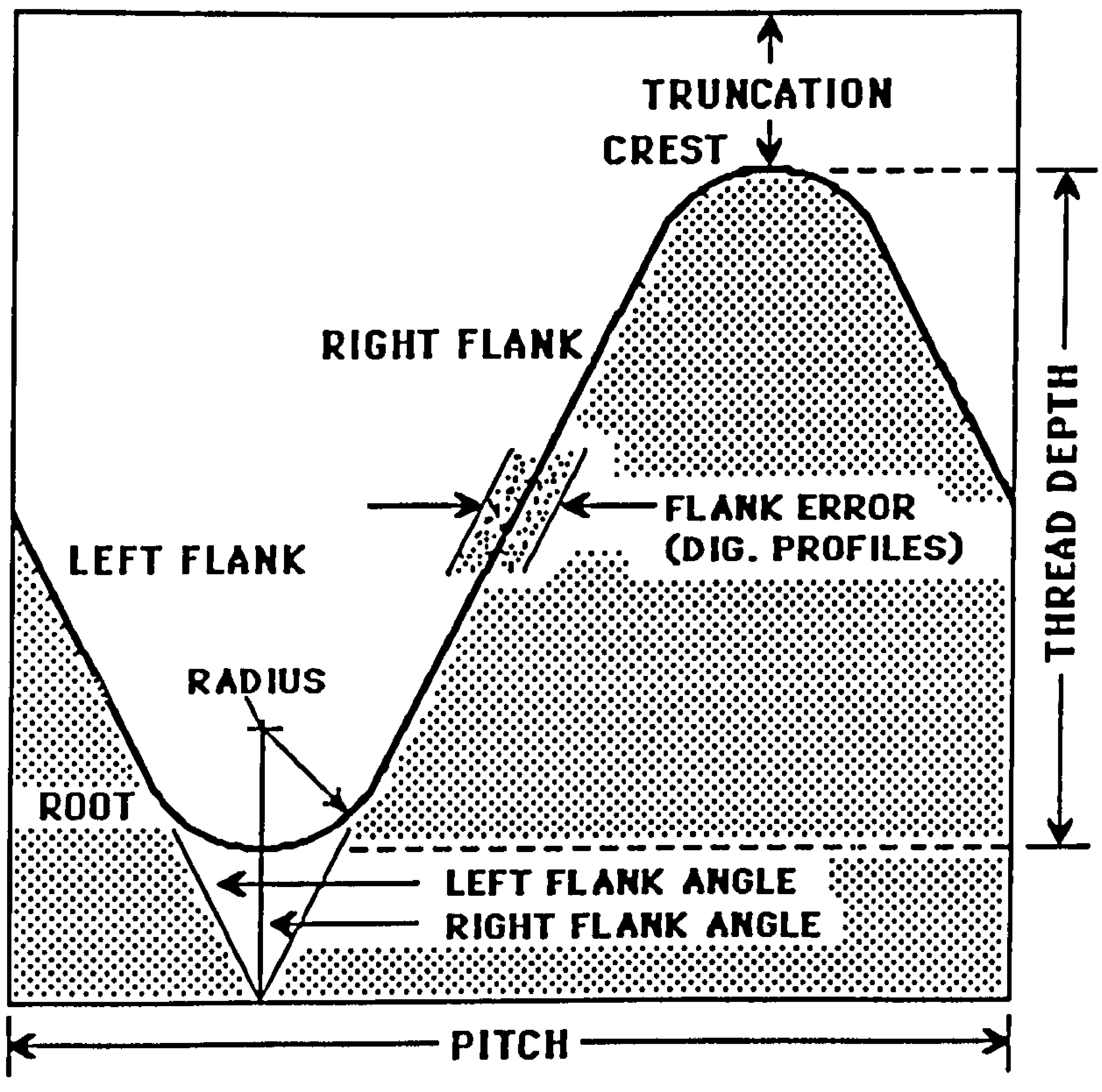
In this thesis a number of terms are used in special contexts. Screw should be construed as the generic term for both screws and bolts, male and female. Screw may also refer to smaller sized male screws, while the term bolt is applied to larger sized pieces. Male and female screw is used when referring to threads on tubes of instruments. Female screw was the term used for nuts well into the 18th century, and is here used to denote internal threads although nut will also be used in the common sense. The term nut was in use by ca.1503-13 having been employed by Cellini in a treatise, **Goldsmithing** (Usher: 1957, p.338/9, ref. 14). Helix and spiral are both used to denote the curling form of screw threads; spiral usually refers to a two dimensional figure but can also refer to a three dimensional figure. The term screw-box or box was used to describe nuts for large screws, e.g. vice screws (Bion/Stone: 1758, p.255) but will normally denote early devices for cutting threads in wood. Screw plates are metal plates for the formation of screw threads; they had one to three columns of holes of increasing size. The screw-plate's equivalent today would be a set of dies. Worm was the term used in the 17th-18th century to distinguish screws too large to be made using screw plates. The origin of our phrase worm and wheel is not far removed from this usage.

2.1.1 The Handedness of Screws:

The handedness of screws is straight forward: left or right-handed screws refer to the direction one turns ones hand toward to insert a screw. Thus right-hand screws insert in the clockwise direction, left-handed in a counter-clockwise direction. The origins of the handedness of screws has not been researched and very little reference to the handedness has been made in any reference perused. A census of handedness of screws from the earliest times would provide knowledge of the preference for handedness in different cultures. Reference to illustrations is unsatisfactory since drawings are notoriously inaccurate in detail through most of the period covered by this thesis (e.g. Battison: 1964, p.107, Fig.1). For instance, Leonardo da Vinci was left-handed and his illustrations most often show screws as left-handed; however, he also reversed his writing so that it was a mirror image of normal writing. Did he also reverse the threads on screws? From a technical view, neither left or right handed screw holds an advantage, although for a right handed person, greater force can be applied when driving home a right handed wood screw. Given the societal bias in European cultures against left-handed people, it may not be too surprising that right handed screws now predominate. One may, of course, speculate that earlier Greek screw makers were mimicking the right handed coil of mollusks and that the Inuit likewise duplicated the twist of the narwhal's tusk. Nicholas Toth (1985) has presented evidence from the chipped edges of flint tools to suggest right-handedness as early as stone age man. A.A. Mills has drawn attention to the fact that threads for textiles can be spun with right or left-handed twist where they are denoted as S-twist or Z-twist; flax naturally has an S-twist and a right-handed spinster normally produces S-twist threads.

2.1.2 The Screw Form:

The figure below illustrates the cross section of a screw thread and the associated terms which are used in this work.



2.1.1 Definition of terms used in this thesis.

2.2 TECHNICAL REQUIREMENTS FOR VARIOUS TYPES OF SCREWS:

Before proceeding, it will be instructive to briefly discuss the requirements of screws. The majority of screws--binding screws--are of course used to fasten two or more components together and are subjected to a variety of conditions of stress. Such screws must possess properties which will allow the components to be separated when necessary without undue friction or wear--the form of the thread determines its durability, efficiency and the surface area of thread to bear end strain. The screw must have sufficient strength to hold the parts together; the depth of the thread determines the cross section of the core left to resist shear. The pitch primarily determines the power or mechanical advantage for each diameter and defines the angle of the inclined plane. As every student of mechanics learns, the more shallow the angle of an incline the less force required to raise an object. A square or Acme thread can exert the greatest force but is not suitable for binding purposes since the relatively large backlash inherent in such threads makes them susceptible to vibration. For micrometric screws one additionally requires that the threads on the screw and nut be perfectly concentric since a drunken screw will result in periodic errors; differences in pitch also compromise the precision of micrometer screws (other errors are discussed in Ch. 3).

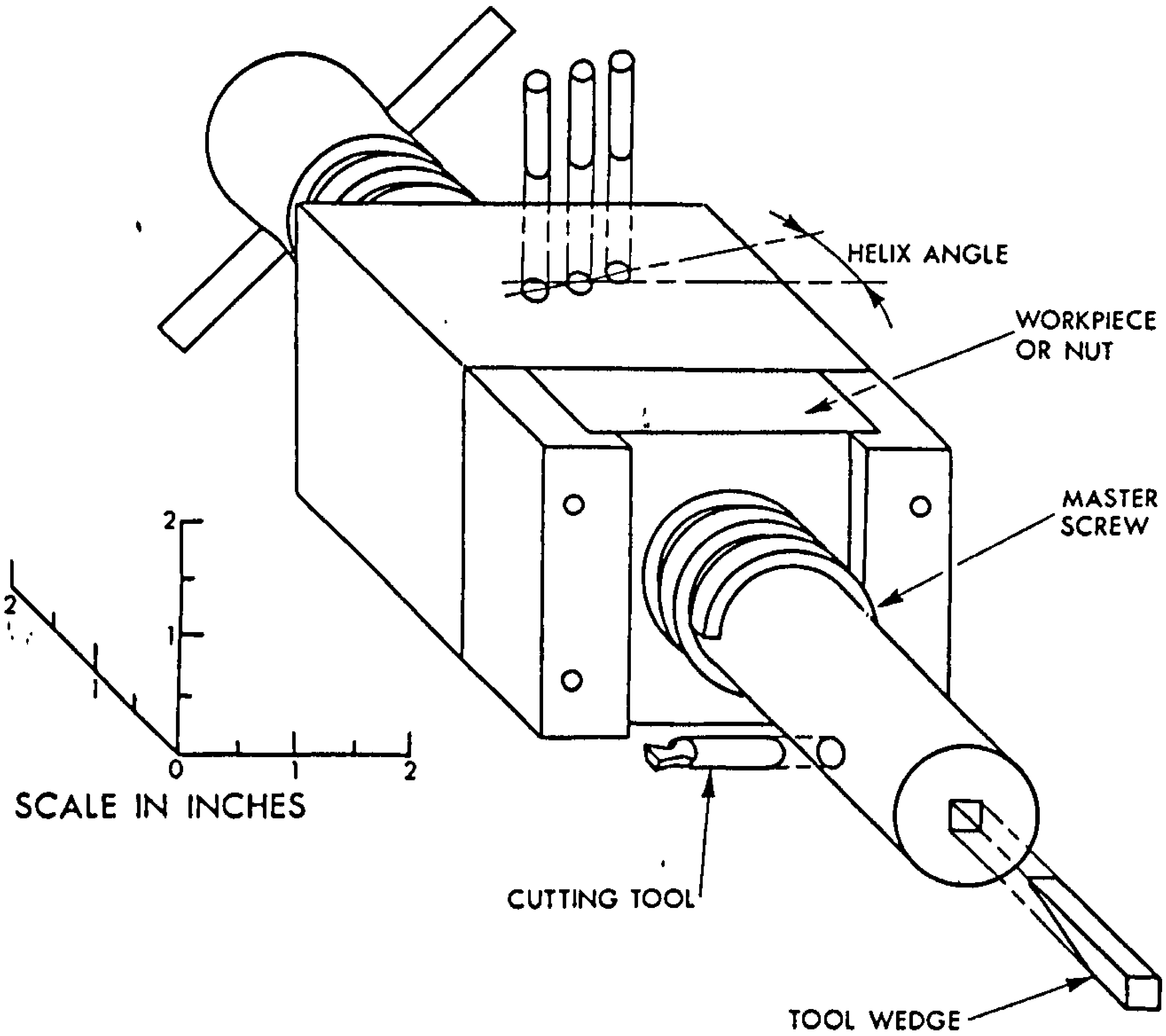
For binding screws, the British Association for the Advancement of Science (BAAS) committee established to define a small screw thread gauge considered four main technical requirements (BAAS: 1884, p.291 or Brooks: 1988, I pt.2). These were: 1) ease of cutting with standard screw cutting tackle; 2) minimum liability to stripping for both male and female threads which were to be correlated; 3) maximum resistance to torsional stress; and, 4) low friction. For micrometer screws only the cutting technique and friction were of real concern--within limits of course; of more concern was the accuracy of production, and on this point many thousands of man-hours of thought and labour have been expended in perfecting the procedures and equipment. Crucial areas of concern were producing a constant pitch, ensuring the contact point of the thread was parallel and concentric with the axis of the screw blank and ultimately with the nut, and later, the accuracy of end bearing surfaces and shoulders of the screws. For adjusting screws the primary concern was achieving minimal friction.

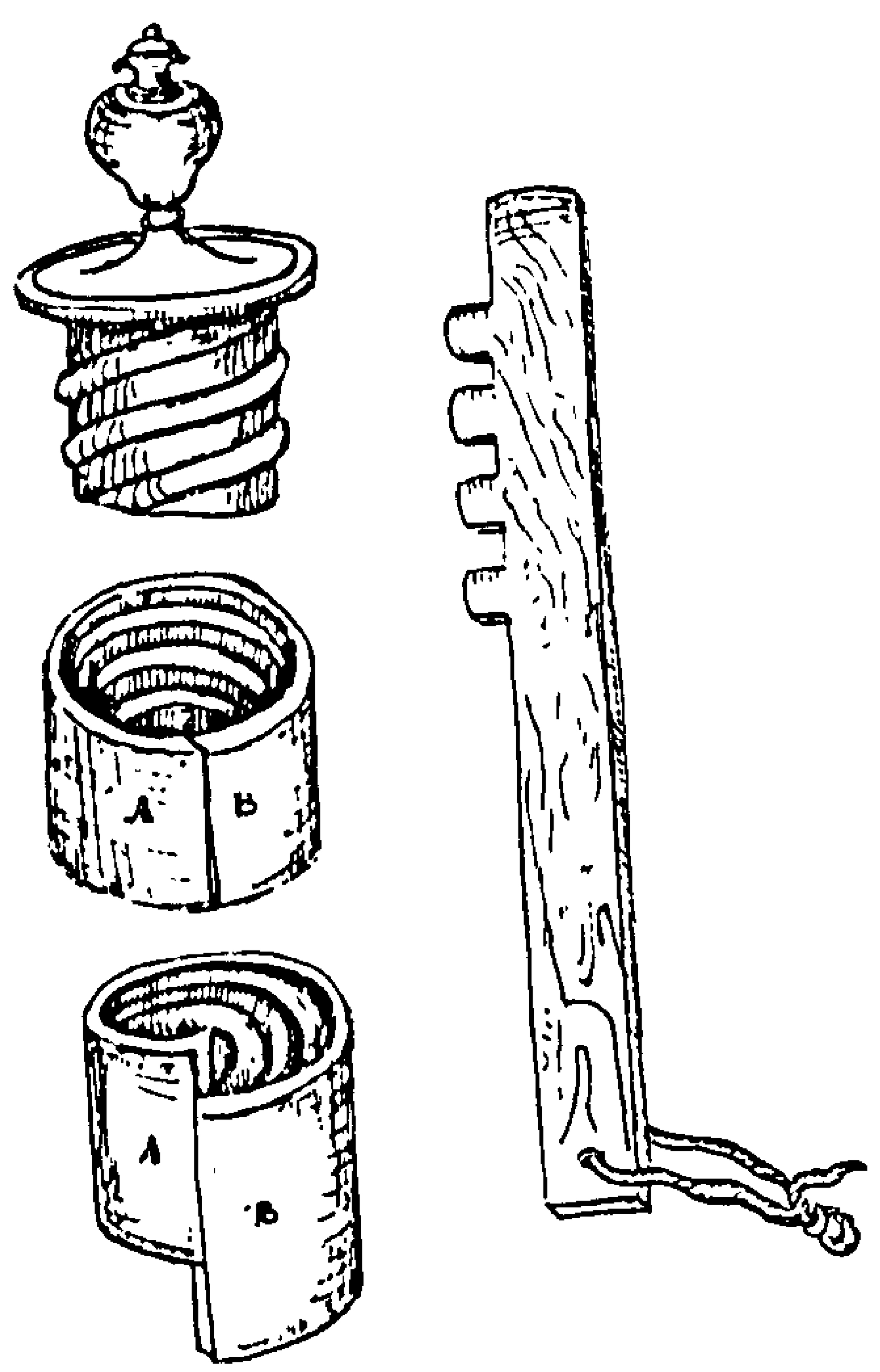
2.3 ORIGINS OF THE SCREW:

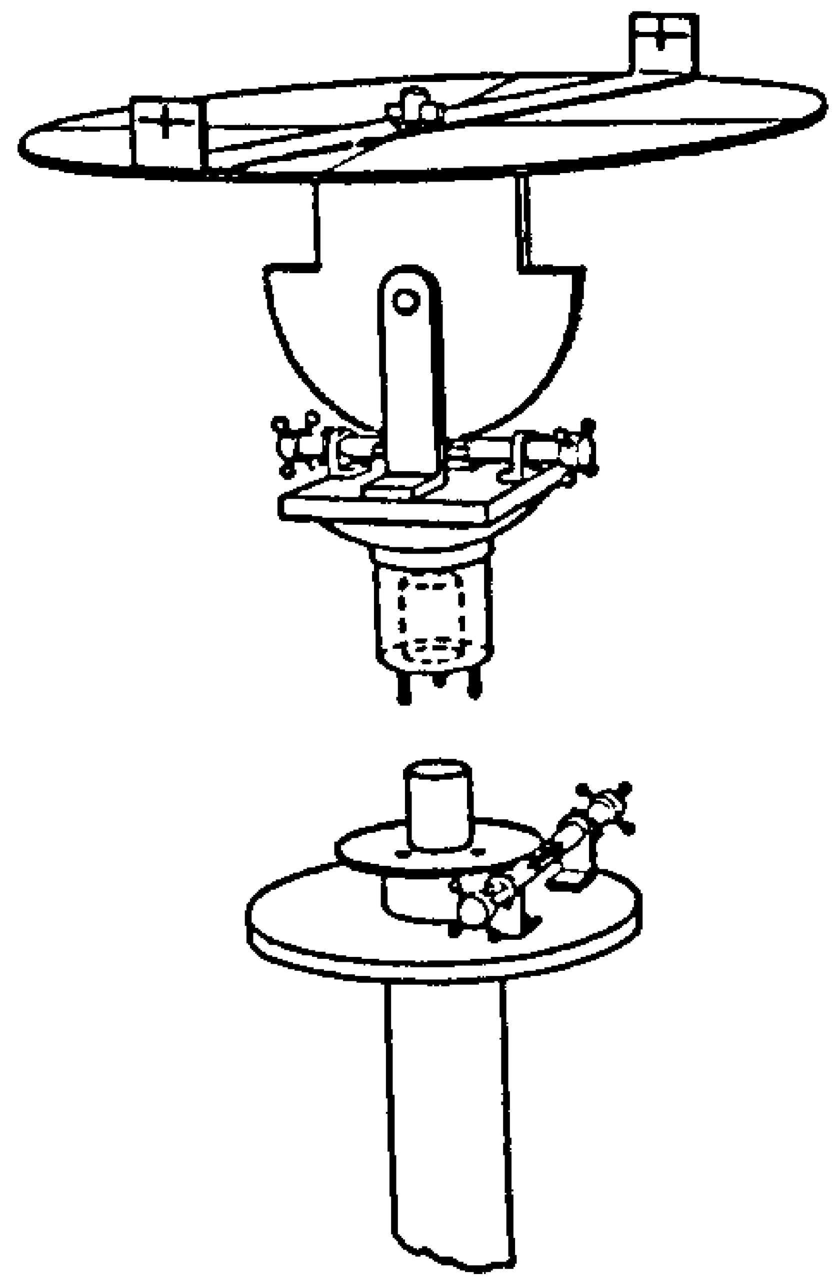
In this section we consider the origins of screws, some of their modes of use and the evolution of production techniques leading to precision screws. Three sources of the screw form are recognized by historians: Greece, China and the Arctic but the shroud of time has clouded our ability to determine precise origins. There are conflicting theories and dates, and it is not the intent to attempt a critical analysis of the various claims.

2.3.1 The Helix in Nature:

Suggestions have been put forth that the idea of the screw originated in natural models such as the tusk of the narwhal or the helical form of some molluscs. The merit of this connection is difficult to assess, but observation of examples of the helix in nature is interesting. Martin Gardner in **The Ambidextrous Universe** touches on some occurrences. Probably the best known occurrence is the double helix of DNA (discovered and unravelled in the last 3 decades) and the helical form of proteins. Less well known is the helical stinger of bees which is fixed into the victim but minute barbs make it impossible for the bee to extract thereby leading to its death in some species. On a more common scale and visible to many gardeners are runners of honeysuckle, bindweed, pole







2.3.1a (right) Hero's dioptra (reconstruction) with worm and wheel adjustments for both azimuth and altitude.

2.3.1b (top) Hero's screw cutter.

2.3.2 (left) Piccolpasso's medieval chaser for making threads on pottery.

beans and climatis which coil around any available support to permit the plant to climb. The coiling direction is the same for each species but varies from left to right-handed. The possible connection between the narwhal and the appearance of screws in Inuit cultures is dealt with in §2.3.4. Hoke (1931, p.555) illustrates a helix form of fossil shell known as Archimedes Wortheni which dates from the carboniferous period. Gille (1957, p.631) has pointed out that the spiral or helical form of screws appeared in Malta as decorative motifs in Neolithic monuments as early as ca.2000 BC. He speculated that this spiral form, and perhaps the shape of some molluscs, may have suggested the pointed spiral auger. This connection to screws must not be carried too far, however, since ancient screws were always of cylindrical form and not conical.

2.3.2 European Origins:

2.3.2.1 Graeco-Roman times to the Middle Ages:

The helical screw, which is reliably documented, had appeared by the time of Archimedes of Syracuse (ca.287-212 BC). Hoover and Hoover (1950) in their translation of Agricola's **De Re Metallica** (p.149n), quoting Diodorus Siculus (1st c BC), say that Archimedes invented the Archimedian screw while he was staying in Egypt where it became known as the Egyptian Screw. R.J. Forbes (1966, p.217/8) echoes this opinion, also quoting Diodorus. According to Gille (1957 p.633), the Archimedian screw for water lifting was not an invention of Archimedes but had, in fact, been in prior use in Egypt. Some evidence suggests that Archytos of Tarentum (ca.400 BC), a Pythagorean philosopher and mathematician, may have been the inventor. The indirect evidence of his supposed invention comes from Diogenes Laertius (3rd c BC) and from Plato. According to the former, Archytos was the first to apply geometry to mechanics, while Plato reproached Archytos for attempting to solve geometrical problems by mechanical devices. We may thus suggest Archytos was one of the first to use 'scientific instruments'. That the screw was extant by the time of Archimedes is known from his researches on the principles of levers, statics and centre of gravity and from evidence from Plutarch (ca.46-ca.125 AD).

Roman use reached a higher state of perfection with Hero's (or Heron) instruments such as his dioptra (Fig. 2.3.1a). This had a finely made screw; the method of production is known. The spiral form was generated by wrapping a piece of soft metal in the form of a right triangle around a cylinder, with one side of the triangle parallel to the axis of the cylinder. The hypotenuse of the triangle gave the desired spiral and acted as a guide for a file, chisel or gouge to cut the initial groove. By moving the triangle along the cylinder, the screw was cut thread by thread. Depending on the pitch of the spiral, multiple threads could also be generated. This 'triangle' method was used to generate screws well into the 19th century, with the quality dependant on the maker's skill and patience--although the thickness of the paper causes a gradual increase in the pitch as the paper helix progresses. A better method, in use by 1582,[1] was to cut a narrow slip of paper with a width equal to the pitch desired and wrap this around the screw blank.

Of interest is the screw cutting device designed by Hero which may be considered the first die (Fig. 2.3.1b). A wood block was prepared with a circular hole equal in diameter to the OD of the screw. At right angles to the axis of this hole, several small holes were drilled to hold the cutters. A slight inclination of the line of cutters defined the pitch generated on the male screw. A reconstruction has been made and described by Burstall (1968, p.24) and was found to be fairly efficient. Hero also made a 'tap' which consisted of a male screw with a plug extending along the axis and with a diameter equal to the ID of the screw thread. An iron cutter was inserted into a slot in the peg and a handle for rotating the 'tap' was inserted through a hole in the head of the device. This device could then generate the groove in a female screw and, as the cutter proceeded, the thread of the tap engaged with the newly formed groove and guided the 'tap' through. It is not difficult to imagine some of the problems using such a device would create and that its cutting action was limited by the power available. The wooden screws of presses found at Pompeii and Herculaneum (the latter is in the Museum of Alexandria according to Forbes: 1965, p.144) may well have been generated with such screw-cutting devices. Mercer (1975, p.273) illustrates a wrought-iron bolt of Roman origin found in Germany and dated 180-260 A.D. Whether these were cast on a threaded shaft is not known but its square form suggests that a wrench may have been employed to tighten it. Hoke (1931, p.558/9) illustrates a surgical instrument found at Pompeii with a screw to separate arms used to dilate openings in the body and a bronze bell found in a Roman site on the Rhine in Germany dated <250 A.D. He also notes that jewellery makers used screws as a holding element as early as the 4th century A.D. A common practice, even to the later middle ages, was to wind two wires around a core, then to remove one and solder the other in place. The same procedure was repeated in a block of metal to make the nut.

The art of tracing out screws with a triangle of paper was long used for press screws, which were by far the most common application of screws until the Middle Ages (Gille: 1957, p.647). Another use of the screw was as a key for a spring padlock (Needham/Wing: 1965, p.241). The key had a female screw which engaged a hidden male screw in the lock. Once engaged, the key was pulled back releasing the spring. Needham and Wang note that these were used by peddlers and the basic idea can be traced from medieval Scandinavia and Russia, down to Egypt, Ethiopia, India, Burma, Japan and China. The medieval appearance of the chaser appears to have been due to Piccolpasso who illustrated a wooden chaser for tracing out threads for stoppers of pottery bottles (Fig. 2.3.2) (Symonds, 1956, p.293).

---

[1] Besson: 1582, fig.1.

In the Middle Ages, screws were also employed in lifting. The monk, Gervais, (ca.1200) recorded this use in a chronicle while Villard de Honnecourt (ca.1250) illustrated a screw jack (q.v. Gille: 1957, p.647) and the fact that he mentioned his astonishment at its lifting capacity suggested to Gille that it was a recent and uncommon device. Winch and lever presses were gradually replaced by screw presses--presumably as the ability to make larger and stronger screws increased--these being employed for wine making, pressing bales of cloth and for printing from ca.1450[1]. Villard de Honnecourt noted the skill required to 'trace' screw-threads and also commented on the 'standardization' of oil-press screws in the south of France. Unfortunately he did not describe the process of tracing the screw form though this was presumably the paper triangle technique.

2.3.2.2 The Renaissance to the Enlightenment:

The appearance of screws on turret clocks has resulted in considerable discussion since J.J. Hall (1925/6, pp.,34,55,68) noted their use with nuts on the Ottery Clock dated ca.1340 and on the Wells Clock of ca.1394. He also noted that bolts were used in construction from ca.1100. However, Beeson (1971, p.27) states "threaded bolts and screwpins fastened by a nut began to be used in turret clocks soon after the mid-17th c.... Wedging continued in use on the Continent long after it had been abandoned in England". If this is correct, then either the Ottery and Wells Clocks are incorrectly dated (unlikely to be that far out) or, as seems likely, have been rebuilt at a much later date. Keller records (1981, p.175) (in discussing Peter Henlein's 'Nuremberg egg') "Since the screw was not recognized as a means of attachment until ca.1550 its (the egg's) iron and steel parts were held together by pins and wedges". It is indeed surprising that the screw's ability to hold components securely together was noted so late. It is difficult to imagine that a screw-powered crane or screw press had not jammed at the end of its travel and suggested this function. Symonds (1957, p.242n) also records that screws were not much used in wood working until the 17th century, having first appeared among the locksmith and clock and watch makers trades.[2]

Regardless of the state of physical use, Leonardo da Vinci made a quantum jump in the theoretical possibilities with his illustration of machines for working metals. Among them is a screw cutting lathe which embodied essential elements such as lead screws, tool holder and change gears (Gille: 1957, p.655). This appears to be the first machine specifically designed to generate screws, though there is no evidence to suggest that practical skills then existed to successfully construct and employ such a piece of 'hi-tech'.

---

[1] R.J. Forbes (1965, v.3 p.142-4) discusses the screw press and its widespread use, e.g. Greece, Pompeii, Herculaneum, the Aegean, Italy, Palestine, North Africa and the Near East.

[2] For a short history of the origins of wood screw manufacture, see Dickinson (1941/2).

Of more immediate consequence were Leonardo's illustrations of taps and dies but here, as for the lathe, it is not certain if he was illustrating and embellishing devices in use or was proposing new tools on new principles. The latter seems most probable.

Fillippo Brunelleschi provided impetus for the employment of screws in engineering practice. Screw-activated jacks and cranes, as mentioned, had been in use from ca.1200 but Brunelleschi invented a crane with vertical and lateral motions and a variety of devices employing screws. These were spin-offs of the raising of the Duomo in Florence in the early 15th c. As the architect, he was forced to devise new apparatus in order to complete the first large scale domed structure since Roman times. The Duomo was the progenitor of all other domed cathedrals of Europe and because of its size required imaginative use of technology. He designed a variety of handling tools, lewises, turnbuckles, etc. and examples of these items are preserved in the Duomo Museum in Florence. Keller (1981) has suggested that Brunelleschi and his contemporaries' interest in screws may have been partially sparked by resurgent interest in Greek ideas and methods--and particularly those of Archimedes.

Needham and Wing claimed (1965, p.120) that metal screws had become common by ca.1490. 'Common' seems to be loosely used but perhaps in the sense that the theory and technology of making screws were widely known although actual application was primarily restricted to town clocks, spreading to armaments and to domestic clocks by the 16th and 17th c. This does not suggest screws and bolts held much of the 'market sector'. Beeson (1971, p.27) does not agree with Needham's comment. He states: "Before the end of the 15th c threaded metal bolts and screws were almost unknown in Europe... By the mid-16th c screwed parts were already developed in plate armour and began to be applied to domestic clocks which were the most complex devices of the time".

Agricola notes use of wood screws for fastening (Hoover & Hoover, pp.141,145). The screws illustrated in Agricola have a conical shape and one with a slot is illustrated (p.356). One employed by surveyors to attach an 'orbis' or target is illustrated with square head and with a handle (i.e. wrench) with a square hole to match the screw's head (p.142). Agricola also described a measuring rod employed by Swiss surveyors which was 'half a fathom' in length but made of three pieces which screwed together. He also described drainage machinery for raising buckets in which toothed wheels had replaceable teeth attached with screws (p.172). Thus the screw as a fastening device was in use by 1552 or earlier since **De Re Metallica** was in preparation from ca.1530. Fremont (Needham/Wang: 1965, p.120) says the tapered wood screw appeared first in Gallo-Roman times and in **Das Mittlelaterliche Hausbuch** (1483) a cross-slide is illustrated with cutting tool fixed with a tapered screw (q.v. Battison: 1964, Fig.2). The figure facing page 364 of Hoover and Hoover illustrates a tapered wood screw with flat head. Ferguson (1976) illustrates many of the uses of screws suggested by Ramelli in his 1588 work. It is worth noting that two screws are illustrated with slotted heads; that in

Pl. 129 has a rounded head with flat bottomed slot while that in Pl. 185 is flat-topped with the bottom of the slot rounded.

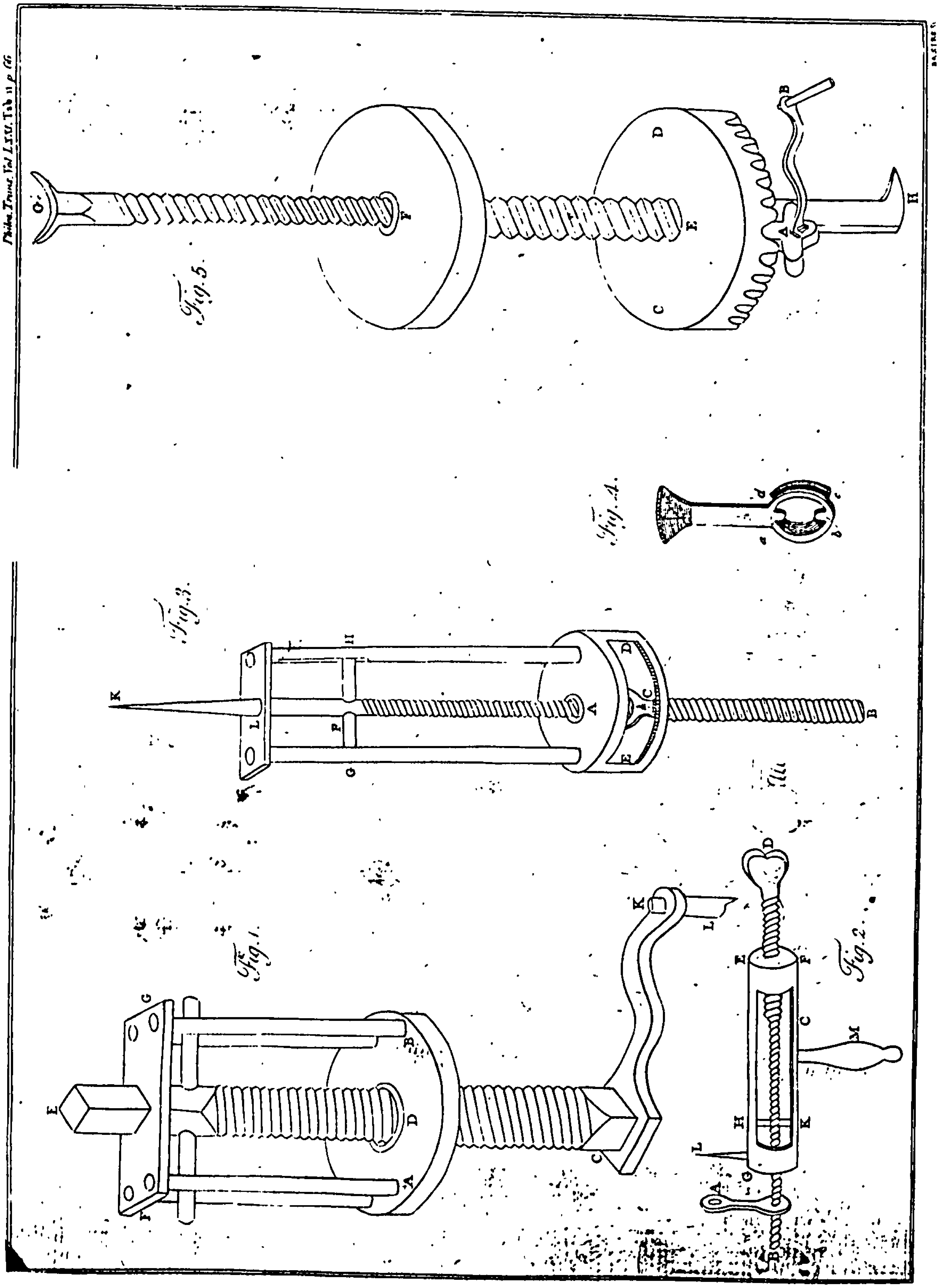
Usher (1957, p.336/7) noted that mechanical production of screws was expensive and limited until the 18th c. He illustrated (f.221, p.338) a screw-jack and bench-vice made in Nuremberg (ca.1570) which is decorative and not for everyday use. The jack has a hexagonal-headed nut, with right-handed square thread and a decorated wrench with which to adjust it. An adaptation of the Graeco-Roman wedge-type screw-press for processing olives and grapes for oil and wine was that of using a screw to produce the compression for the printing process. However, this style of press did not last much beyond the beginning of the 16th c. The use of screw-presses for die-stamping metals dates from 1503-13 when Bramante struck a medal for Pope Julius II. Usher also noted the substitution of wooden screws by copper screws in a printing press made, ca.1550, by the Nuremberger, Danner, which provided finer impressions. Cellini described a screw-press in his treatise, **Goldsmithing.** It is worth noting his terminology: "This male screw is indeed what we commonly call a 'screw'; and the female screw is called a 'nut'" (Usher: p.338/9).

A non-scientific but economically important use of screw presses was that of pressing linen for several cycles of 10-12 hours each while either hot or cold. After applying water and gum-arabic to the linen, the cloth was folded and intermixed with wood and steel plates making bundles several feet in height. After pressing for a cycle, the cloth was removed, re-folded and re-stacked and pressed again. The whole process was repeated until the linen was shiny and compressed.

Screws for guns were probably the most carefully made examples until the late 17th century. Greener (1924/5, p.62) found a breech plug that could be inserted one turn and would not shake or have lateral motion; it could also be screwed in 10-12 threads by fingers only. They were made to bear both on the shoulder of the head and at the end and were said to be 'bottomed'. According to Greener, larger threads were formed on lathes and finished with chasers and dies. He also refers to 'grinders' for making screw-pins but the term was a reference to the mode of forming the thread (with a file?) rather than to use of a grinding medium to finish a screw. Grinding threads to correct errors was a late 19th century innovation.

2.3.2.3 Application of screws in science:

In **History of the Royal Society...**, (Birch: 1757, p.43) one finds Robert Hooke's suggestion of employing the screw-press of the Mint at the Tower of London for making



2.3.3 Hunter's (1781) configurations for his differential screw. Use as a micrometer is illustrated in Fig. 3.

telescope mirrors. This followed Chris Cock's report on a mirror he was making for a Newtonian telescope for the Society.[1]

> Mr. Cock having produced a concave of steel for a reflecting telescope, which he said, he was not able to make all over the same hue, it being in its greatest part darker than in the rest about the edges; he was ordered to polish it as it was.
>
> Mr. Hooke proposed a way of making these reflecting concaves in great numbers, and polished by the means of two dyes, one concave and the other convex, putting between them a plate of silver, and then stamping them with the mint-mill.

Hooke, despite occasional reminders by the Society, never reported success of this suggestion. He also conceived the idea of a screw-log for measuring a ship's speed through the water. This model was successfully applied in the19th c. by Edward Massey in his 'harpoon log'.

The most significant technical advancement of 16th and 17th c science was the progress in the application of screws and gears to provide positive motions, along with achievements in precision instruments and light engineering which led to large scale industrial engineering. The development of tools incorporating screws and for screw making will be discussed in §2.6. The origins of the micrometer were in this period and represented the peak of instrument making. Micrometers and scale dividing are loosely associated here as being a slightly different application of the same basic technique.

In 1629, le Chevalier de Ville illustrated a use of screws relevant to micrometers. The illustration appeared in his **Traite de Fortifications de l'attaque et de la defense des Places** (p.228, plate 37); the concept was also developed ca.1726 by LeMaire (1735, p.479). de Ville's invention consisted of a pair of right and left-handed screws, of equal pitch, held between two bearing plates and with a third plate free to move. As one screw is rotated, that motion is transmitted to the second screw through identical gears attached to the screws. The moving plate is then traversed forward or backward. In some 18th century astronomical micrometers, this plate is replaced by two wires free to move separately, but the idea of transmitting motion through the gears is due to de Ville.

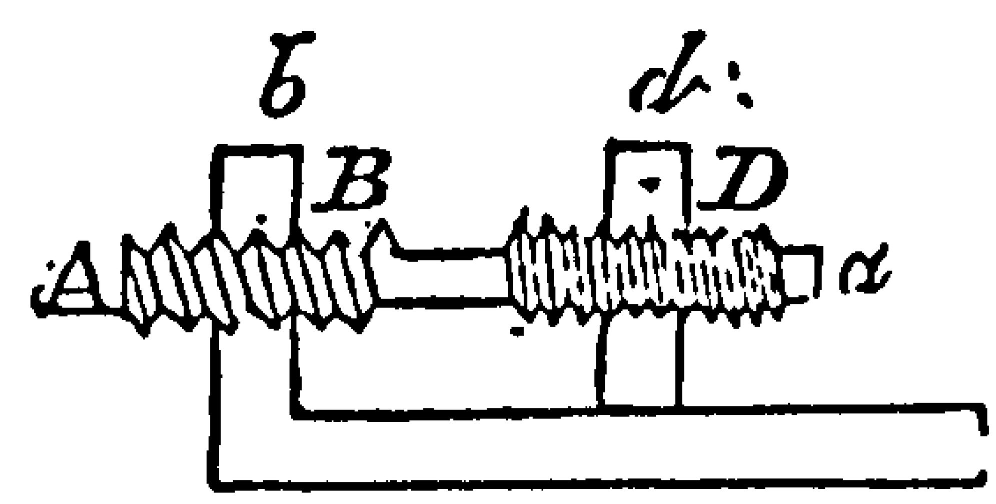
Another application applicable to micrometers is that of William Hunter (1781) illustrated in Fig. 2.3.3.[2] A large diameter screw is drilled longitudinally and an internal thread of slightly different pitch tapped into this hole. If a nut is made in a frame which holds and fits the larger diameter screw and a smaller screw to match the internal thread also held fixed by this frame, then when the larger screw is rotated, the

---

[1] The date of this suggestion was 18 April 1672 about 4 or 5 months after Newton had sent an example of his reflecting telescope to the Society for inspection (see Birch, 1757, p.1ff.)

[2] Edward Troughton adopted this scheme for the adjusting feet of sensitive, portable surveying instruments(Troughton: 1822, p.37).

motion transmitted will be the difference in pitch between the inner and outer threads. Thus a very small longitudinal motion can be achieved with a large turn of the mechanism and the mechanical advantage can be exceedingly large. Such a 'differential screw' device is suitable for jacks and micrometers but with a slight modification--i.e. using screws of the same pitch but of opposite handedness--was adapted for dynameters. The wires or half lenses could be attached to moving frames activated by the rotation of the screws; this was a particularly useful design for very compact items and was particularly popular in the 2nd quarter of the 19th century, and it can occasionally be found on high precision drum micrometers even today. A major problem with this arrangement is that errors of the threads are additive and a 'Hunter's screw' is more suited to fine adjustment than to measuring. A similar difference-screw arrangement was claimed by White and by Prony (Willis: 1841, 357). A simple figure is sufficient explanation.



2.3.4 'Difference' Screw

2.3.3 The Chinese Origins of the Screw:

Given even a rudimentary appreciation of the attainments in technology of ancient China, one might reasonably wonder whether the screw made its first appearance as a man-made mechanical device there. However, the screw was the only major mechanical device not independently developed by the Chinese and its use in China dates only from early trading contacts with Arabia and, through it, to Europe. Despite some recent hints that the screw's origin in China may have predated the Greek appearance, nothing has been found in the literature to substantiate this. The 'deans' of historical studies of Chinese technology, Needham and Wang, have consistently given a much later date for the screw's appearance there. They noted (1954, p.241): "The screw in its simple form had reached the Chinese earlier through Arab contacts, but the Jesuits brought it in the form of the Archimedian water raiser". The lag in transmission between European invention and Chinese use was approximately 14 centuries (p.243). One might speculate that the Chinese had seen screws from European contacts, but had not had need of such devices since other means of achieving the same end had been long in use, e.g. wedges and treadles for presses and motion.

The first surviving illustration of a screw in Chinese literature is dated 1609 (**San T'shai Thu Hui**--an encyclopedia) and shows, according to Needham and Wang (1965, p.121), "a continuous screw or worm and its male and female threads". Their use of worm is, however, not what is normally considered a worm and wheel and their designation of 'male and female threads' is also curious and apparently meaningless. The illustrated screw is for a screw cap for a flint-lock musket and in the original Chinese inscription is referred to as a 'silk coil'. The inscription also states "if you turn it to the right it comes out, if you turn it to the left it goes in" (p.121). Thus it was a left-handed screw.

Precisely what Needham and Wang meant by "the screw in its simple form" is not clear--one might assume screws for presses since Arab contact ca.1000 AD would have predated use in Europe of screw driven hoists and fastening applications. The traditional Chinese press was a wedge press with the wedge driven home by a battering ram which was the form used in Europe prior to the 1st c AD.[1] Needham, et al. (1970: p.62) add that the Jesuits were responsible for the introduction of worm gears and presumably also the simple wood screw and metal screw. In 1965 Needham and Wang were musing about the reasons the Jesuits had done so much to popularize the Archimedian screw but had conveyed so little about screw presses. Keller (1981) noted the 15th century resurgence of esteem for Greek knowledge and philosophy; vestiges of this esteem were still extant in the 17th century and may have been a factor in the approval of the Archimedian screw. Perhaps this is an illusory promotion of the Archimedian screw though there is no question about its popularity. This may simply have been a result of the Chinese lack of the Ctesibian double force-pump (Needham/Wang: 1954, p.241). Thus the Chinese had urgent need for water pumps whereas they had wedge presses so need for that application was not urgent. Thus the Jesuits may have seen little need to promote the adoption of screw presses or else the Chinese saw no advantage to be gained from their adoption. The problem of artisans with the requisite skill no doubt played a role.

Several examples of Chinese cotton gins survive and show the use of parallel worms for driving one roller by another parallel to the first. This use was uncommon in Europe until the early 19th century but found wide application in the East. Binding screws inspected by Eldon Worrall (personal communication) from items of Chinese provenance dating from the 17th-19th centuries were crude (even by most European standards of the same period) and obviously hand made. The pitch was very variable as was the thread form. Even mid-19th century screws showed little improvement. No scientific instruments falling within the scope of this work have been inspected although a small spyglass in the Merseyside Museum (Liverpool), previously thought to have been Chinese, was identified as of French manufacture.

2.3.4 Inuit Origins

The discovery of threaded items among artifacts from Greenland through the Canadian Arctic to Alaska in the late 19th century brought the suggestion[2] that the screw may have been independently developed and used by the Inuit. Several of the artifacts were

---

[1] See Needham/Wang: 1965, p.209, Table 57 for a summary of Greek and Roman screw press origins and Fig. 462, p.210 for schematics of the various types of presses.

[2] Franz Boas, 6th Annual Report, Bureau of Ethnology, Washington, 1888

illustrated in Boas' 1888 report. More evidence was found by C. Ryder in East Greenland at Scoresby Sound. Ryder noted that arrowheads were fastened to the wooden shafts by means of screw-bearing tongs and he claimed (Porsild: 1915, p.2 translated from Ryder 1895: 310):

> The screws are nearly always left-hand ones, these being the easiest in making such an arrow, as the maker grasps the arrow with his left hand, the knife with his right, and holds the cutting edge of the knife slantingly toward the outer side of the arrow. By a revolving movement of the arrow, the knife cuts a left-hand screw. A left-handed person will grasp the arrow with the right hand, the knife with his left, and the screw thus becomes a right-hand one.

By 1915 Marten Porsild was convinced that the screw had been independently invented. He stated "It is interesting to know that the *primitive Eskimos knew also the principle of the screw and that he invented the device himself."* Porsild listed 30 samples carrying the thread-like features most of which were from Greenland--his home at the time. Boas had indicated that arrowhead shafts from Alaska and from Frozen-Strait (Northwest Territories) carried 'slanting knobs'--i.e. screws of half a pitch length. About the same time Krause (1901, p.8/9) reported 3 samples from Alaska and concluded independent discovery by the Inuit though von Steinen responded and did not agree on the basis of probable contact with Russians and Chukchee across the Bering Strait. Porsild, on the other hand, was further convinced by the fact that plugs[1] and other implements of unknown use were found, and he listed a further 7 samples from Greenland and noted that Boas also found similar samples in northern Canada.

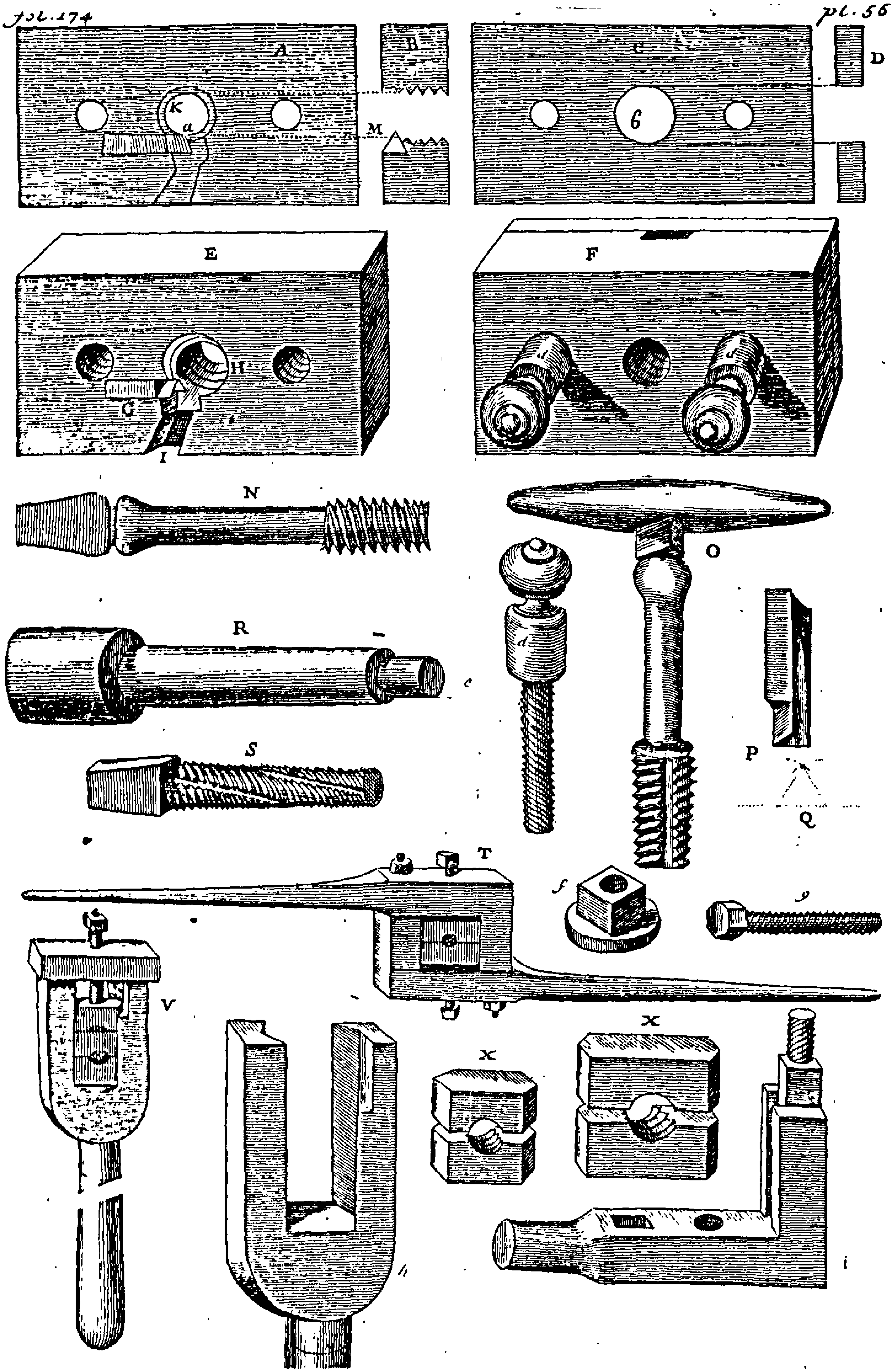
Porsild summarized his arguments in favour of independent invention as follows (1915: p.15). The handedness of the samples were invariably left-handed; Porsild explained this as an artifact of cutting the screw with a knife held in the right hand while rotating the shaft. Most Inuit are right-handed[2]. The inevitable question was first asked by Miss H. Newell Wardel: Was the model of the Inuit screw the narwhal's tusk? The handedness may point in this direction for the tooth of the narwhal is also invariably left-handed. The majority of narwhal[3] have the tooth growing from the left side of the skull but in the rare occasions where the tooth grows on the right side of the skull the twist of the tusk is also left-handed. However, none of these arguments nor the evidence eliminates the possibility of technology transfer from European contact. Certainly Laufer

---

1 The plugs had a rather interesting use. They were employed to plug the holes in seals after having been shot with an arrow. The body was filled with air and the plug inserted to keep it afloat and thereby allow it to be towed back to shore for processing.

2 Gardner in **The Ambidextrous Universe** (p. 85) states with respect to humans "...to favour the right hand is universal throughout the human race...Cultural anthropologists have yet to find a sect or even a local tribe in which left handedness is the rule. The Eskimos, the American Indians, the Maoris, the Africans--all are right-handed. The Ancient Egyptians, Greeks and Romans were right handed."

3 For a discussion of narwhals see Ivar Silis, *National Geographic,* **165**, Ap.1984, 520-539.



2.4.1 Examples of taps, screw-boxes and screw-stocks illustrated by Plumier (1701).

(1915) was not wholly convinced by the conjectural arguments. His concerns were that the diversity of screw forms and use and lack of female screws should be investigated as a clue to the origins.

No further information has been found in the literature dealing with more recent discoveries of Inuit screws. The foremost Canadian expert on Inuit artifacts, Dr. Bob McGhee[1] of the Museum of Civilization in Ottawa, was consulted and although Porsild's finds were known to him, he knew of no other relevant finds. He was also aware of the artifacts with the bumps which superficially resemble screw threads but he was not convinced that there was a link. These, he said, had been found on artifacts dated to several hundred years but were employed only as an aid to binding arrow heads to shafts.

2.4 METHODS OF SCREW AND NUT PRODUCTION:

Several aspects of screw making will be considered leading to a discussion of special techniques for producing precision screws. The tools of screw production have evolved as demand, variety of application and requirements for precision have advanced. Hand production techniques will be reviewed since micrometer screws were basically made by hand for the first century. Lathes evolved from simply being a means of rotating the work piece to the means of producing fine pitched screws and eventually became the basis of the thread grinding machines of the 20th century which permit very exacting tolerances to be maintained. Thread rolling machines were conceived as a means of originating accurate micrometer screws but this application was never very successful. The concept, however, became the basis of the means of mass production of binding screws in the late 19th century. Finally, the correcting of errors in screws used for generation of spectroscope gratings will demonstrate the lengths taken to generate 'the perfect screw'.

2.4.1 Hand Production Tools:

Burstall (1963, p.155) notes that screw plates, taps and dies (Fig. 2.4.1) were used as early as the 14th century in Europe. These tools were traditionally made by smiths for their own use[2] and retained the same basic form for centuries; Mercer (1975, pp.229-234) illustrates early examples of taps and screw boxes used by carpenters. Plumier (1701 or q.v. Holtzapffel:1854, p.593) described a hollow tap with a hole cut through to the hollow near the point where the cutting was achieved. Plumier's device was only suited for wood. The screw plate began as a single row of threaded holes, but was later modified to have two or three rows. 19th century versions had the holes for a particular sized screw grouped together, and occasionally had up to 6 holes for each size of screw to be made. The plate's thickness was, according to Holtzapffel (1854, p.595), two-thirds the full diameter of the largest screw to be made with the plate. The forming action by a

---

[1] Private communication.

[2] Tools were initially made during their apprenticeship then renewed as required.

screw plate was to squeeze the metal blank into the threaded form; this limited the ability to create anything but a rounded thread form. The addition of more rows of holes permitted a more gradual forcing of the shape into successively deeper threads.

The best screw plates of the 19^{th} century had slots cut into the sides of the forming holes.[1] These served the purpose of allowing some actual cutting by the edges of the slots, allowed particles to escape, and also facilitated the removal of broken screws from the holes by means of a small saw blade. Samples of older screw plates frequently have broken screws remaining. When too many of the holes had broken screws lodged in them, the plate was useless until a smith removed them by heating, followed by re-hardening. Dies as we know them began to gain acceptance in the 19^{th} century as both taps and dies began to achieve better efficiency as a result of experiments designed to achieve a proper cutting action by Maudslay, Gill, Nasmyth, Holtzapffel and others.

Once a screw has been made, it may be turned into a tap by removal of portions of the thread. In the most primitive form, four sides were filed away. In such taps the action was one of indenting the thread form in the hole since the edges of the tap threads were obtuse. Such taps were useless in metals of crystalline structure, e.g. cast iron. Filing three faces improved the action somewhat but were still not of a form which would provide cutting action. Other forms appeared to improve cutting action, e.g. the half-round tap or one with two-thirds of the circumference remaining, but these were liable to lose their line. Taps which had the now familiar three flutes began appearing in the early 19^{th} century as the result of Maudslay's experiments. Early versions had three round or elliptical grooves ground in the diameter or had flutes ground with sharp leading points. The origin of the modern tap was in the workshop of G. Bodmer in Manchester.[2] He was able to grind the flutes of the tap so that the trailing part of the circumference was slightly tapered or backed off reducing the friction and providing a sharper cutting edge (Holtzapffel: 1954, p.586; see fig. 543). This was achieved after threading by remounting the tap eccentrically three times and grinding down each flute.

Efficient screw-stocks[3], which evolved into today's form of die, were designed in the first half of the 19^{th} century. Gill illustrated his stocks (1823, p.35[4]) which had a micrometer to monitor the depth of each passage of the screw through the stocks, but the form of the cutting die was still to be improved by modifications such as those made by Bodmer and Whitworth[5] (Holtzapffel, 1854, p.606). Why it took quite so long to adopt a single piece die is not obvious but it was late in the century before the modern form

---

1 The idea of connecting the holes was simultaneously conceived ca. 1815-20 by Gill and by Thomas Peek of Clerkenwell (Gill: 1823, p.69).

2 See Roe (1914, p.71ff.) for information on Bodmer and his business.

3 Nollet illustrated screw-stocks in 1770 (Torlais: 1954, p.249).

4 This paper gives a good overview of the state of screw making tools of the period.

5 Whitworth set up as a tool-maker in Manchester in 1833 (Derry & Williams: 1960, p.353).

appeared. Solid dies are illustrated in **Screws and Screw-Making** (1891, p.85) but several pages (pp.88-97) illustrate and discuss two or three part die stocks including the second form patented by Whitworth and were obviously the more popular tool if one goes by the relative number illustrated.

2.4.1.1 Tempering of Cutting Tools:

It should be noted that case hardening was commonly practiced in making files, etc. (Moxon: 1703, p.56) and examples of early micrometer screws show signs of having undergone such treatment. Briefly, the method described by Moxon is as follows. Cow-horn or hoof was dried in an oven and then beaten to a powder. To this source of carbon was added 'bay-salt' (i.e. salt obtained by evaporation of sea water) and 'stale chamberly' (i.e. urine) or white-wine vinegar as a source of acetic acid. This mixture was combined with prepared loam, then coated on the item to be hardened and dried on the hearth of the forge. Once dried the piece was heated to blood red heat for several hours to allow carbon to diffuse inwards and then quenched.

The tempering of cutting tools was accomplished in Bion's France as follows (Bion/Stone: 1758, p.257):

> When the tools are forged and filed, and you have a mind to temper them, you must heat them red-hot 'till their Colour be something redder than a Cherry, and then they must be tempered in Spring or Well-Water: the colder the Water is, the better. And when they are cold, they must be taken out of the Water, and laid presently upon a Piece of hot Iron, so long, 'till the Colour they have contracted by tempering is lost, and they become yellowish; and then they must be thrown again into the Water, without staying 'till they become blue, because they will lose their Force.
>
> To temper Bundles of Files, or other Pieces of Iron, you must take Chimney-Soot, the oldest and grossest being the best, and having finely powered it, temper it with Piss and Vinegar, putting a little melted Salt therein, until the whole be as a liquid Paste. The Soot being tempered, the Tools must be covered over with it, and this covered with Earth, and the whole Bundle thrown into a strong Charcoal-fire; and when it is become something redder than a Cherry, it must be taken out and thrown into a Vessel full of very cold Water, and the Files will be sufficiently hard.

2.4.2 Techniques in the Early 18th Century--Some important features materialize:

Moxon (1703) discussed screw cutting at some length and it will be useful to note several points referred to in his **Mechanick Exercises**. For him, taps and screw-plates were the 'most Essential Tools of the Black-Smith's Trade'. The screw-plate illustrated by Moxon (Plate 1) has but a single row of holes and the tap is tapered the full length of the cutting threads, although this may well be an error on the part of the engraver. There was a matching tap for each hole of the screw plate.[1] His description of screw making provides a vivid picture of the state of the screw making art at the beginning of the 18th century. It should be noted that this is essentially the means used by Robert Hooke to make his micrometer screws ca.1667 and after reading Moxon's description one can readily appreciate Hooke's lack of success with his micrometer--however, that instrument will be treated at the appropriate time.

"The *Shank* of the *Screw* .... must be *forged* square near the *Head*, because it must be let into a Square-hole, that it may not twist about when the *Nut* is turned about hard upon the *Screw-pin*. Therefore take a Square-bar .... and taking a *Flame-heat* of it, ... and *hammer* it down to your intended Thickness: . . .so shall the two other Square-sides be made; then *hammer* down the Corners .... and round it, as near as you can, with the *Hammer;* set then the *Chisel* to the thickness you intend the *Head* shall have, and strike it about half through, then turn the Sides successively, and cut also half through, till it be quite cut off. . . .

Having *forged* and *filed* your *Shank* square, and the Head either Square or Round .... *file* .... it a little Tapering towards the End, that it may enter the *Screw-plate*; the Rule how much it must be Tapering is this, consider how deep the Inner *Grooves* of the *Screw-plate* lie in the outer *Threds,* and *file* the End of the *Screw-pin* so much small than the rest of the Screw-pin, for the outer *Threds* [sic] of the *Screw-plate* must make the *Grooves* on the *Screw-pin,* and the *Grooves* in the *Screw-plate*, will make the *Threds* on the *Screw-pin.* Having fitted your self with a Hole in your *Screw-plate* .... *screw* the *Shank* with the *Head* downwards in the *Vice,* so as that the *Screw-pin* may stand directly upright, and take the *Handle* of the *Screw-pin* in your Right-hand, and lay that Hole flat upon the *Screw-pin,* and press it very hard down over it, and turn the *Screw-plate* evenly about with its *Handle* towards you .... so shall the outer *Threds* of the *Screw-plate* cut *Grooves* into the *Screw-pin,* and the substances of the Iron on the *Screw-pin*, will fill up the *Grooves* of the *Screw-plate*, and be a *Thred* upon the *Screw-pin....*

To fit the *Pin* therefore to a true size, I in my Practice, use to try into what *hole* of the *Screw-plate*, the *Tap* or place of the *Tap,* (if it be a tapering *Tap,*) I make the *Nut* with, will just slide through; (*Threds* and all;) .... for then turning my *Pin* about in that *hole*, if the *Pin* be irregularly *filed*, or but a little too big on any part of it, the *Threds* of that *Hole* will cut small marks upon the *Pin*, on the irregular places, or where it is too big; so that afterwards *filing* those Marks just off, I do at once *file* my *Pin* truly round, and small enough to fit the *Hole* I make my *Screw-pin* with. [This should be particularly noticed as it provides us with an approximation of the ratio of successive sizes of holes in the screw-plate.]

As the *Hole* of the *Screw-plate* must be fitted to the *Screw-pin*, so must the *Screw-tap* that makes the *Screw* in the *Nut*, be fitted to the round *hole* of the *Nut*; .... *Screw* the *Nut* in the *Vice* directly flat, that the hole may stand upright, and put the *Screw-tap* upright in the *hole;* then if your *Screw-tap* have an *handle*, turn it by the *handle* hard round in the *Hole*, so with the *Screw-tap* work it self into the *Hole*, and make *Grooves* in it to fit the *Threds* of the *Screw-pin*. But if the *Screw-tap* have no *handle*, then it hath its upper end filed to a long square, to fit into an hollow square, made near the *handle* of the *Screw-plate;* put that long square hole, over the long square on the top of

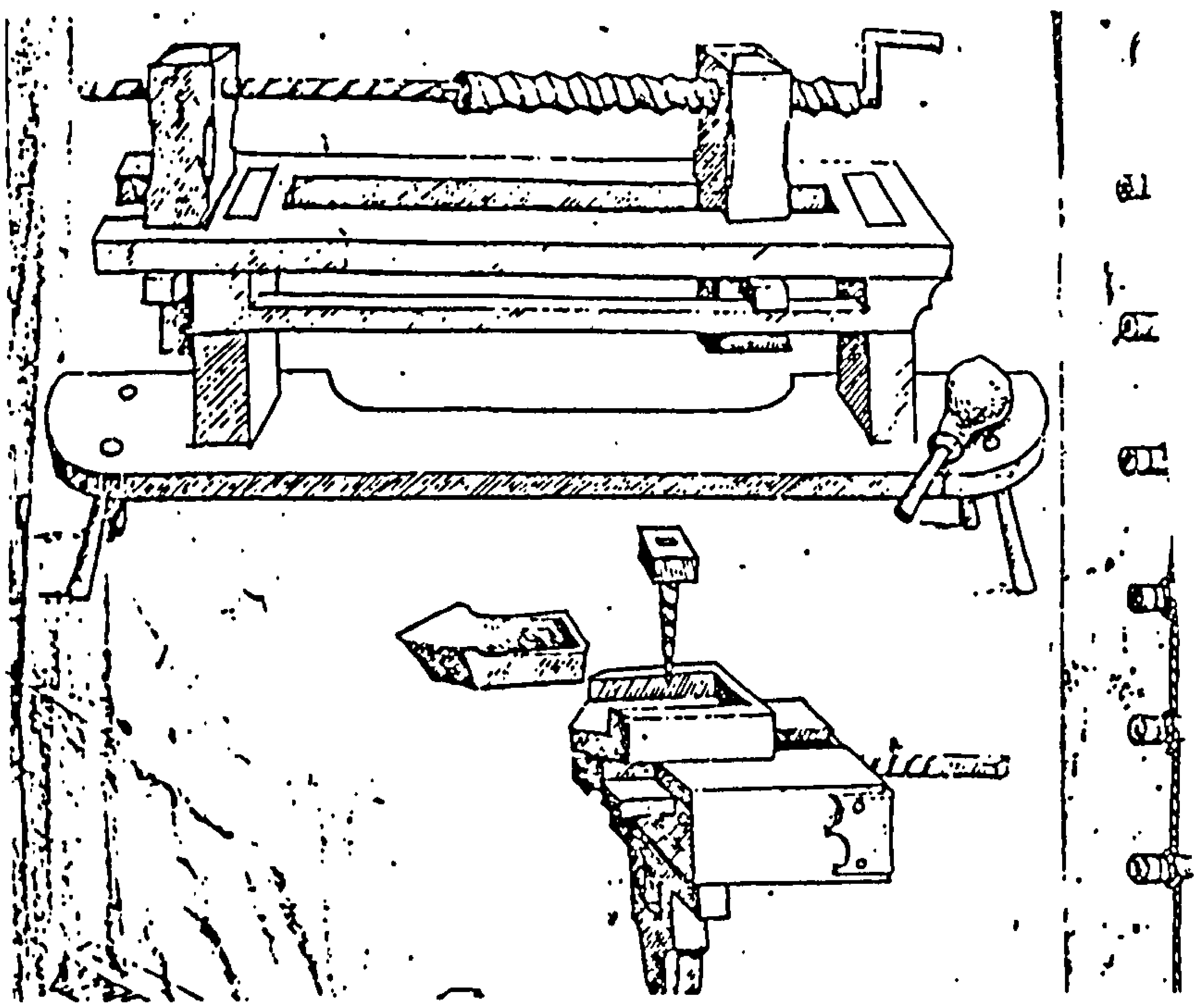
[1] Screw plates were made of an iron-carbon alloy--i.e. the steel had high carbon content--which allowed it to be drilled and threaded while annealed or soft and then hardened and tempered.

> the *Tap,* and then by turning about the *Screw-plate,* you will also turn the *Tap* in the *hole,* and make *Grooves* and *Threds* in the *Nut.*

The tapered shape of the tap should be noted as it was in use well into the 19th century. Holtzapffel (1854, p.587) illustrates it beside a 'modern' tap which had a full-diameter cylindrical portion with which to finish off the thread. A tapered tap would leave an imprint on the nut made with it; the thread would have a slight taper and a screw inserted in it would be loose when not driven home tightly. This effect may also explain the choice of pitch to thread depth used and the ratio of depth of thread to screw diameter (1:7 was recommended by Moxon).

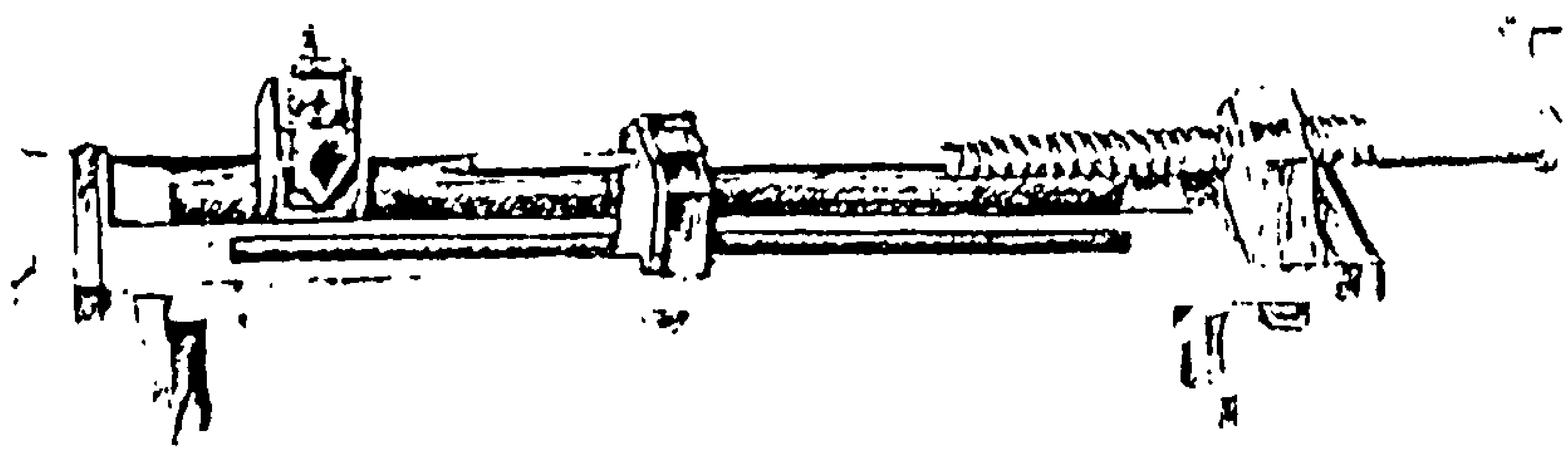
Moxon's description of the procedure for making bolts is also instructive to relate since it has a direct link with the mode of micrometer screw making at the end of the 18th c.

> The Rules and Manner of Cutting Worms upon great Screws.
>
> The *Threads* of *Screws,* when they are bigger than can be made with *Screw-plates,* are called *Worms.* They consist in length, breadth and depth; the length of the *Worm* begins at the one end of the *Spindle,* and ends at the other; the breadth of the *Worm,* is contain'd between any two *Grooves* on the *Spindle,* viz. The upper and under *Groove* of the *Worm,* in every part of the *Spindle;* the depth of the *Worm,* is cut into the Diameter of the *Spindle,* viz. The depth, between the outside of the *Worm,* and the Bottom of the *Groove.*
>
> The depth ought to be about one seventh part of the Diameter, on each side of the *Spindle:*
>
> You ought to make the *Groove* wider than the *Worm* is broad, because the *Worm* being cut out of the same intire piece with the *Spindle,* will be as strong as the *Worm* in the *Nut,* tho' the *Worm* on the *Spindle* be smaller; for you cannot come at the *Worm* in the *Nut,* to cut it with *Files,* as you may the *Spindle,* and therefore you must either Turn up a Rod of Iron, to twist round about the *Grooves* on the *Spindle,* and then take it off, and *Braze* it into the *Nut,* or else you must cast a *Nut* of *Brass* upon the *Spindle,* which will neither way be so strong as the *Worm* cut out of the whole Iron, by so much as *Brass* is a weaker Mettal than Iron, and therefore it is that you ought to allow the *Worm* in the *Nut,* a greater breadth than the *Worm* on the *Spindle,* that the strength of both may, as near as you can, be equal strength. The Worm may very well be the one seventh part smaller than the *Groove* is wide, as aforesaid.
>
> Having consider'd what breadth the *Worm* on the *Spindle* shall have, take a small thin Plate of Brass or Iron, and *file* a square notch at the end of it, just so wide, and so deep, as your *Worm* is to be broad and deep, and *file* the sides of the Plate that this notch stands between, just to the width of the *Groove.* This Plate, must be a Gage to *file* your *Worm* and *Groove* to equal breadth by; then draw a straight and upright Line the whole length of the *Spindle;* divide from this line the Circumference of the whole *Spindle* into eight equal Parts, and through those divisions, draw seven Lines more parallel to the first line; then open your *Compasses* just to the breadth of one *Worm,* and one *Groove,* and set off that distance as oft as you can, from the one end of the *Spindle* to the other, (but I should first have told you, that the end of your *Spindle* must be square to the outside) and with a *Prick-Punch,* make a mark to every setting off on that line: Do the like to all the other straight upright Lines....



2.4.2 Illustration of a screw lathe with lead screw and cross slide taken from **Das Mittlealterliche Hausbuch** (1483).

2.4.3 The screw lathe with lead screw illustrated by Mertz in his treatise on guns (ca.1470-5).



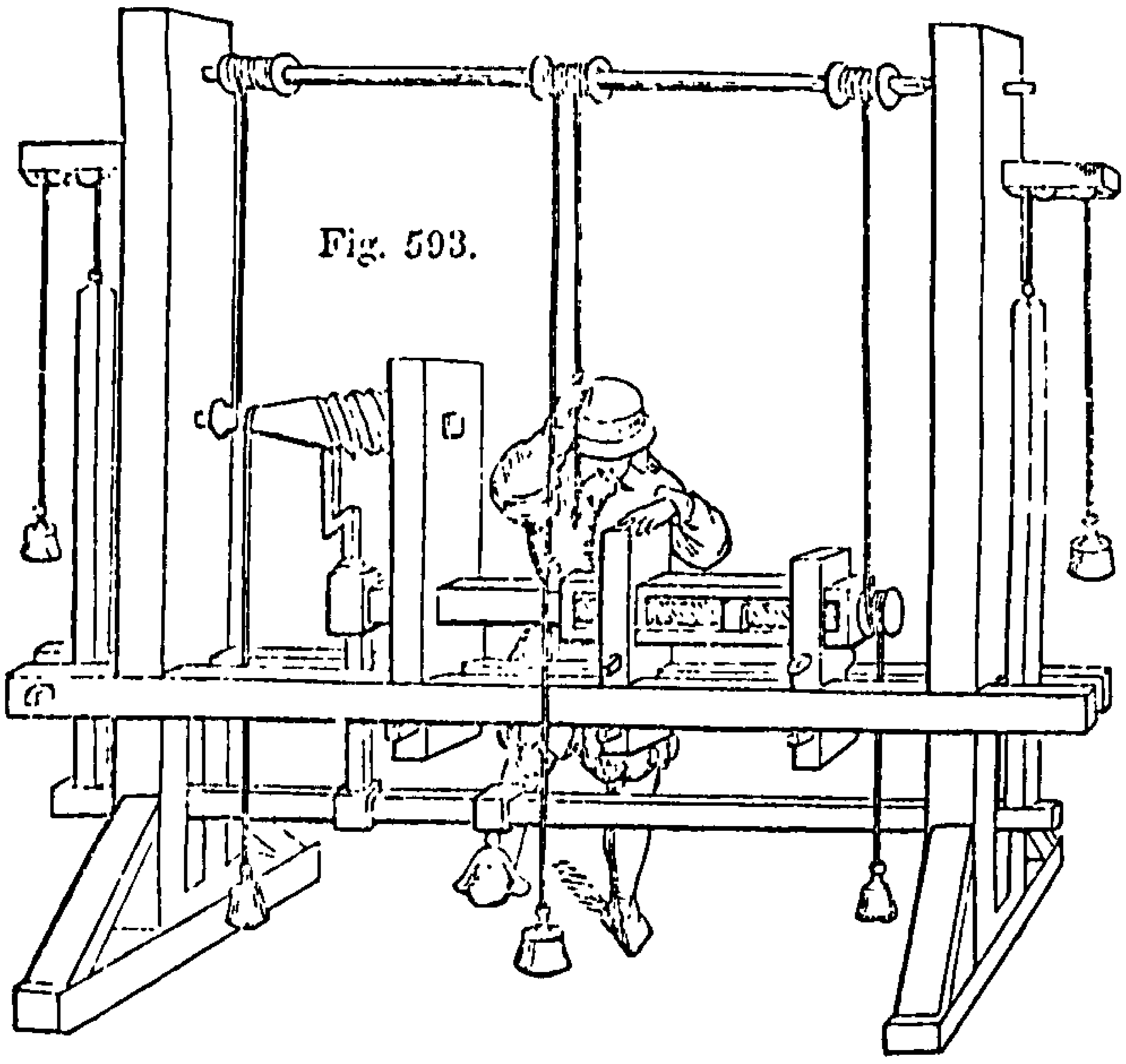
Having marked one of those eight Lines at the top of the *Spindle,* to begin the winding of the *Worm* at, with a Black-lead Pencil, draw a line from that Mark to the second Mark .... and so onwards, till you have drawn over the eight straight Lines, which when you have done, you must still continue on, drawing downwards to each lower Mark on each successive upright Line, till you have drawn your *Worm* from end to end: Then examine, as well as you can, by your Eye, whether the *Worm* you have carried on from the Mark to Mark with the Black-led Pencil, do not break into Angles, which if it do any where, you must mend it in that place: Then with the edge of an *half-round File,* file a small Line in the Black-lead Line .... This small Line is only for a guide to cut the *Groove* down by; for the making of a *Screw* is, indeed nothing else, but the cutting the *Groove* down, for then the *Worm* remains: But you must not *file* in this small line, but leave it as a guide to lie on the middle of the *Worm* (as I said before): Therefore to cut down the *Groove,* take a *Cold-Chissle,* somewhat thinner than you intend the *Groove* shall be wide, *viz.* about the thickness of the breadth of the *Worm,* and with heavy blows, cut out the *Groove* pretty near.... Then with a *Flat-file* open and smooth the *Groove,* filing in the middle between the two next fine Lines cut by the *half-round File,* till you have wrought the *Spindle* from end to end, so shall the *Worm* remain. But you must not expect, that through the *Groove* be cut, it is therefore finished, for now you must begin to use the thin *Plate-Gage,* and try first, whether the *Worm* have equal breadth all the way. Secondly, whether the *Groove* have equal breadth all the way. And thirdly, whether the *Groove* have equal depth all the way; and where ever you find the *Worm* too broad, you must file it thinner, and where the *Groove* is not deep enough, file it deeper; therefore in cutting down the *Groove* you may observe, that if, at first, you file the Worm never so little too narrow or the *Groove* never so little too deep, you shall have all the rest of the *Worm* or *Groove* to file over again; because the whole *Worm* must be brought to the breadth of the smallest part of it, and the whole *Groove* to the depth of the deepest place all the way, especially if the *Nut* be to be *Cast* in *Brass* upon the *Spindle;* because the Mettal running close to the *Spindle* will bind on that place, and not come off it; but if the *Nut* be not to be *Cast* in *Brass,* but only hath a *Worm* brazed into it, this niceness is not so absolutely necessary, because that *Worm* is first *Turned up,* and bowed into the *Grooves* of the *Spindle,* and you may try that before it is *Braz'd* in the *Nut,* and if it go not well about, you may mend, or botch it, either by *Hammering* or *Filing,* or both.

2.4.3 Early Lathes for Screw Cutting:

Although Leonardo da Vinci's notebooks (q.v. §2.3.2.2) have illustrations of what may be construed as lathes on which screws could be made and screw cutting machines (Keller: 1981, p.153) lathes do not appear to have been generally used for generating screws until the late 16th century. However, two early lathes must be noted. An illustration of a screw cutting lathe (Fig. 2.4.2) was given in **Das Mittlelalterliche Hausbuch** of 1483[1] incorporating a lead screw co-linear with the work piece, but in the illustration the formed thread is of opposite handedness from the lead screw demonstrating the artist's lack of understanding of the process! The cross-slide is illustrated separately and incorporates a cross-feed screw and the cutting tool, sharpened for wood, is fixed to the cross-slide by a tapered screw with a head incorporating a square

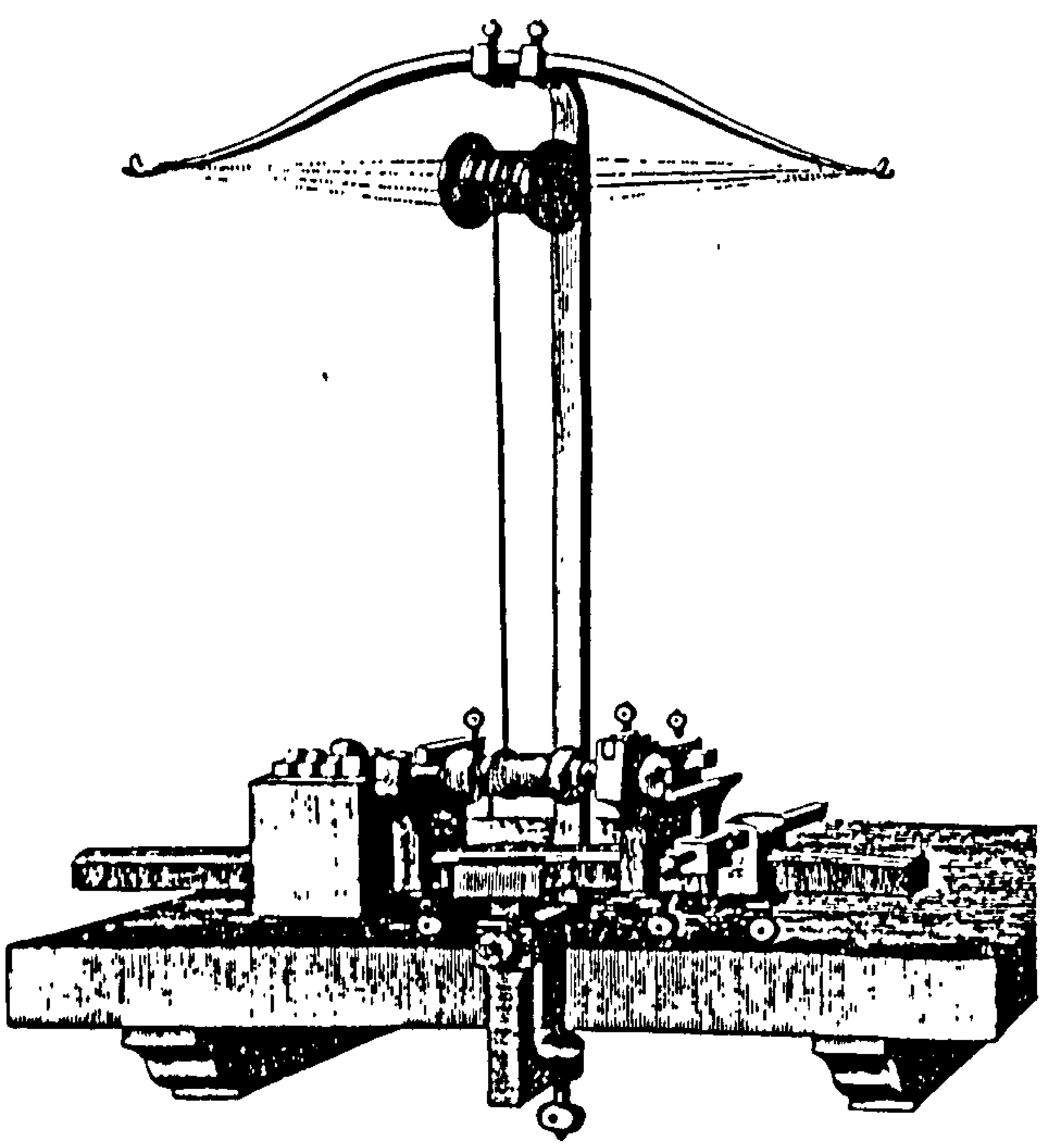
---

1 Reproduced and discussed by Bossert & Storck (1912) and by Battison (1964).



2.4.4 Besson's treddle driven lathe with lead screw and cross-slide for turning wood.

2.4.5 Plumier's (1701) mandrel screw lathe driven by a bow for watch makers.



hole. This machine is more sophisticated than that (Fig. 2.4.3) illustrated by Martin Mertz[1] (ca.1471-5) (Foley, et al.: 1986, pp.25ff.) but with similar features.

With Jacques Besson's lathe[2] (oft reproduced in illustration, Fig. 2.3.4), large screws could be produced such as might be used in wine presses or decorative woodwork (Besson: 1569, pl.9). In principle it could be used to produce screws of any pitch, right or left handed, straight or tapered, circular or elliptical. It was, however, clumsy to manipulate and was not capable of precision work. In this machine, the work rather than the cutting tool was the traversing component. This principle was also attempted ca.1729 by Grandjean de Fouchy (1735, v.5). Grandjean used a lever to force the work, once threaded, through a matching female screw, i.e. a form of lead screw. The pivoted lever suffered a sine term in the motion transmitted which he attempted to correct by running the controlling cord over a specially shaped cam attached in place of the straight lever. This method was not widely adopted.

In 1701, Plumier (Zagorskii: 1982, p.53) considered the best method of screw production to be a chaser employed on a work piece rotated in a lathe (Fig. 2.4.5). This method had the advantage of imparting no progressive errors, but the results were directly related to the turner's skill. Plumier also illustrated a watchmaker's screw-cutting lathe with master threads on a sliding spindle. Slightly later, ca. 1709, Bion described the tools required for scientific instrument making (Bion/Stone: 1758, pp. 255-7). Among them he described the vices, anvil, files, saws,[3] taps, screw-plates and lathes (or leath as Stone termed it). Bion's description of the lathes suggests a small bow lathe like a watchmakers lathe was employed in a vice, and we can probably assume such a device was used to make screw blanks to be threaded in a screw-plate. The larger treadle lathes were equipped with an arbor with several "Threads of Screws of different bignesses, that so Screws may be turned" (p.256). He goes on to say (p.257):

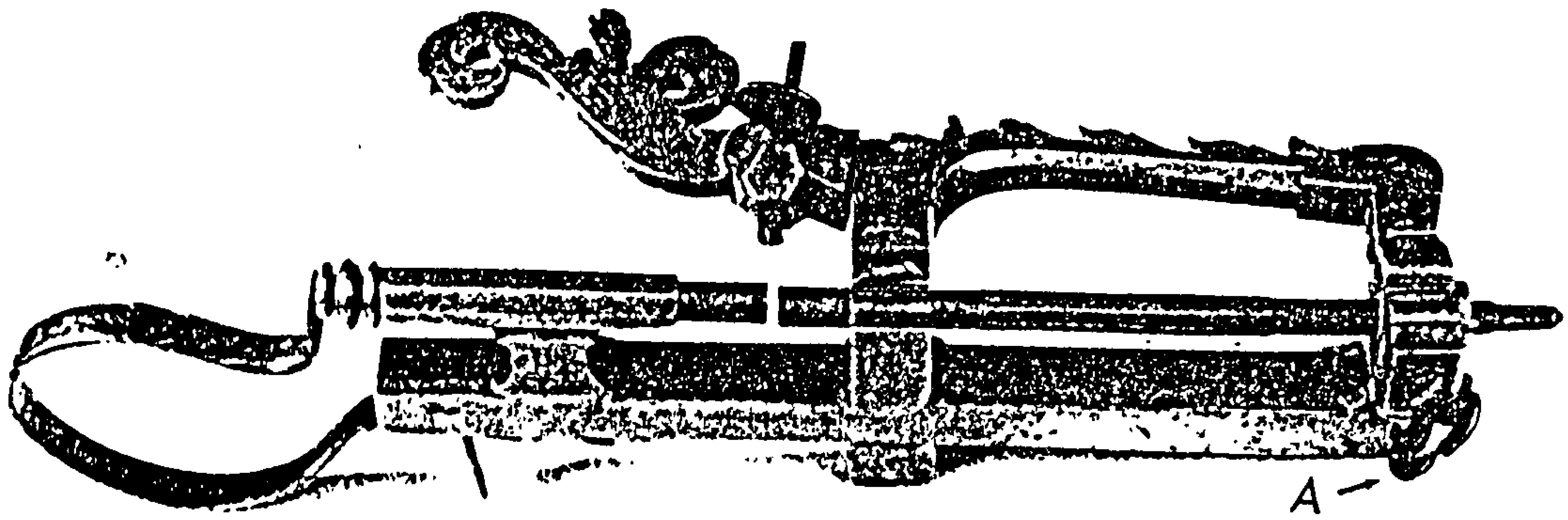
> Male and Female Screws are formed, by putting the proper Thread on the Arbor into a piece of Wood hollowed into a Screw of the same Thread, which is placed at the Poupet carrying the End of the Arbor. And the other End of the Arbor, where is a Colet of the same Thickness, is put exactly into the Hole of the above mentioned piece of Wood; then if the Treader be put in motion by your Foot, the Work will move backwards and forwards, so as that you may form a Screw or a Nut, with toothed Tools made on purpose, according to the Treads marked upon the Arbor. Note, for turning of Wood, Googes, Chissels, etc. are used. But for

---

[1] This was found in a manuscript entitled: "Kunstaus Buchsen zu Schiessen" ("The Art of Shooting Out of Guns").

[2] Holtzapffel (1854, p.615) noted this was the earliest screw lathe of which he was aware. Besson's work also illustrates how to lay out a screw with a narrow strip of paper wound around a shaft (Fig. 1)and several other interesting uses of the screw, e.g. a device to draw spiral involutes (Fig. 6), a double screwed and balanced pile driver (Fig. 22), several forms of lifting cranes, adjustable music stand (Fig.42) and a triple screw press with force exerted through worm and wheels (Fig. 58). Keller (1973) gives biographical information on Besson.

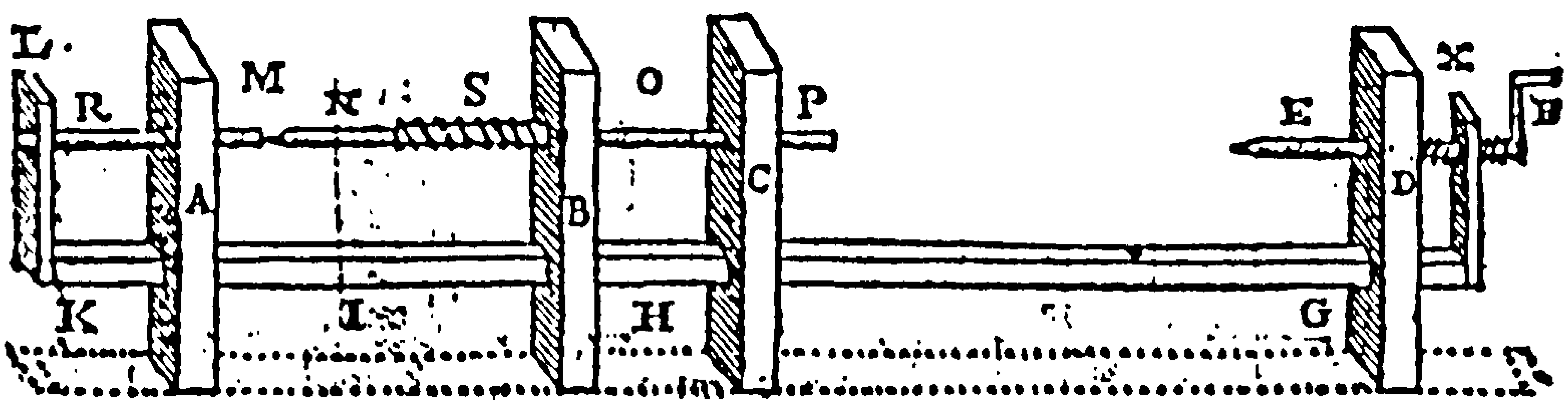
[3] The screw-tightening feature of the modern hack-saw was in use in Bion's time.

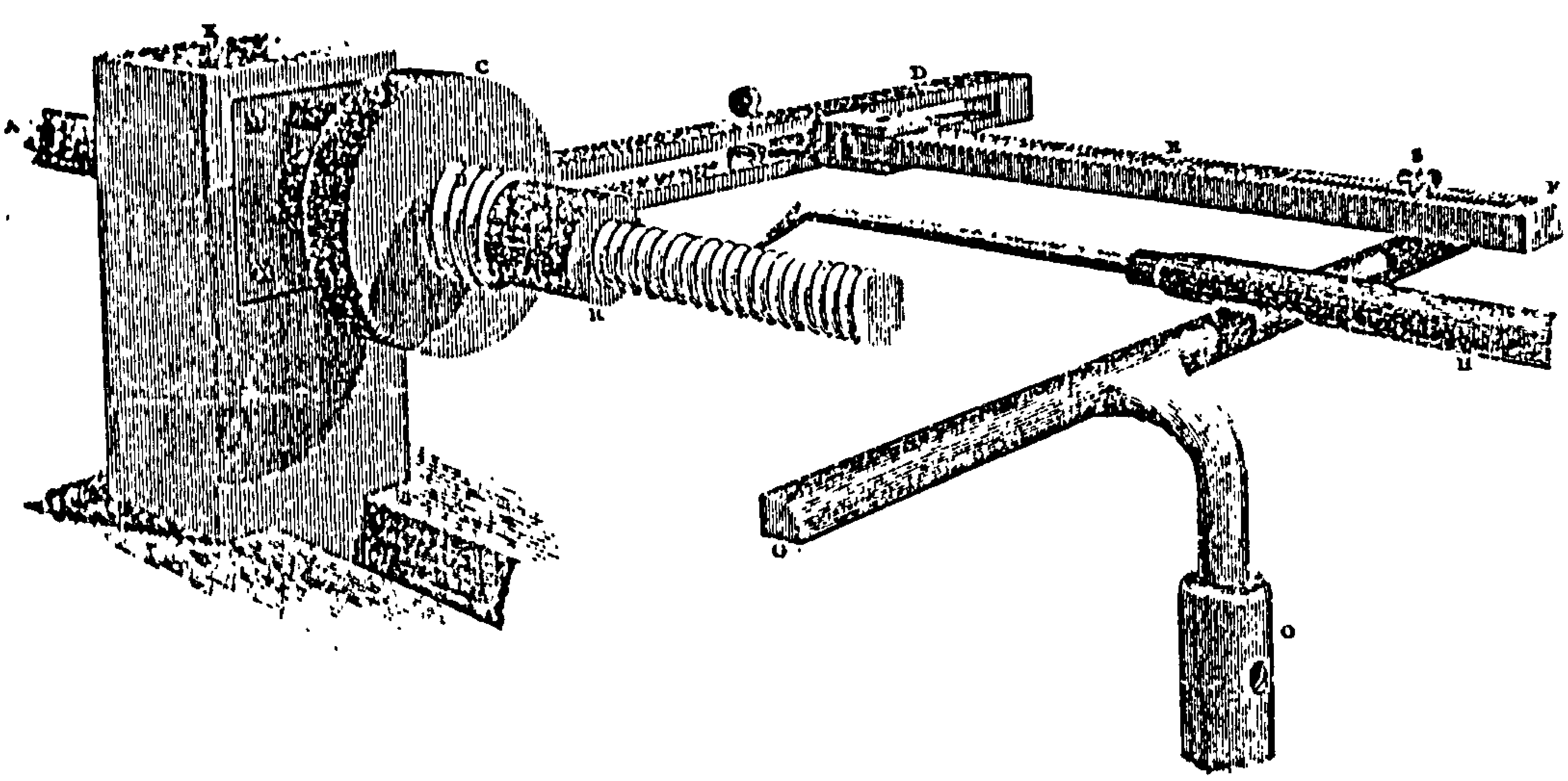


2.4.6 (above) Manuel Wetschgi's small screw 'lathe' (e. 18th c). The lead screw was pushed forward by the curved spring on the left.

2.4.7 The screw lathe with colinear lead screw figured by 'IBN' (1753).

2.4.8 (bottom) Healy's screw lathe (1804) with colinear lead screw and adjustable and moveable slide rest.





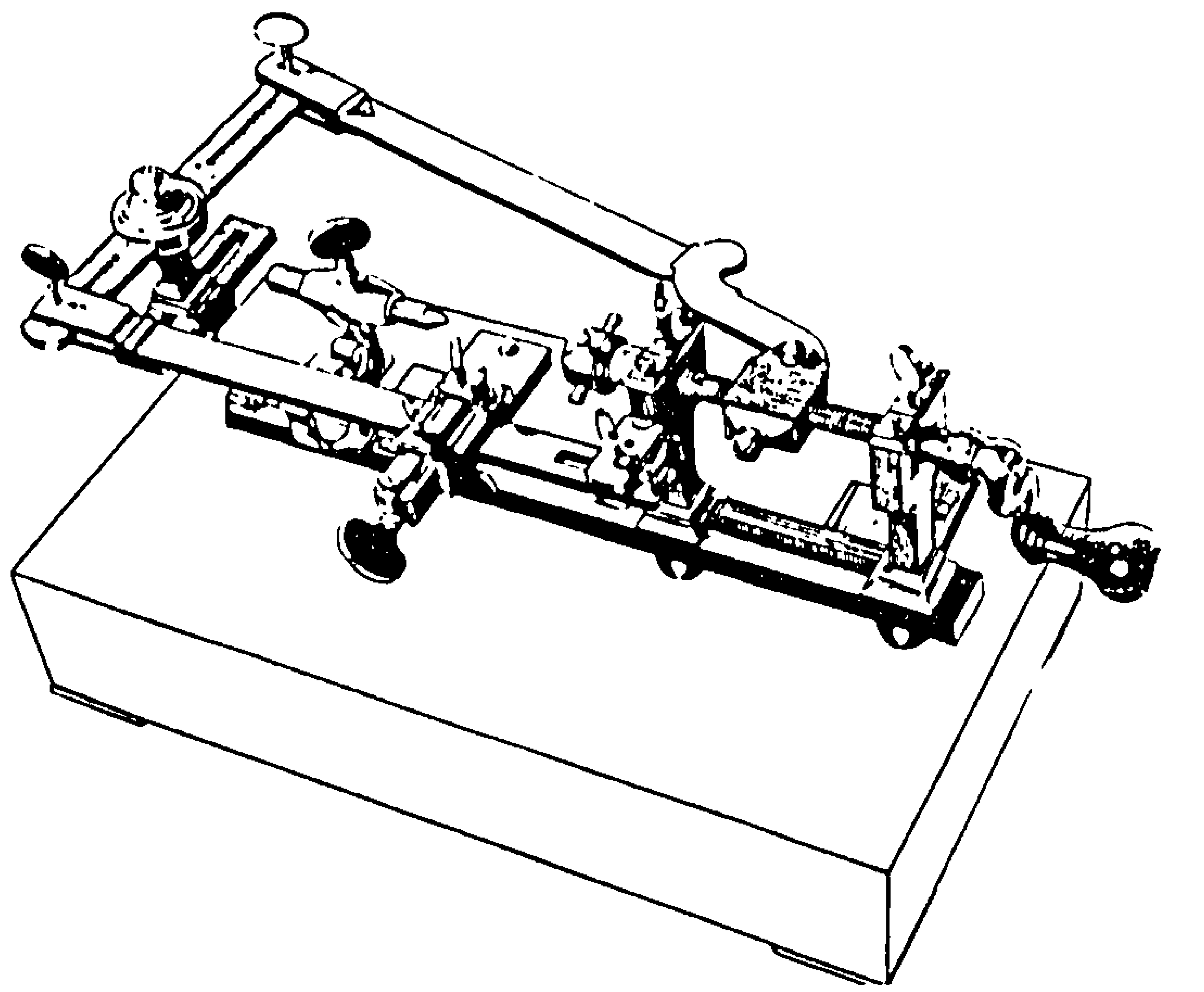
Brass and other Metals, smaller Tools of tempered Steel must be used, as Graving-tools, etc.

Of interest is the device (Fig. 2.4.6) for making small screws (up to 1/2" diameter and approx. 0.5-1.5" in length) signed "Manuel Wetschgi, Augspurg" which is in the Smithsonian Institution (Battison:1964, pp.107-111). It was designed to be used in a vice with a threaded spindle (interchangeable) driven forward by a crank working against a curved spring. The work piece was held between the spindle and spring while the cutting tool was pressed by force of hand against the turning work. The single-pointed cutting tool (more properly 'scraping' tool) is very pointed and one must speculate that the form was filed, rounded and finished once removed from the 'lathe'. Battison's close-up of the binding screw to fix the spring shows a well rounded thread form although not of very uniform pitch or depth. The fineness of the cutting tool and lead screw suggest use for instrument sized screws. The piece was tentatively ascribed by Battison to Manuel Wetschgi (1678-1728) on the basis of his skill as a rifle craftsman, who in later life became chief of artillery to the Landgrave of Hesse-Kassel. A later Manuel Wetschgi was living in Augsburg in 1740.

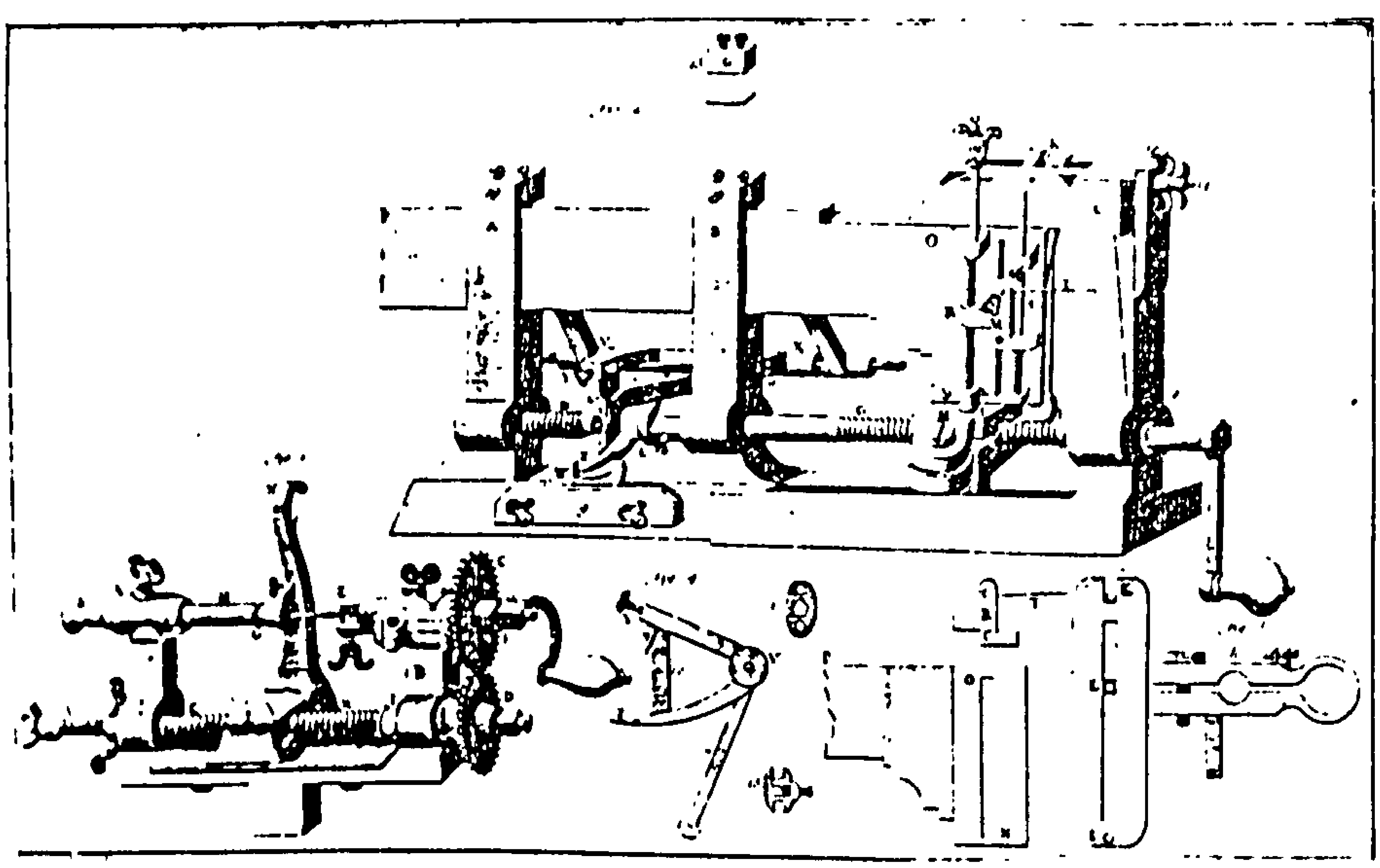
Other lathes using the principle of advancing work included those illustrated in Diderot's **L'Encyclopedie** (1765, v.9 pl.1,2,13,16). One was little different from the German lathe of 1483 described above (Fig. 2.4.2), while a second lathe had a spindle with multiple threads for changing the lead screw with minimal effort. Mandrel lathes remained in use well into the 19th century, e.g. the instrument maker's lathe in the Smithsonian Institution (Battison 1964, fig.16) but gradually lost ground to the more flexible and less limiting lathes with lead screw and change gears. An intermediate means of screw production was the modifications proposed by "I.B.N." (1753) illustrated in Fig. 2.4.7[1] and by Robert Healy in 1804. Healy made a screw thread on chuck 'B' for a lathe as illustrated in Fig. 2.4.8. A female thread was formed on block 'C' which transmitted the motion to the tool 'H' through the arms 'DEF'. Though not shown, the tool was fixed to arm 'F' so that motion of 'C' forward or backward was transmitted to it. A single pointed tool was used to form the screw 'R'. Thus this apparatus had a lead screw though limited in flexibility.

Daumas (1972, p.113) states that screw makers of the 17th-18th centuries most often used hand held tools with a lathe, such as screw-dies, screw-boxes or chasers which gave inaccurate results and off-axis screws. More skillful workmen used a tap or die mounted on the tailstock which was allowed to slide along its bed; the screw tap functioned as its own guide, but could only cut as far as the tap was long. The screws were finished with a file or three tooth chaser. A problem arose since chasers were not as effective when making female screws (Zagorskii: 1982, pp.50-51). In some cases it was

[1] This lathe depends on a rotating mandrel not too different from that preferred by Père Plumier (Holtzapffel: 1879, vol. 4, p.59/60).



2.4.9a Thiout's screw lathe illustrated in his 1741 work on clockmaking. Motion was transmitted from the lead screw to the tool through the adjustable lever arms. These allowed screws of any pitch to be made.



2.4.9b Another of Thiout's screw lathes and his fusee engine which employed change gears (bottom left corner). This was thus one of the first applications of gears to transfer motion in a machine tool.

necessary to make the nut by casting a brass nut on the finished screw rather than using a tap or chaser.

2.4.4 18th/19th Century Methods of Screw Production:

During the introduction of any new technology, the changeover takes time and old and new overlap. Although we described some screw lathes of the 18th c, the designs were not very different from earlier times. But this was about to change. Thiout's screw-cutting lathe (Fig. 2.4.9a) (Woodbury: 1961, p.67/8 or 1972, p.57) relied upon a lead screw connected to the tool through an adjustable linkage. The lead screw was an integral part of the head stock while the tool carriage was moved forward by the adjustable linkage which provide the same function as change gears. Thiout also illustrated a fusee engine with lead screw and change gears in his 1741 work with which he was apparently able to make screws of any pitch for use in clocks with his fusee-engine (Fig. 2.4.9b). The first use of change gears in Western Europe was apparently in a lathe by Henry Hindley (Steeds, 1969, p.17).

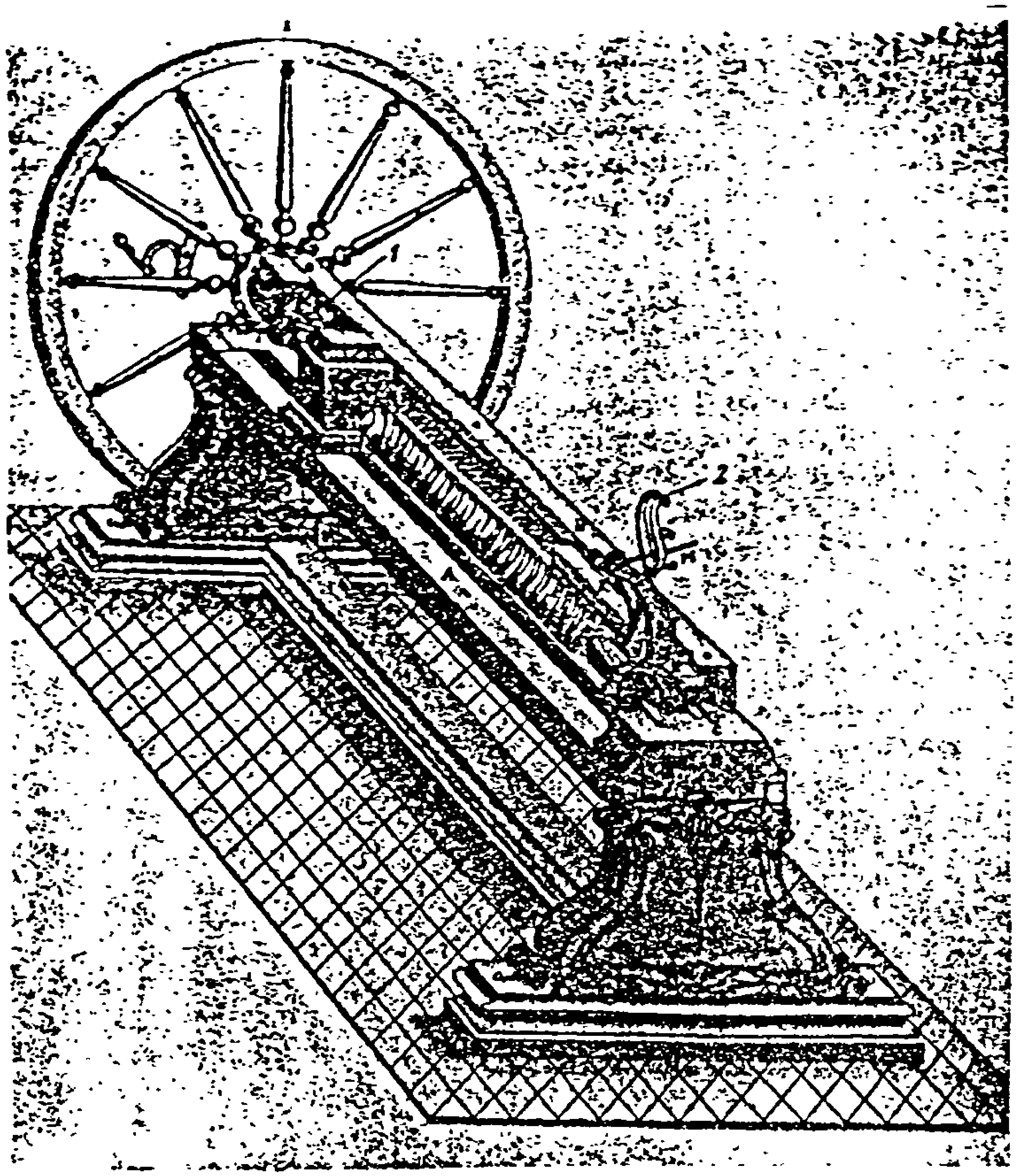
In Russia, Andrei Nartov[1] (1693-1756) (Zagorskii: 1982, p.63-5) made screw lathes (Fig. 2.4.10a,b) in the period 1735-50, one of which was intended for small screws. Specimen screws moved in a nut to drive the work piece past the cutting tool. A larger lathe designed (Zagorskii: p.66) about 1738 incorporated a mechanized side rest[2] and change gears, predating those of Vaucanson by several years and those of Maudslay by some 60 years. Jesse Ramsden (q.v. §2.6.3.1) made a succession of screw lathes including one in 1773/4 which incorporated a lead screw accurate in pitch to 1 part in 100; this small error was then corrected by use of a special change gear (Woodbury: 1972, p.70). Forward (1924/5, p.30) noted that a gun boring mill with a screw feed used in Sweden, was illustrated in the *Memoires* of the Swedish Academy for 1782 and was built along the lines of the machine patented by Wilkinson in 1774.

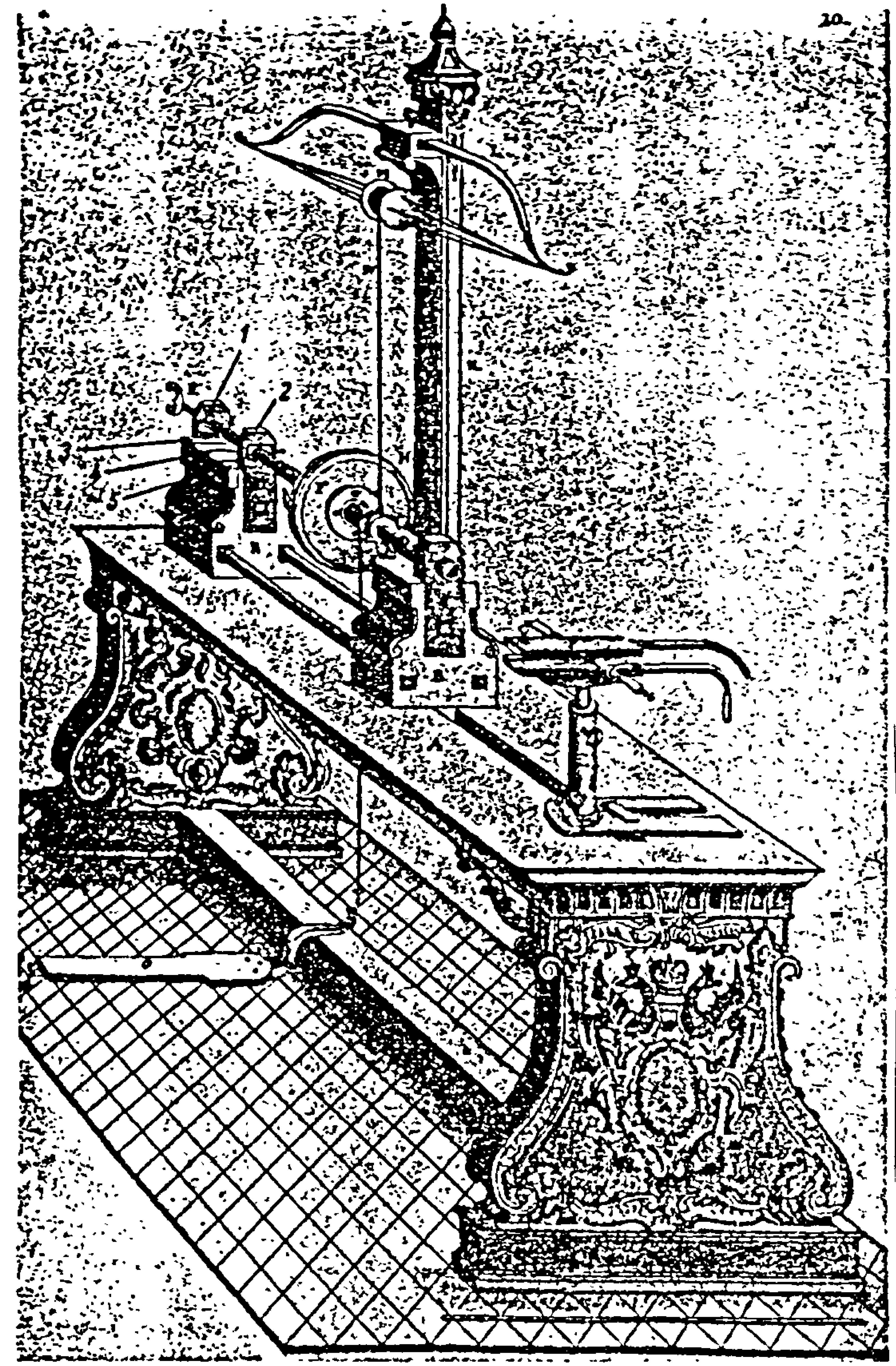
The earliest surviving screw lathe for engineering sized work is that of Jacques de Vaucanson (1709-82) made in the 1770's. It is of metal construction with 'V' shaped ways, a lead screw which permitted travel of the slide rest along its entire length (a first), and is also notable for its square, rather than 'V' shaped, thread. The lathe's purpose is not known and lacks several features found on some earlier machines, e.g. change gears. Holtzapffel, founder of a London tool and manufacturing firm, made a screw lathe in 1785 which was for industrial use and had 10 threaded portions but had no innovations and only had a simple tool rest (Steeds, p.21). Senot's screw-cutting lathe (1795) (Woodbury: 1972, p.87-8) for industrial purposes is sometimes mistakenly

---

1 See Britkin and Vidonov: 1964.

2 The slide rest is often incorrectly attributed to Henry Maudslay (e.g. Nasmyth in Buchanan: 1841, p.401) although it is true that he was primarily responsible for its wide acceptance in the early 19th century.





2.4.10a/b Two of Nartov's screw lathes; that on the right was earlier but had slide rest and specimen screw, I. The lathe above (1738) has lead screw, slide rest and change gears.

claimed to be the first with change gears but it is more notable for its large, well finished lead screw; this is two inches in diameter and 4ft long. Like Vaucanson's, the lead screw's thread was of square section but would have been more convenient to use; both these machines are conserved in the Conservatoire National des Arts et Métiers in Paris.

To demonstrate the slowness of machinists to adopt new methods and equipment, Mercer (1975, p.225),[1] in his description of cutting tools used with lathes, quotes one Thomas Martin from **The Circle of Mechanical Arts** by Richard Rees (1813):

> The operation [i.e. screw cutting], also practiced on metal, is called "cutting flying"...with great sleight of hand, the master turner moves these tools sideways on the revolving but not advancing material, so as to cut the requisite spiral, rather than a series of parallel grooves which if held at a fixed point, it would do. This extraordinary and very delicate work, performed both on the back action and continuous lathe, the skilled turner could and did do when he chose, by hand, notwithstanding the fact, previously noted, that long before this time, automatic devices by means of guide screws to advance the chasing tool along the revolving cylinder, or advance the reversing cylinder itself against the fixed chasing tool, had been in use.

Perusal of Bergeron's (1816) chapters on screw cutting demonstrates that the methods of French mechanics were even more outdated than those of their English counterparts. About 1820, Samual Varley invented a screw lathe[2] (Fig. 2.4.11) (C. Varley: 1825, pp.90-3) which was a link between the old and the new; it was a cross between a mandrel lathe and a lathe with lead screw and change gears. It had the guide threads connected to the chaser through a single pointed thread follower and a guide bar so the cutter moved instead of the work. The bar acted as a slide rest but the apparatus took greater care to adjust.[3] Finishing was completed with a chaser. The Germans adopted a similar set-up for an instrument maker's lathe of the mid-19th c (Fig. 2.4.12). This lathe has interchangeable sample screws and where Varley used a single point as a thread follower, the German lathe has a follower which is several threads wide and has 6 samples.

2.4.4.1 Maudslay's revolution in lathe design:

It is generally conceded that the greatest advances in metal processing were made by Henry Maudslay (1771-1831). Other than the tools designed and made by Maudslay, few machinists had lathes specifically set aside for screw making before ca.1810-20. According to Gilbert (1958, p.423) Maudslay was using micrometers on the tools he designed when he was foreman to Bramah (1789-97).[4] He had made the tools to make

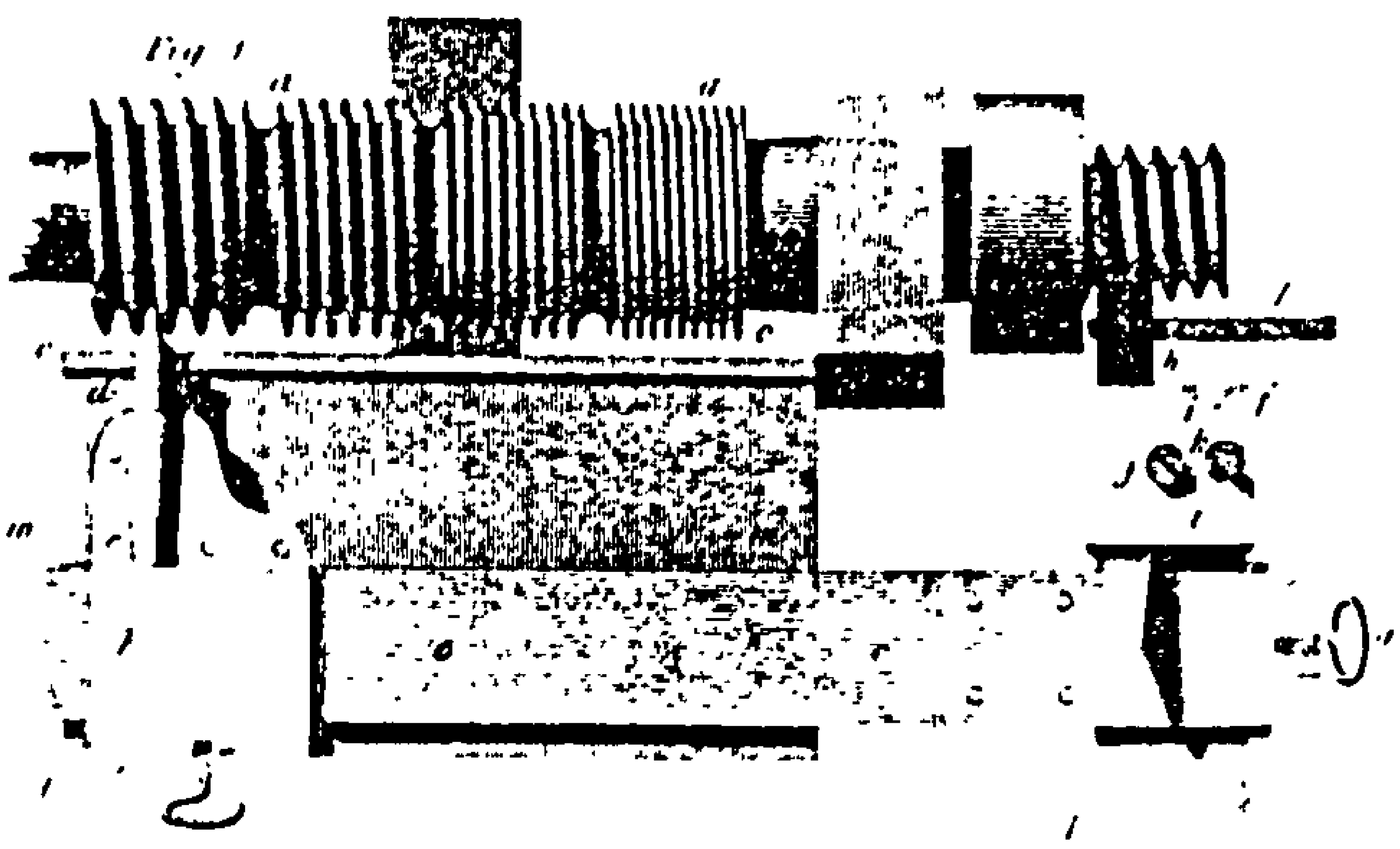
---

[1] Mercer (pp.215-34) provides many illustrations of hand tools for producing screws to the early 19th c. including screw boxes, taps, chasing tools, pole lathes, etc.

[2] He also designed various forms of improved screw-stocks and dies (Gill: 1823, p.33).

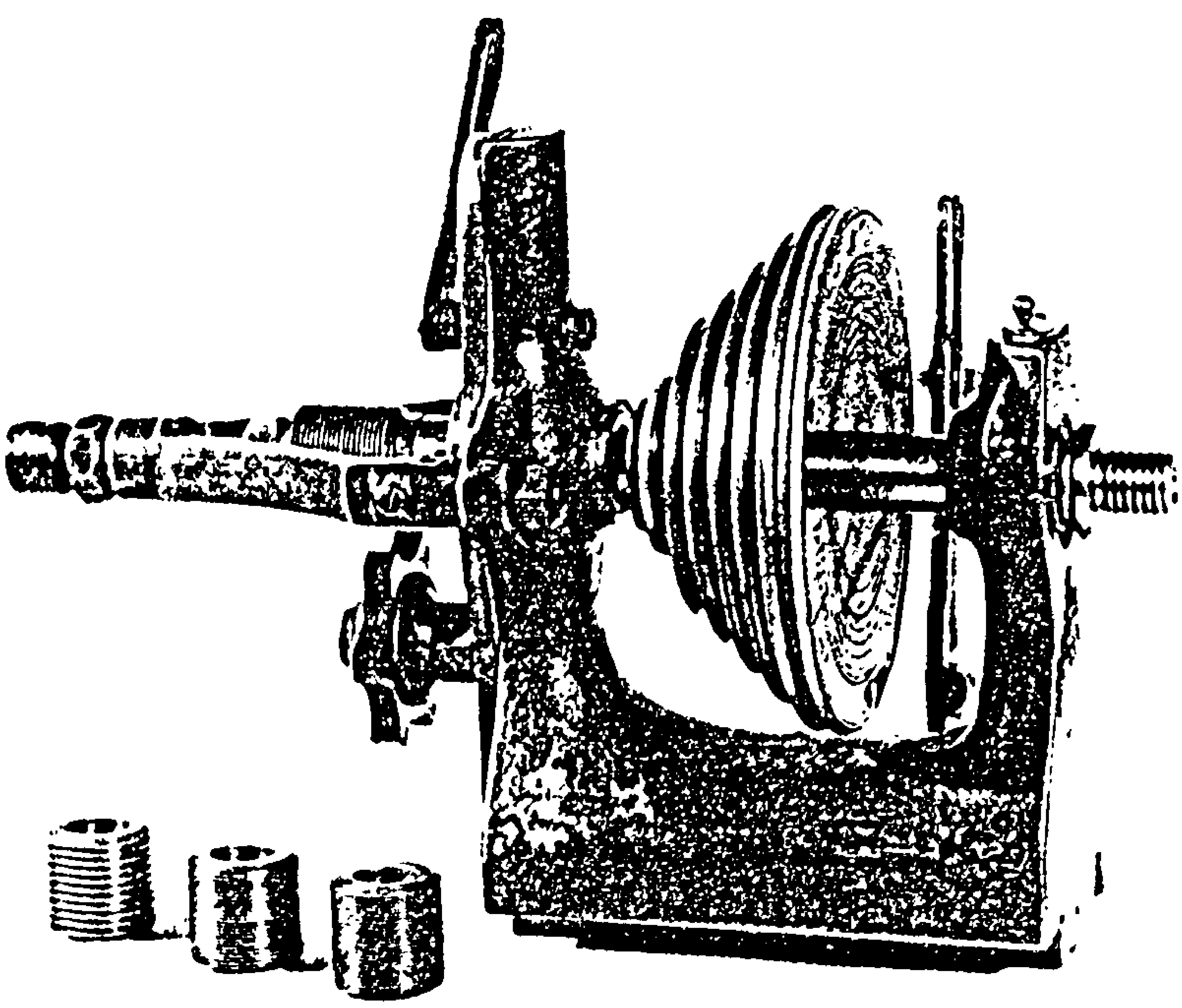
[3] This apparatus was described by Cornelius Varley, Samuel's nephew (1825).

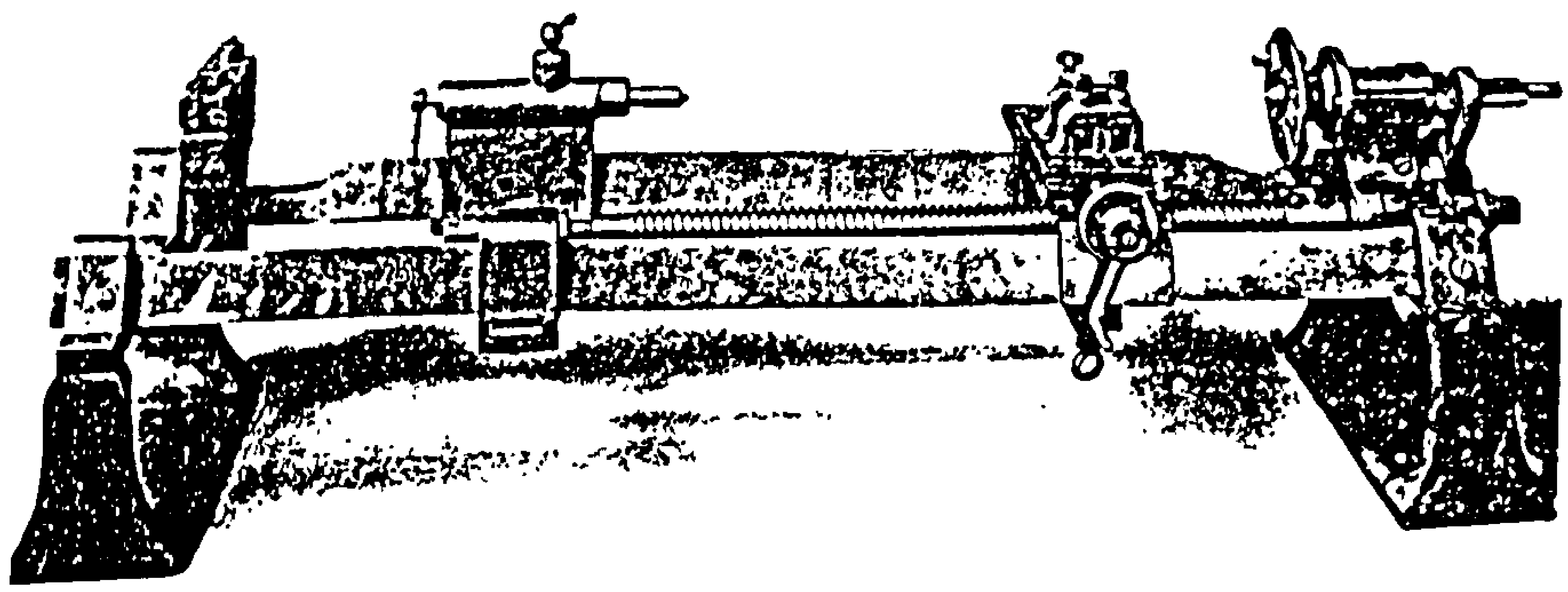
[4] Maudslay also made and used a bench micrometer accurate to 0.0001in as a workshop standard. This was one reason his machines performed better than his competitors. The later use of standard planes beside each workman's bench was another (Gilbert: 1958, p.424).



2.4.11 Samuel Varley's scheme (ca.1820) for copying master screws using a thread follower.

2.4.12 A German instrument making lathe (m 19th c) (Smithsonian Institution) with thread followers (below sample thread on left).





2.4.13 Maudslay's screw lathe (ca.1800) (Science Museum) with lead screw and micrometer adjusted cross-slide.

Bramah's locks and some were so far in advance of those generally available, that Bramah kept them in a secret workshop. Even there, as a result of non-mechanized motions of the cutting tool, the pitch and diameters of most screws continued to vary in pitch. This was also true of threads cut in screw plates since the taps used to make the screw plates had a similar origin.

To make screws of reasonable accuracy requires a mechanized slide rest, first to make the blank cylindrical and concentric, and then as a means to make the depth of the thread constant. Although Nartov had used this means of producing large screws, his achievements were forgotten due to his remoteness from the centres of the mechanical world. Maudslay, by contrast, was in London at the height of the Industrial Revolution and his adoption of this feature had great impact because he was able to demonstrate that superior results were possible when a means to control the position of the cutting tool was incorporated in the lathe. Such means of tool control were an essential element of Maudslay's success in producing revolutionary tools.[1] The slide rest made practical the idea of standardizing screws and Maudslay took the lead in investigating this possibility. The slide rest also facilitated more rapid production since greater amounts of material could be removed in a single passage of the tool. For making accurate mechanisms, Maudslay incorporated micrometers (Fig. 2.4.13) to position the tool. From ca.1795 he was the first to adopt flat test surfaces.

2.4.4.2 Mechanization of screw making:

The screw making apparatus patented by Colbert[2] was complex with several separate pieces to carry out specific functions in the process. Though some were mechanized to a degree, it was still essentially a hand process for making binding screws. But mechanization was developed rapidly. By 1840 Routledge (1876) reports that 20 men using machines for cutting, slotting, shaving, threading and heading screws could make 20,000/day and that by 1875 2 girls each tending a machine could make 240,000/day!

For the small screws used in watch-making, the traditional use of the bow lathe continued well into the 19th century. About 1850-5 the Swiss converted small screw and watch component production to mechanized methods thereby wresting a large portion of the clock and watch market from the British (A.C. Davies, private communication). 'Horologer' (1867, p.108) described the old techniques and the cutting tools used in Lancashire for small screw production. A screw ferrule attached to a small bow lathe was

---

[1] For illustrations of many Maudslay tools as they were found in 1901 in his Lambeth works when the firm of Maudslay, Sons & Field was wrapped up, one is referred to Benson (1901).

[2] Patented 13/05/1817, # 4117; see the **London Encyclopedia** (1832-6), entry 'Screw', p.588/9 or Dickinson: 1941/2, p.82/3 or **Lardner's Cyclopedia** (1829), p.205/6. The later reference also provides a description of the equipment and method of making binding screws using a lead screw to force the screw blank between two cutters.

employed to cut a piece of 'wire'[1] to the required diameter this being determined by a wire gauge with holes slightly larger than the holes in the machinist's screw plate. The turned wire was then threaded in the screw plate, cut to the desired length, slotted with a nicking file or fine saw, and, if desired, had the head rounded and burnished with a screw head tool.[2] An even more detailed description of later practice of screw making for watches is provided by Hewitt (1894, pp.621-2, 652-3).

Holtzapffel (1854, vol.2, p.628) noted that it was most usual and expeditious to make screws with the use of multipointed chasing tools which were produced with a rotating cutter or hob. These were necessary, he says, for the production of all screws with rounded roots and crests. In the 18th century, steel screws had shallow threads due to the difficulty of forming the relatively hard material, whereas, in the 1850's, it was standard practice to vary the depth of thread depending on the material; threads of mid-19th c steel screws were normally cut deeper than those in brass.

Moxon had noted a simple gauge for testing width and depth of threads.[3] His technique was to use a piece of sheet metal of the desired thickness and to insert and run it along the thread he was filing. If the 'gauge' did not bottom or bind between the flanks then he had to file those parts of the thread; if he filed to much, the gauge would be loose and the screw started again. It is probable that Maudslay used gauges to test thread form but no written account has been found. However, Nasmyth (Buchanan: 1841, p.417) appears to have been the first to discuss and illustrate a gauge used for testing the angles of cutting tools. Holtzapffel (1854: 628-629) described how the form of screws could be checked by hammering lead into a chaser or hob thread and then, with a light behind, holding the lead form against a screw to check conformity. This is the first written reference to a test for the form of a screw which has been found, but the technique is likely to have been standard practice among better machinists. The lead form test was also applied to master taps. Chasers at this time were formed by using hobs (similar to a tap but untapered and with several longitudinal groves--usually 8 or 10) rotating in a lathe while traversing the soft steel chaser by use of change gears at a rate equivalent to that of the pitch of the hob. The tools were then sharpened for cutting purposes by filing (ideally using a guide designed to maintain the desired thread angle) followed by hardening. Hardening was liable to be accompanied by deformation which could only be corrected by grinding and hence the need to check form with gauges.

---

1 Horologists still refer to pinion 'wire'.

2 Gordon (1949, p.112 and pl.XXXV) briefly discusses the shape of the heads of screw used in clock-making during various periods.

3 See the §2.4.2 quote on making accurate 'great screws'.

2.5 Standardization of Screw Threads:

As anyone who has worked on old scientific instruments is aware, few screws are interchangeable even if nominally of the same size and found on the same instrument. The reasons are threefold: first the tools with which screws were made were not of an efficient design for cutting and were themselves imprecisely made thus causing variations of pitch and form; secondly, smelting and casting techniques left inhomogeneities of composition and density in the metal; and thirdly, makers used tools with different pitch and form from their competitors in an effort to ensure continued patronage from customers when repairs were required. The first thoughts of standardization came from Boulton and Watt during production of the steam engine, but standardization was not practical on even a moderate scale until screw blanks could be made to uniform size and until cutting action was accuately controlled by slide rests and micrometers mounted on lathes.

The Whitworth and Sellers standard systems are not particularly relevant to precision screws but one can certainly anticipate their influence on other parts of scientific instruments. These systems emanated from the workshops of the most innovative tool makers of the time. Doolittle (1903, p.247) notes of these firms "A.J. Whitworth & Co. were the leading exhibitors at London in 1851 (the Great Exhibition), so were William Seller & Co. of Philadelphia, the leading exhibitors in the 1876 (Philadelphia) exhibition". The fact that these companies had made advances in precision by improved design and production was in no small measure responsible for screw standards becoming a practical possibility. Prior to the mid-19th century, screws could not be manufactured with sufficient consistency to warrant screw standards and even the specialized techniques for making the comparative gauges was lacking for the remainder of the century--at least for small instrument sized screws.

The origins of the ISO metric screw standard began ca.1860; after the development of almost 50 thread forms in France alone, the Systeme Francais (or Sauvage standard) took the lead and within a short time had been widely adopted in France. It was the basis of the first International metric system of 1898. As an offshoot, the Filière Suisse (FS) and British Association (BA) screw threads were specifically developed for fine work such as horological and scientific instruments in the fourth quarter of the 19th century. The resultant cost savings to manufacturers and convenience to users of scientific equipment were long overdue, and the new systems were more rapidly adopted than Whitworth's pioneering standard screw thread system proposed for engineering work some forty years previously. The machine fabrication of watch movements was the driving force both on the Continent and later (>ca.1855) in England where the Preston watch manufacturers were fighting to keep a market share. One is referred to Brooks (1988 I, pts. 1 and 2) for a detailed discussion of the development of screw standards. Only the following sections have been abstracted from these papers as being most relevant to this research.

2.5.1 The Royal Microscopical Society thread:

In 1857 the Royal Microscopical Society adopted a standard screw thread to be used on all microscope objectives. This was of Whitworth form, of 16 TPI, and with a diameter of 0.780 inches. The 'Society Thread', as it was called, was modified in 1896 and 1899 (Beck: 1938, p.18/9) and was later covered under B.S. 3569: 1962. Because of pressure from organizations such as the Society for the Encouragement of the Arts, this standard thread was rapidly adopted by the large number of British manufacturers of microscopes.

2.5.2 The Royal Astronomical Society thread:

The situation in the astronomical community was somewhat different since the number of manufacturers, and the output of telescopes, was much smaller. In 1867 a correspondent to the *English Mechanic* writing under the pseudonym 'Harry' (1867, p.270) notes with respect to telescope eyepieces that "...you will observe there is a rather coarse screw upon the outside (of the eyepiece), the outside part that screws upon the tube..., that is an universal screw. It is called the `society's thread' meaning the Royal Astronomical Society, as these eyepieces are expected to fit any telescope, no matter whose make." Despite 'official' sanction, this thread was not universally employed for we note the comments of one 'J.C.L.' also writing in the *English Mechanic* (1881, p.126). "The number of threads generally used for the eyepiece fitting is 16 to the inch; but as the number of threads required is only 3 or 4 as a rule, a tap or chaser differing slightly from this may be used." To date no original source and specification for the RAS thread has been located and its universality is further put in doubt when we note that a question posed to Maunder (1899, p.90), Editor of the *Journal of the British Astronomical Association*, brought the response that no standard screw existed for either eyepieces or for Sun caps. Many 19th century telescope eyepieces and accessories certainly have threads (rather than being of slip-in design currently used) and those tested are of 16 TPI, of Whitworth form, and with an O.D. of approximately 1 1/4in. Sun caps of the period, however, have a finer thread of 28-36 TPI and 1 3/8in diameter. Mention has been found of a 'Tulley' thread which may have been the progenitor of the RAS thread. Burton and Grubb (1880/1, pp. 41,59-63) describe a ghost micrometer and state "the first of these tubes is attached to the drawtube by an ordinary 'Tulley' screw....and carries at its lower end the eyepiece". The Tulley referred to is presumably Charles Tulley & Sons who were prospering in London until 1846. If this connection is valid, the RAS thread may have begun in the Tulley workshop, and after Whitworth's proposal of 1841, may have been modified slightly to conform to the new standard while among older RAS members, retained the early connection to Tulley. The origins of threaded eyepieces is itself obscure though it was certainly in use by 1829 since George Dollond was modifying his dynameters. Pearson (1829, p.192) noted specifically that the adapting tube was to be threaded and he illustrated the device in plate III, fig. 2. Thomas Jones made a binocular micrometer for Pearson ca.1822 which also incorporated a threaded tube for mounting on the telescope. Troughton's spider line micrometers (Pearson: plate XI, fig.1) also had this feature but the date when the threaded mounting flange appeared is not known. However, it may be suggested that the widespread use of micrometers may have been the impetus for this feature since observers would have wanted the utmost rigidity when attempting to measure position angles.

2.5.3 The Photographic Society of Great Britain's thread for optics:

According to W. Taylor of Leicester (1894, pp.58,568) the Photographic Society of Great Britain had considered the problem of standard screws for lenses, and he himself had spent considerable time on the selection of a suitable thread and gauges. Since lenses for cameras were made by optical instrument makers, one can envision that screws adopted for one industry may have been used by these workshops for instruments where standard sizes and forms had not been adopted. Hence a short discussion of this specialized thread is also appropriate.

Taylor had developed a double ended gauge of go/no-go design to measure the OD of the thread, the difference being just 0.001in between the ends. He indicated that of 'millions of combinations' which had been made and tested with such a gauge, not one combination had failed to fit together. That such a large number had been made suggests this style of gauge had been in use for some years. When the standards were adopted by the society has not been determined although it was obviously by 1894. The standard used Whitworth form and sizes beginning at 1in rising by 1/4in increments. The TPI was 24 from 1in-3.5in diameters and 12 TPI above 3.5in. Taylor notes also that a tolerance of 10/1000in in the pitch was sufficient for this work.

2.6 Techniques Applicable to Creating 'Precision' Screws:

Considerable advances were made in production of micrometric screws through the first half of the 19th century by such mechanics as Henry Maudslay, James Allan (or Allen), John Barton and Alfred Nobert, but these were always made with mechanized screw lathes incorporating contrivances to correct a variety of errors--chiefly of pitch. Where precision was required for screws in scientific instruments, (e.g. microscope focus mechanisms and filar micrometer screws) finishing was carried out on the steel screws with a triangular file, followed by polishing with fine emery and oil. The manufacture of binding screws progressed through development of improved cutting tools and methods initiated by Maudslay, and as a result of techniques and equipment developed for producing precision screws. Maudslay was particularly interested in improving cutting efficiency and the results of some of his experiments may be seen in examples of his taps and dies held by the Science Museum. The Society of Arts provided impetus for improvements in technique or equipment by awarding prizes during the first half of the 19^{th} century. As the century neared its end, the impetus was the need for better spectral gratings which required nearly perfect screws for their production. Those chiefly responsible for this phase of the evolution of the precision screw were Rutherford, Rogers and Rowland.

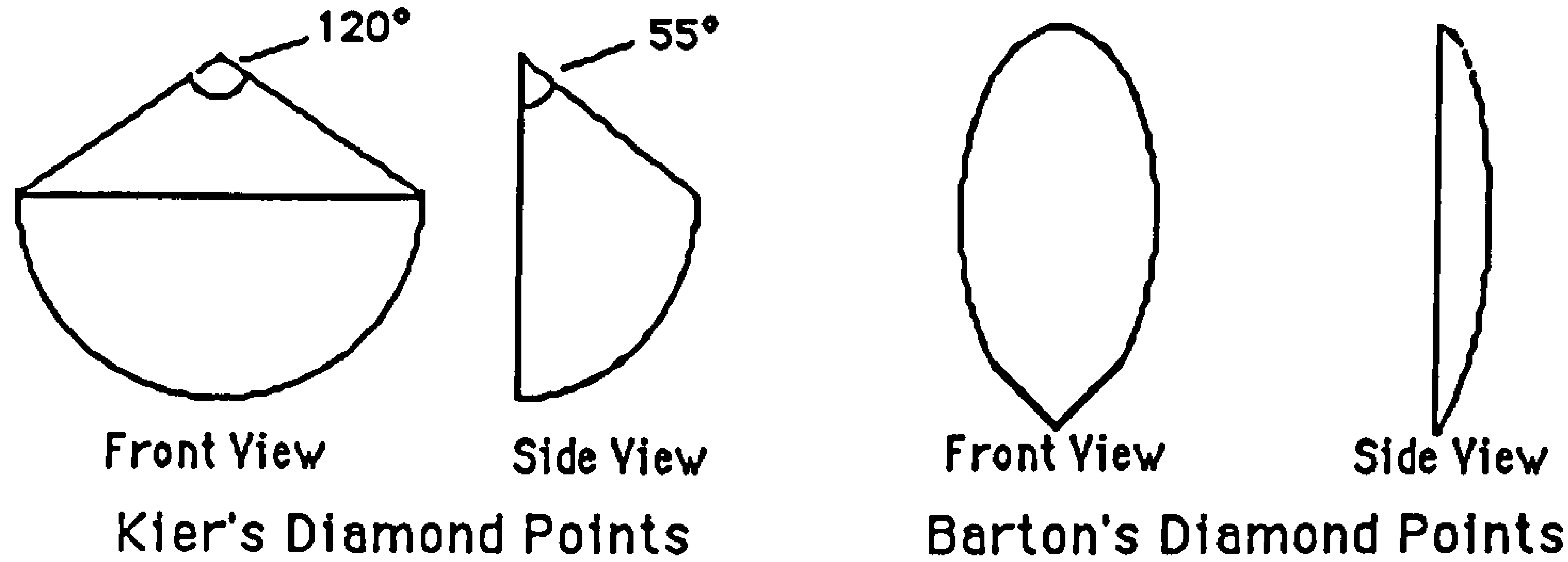
2.6.1 Thread Grinding and Polishing Techniques:

The high degree of polish and finish on adjusting and micrometric screws confirms that a final additional stage of production was used for these screws. One practice was to use a piece of soft wood charged with an optical grinding powder and held against the thread. The wood being soft allowed it to deform to the thread form and polish the thread. Hindley used such a technique to grind the worm and wheel of his dividing engine of 1739 (Smeaton: 1786, p.20). By the mid-19^{th} century Holtzapffel (1854, p.614n) records that threads on glass bottles--which obviously could not be cut with steel dies--were cut by using a traversing mandrel which was slowly moved by hand. The cutting tool was a "metal disc revolving rapidly on fixed centres, and having an angular edge fed with emery and water; in some rare cases a diamond is used as the cutting tool". An application of this technique was useful for micrometer screws since the hardening process often rendered the screw distorted and the pitch irregular. The hardened screws were therefore returned to the original lathe and refinished with a grinding disc tool to remove the irregularities. Such equipment was the progenitor of the modern thread grinding machine with which high precision screws can be manufactured on a routine basis. The 20^{th} century development of these machines has been dealt with by Woodbury (1972)

2.6.2 Use of Diamond Tipped Tools:

Diamond tipped tools have been used for precision work for longer than one might first imagine. In this century they became commonplace in manufacture of high precision screws for the aircraft industry but an investigation of its prior use traces back to the mid-17^{th} century. The first use by Divini in 1649 (q.v. §3.4.5) was to rule a net of lines on the curved surface of a convex eyepiece lens (Petit: 1667, p.103); LaHire (1701, p.119) likewise advocated the use of diamonds to rule lines on glass as a substitute for wires in micrometers. His compatriot, Nicholas Bion (1758, p.156) described a similar application for making a cross on glass to replace wire crosshairs in telescopes: "Note, these lines must be very lightly drawn upon the Glass with a small diamond whose Point is very fine". A succession of other well known names of the instrument making trade followed these leads including Benjamin Martin, John Cuff, John Barton, Joseph Fraunhofer, etc.

We know something of the form of diamond points used by Peter Kier[1] and John Barton from the extensive review of diamond use by Edmund Turrell (1827). The shapes are illustrated here:



2.6.1 Kier's and Barton's Diamond points for screw cutting.

Wilson Lowry (FRS 1812) was the first to use diamonds to engrave plates for publications, in particular those for **Rees' Cyclopedia** some of which are reproduced in this work. Barton had noted that the interior of a diamond was softer and more susceptible to breaking--hence the reason he used natural, rounded, uncut diamonds.[2] In making a grating for Brewster, his diamond broke after completing a large portion; as a result, he did not complete the ruling (Warner: 1986, p.126). Turrell (1827, p.72) drew attention to properties of natural diamonds noting that ones which had been ground, or cut, caused glass to splinter but that he had made rulings on crown-glass with natural diamonds with great success. Mayall (1885, p.713) describes Nobert's method of cutting diamonds and even this great craftsman had difficulty with points breaking during work, despite the fact that his ruling force was only 3-30 grams depending on the number of lines required per inch. Nobert used fragments from a diamond cleaver; chips which would allow a 1/16-1/20 inch long edge to be cut were chosen. One face was ground to an angle parallel to a cleavage-face. The chip was then cleaved to create the other face of the point since grinding frequently left the point rounded--Nobert wanted a perfectly sharp point for ruling glass. He replaced diamond points when glass fragments appeared around the ruling point. The diamond was mounted in a notch in the end of a piece of brass wire.

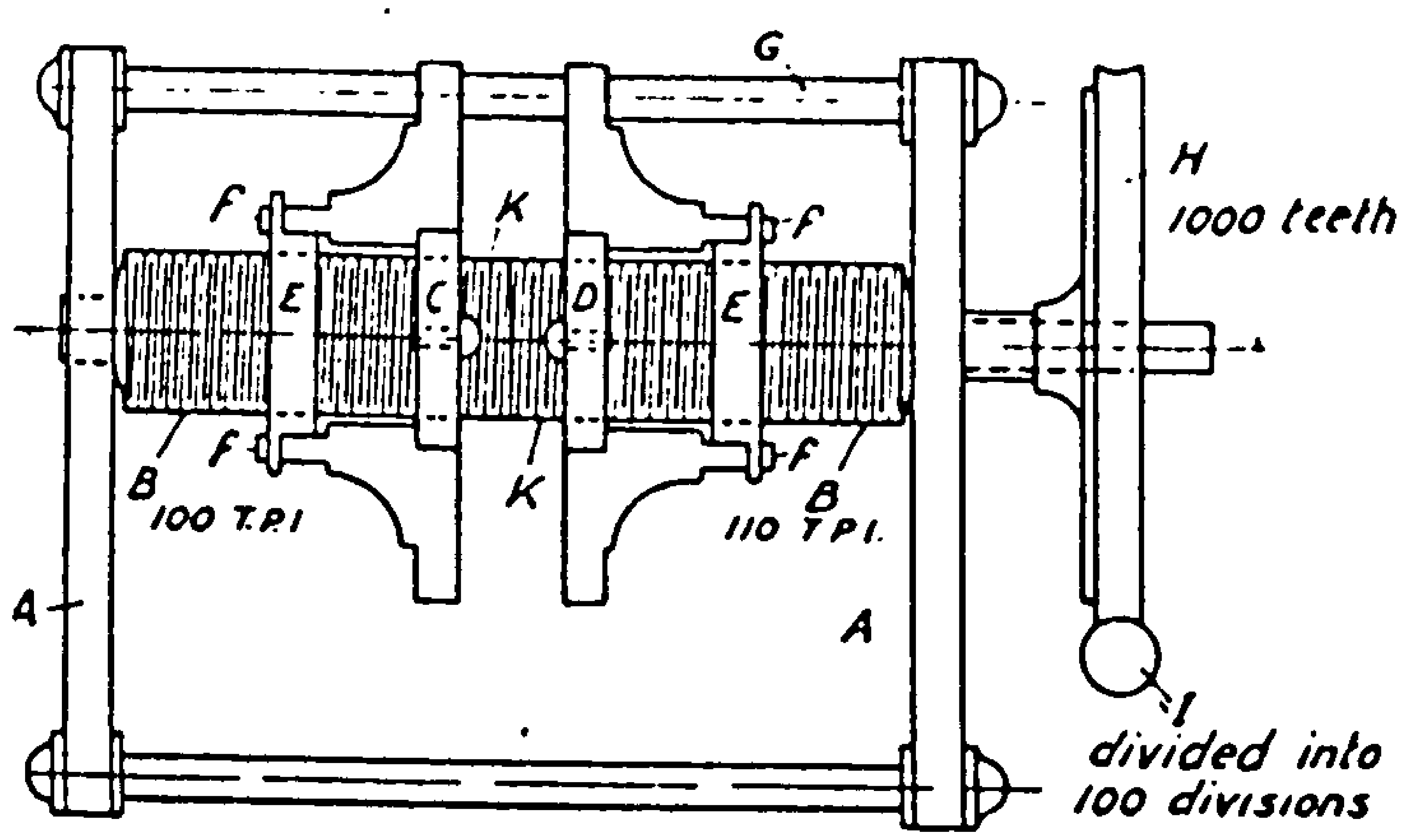
2.6.2.1 Diamonds for cutting screw threads:

The first person to use diamond tipped cutting tools for making screws was Jesse Ramsden. He noted their use in his paper of 1779 on the construction of his linear

---

1 An engineer related in business to James Watt. He also designed new screw-stocks which were described by Gill (1823, pp.182ff).

2 The thread form of the screws on Barton's 'Atometer' (1805) have rounded roots and were probably cut with a diamond tipped tool although a steel tool would have been capable of the job. They are certainly the finest pitched, though not the best, threads encountered for quite a long time.



2.6.2 Barton's 'Atometer' (1805) with differential screws. The instrument, in the Science Museum, does not have very fine movement despite the care which Barton must have used in making the screws.

dividing engine.[1] He made the screw of hardened steel and finishing the thread after the hardening process in an attempt to correct the errors caused by the hardening process.[2] The tool holder and slide are illustrated in Ramsden's original paper and in *Industrial Diamond Review* (IDR) (1944, p.228). Barton used long oval shaped diamonds to tip turning tools and was able to turn a cylinder down to an accuracy of 1/12,000in for Edward Troughton. Turrell noted that diamond tipped tools were always used in conjunction with slide rests and were capable of turning hardened steel with facility. Barton also turned the deferential threads for his 'Atometer' (Fig. 2.6.2) with a diamond according to a letter to Matthew Bolton which is in the Library of the Science Museum (IDR: 1944, p.228/9)

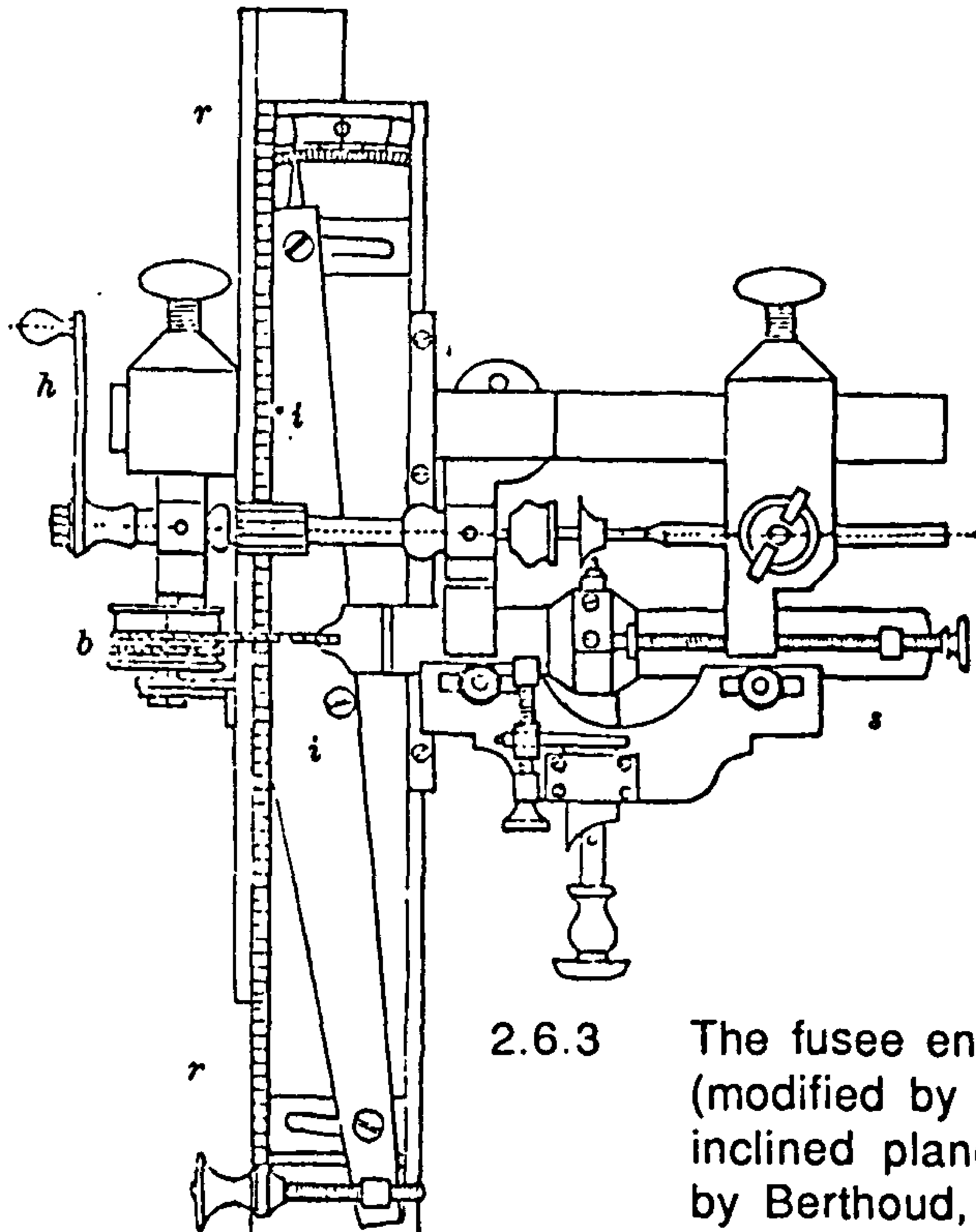
Turrell (1827, p.11) notes that diamond dust was used to charge laps of tin and zinc to polish diamonds. It takes little imagination to suggest that precision screw makers may have adopted similar techniques to polish very fine pitched micrometer screws since the pitch would deform to fit any thread profile. However, it is not until near the end of the century that the method is recorded. The methods adopted by Taylor, Taylor & Hobson of Leicester beginning ca.1888 to make threads for optical components were adapted to make bench micrometers and high precision binding screws for the aircraft industry. William Taylor described the method which included employing diamond dust to maintain the shape of cutting tools (1926, p.601/2). Several standard methods originated in the Leicester firm for production of threads for lens elements, including needles and prisms for measuring threads trigonometrically, optical projection of threads (including the 50 times magnification), 'go' and 'no go' gauges, correlation of errors of pitch and effective diameter, circular chasers for production of screws to 0.001in, etc. Taylor notes:

> In the original shaping of Whitworth threading tools I used the artistic method. The appliances were:--means for lapping the two straight sides of a tool at the proper angle; a flat oilstone set upright on an angle plate; and a tool-holder with three adjustable feet. These were rested on a piece of plate glass, and with them the point of the tool was rounded freehand. The truncation was measured trigonometrically by means of a notch in a steel bar calibrated by the needles, and the accuracy of the rounding was observed by optical projection on the scale of fifty diameters....
>
> On the spindle used to-day for milling accurate screw threads, there are two little circular cutters with the Whitworth thread form lapped at their edges, which are notched radially to present cutting edges. The lapping is done on a special machine by means of a diamond-charged rotating annulus with an eccentric motion so that it maintains its surface in a true plane. This annulus grinds the sides of the thread cutters perfectly straight and to the correct angle, and rounds the crest in a circular arc.....

---

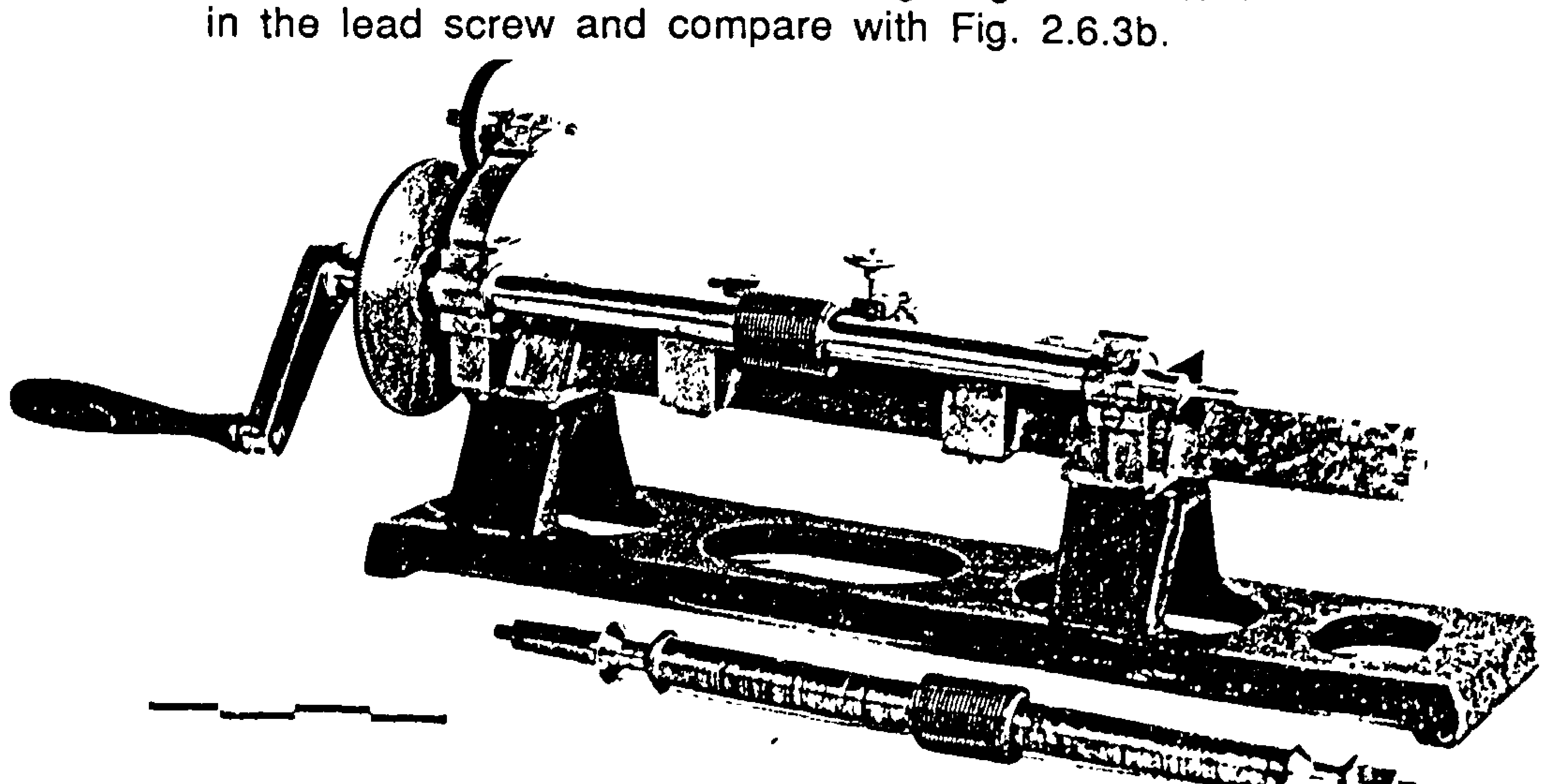
[1] Steeds (1969, p.19) claims that Ramsden used diamond tipped cutting tools on his screw-cutting lathe of 1773/4 but what his source for this was is not given though the implication is Ramsden's description of the machine.

[2] See also entry 'Graduation' in Edinburgh Encyclopedia, (1830), vol.10, p.360. Holtzapffel (1854, p.646n) noted that he had incorrectly ascribed the first use of diamond tipped tools to Sir John Barton on p.42 of vol.1 of his work but had corrected it on p. 14/15 of vol.2.



2.6.3 The fusee engine made by leLievre (modified by Duval) employing an inclined plane. This was illustrated by Berthoud, the French chronometer maker (1763).

2.6.4a Ramsden's screw lathe (1773/4) (Smithsonian Institution) for making his second circular dividing engine. Note the slanted slot in the lead screw and compare with Fig. 2.6.3b.



> If a piece of cast-iron is tapped, the tap comes out freely, but in the case for example of phosphor-bronze a wrench is needed to take it out. From this it is evident that threads cut in cast-iron are thinner than those cut in phosphor-bronze. In fact, when cutting a thread or groove in a lathe one cannot produce within close limits of accuracy a real counterpart of the tool. But we accomplish it in this way: After cutting the groove in the lathe we take one of these discs lapped with the thread form but without the segmental notch which converts it into a cutting tool. We use the complete circular disc as a roller to finish the groove. The slight plastic movement near the surface of the tool steel under the pressure of the roller forms the groove into a near perfect counterpart of the roller. The three cutters are finally adjusted on the milling machine spindle by means of a microscope... With the cutters and spindle described it is practicable to mill screw threads whose surfaces lie correctly everywhere within the very small tolerance of .0002 inch.[1]

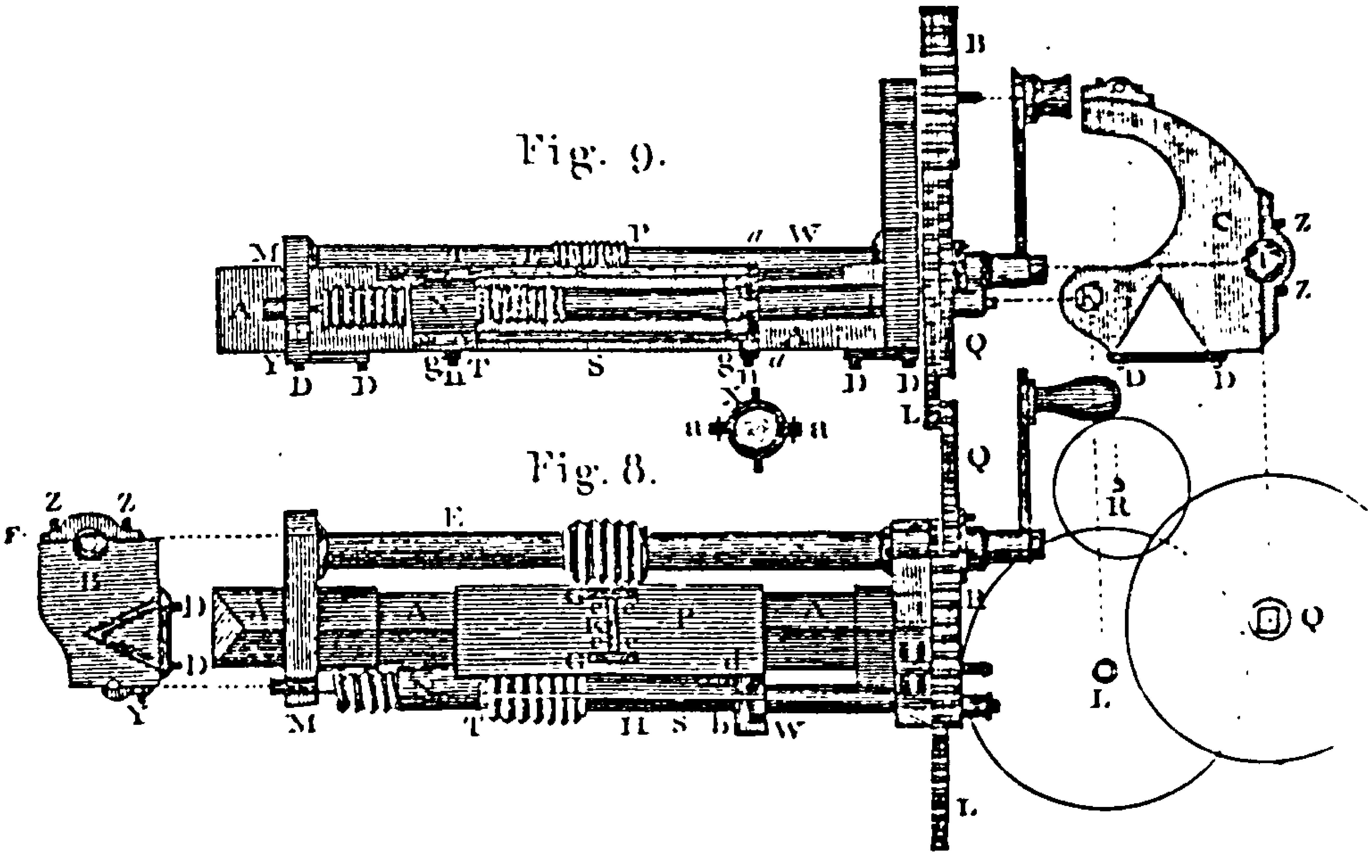
2.6.3 Methods of Generating Precision Screws:

Regulating screws need only have a regular thread with constant pitch, but micrometrical screws often need the added property of having the pitch related to some standard measure such as the foot or meter. Hand-made precision screws appeared ca.1600 but the origin of machine-made precision screws was in the clock maker's fusee engine. The one illustrated (Fig. 2.6.3) employed an inclined plane or wedge. This machine was made by leLievre, improved by Gideon Duval and described by the French chronometer maker, Ferdinand Berthoud in his **Essai sur l'Horologerie** (1763). Motion of the tool is set by the bar *'ii'* which can be set left or right of '0' to produce left or right handed screws with the cutter mounted on the slide '*s* '. The maximum length of the screws was 1in and screws were always of 10 turns if the maximum length of screw was made. Thus this device was severely restricted in its application. Henry Hindley apparently also made a fusee engine based on an inclined plane which is illustrated in **Rees Cyclopedia.**

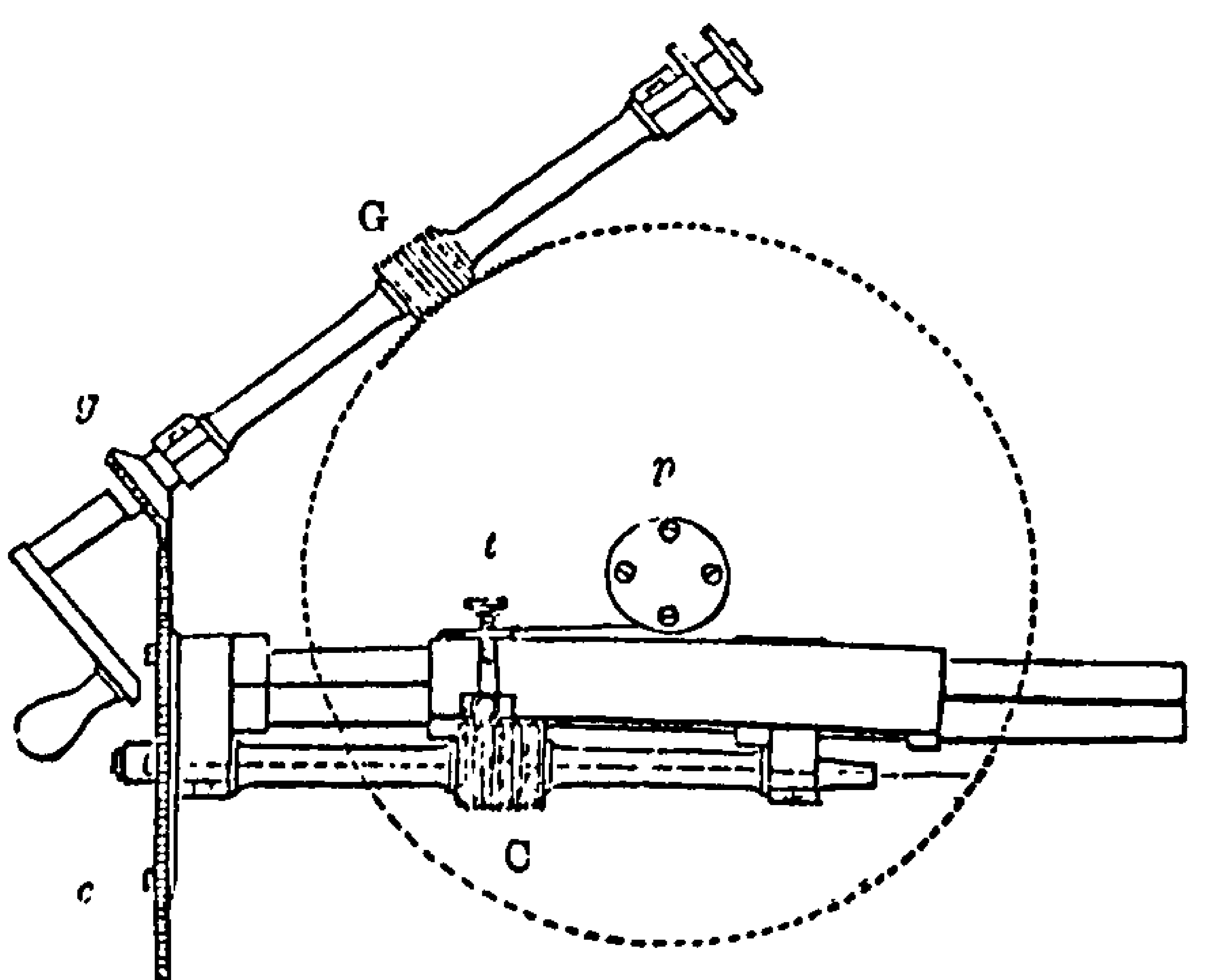
In 1769 'S.W.' (p.286) stated his desiderata for a screw-making device:

> 1) The Screw is to be of any moderate length and diameter.
> 2) Either cylindrical or conical.
> 3) Not to be turned by, or in any wise depend upon any screw already made.
> 4) Any complete number of threads or revolutions, or a complete number and any part of a given revolution, and that with the greatest mathematical accuracy.
> 5) It shall be absolutely certain, that all the threads are every where parallel, or equidistant, or of equal thickness, and every part cut of an equal depth.
> 6) The screw shall be a right or left handed one, as may be required; i.e. the machine shall turn both.
> 7) It may be a single, double, treble, quadruple, &c. threaded screw; i.e. of one, two, three, four &c. sets of parallel threads, with the greatest mathematical exactness.
> 8) The female screw is to be turned with the same accuracy, and to fit the

[1] An analysis and illustrations of the respective quality of small screws made by forcing dies, cutting dies, thread rolling and grinding techniques is given in Brierley (1957, p.701).



2.6.4b Ramsden's screw lathe for making the worm of his second circular dividing engine. Note that the groove in the lead screw of the extant machine is slanted while that illustrated (T) is parallel to the shaft; the extant screw is thus a replacement since Troughton conceived the slanted slot >1793. Replacement of the change gears allowed him to correct errors in pitch.



2.6.5 Ramsden's screw lathe (1773/4) for making the screw of his linear dividing engine. The pitch could be altered by substitution of the change gears. It is interesting to note that he employed a straight master screw in the screw intended for the circular dividing engine but replaced this with a divided circular plate for the screw intended for the linear engine.

male above.
9) After any one cylindrical and single threaded male and female screws are thus obtained, the machine by the help of these, shall turn all others of any number of threads, male or female, &c. as above, and with the same accuracy, but with somewhat less apparatus.

2.6.3.1 Ramsden's Method for making precision screws:

Was the above perhaps the note which stimulated Ramsden to think about a means of producing a screw lathe? His screw lathe certainly met some of the objectives of 'S.W.' and although Ramsden's depended upon another thread, his method would have satisfied the author of the above.

The screw cutting apparatus used by Ramsden for making the screws for his second circular dividing engine (1774/5) is illustrated in Fig. 2.6.4a/b having been taken from Gregory (1806).[1] The base was a triangular steel bar with the cylinder 'E' mounted parallel to the bar being the would-be screw. 'E' had pivots with frustums on each end to fit into bearings to prevent end motion. Ramsden's description (Gregory: 1806, p.319-20 or Steeds: 1969, p.18/9) will provide the relationships of the various components:

> H represents a screw of untempered steel, having a pivot I, which turns in the hole K. At the other end of the screw is a hollow centre, which receives the hardened conical point of the steel pin M. When this point is sufficiently pressed against the screw, to prevent its shaking, the steel pin may be fixed by tightening the screws Y.
>
> N is a cylindric nut, moveable on the screw H; which to prevent any shake, may be tightened by the screws O. This nut is connected with the saddle-piece P by means of the intermediate universal joint W, through which the arbor of the screw passes. A front view of this piece, with a section across the screw-arbor, is represented at X. This joint is connected with the nut by means of two steel slips S, which turn on pins between the cheeks T on the nut N. The other ends of these slips S turn in the like manner on pins (a). One axis of this joint turns in a hole in the cock (b), which is fixed to the saddle-piece; and in the other turns in a hole (d), made for that purpose in the same piece on which the cock (b) is fixed. By this means, when the screw is turned around, the saddle-piece will slide uniformly along the triangular bar A.
>
> K is a small triangular bar of well-tempered steel, which slides in a groove of the same form on the saddle-piece P. The point of this bar or cutter is formed to the shape of the thread intended to be cut on the endless-screw. When the cutter is set to take proper hold of the intended screw, it may be fixed by tightening the screws (e), which press the two pieces of brass G upon it.

Ramsden's method of making the screw for his linear dividing engine is instructive and was considered by the author of the article 'Graduation' in the **Edinburgh Encyclopedia** (1830, vol. 10, p.360 or Steeds: 1969, p.19/20) to be as good as any known even to his time some 50 years later.[2] Ramsden knew that the screw for a circular dividing engine

---

[1] Daumas (1972, p.203 and note 33,p.320/1) noted that the Paris instrument maker, Jecker, made a simplified screw cutting apparatus along the lines of Ramsden's.
[2] Edward Troughton never described his method.

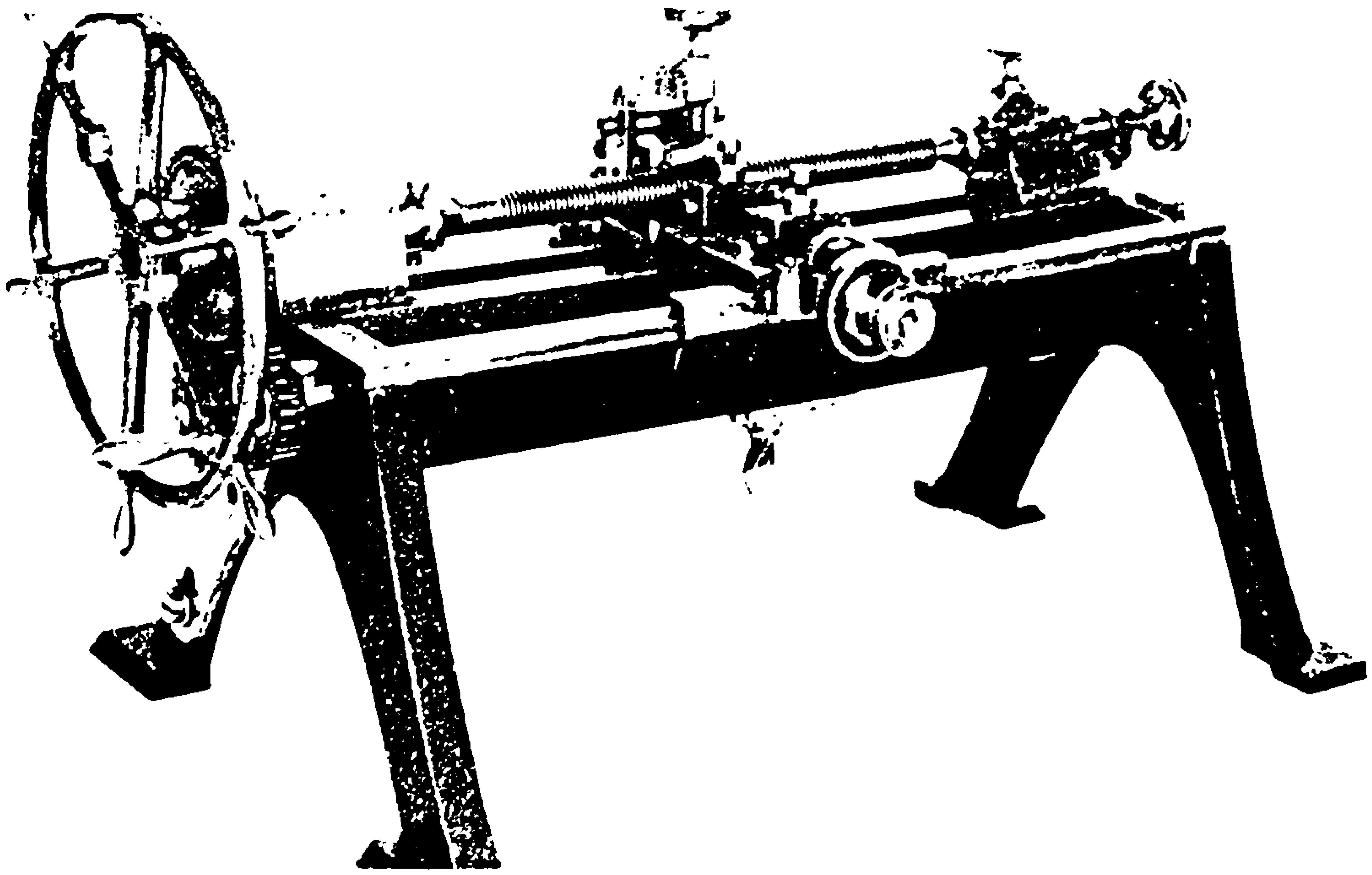
only needed a few accurately made threads and that these required the angles to be of equal inclination to the axis of the screw; but the screw for a linear dividing engine must have threads of equal pitch along its entire length since all teeth are in constant contact with the rack. The concept for his apparatus was similar to that for making the screw of his circular dividing engine though the rectilinear slide was altered to a circular toothed wheel, i.e. he adopted features from the circular engine. The machine for making the screw of the linear dividing engine is shown in Fig. 2.6.5.

To achieve the desired 20 TPI, Ramsden applied his screw lathe in the following manner (1779, pp.13-16). The toothed wheels, 'c' and 'g' (ratio of 6:1) of the machine had to be related to the desired pitch by ratios through the pulley 'p'. Thus the diameter of the pulley defined the final pitch of the screw being made. The pulley's diameter was found as follows: The wheel 'c' was disengaged and the slide drawn back and two dots separated by 5 inches made on the slide attached to the triangular bar. The wheel was then engaged with the endless screw 'G' and one of the dots centered under a wire as viewed with a microscope. The index of the wheel 'g' was set to its zero. The size of the pulley was then decreased by trial until exactly 600 revolutions of the endless screw brought the other dot under the wire of the microscope. 600 revolutions was the number required to give the required ratio between the gears 'c' and 'g' of the lathe. As for the apparatus for making the screw for his circular dividing engine of 1773/4, it is assumed that Ramsden used the most accurate screw he could make using methods for originating screws; it may be that he employed the same screw ('G') but remounted in the new apparatus.

As noted in the section on use of diamonds, Ramsden was the first person to use a diamond-pointed tool to cut a screw and that was probably done for the screw of his linear dividing engine. The screw blank was hardened and then cut with the diamond tool. To make the rack which was 25.6in in length, Ramsden first divided the rack into 0.8in segments by continual bisection. The screw cutter was then placed at the zero of each of these sections and pressed into the edge, rotated 16 times, then advanced to the next section; this was done three times after which the cutter was ratched continuously from end to end until the teeth were completed. Ramsden claimed the accuracy of his engine was 1/4000th of an inch but Shuckburgh, when he was comparing British national standards, was unable to confirm this value since he could find no examples of rules made by Ramsden.

2.6.4 Early 19th Century Attempts of Making an Original Screw:

The name of Henry Maudslay must appear first in this section as the father of precision screws for tools e.g. a lathe's guide or lead screw. According to his one time



2.6.6a Maudslay's small screw lathe (ca.1800) which has interchangeable lead screws and micrometer for the cross feed. This was probably used as a model for a larger lathe and/or to make small screws for instruments and the like.

personal assistant and biographer, James Nasmyth (Smiles (ed.): 1905, p.135)[1] "The production of perfect screws was one of Maudslay's highest ambitions and his principal technical achievement. It was a type of his invaluable faculty of solving the most difficult problems by the most direct and simple methods". Nasmyth said--with some justification--that virtually every precision screw made could be traced back to and to rely on the ingenuity of Maudslay in some manner or other.[2] Maudslay was certainly not the only workman to attempt to make precision screws but because he made many tools sold to other workmen, his lead screws had a tremendous impact.

2.6.4.1 Maudslay's screw experiments:

In his experiments Maudslay tried to perfect methods of screw production (band or chain drives, inclined knife or inclined plane) but settled on the inclined knife method as superior. This he applied in such pieces of apparatus as the screw originating machine now found in the Science Museum (SML-32, see Petree: 1964, p.103) but was also applied to lathes because it simplified the mechanism reducing the necessity to make many complexly interconnected components each liable to add to the errors of the finished screw. Choosing the inclined knife method made the process depend almost entirely on the homogeneity of the material being cut and the relation between the diameter of the cylinder and the inclination of the knife.[3]

Maudslay began by testing the angle of the cutting knife on pieces of alder. The angle of the cutter was adjusted until he could make several screws of the same pitch; he then attempted screws on tin, brass and other soft metals which were of the same diameter as the alder. These were tested with rules and compasses and were also used to drive a nut to see whether the nut advanced smoothly and was free of drunkenness. The best screw was used in a lathe similar to his early examples in the Science Museum and the Museum of Science and Technology in Birmingham (MSTB-1).[4] This lathe had two parallel triangular bars with the lead-screw mounted between them and was driven by a wheel

---

[1] Roe (1914, p.33ff.) gives interesting background on Maudslay and his influence. Nasmyth also worked for Maudslay from 1829-31. See also Petree: 1964.

[2] e.g. Richard Roberts (1789-1864) worked for Maudslay then made his own screw lathes (1817,1820). These are described briefly by Steeds (1969, p.31/2) with the latter being back-geared with 'V'-shaped ways--both features which were widely adopted. Roberts made a planing machine for iron in 1817, possibly the first. See also Dickinson: 1945-7, pp.125-6 and *The Engineer*, **110** (1910), p.431. Some biographical information and a portrait can be found in Roe: 1914, p.59/60.

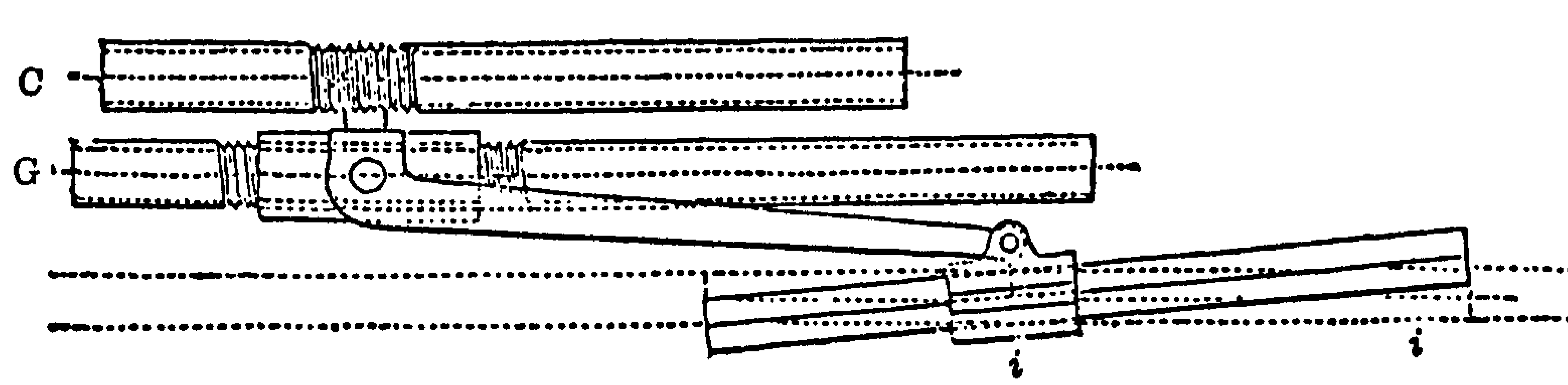
[3] Burstall (1968, p.26/7) illustrates the functioning of a related screw originating machine.

[4] Maudslay's first screw lathe was made in 1797 and had a lead screw of 4 TPI and 1in diameter. The second lathe was made in 1800 and was described as being of instrument maker's size. It had a 3in swing and was 3ft long. Another made in 1800 (Fig. 2.6.6a, SML-21) was described as a tool room specimen (Steeds: 1969, p.22) and is briefly described by Roe (1914, p.41). Other lathes incorporating design features found in this lathe (probably intended as a mock-up model) were used to make numerous precision screws such as the 5ft screw.

attached to the mandrel rather than by a pulley system. The lead-screw was driven in turn through three gears (or 2 or 4 if screws of opposite handedness were desired).

Using the cutting knife method Maudslay made an accurate screw used as a guide screw on a lathe; he made a 5ft long, 2in diameter screw of 50 TPI and matching nut of 12in length (i.e. with 600 threads) which was used for many years to divide scales for "astronomical and other metrical purposes of the highest class" (Smiles:1905 , p.136). Because he distrusted other mechanical means of measuring, Maudslay made another of his masterpieces, the 'Lord Chancellor', a bench micrometer/comparator some 16in long which he considered the 'Court of Final Appeal'. The scale was divided to tenths of an inch and by a wheel to hundredths or thousandths. Nasmyth claimed it could have been divided to a millionth of an inch but to no purpose in the shop.

Holtzapffel (p.643) states that Maudslay attempted many experiments in the relationship of the guide-screw and copies to improve the accuracy. Maudslay changed the lead-screw end for end and made screws with different parts of the lead-screw. Sometimes he used two screws of the same pitch side by side and driven by 3 equal gears and connected by a nut attached to a yoke which in turn was linked to traverse the work; thus the motion was the mean of the two screws. Steel taps were made and converted into original taps which were then used to correct minor errors of other screws. By such means Maudslay made a 7ft long screw which was in error by 1/16in in its entire length; this could have been partially corrected by using gears of 1000 and 999 teeth but he chose instead to use a lever system as illustrated below. The inclination of the



2.6.6b Maudslay's bar to correct errors of pitch of a lathe's lead screw.

lever 'ii' could be adjusted to give any correction required to the guide screw 'G'. A new corrected screw was made which was 7ft exactly. The correction by this means was of course linear, but he realized that the bar 'ii' could be slightly curved to correct other errors if desired. Holtzapffel does not mention whether any screws were made with such a modification.

Maudslay was also the person responsible for the introduction of cutting taps and dies rather than those which squeeze the metal into a thread. His specimens had the 3 fluted form used today[1] and he also introduced the three types of tap, viz. entering or taper, middle and plug or bottoming tap. Samples of Maudslay taps and dies are found in the Science Museum (SML-15). Between 1800 and 1810 Maudslay revolutionized screw making not only with the above advances but also by adopting a systematic series of screw sizes from watch screws up to bolts 6in in diameter as were used on pistons of steam engines. The series was chosen to make a regular progression in the strength of the screws with the diameters being multiples of 1/16in and the pitches chosen as simple numbers, e.g. 3,31/4,4,41/2,6,8,10, etc.; such screws found their way into the workshops of Britain. Maudslay's efforts to improve screws and their methods of production continued until his death in 1835 and set the stage for Whitworth's efforts to standardize screw threads; without the ability to make quality screws, Whitworth's efforts would have been futile.

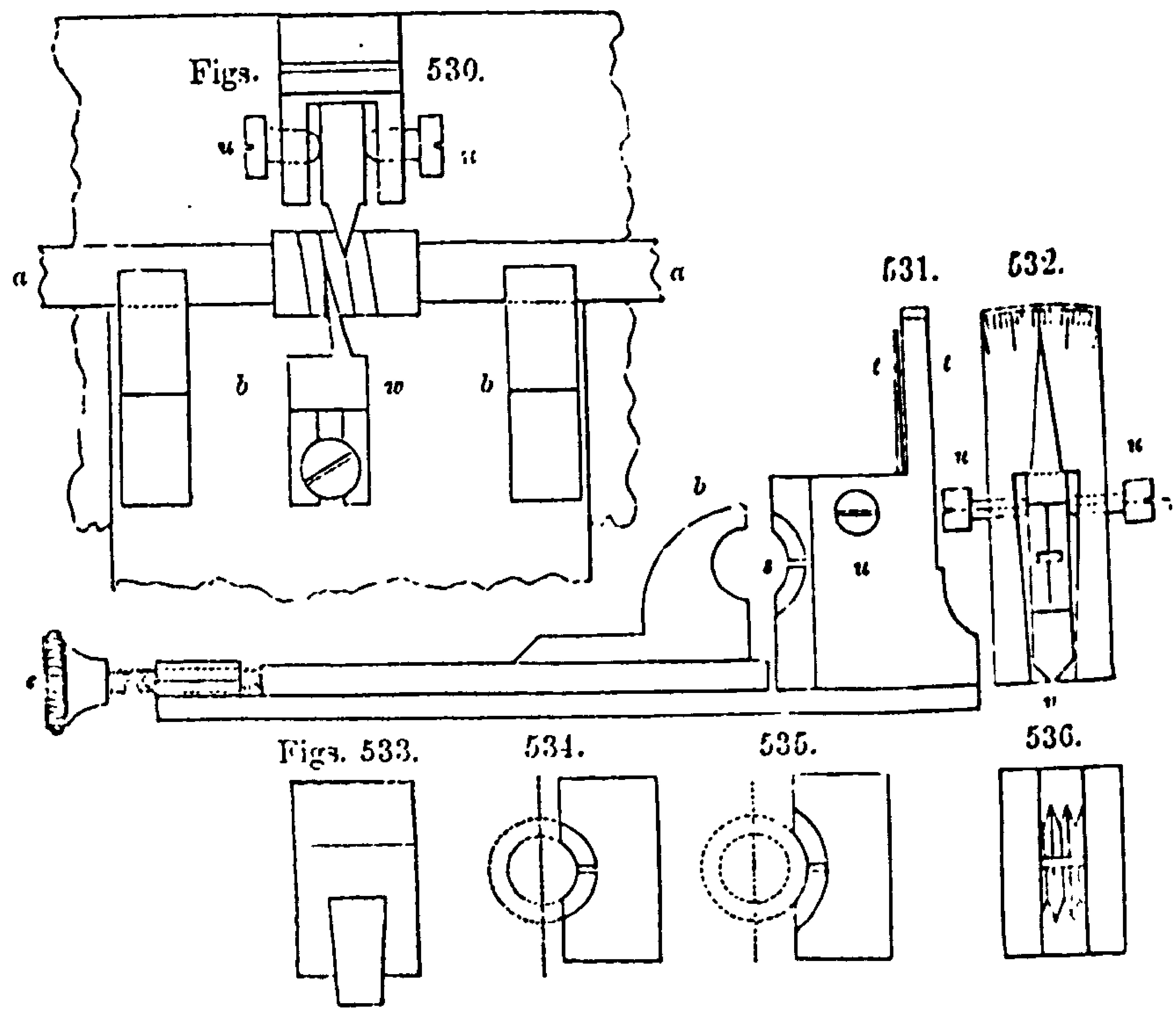
2.6.4.2 Robinson's precision lead screw:

Anthony Robinson of Birmingham made an original screw by the following method (Holtzapffel: 1854, p.580 or Roe: 1914, p.39). A cylinder of 7ft was accurately turned to 6in diameter and then a long piece of paper was cut to precisely wrap around the cylinder. This was removed and precisely marked with parallel oblique lines before being returned to the cylinder. A centre punch was used to delineate the desired triple thread. A hammer and chisel were used to cut out most of the material and the square thread smoothed with a file. A box was then constructed around the screw and a lead/tin nut cast on it; this was used as a sort of guide nut or slide rest to guide adjustable cutting tools to correct the thread. The nut was advanced by turning a lever about the screw. Holtzapffel speculated that a gun-metal nut replaced the working nut. The results generated, at the time, a certain amount of admiration.

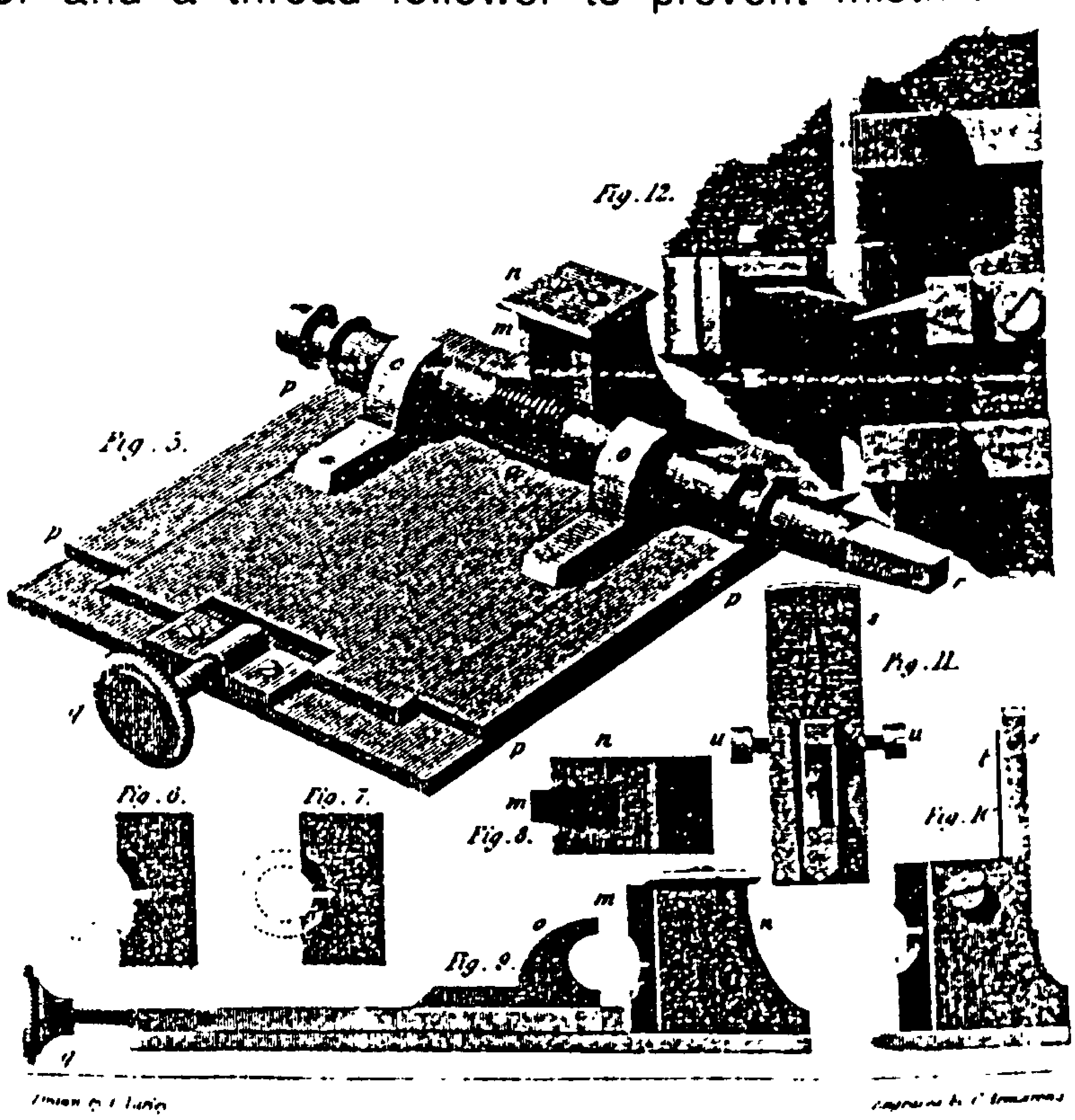
2.6.4.3 Barton's precision screws:

Sir John Barton frequently visited Maudslay and made precision screws as well. However, he preferred to use a chain or flexible band to traverse the cutting tool because the diameter of the pulley or drum afforded a ready means for adjusting the length of the screw being made. This technique was susceptible to errors due to the elasticity of the band or chain especially as more of the band or chain was uncoiled. Both Barton and Maudslay made a screw of the same pitch and 15in length and these were submitted for comparison to Edward Troughton who used two reading microscopes with cross wires as were used for scale reading on astronomical instruments. Mounted as a pair of compasses, Troughton compared the equality of 20, 50 and 100 threads chosen indiscriminately. He found the screws--which appeared be very accurate to the unaided eye--"to be full of all kinds of errors, being unequally coarse at different parts, and even irregular in their

[1] Bodmer introduced the chamfered flutes which improved the cutting efficiency.



2.6.7 James Allan's screw originating machine (1816) with oblique cutter and a thread follower to prevent misthreading.



angles, or 'drunk'. This rigid scrutiny led both parties to fresh and ultimately successful efforts...." These tests were made about 1810.

Barton's technique for correcting the screw (similar to the one used by Rogers 75 years later) was to use two dies separated but linked together and run back and forth along the screw to correct the minute errors. Barton used this method in production of the screw for his dividing engine discussed in §4.4.2. As a testimony to the accuracy of that apparatus, he claimed that if, in ruling a grating of 2000 lines per inch, he missed a line he could reposition the graver and rule it in its correct position.

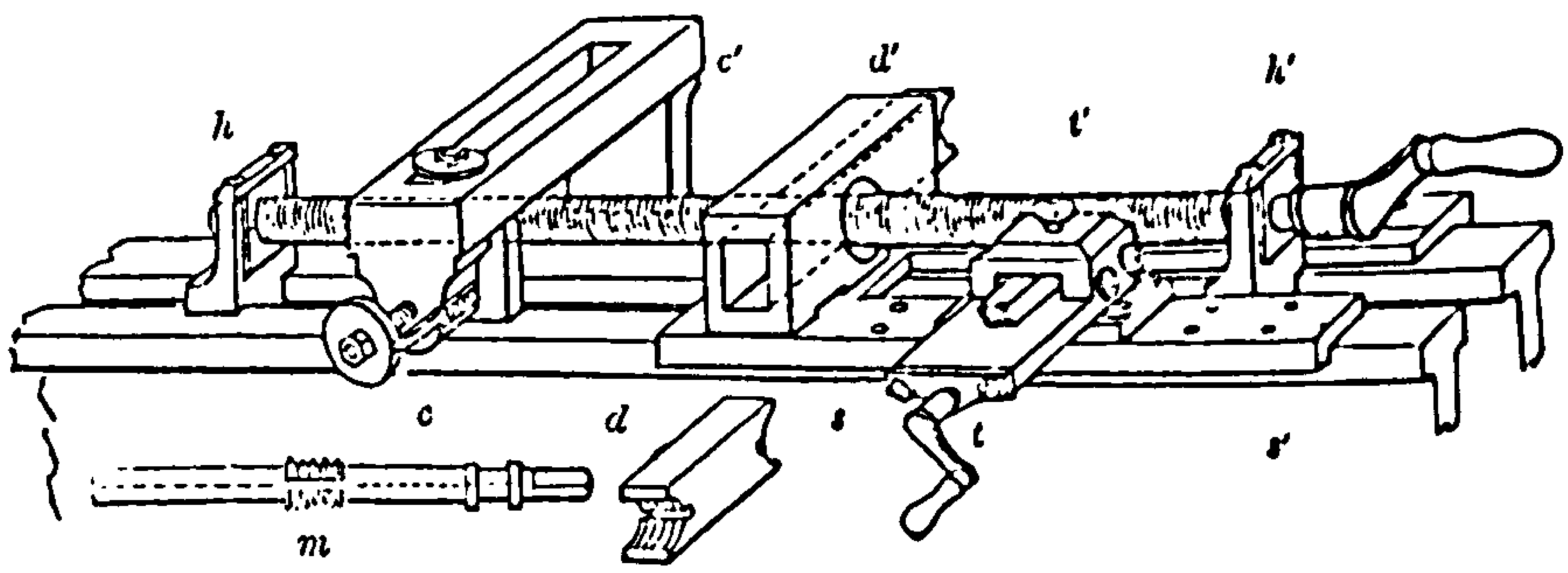
2.6.4.4 Allan's method:

James Allan received the Society of Arts' Isis Medal in 1816 for his method of making micrometer screws (Allan: 1816; or see *The English Mechanic*, 1865, v.1, p.91). Allan notes that his interest in screw making began late in the 18th century when employed by the instrument maker, Charles Fairbone. He was required to make the screws for imparting the vertical and horizontal motions of telescopes, but found that the methods used caused two errors which were objectionable, i.e. the pitch was not regular, and the force required to advance the dies or screw-plate was sufficient to bend the screw which meant that they would not be true in their bearings and the motion irregular. Allan's method of screw originating, like Maudslay's, used a knife or oblique cutter. Allan's apparatus is illustrated in Fig. 2.6.7. The cutter was a single edge of somewhat elliptical shape so that it would fit the largest screw that was to be made with it. After the cylinder being cut had been turned around once, the tooth 'w' was inserted into the groove and screwed fast thereby acting as a guide for the following teeth; though not strictly required, it was simply used as a precaution. The angle of the cutter and the pitch was set by the pointer and dial shown in 532, and as is immediately obvious could be set for right or left-handed threads. In practice Allan used two cutters, the first a bit larger than was required for the depth of the thread and the other to finish the thread; he also noted that with this second cutter, he could reverse the direction and run back across the completed thread to further reduce any errors. When long screws were desired, Allan marked off a number of sections and began cutting the thread at the beginning of each section (Allan: p.210). Ordinary screws could be quickly made by substituting the dies shown in 536 for the single-bladed cutter. The simplicity of the apparatus is obvious.

2.6.4.5 Ross' modification to Allan's method:

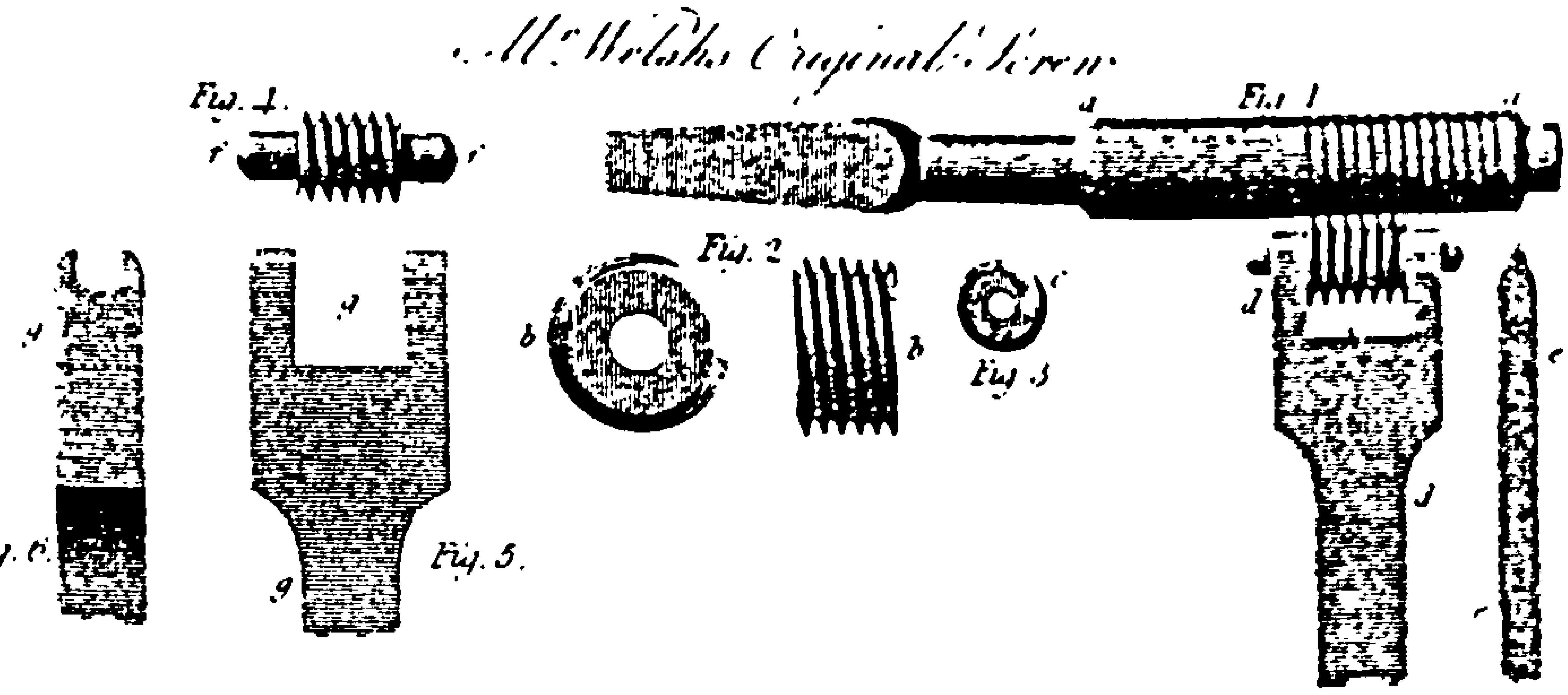
Andrew Ross objected to the friction encountered with Allan's apparatus (he noted that the root would, as a result, be a bit too broad or rounding) so he modified the process slightly (Holtzapffel: 1854, p.648n). Ross used large and small dies at the commencement and end of the process but most of the cutting was done by a fixed cutting radial mortise mounted in the centre of a copper die. The die was indented more and more

Fig. 613.



2.6.8 Clement's screw originating machine where the cutters were made from hobs. The cutters cc' were advanced to deepen the threads by the cross slide and motion of the cross slide was provided by the cutter and by the dies dd'.

2.6.9 Walsh's thread rolling technique for producing accurate original screws. The rollers were either the same or twice the diameter of the screw blank. This was the basis of a common method of forming screws.



as the cutting progressed and also acted as an efficient guide. It was suggested to me during this research that Ross made his micrometer screws by hand, (i.e. by guiding the chaser with his hand) but this is unlikely to have produced screws of adequate precision, and this note by Holtzapffel adds credence to my skepticism.

2.6.4.6 Clement's procedures for generating original screws:

Joseph Clement (1779-1844)[1] made a number of accurate screws for lead-screws of lathes. His method of proceeding is given in Holtzapffel (1854, p.648-50). It was based on creating an improved set of die and cutting tools from a set made with a hob by progressively making better guide-screws. Fig. 2.6.8 shows the machine that these tools were used on. The dies dd' were pressed against the cylinder being threaded by the clamp cc' and the screw c' had a graduated head to read how much the dies were closed. Two sets of dies, one large and one small, were only used as a guide for the cutting tool mounted on the cross slide tt'. Clement made a few screws of the same length but found only two of exactly the same pitch; this he ascribed to a difference in the penetration of the die on the first passage or to a variation in the friction of the slide. On this apparatus, he made screws which were 2ft long and one of 8ft as well as a 5ft steel screw of 3in diameter. From one screw of 2ft and 9 TPI, Clement made others, but because of the pitch he used change wheels of 50 and 56 teeth to make a new one of 8 TPI. He found that by using the change wheels in marking out the first grooves, the problem of slippage was overcome. His methods achieved some popularity because Whitworth used the technique to make his standard screw from which he made his standard taps and dies. Whitworth began with a screw made by Clement of 2ft and of half-inch pitch and then used a clasp nut rather than dies as a guide. The correctional process took two months (Holtzapffel: 1854, p.650n).

2.6.4.7 Walsh's thread rolling method:

G. Walsh was given the Silver Vulcan Award and 10 guineas for his method of originating a screw by the Society of Arts in 1824. It consisted of making a rolling thread on a cylinder of soft steel **b** and twice the diameter of the screw desired. This thread was double threaded and hardened to make the actual cutting tool **c** as illustrated in Fig. 2.6.9. The process was to use the roller to make an impression a thread at a time; the roller was occasionally reversed and run back and forth to make a groove sufficient to guide the

---

[1] Clement worked for Maudslay until 1817. From 1828, he made taps and dies of Maudslay's form. It is noteworthy that Whitworth worked for him for a time before he went on to develop his standard thread. Clement was the engineer and machinist responsible for making Babbages's Difference Engine between 1823-33 (Hyman: 1983, pp.123ff.). When the association with Charles Babbage began, Clement had only one lathe which was in his kitchen, but he was soon making special lathes and other tools necessary for the engine. This caused some stormy relations between them. None-the-less the collaboration resulted in a first class piece of mechanism which is now in the Science Museum. Roe (1914, pp.57-9) provides biographical information.

single pointed cutter **e**. As illustrated, the screw was made to be a tap **aa'** which could then be used to make dies. Once the screw was almost completed with the cutting tool, the roller was once again employed to finish and correct the thread by running it back and forth and reversing it several times. Screws thus produced were not of micrometric quality but were measured to be correct to 1/250th inch in 34 threads (Walsh: 1824, p.127) which was much better than was achievable with other screwing tackle of the day save Maudslay's or Roberts' screw lathes. This method was the basis of the thread rolling apparatus later used for mass production.

2.6.4.8 Donkin's curved correction curve:

Bryan Donkin (1768-1855) observed in 1823 that a perfect screw was impossible to make when micrometrically tested. He adopted Maudslay's method of applying a correction bar but extended the method by developing a correction curve by testing the original screw by continual bisection as was used in hand dividing. Intermediate errors could then be corrected with this curve. He demonstrated this technique in 1826. He began with a screw made by Maudslay and found the maximum deviation of the compensation bar was 1/8in which corresponded to an error of 1/400th inch in the screw. Applying the method he was able to reduce the error by a third, so that the maximum deflection of the compensation bar for a further reduction would have been only 1/20th inch. The concept was applied by Donkin to the design of his dividing engines which are described in §4.3.5. George Sellers visited Donkin's Bermondsey shop in Nov. 1832 and was there shown two of Donkin's precision steel screws 1 1/4in diameter but only 1 3/4in long (Ferguson: 1965, p.112,117,121). One was of 25 and one of 50 TPI, and these were laid in contact side by side. A micrometer microscope was attached, and when one screw was rotated the slightest motion due to errors in either was detectable.

2.6.4.9 Precision screws for dies:

'Workman' suggested in the Repository of Arts (see **London Encyclopedia**, entry 'Screw', p.589) that he made micrometer screws with "new and sharp dies, and great care [indeed!] and slowness, is undoubtedly one of the best". 'Workman' claimed the main source of error was when switching from one hand to the other in order to continue rotation. If the rotation is not continuous or slows, a small imperfection results or if one handle was pushed down harder than the other an obliquity of the thread would occur. This could be counteracted by using long dies but these were difficult to make accurately. He noted:

> In minutely considering the action of the dies it will be seen that the opposite sides of the thread incline towards different regions, and therefore, in effect, cross each other. Hence it is impossible for the dies to be made to approach each other in the plane of the helix. (A tangential plane to the helix, having a vertical axis, will in fact revolve around the axis itself, preserving a constant angular inclination to the same.) But the dies approach in a plane at right

> angles to the axis. It follows, therefore, that there are limits to diameter, depth of cut and inclination, beyond which the dies cannot operate. Those limits are the cause why a true flat thread screw cannot be cut in dies; and a many-threaded screw, or screw of great obliquity, in a single pair of dies, is impracticable, and can only be cut by a succession of different pairs of dies. If dies are not well fitted in the stock, and the stuff be veiny or unequally hard, they will yield to the hard parts, any by the effect of this shake produce an undulating thread. Long dies do indeed greatly remedy this imperfection; but it must exist, however small. As a pair of well fixed dies can never both run along the same stroke till quite home to their natural place, the cut made by the one will tend to draw the other along the cylinder, so that while one die cuts the upper side of the thread, the other will cut the opposite or under side. In this cross action the frame and dies themselves will yield from elasticity, and the more, where the stuff is most hard or the work forced. Hence, with a like pressure, the soft side will have the widest cut, and be soonest cut down, and the sides will be waving. This seems to the the chief reason why tapping a screw throws it out of centre and roundness.

'Workman' thus makes the case perfectly as to why use of a pair of dies was inappropriate for making micrometer screws. He also shows that his understanding of the cutting process was not accurate but since the article was in a major encyclopedia, it must have reflected popular conception. Perhaps it was to solve such conceived problems that John Ramsden patented his screw cutting die in 1852 (#14,213). His apparatus incorporated four cutting points each individually adjustable in radial position.

2.6.4.10 Rutherfurd's method of making the screw for his ruling engine:

The method used by Lewis M. Rutherfurd[1] for making a precision screw was described in 1881 (**American Cyclopedia**, v.15, p.224 under 'Spectrum'). He first made a screw on a lathe with a single pointed tool. This screw was then hardened to obtain a tap which was centered on axis with cylinders mounted on each end so that they were concentric with the axis of the tap. These were placed in 'V's' cut in blocks mounted on a planer. Blank dies were mounted on the planer and run against the screw tap. The stock was then firmly screwed to the tool holder and the threads of the dies cut by rotating the screw tap through the dies 2 or 3 times and tightened on the screw tap. The stock was then firmly attached to the tool holder and the screw tap traversed through the die again; after several repetitions, the dies were hardened. The screw to be used in the ruling engine was cut on the lathe with the single pointed tool which cut the master tap. The new screw was placed on the same 'V's' attached to the planer and finished with the dies previously made. The screw was then rotated in a long cast-iron 'V' with shoulders being turned down on its ends. The nut for the screw was cut with a single pointed tool and the screw run onto it and ground together with fine powered pumice stone. A peculiarity of this screw was that it had a shoulder cut on one end only; it was on the end next to the wheel defining the rotation. The other support for the screw was the long nut. Rutherfurd found this to be the only configuration which cut regular gratings.

---

[1] B 25/11/1816-d 30/05/1892. See Warner (1971) for a discussion of Rutherfurd's work.

2.6.4.11 Rogers' contributions:

The most complete description of late 19th century methods for making a 'perfect' screw is the 1884 account of William Rogers of Harvard University which was presented to the American Society of Mechanical Engineers.[1] He first reiterated the three types of errors he was concerned with, viz. 1) error in total length; 2) errors of pitch for whole revolutions; and, 3) errors which are a function of parts of single revolutions. Errors of the first type were corrected with corrector bars by most manufacturers of precision screws as he was able to confirm by visits to their works or by analysis of the errors of sample screws. Errors of the 2nd and 3rd types were both corrected by grinding, but as he pointed out the method was inadequate as practiced by all except Rowland. The problem was that threads were ground in combination rather than singly which meant that the operation was not very efficient. The action was also mutual in that the nut was ground down as errors of the screw were corrected. Thus grinding was inefficient or incapable of correcting larger errors or ones over longer intervals. In making a dividing engine for Rogers, Buff & Berger of Boston used, as was usual, a nut fixed to the carriage but after two years of use, Rogers decided to use a floating or free nut which eliminated binding between the screw and nut fixed to the carriage. George Clark also used a similar scheme with success in micrometers for the Harvard meridian circle (Rogers: 1884, p.223).

Rogers pointed out three absolute requirements for production of a perfect screw (p.224/5): 1) the shaft to be made into the screw must be a true cylinder; 2) the tool must travel in a line exactly parallel with the axis of this cylinder which requires the bed of the lathe to be parallel to the cylinder and without curvature--either vertical or horizontal, and; 3) the cutting tool must give each single thread, independently of every other thread, its proper form and pitch during each cutting operation. The limits he was striving for were the mechanical limits measurable by a good machinist with calipers, and a good sense of feel, ≈1/40,000th inch for the diameter of the cylinder and about 1/50,000in for lengths of 2 or 3 inches; but, if longer distances were measured which were susceptible to flexure, the errors were 1/20,000 to 1/30,000th inch.

In 1882 Rogers and George F. Ballou combined efforts to make a perfect screw. Ballou had been at the Waltham Watch Corp. and had assisted Charles van Woerd[2] in making a dividing engine for Rogers in 1878 but, after working with Rogers, Ballou set up his own company to make precision lathes and screws by their process which became known as the Rogers-Ballou process. Normal techniques had failed to yield a 4in screw which could

---

[1] Rogers' experience was gained with George M. Bond while making comparisons of English and French standards of length ca.1878-80 for Pratt & Whitney. For this purpose they collaborated in producing the Rogers-Bond comparator (q.v. Roe: 1914, p.180ff.). Bond went on to be closely involved in the development of test gauges for the BA thread (see Brooks: 1988 I, pt.2).

[2] Van Woerd obtained U.S. Patent 293,930 (19/02/1884) for his 'Machine for Threading Sectional Leading-Screws'.

make a grating to surpass others in quality, and they found it impossible to go beyond a certain limit of accuracy in a screw of half a meter length. The solution was to make a sectional screw with a number of ferrules made from the same part of a leading screw, which were then attached and adjusted on a cylindrical shaft. Whitworth had unsuccessfully attempted this method but van Woerd was successful in 1882.

The screw for the ruling engine made for Prof. Anthony of Cornell University was made by Ballou in just 27 hours. What is more astounding was that it was made on a standard type of lathe with large errors in the lead screw. The following equipment was used:

1) common lathe on which the ways were made as straight as possible;
2) shaft mounted between dead centres which retains its cylindrical form for every revolution and part of a revolution;
3) microscope with Tolles' opaque illuminator attached to the carriage moved by the lead screw;
4) graduated bar mounted behind but independent of the carriage and graduated in multiples of the pitch of the thread being made;
5) slide moving parallel to the lead screw and firmly attached to the carriage by means of large diameter micrometer screw. The tool is attached to this slide; and,
6) indicator to show when the lead screw has made one revolution.

Rogers described the method as follows (p.226):

> (1) The graduated bar having been leveled up and set parallel to the axis of the screw to be cut, the micrometer of the microscope was set upon the initial line. The lathe was then started with the leading screw "in feed." After the screw had made, for example, nearly ten revolutions, the lathe was stopped and the remainder of the even revolution was completed by hand manipulation. The deviation of the micrometer line from the corresponding graduation upon the bar was then measured in terms of the screw-head of the secondary micrometer screw. In this way the errors of the leading screw with respect to the graduations of the standard bar were determined and written down upon a strip of paper pasted to the vertical face of the bar.
> (2) The carriage was then started again with the cutting tool in operation, and by means of a rough pointer, the micrometer screw working in the secondary slide was fed either forward or backward, in accordance with the corrections before determined. Hence, when any even revolution was completed, it would be found that the line of the bar would be nearly under the cross wire of the microscope. This operation was kept up until the screw was finished.

Rogers reiterated, in finer detail, the operations--particularly of the manipulation of the micrometer--during the discussion following his presentation (p.239/40).[1]

[1] This long discussion is a wealth of information on loosely related mechanical topics including speculation on the effects of the molecular structure of metals (p.245). Also of note is Oberlin Smith's suggestion of making a 'perfect screw' by a means similar to that used by Andrew Ross for his circular dividing engine. Smith proposed making a drum with screws inserted in its exterior in a helical pattern and the heads could then be adjusted to provide the thread. He was unaware of Ross' earlier usage, and Rogers referred to a similar attempt by a Mr. Hoe.

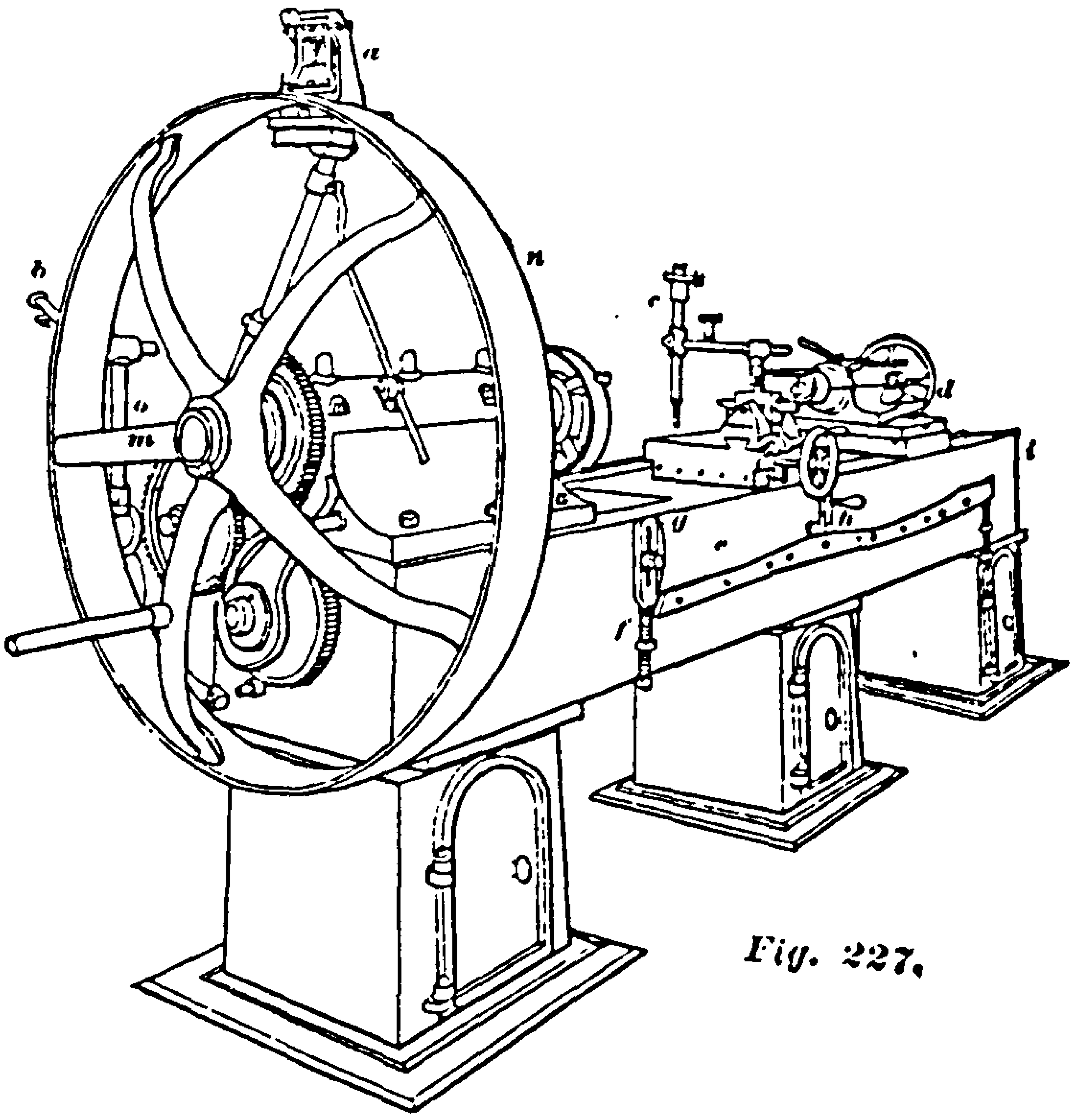


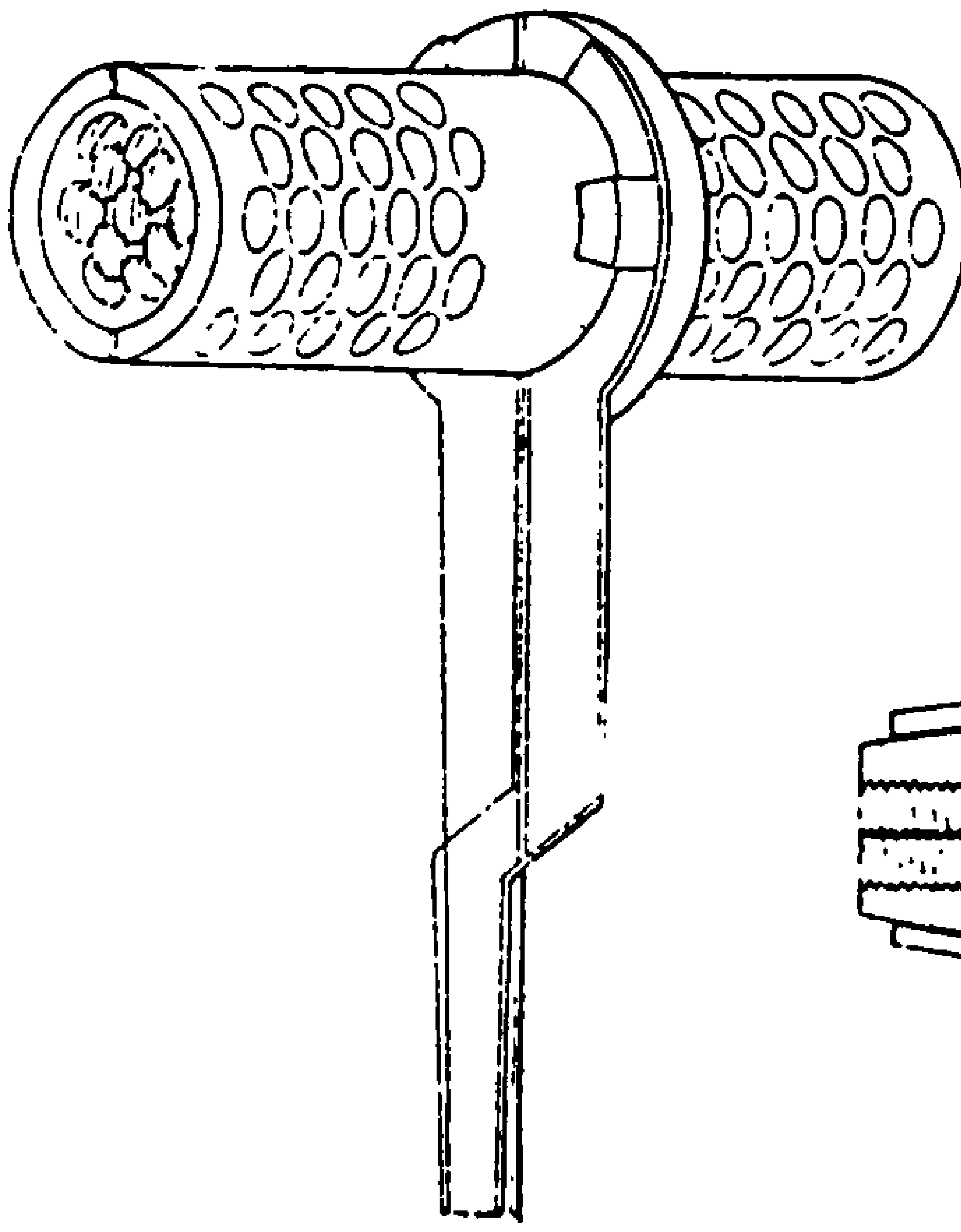
Fig. 227.

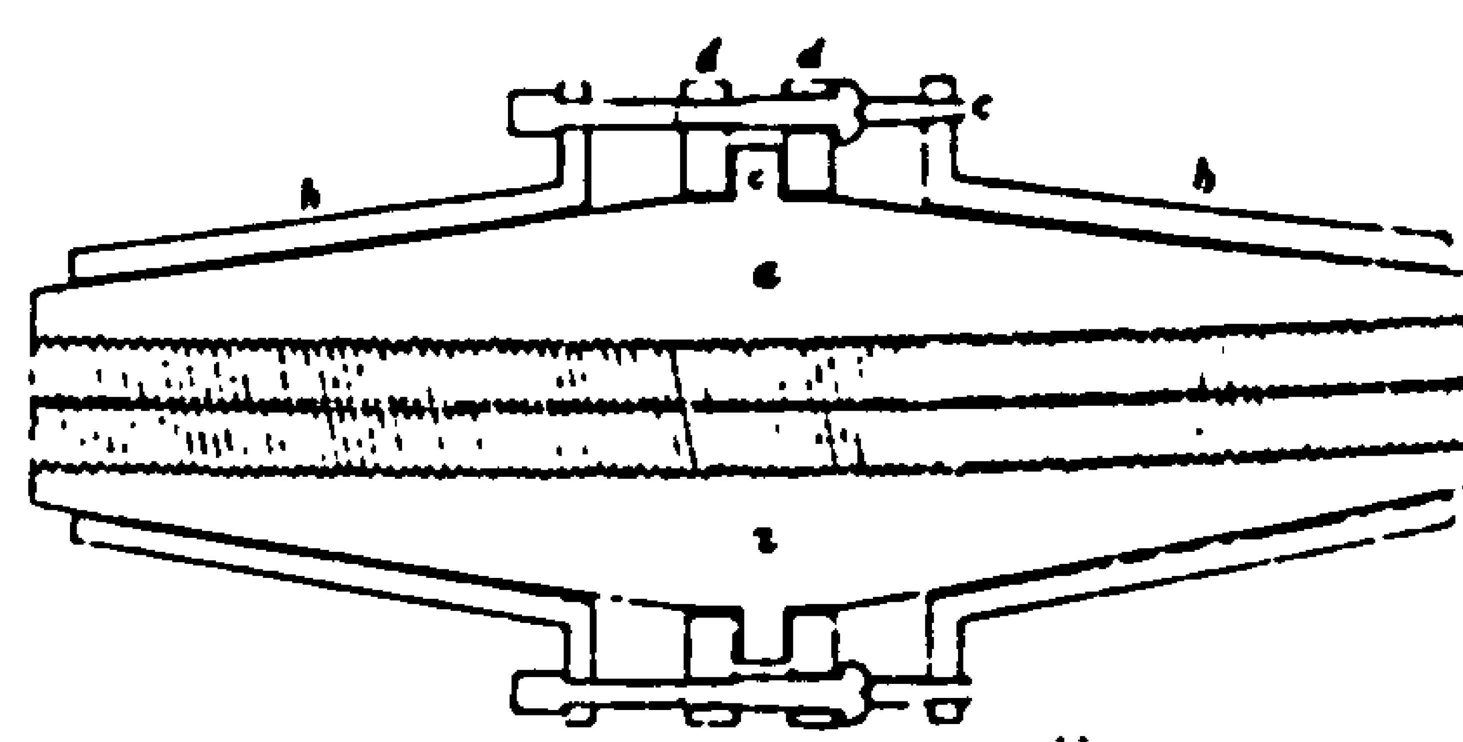
2.6.10 The lathe made for Rogers (1891) which incorporated a correcting bar f on the front of the lathe. The follower advanced or retarded the motion of the lead screw by an amount equal to the error in pitch. A prime objective in making this lathe was to have the face, against which the tool-carriage pressed, perfectly vertical. Scale reading micrometers are shown at b and c.

An hour's grinding with a brass nut removed the minute errors which remained after the correction process. Testing was accomplished by using two half nuts with projecting arms and with a micrometer microscope mounted on one to read a line drawn on the other. As the first nut was advanced the other was pushed along and if correct, the microscope wire would remain coincident with the line on the second nut. This was found to be true for distances to 20in but then the nuts began to separate to a total error of 1/5000in and then to return to the correct position at the end of the screw indicating that the total length was correct.

The correcting process was most important and, as a result, is described in detail. The grinding nut was made in such a manner that, when divided in two, it could be used either in the normal or reversed sense while maintaining a constant relation. A cast-iron cylinder to hold sperm oil was made in which the screw was vertically mounted. This was done so that the grinding would not disturb the relation between the threads. The grinding nut was driven by the weight of the oil and by a guiding rod. Grinding was carried out for 3 weeks with the halves of the nut first in the normal relation and then reversed sense, this reversal being carried out every hour. The error was rapidly halved but it was found that new small errors had been introduced through transfer of screw errors to the nut and then back to the screw which, after the second week, was clearly not as perfect as when grinding began. Ballou thus recut the nut making its diameter slightly smaller than the screw with improved results observed within hours of recommencing grinding. At the end of the second week the nut was recut again still smaller in diameter and, with this, errors introduced in the second week were removed. A discussion of the comparison of the errors of this screw with those of van Woerd's is given in Chapter 6 and an analysis of the errors of the Cornell screw is also carried out.

Alhough the first paper by Rogers was entitled 'On a Practical Solution of the Perfect Screw Problem', it was followed by a second (1891) which admitted that the method of correction of errors in the lead screw with the micrometer was in fact impractical. He then went on to describe the machine made to his order by Webber & Philbrick of Waterville, Maine. In addition to the first two conditions he strove to meet in the above Roger-Ballou process, the new lathe required that the vertical wall against which the tool carriage pressed be perfectly vertical and adjustable with spring loaded bolts. Rogers also wanted the correction of the periodic errors to be independent of the correction of the linear errors which itself should allow for wear of the lead screw. Achieving the vertical wall was the most serious obstacle but was achieved with a maximum deviation of 0.0002-0.0004in along the lathe bed. Rogers did not describe the process to correct the periodic errors but simply used a template shown on the front of the lathe bed (right of the screw 'f'). In Fig. 2.6.10 the large wheel was divided into 1000 equal parts and was used for the correction of the periodic errors by means of the micrometer microscope at 'b'. To test for the linear errors a line 40in in length was divided into 1in intervals and





2.6.11a (right) The four piece grinding nut employed by Rowland on his ruling engine. It was 11in long and used with emery and oil in a water bath. During grinding the screw was mounted vertically or, if horizontal, the nut had to be counter balanced during grinding.

2.6.11b Rowland's two-piece, free floating nut of cast iron which was perforated and filled with lignum vitae or boxwood plugs. The pieces of sheet metal attached to each half of the nut were to prevent rotation.

corrected for use at 62°F. This was then placed on the bed of the lathe and with every fifth revolution of the screw the lines of the scale were observed with the microscope 'c' and the error read off the wheel at 'b'. By this method the maximum error was found to be 1/6000in.

2.6.4.12 Brashear's observations:

Commenting following the discussion of Roger's 1884 paper, Brashear did not advocate emery for grinding because particles embedded themselves and remained in the material after completion of the process. He preferred 'Arkansas Oil Stone' or, even better, 'Water of Ayr Stone'. The process of separating fine particles was the same as used in preparing grinding particles for optical purposes, i.e. progressive settling in water suspensions. Brashear directed attention to the parallels between working telescope mirrors and the grinding process for making screws, in particular the effects of heat and temperature disturbances. He noted Hastings' technique of using Newton's rings to detect errors of 0.000002in in optical surfaces. It should be noted, if not obvious, that methods of determining the accuracy of screws (q.v. §4.4.7) by looking at the quality of spectra are susceptible to errors of flatness of the glass surface upon which the gratings are made.

2.6.4.13 Rowland's perforated grinding nuts:

Brashear noted during the discussion of Rogers' presentation that he hoped Henry Rowland[1] would prepare a paper on his method but this does not seem to have been done. Rowland published a related paper on results with his gratings (1882) and wrote the entry 'Screw' for the 11th edition of the **Encyclopedia Britannica.** Rowland used a modification of the deal and emery grinders in producing the screws for his grating machines. He corrected his screws with grinding nuts cut into four sections, and for long screws he used pairs of grinders separated by a significant and changeable portion of the screw's total length. He also used the reversal of sections as Rogers had used. Though Rogers was able to meet the quality of Rowland's screws, Rowland was first to provide a large number of gratings for scientific use and therefore is the more widely recognized for his accomplishments. According to Brashear (Rogers: 1884, p.258), the grinding nut used by Rowland was varied up to the whole length of the screw with the grinding carried out under water with emery. Fig. 2.6.11a shows the appearance of Rowland's grinding nut while Fig. 2.6.11b shows the actual free floating nut. The grinding nut was made of wrought iron with the holes filled with boxwood or lignum vitae plugs; the appendage maintained the position of the nut and prevented rotation. With a screw made with these

---

[1] A.D. Moore (1982, p.150) discusses and illustrates his ruling engine though not with the details of its construction.

features, Rowland claimed an error of 0.00001in (1882, p.470 or 1911, v.24, p.482)--the ultimate precision screw made to the end of the 19th century.[1]

[1] The screw of the Blythswood ruling engine also reached this accuracy but whether it was actually made in the 19th c is not known. See §4.4.6 for a description of how it was made.

Chapter 3

Development of Screw Micrometers

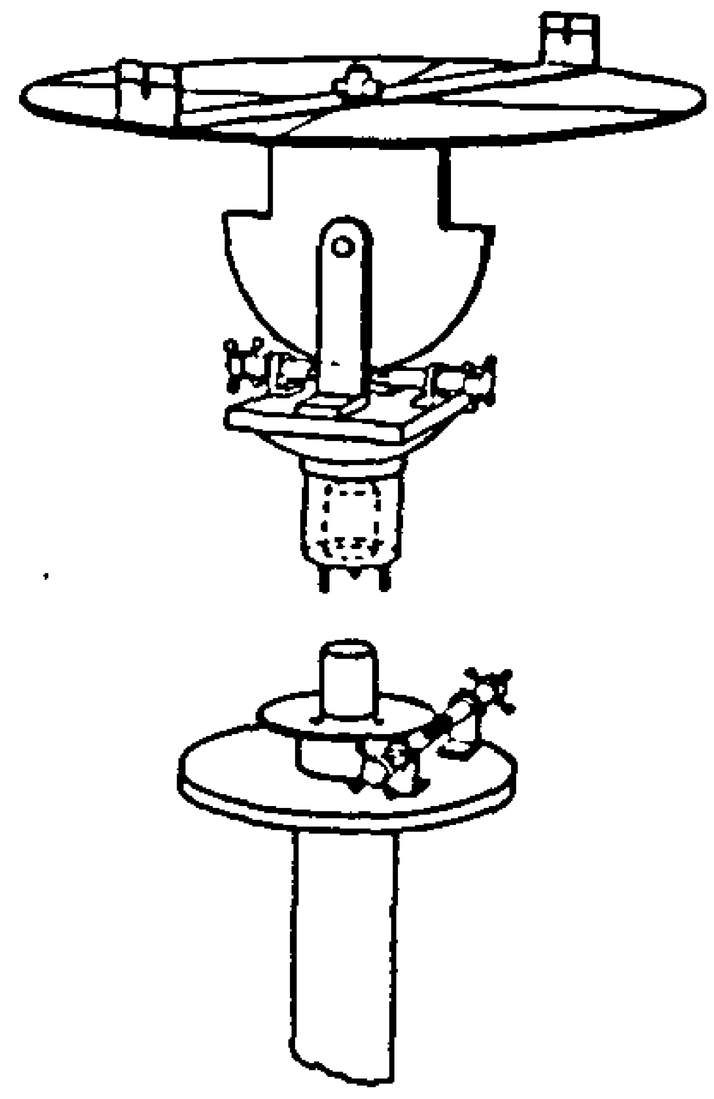
3.1 Precursors to the Micrometer:
3.1.1 Introduction:

This chapter investigates the development of micrometers with particular reference to instruments employing a precision screw(s) in their operation or manufacture where such precision screw(s) defined the precision of measurement, e.g. filar micrometers or micrometers consisting of lines engraved on glass or other transparent material, etc. McKeon (1971,1972) has investigated the documentary evidence of the 17th c invention of the micrometer.[1] The period covered here, ca.1600-1900, corresponds with virtually the entire period of serious usage of the astronomical micrometer, for by 1900 astronomical interests were rapidly shifting away from positional astronomy to the study of astrophysical processes by means of the spectrograph and photography. In this thesis several classes of micrometers are referred to: viz. **filar micrometers** (little distinction is made between filar and bifilar micrometers) which are intended for measurement of objects through a telescope or microscope by means of a screw; **scale micrometers** intended for measuring sub-divisions on instrumental scales by means of a screw; **ocular micrometers** which used fixed fiducials, fiducials drawn on glass, etc. and which were in a sense the precursors of spectral gratings; and **bench micrometers** intended for use in the workshop and which class will include comparators. Except for the very earliest development of the heliometer by Savery, Bouguer and Dollond, the heliometer will not be considered; for a developmental history of this instrument see Fauque (1983). However, the related divided eye-glass micrometers and dynameters will be dealt with since they employ a precision screw.

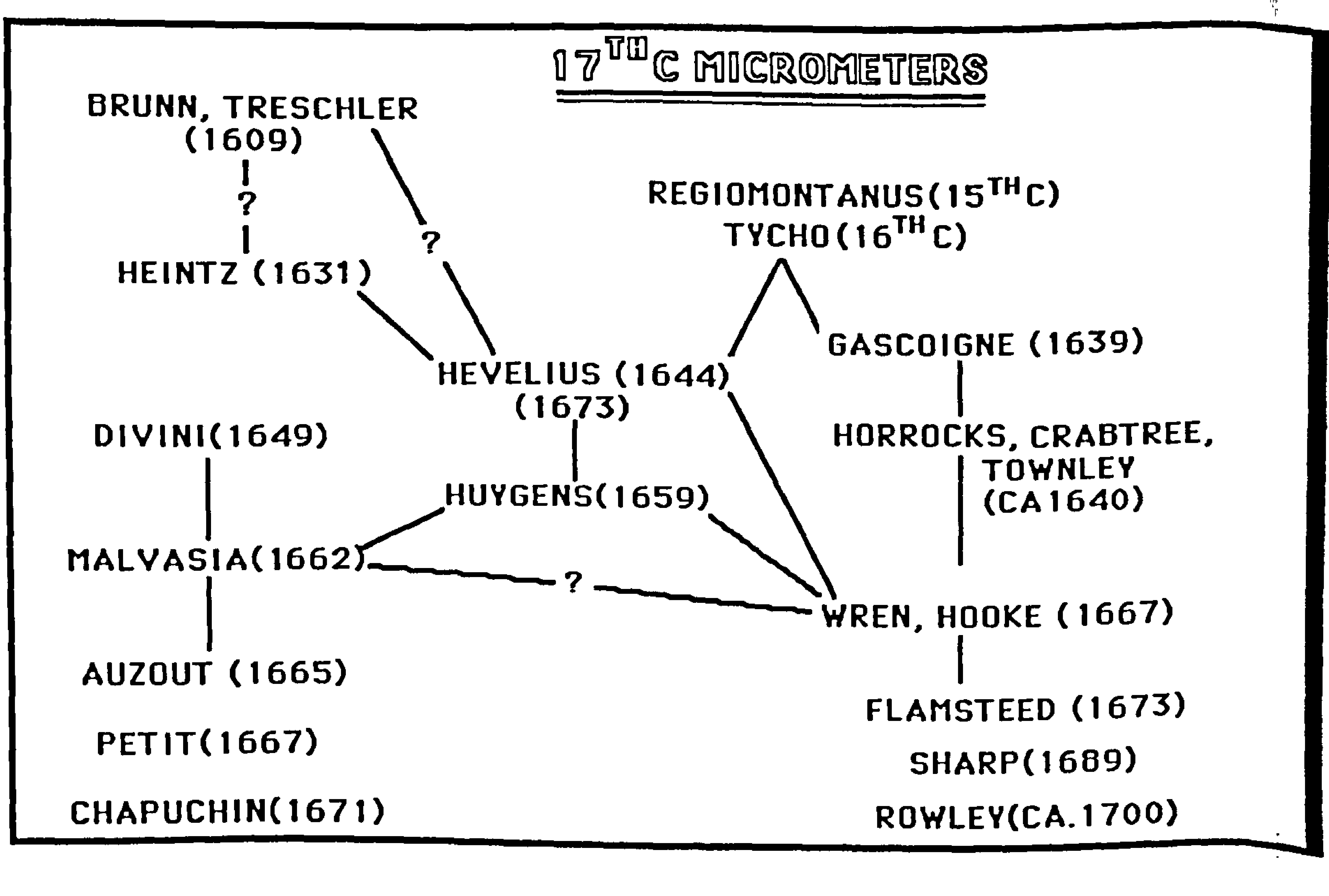
Micrometers may be used to determine separations in relative or absolute terms. For many applications it is only important to know the size of an object or angle relative to another, and not necessarily the absolute measure. Astronomical micrometer screws were made with pitch suited to the scale divisions or magnification of the instrument and used pitches near 25,40,50,60 or 100 TPI. For bench micrometers the linear size is important, and in the extreme require a precise determination as for national standards bars. In these instruments, the screw had to be of predetermined and precise pitch related to the units being measured. Although Whitworth managed to measure differences of one millionth inch (0.000025mm) this was a relative measurement, and as will be demonstrated, he was unable to achieve (in absolute terms) an accuracy anywhere near this tolerance.

---

1 Govi (1887) had previously written a short history of micrometers though his work, in Italian, is virtually unknown.



3.1.1 Heron's dioptra--reconstructed diagram.



3.1.2 'Family tree' of micrometers of the 17th c (after McKeon: 1971 with additions).

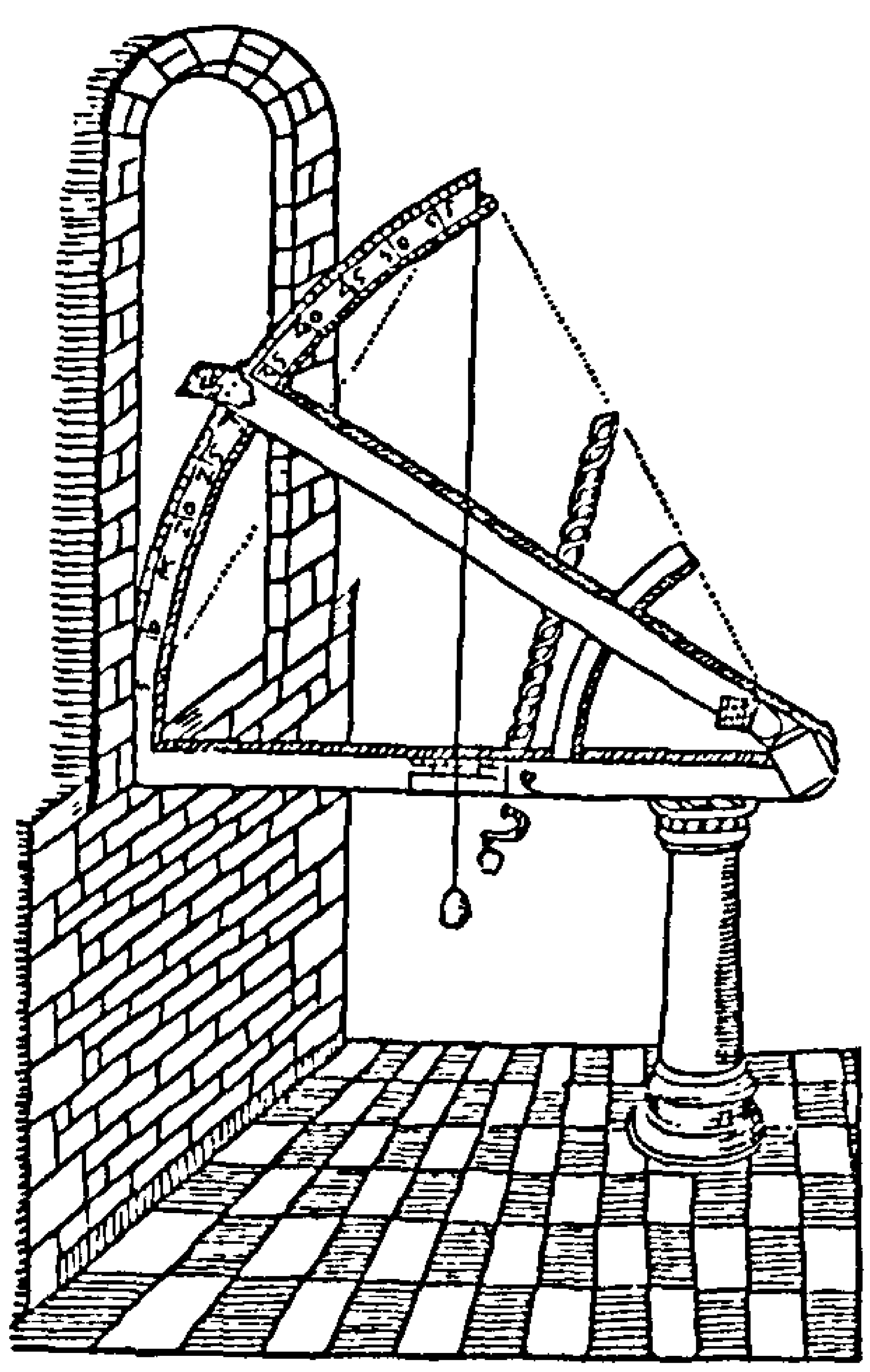
3.1.2 Early Use of Screws on Scientific Instruments:

According to Pearson (1829: p.89), the first person to divide the sphere into zones was the Greek philosopher Thales who was working ca.600 B.C. He introduced the five imaginary circles which we still use to divide the Earth into polar, temperate and tropic zones. Since these circles are based on the Sun's position, he must have observed its altitude. It is also known that he had measured the Sun's diameter to be ≈1/2°. Thales' disciple, Anaximander, described the circles more precisely and were recorded by Anaxagoras in his **On the Quadrature of the Circle.** Hipparchus constructed an armillary sphere which had scale divisions but was suited only to explaining the motion and places of celestial objects; Ptolemy's small radius astrolabe was planispheric and better suited to taking observations. The small size did not permit fine division, but it was with this instrument that he supposedly made his observations for the **Almagest.** Delambre (1792, v.1, p.290) suggested that Hipparchus could make the observations for his star catalogue, with longitude and latitude, only from the use of the sphere. Three centuries later, Ptolemy discovered precession by comparing his observations with those of his predecessor and found a difference of 2 2/3°. This suggests that Hipparchus and Ptolemy were able to divide a circle into degrees and Ptolemy, if not Hipparchus also, was able to appreciate subdivisions of thirds of a degree. One of the first uses of a screw on an instrument was found on Heron's Dioptra (Fig. 3.1.1) where he employed a tangent screw (i.e. a worm and wheel).

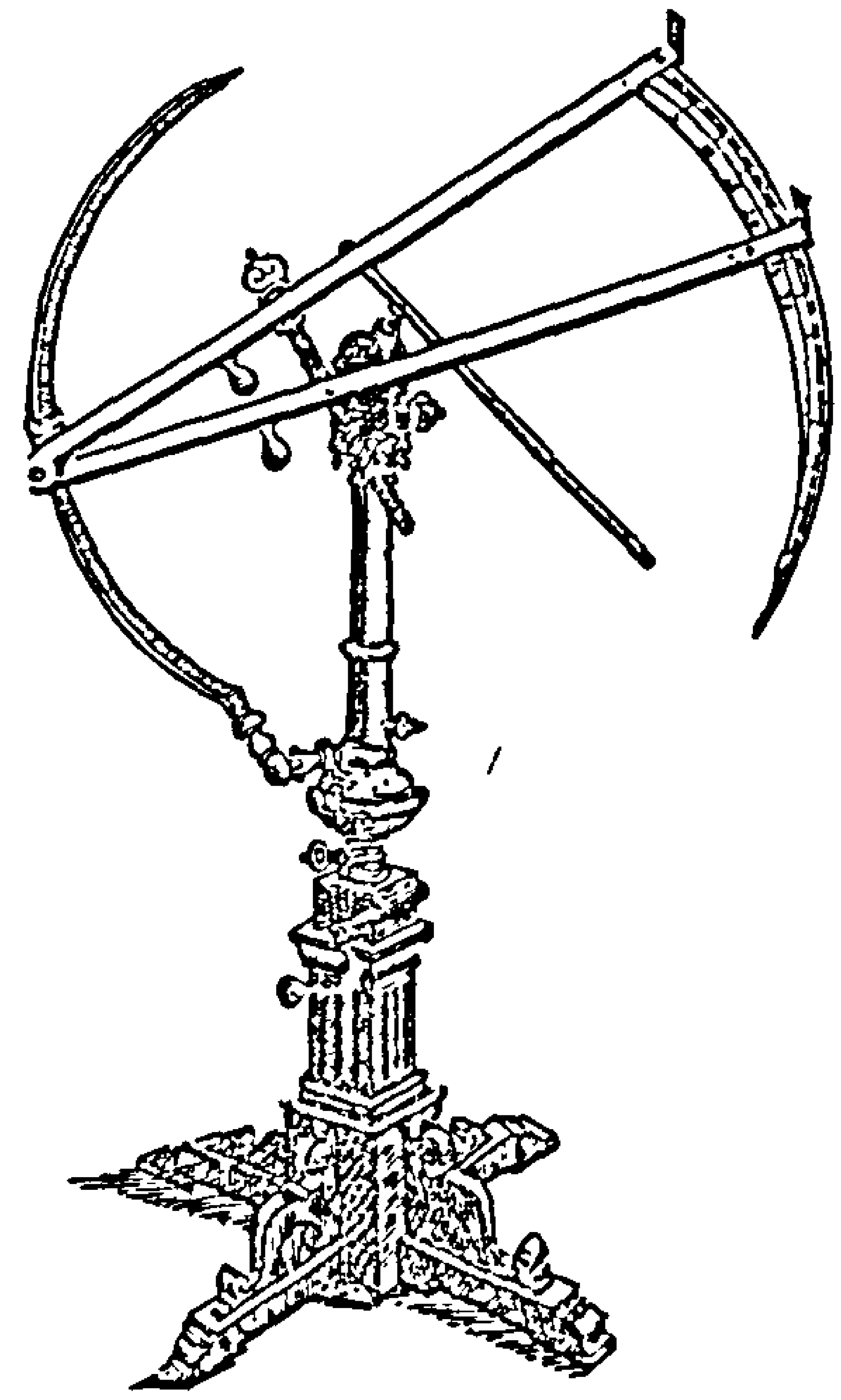
Regiomontanus (Johannes Müller, 1436-76) studied Greek works including the **Almagest** and with Bernard Walther (1430-1504) made a long series of important observations with instruments of his own design. These were described in his **Scripta clarissimi Mathematici M. Joannis Regiomontani de Torqueto, Astrolabioarmillari, Regulá magná Ptolemaicá, Baculoque Astronomico** (1544) and included a description of his regula. This instrument was suited for observing the altitude of the Sun and Moon. Other than that it was made of tin, little is known of its shape, how it was constructed or how it was divided (see Fig.3.1.2 for a 'Family Tree' of 17th c micrometers and their makers). A number of other instruments could be mentioned, e.g. the Baculum Astronomicum--probably a prototype of the cross-staff--or the torquetum of Peter Apian, which were of similar size and accuracy. The quadrant built by Copernicus for his observatory in Thorn was claimed by Benjamin Martin to be of four cubits[1] radius and had its limb divided into 1414 divisions which corresponds to 3'49.1". This instrument may well have provided the first observations of near micrometrical quality. However, to take solar altitudes, a pin was inserted at the centre of the radius of the quadrant to cast a shadow on the divided limb; for this type of measurement, the accuracy must have left something to be desired!

---

[1] The ancient cubit was one arm's length or 18-22in in length. The Tychonic cubit was 16.1in in length (see J.L. Dreyer: 1890, p.39 fn).



Astronomischer Höhenmesser nach TYCHOS *Mikrometer, 1602*



Stahlsextant des TYCHO DE BRAHE, *vor 1575*

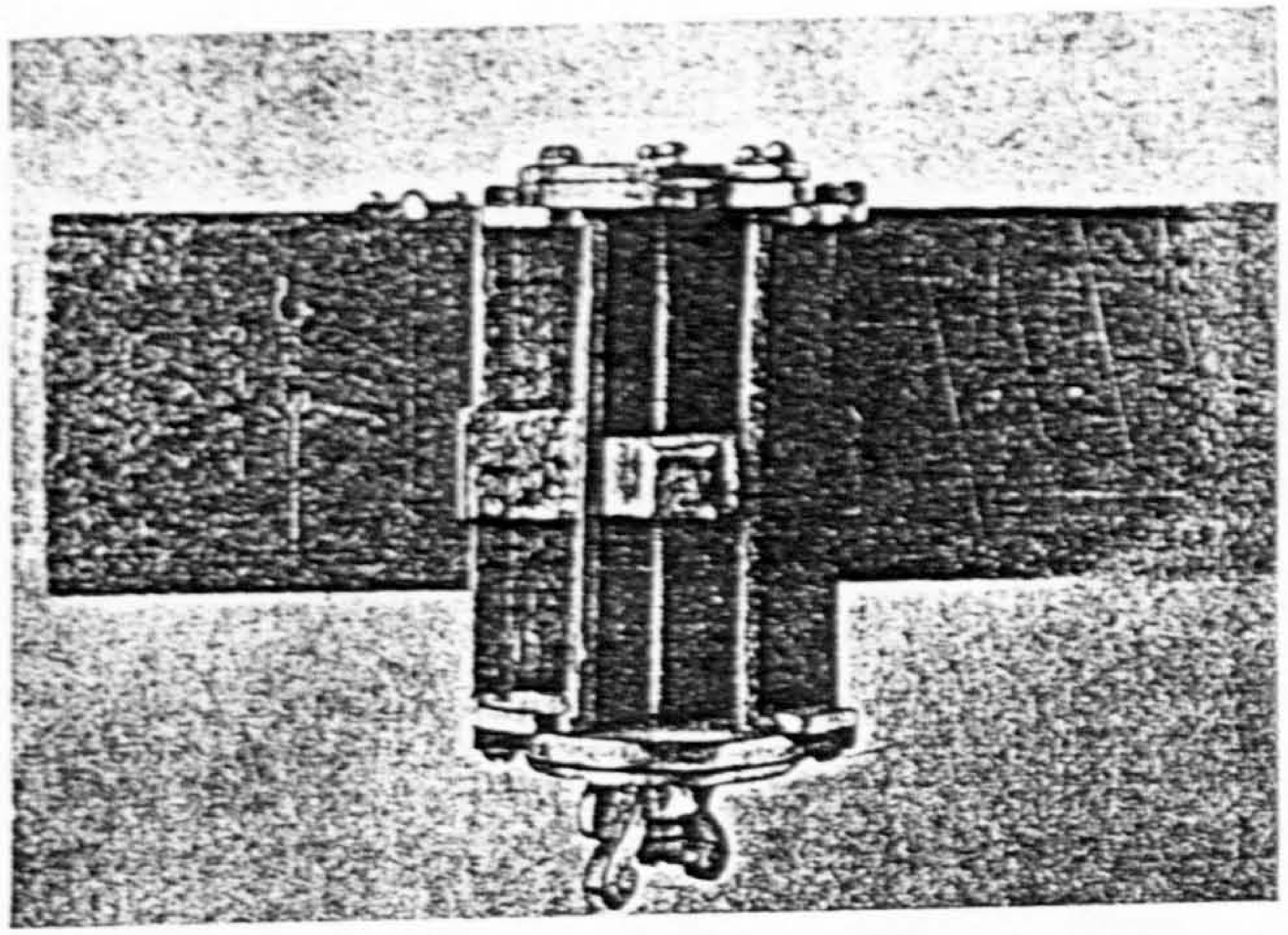
3.1.3 Two of Tycho Brahe's astronomical instruments. Both have screw adjustment mechanisms but that on the left has been identified as having a 'micrometer' function of Tycho's design. It is very questionable whether this was a micrometer function as normally interpreted.

Peter Nunez (or Nonius, 1497-1577) described his method of sub-dividing scales in his **De Crepusculis**. This consisted of dividing a quadrant with 45 concentric circles divided into 90, 89 ....46 divisions from the outer to inner circle. But since several of these numbers are prime numbers, these were difficult to divide accurately. Richard Chancellor's (Chanzler, ca.1525-73) method of using a diagonal scale was described by Thomas Digges in his **Treatise** (1573). Tycho employed the diagonal scales on most of his instruments erected at his observatory at Huen after its founding in 1576. The utmost precision of this division method might have been reached had Tycho had telescopic rather than open sights. The Jesuit astronomer, Scheiner, observed the Sun with telescopes but did not accurately measure the positions or sizes of sunspots which would have made his long series of solar observations of greater historical importance.

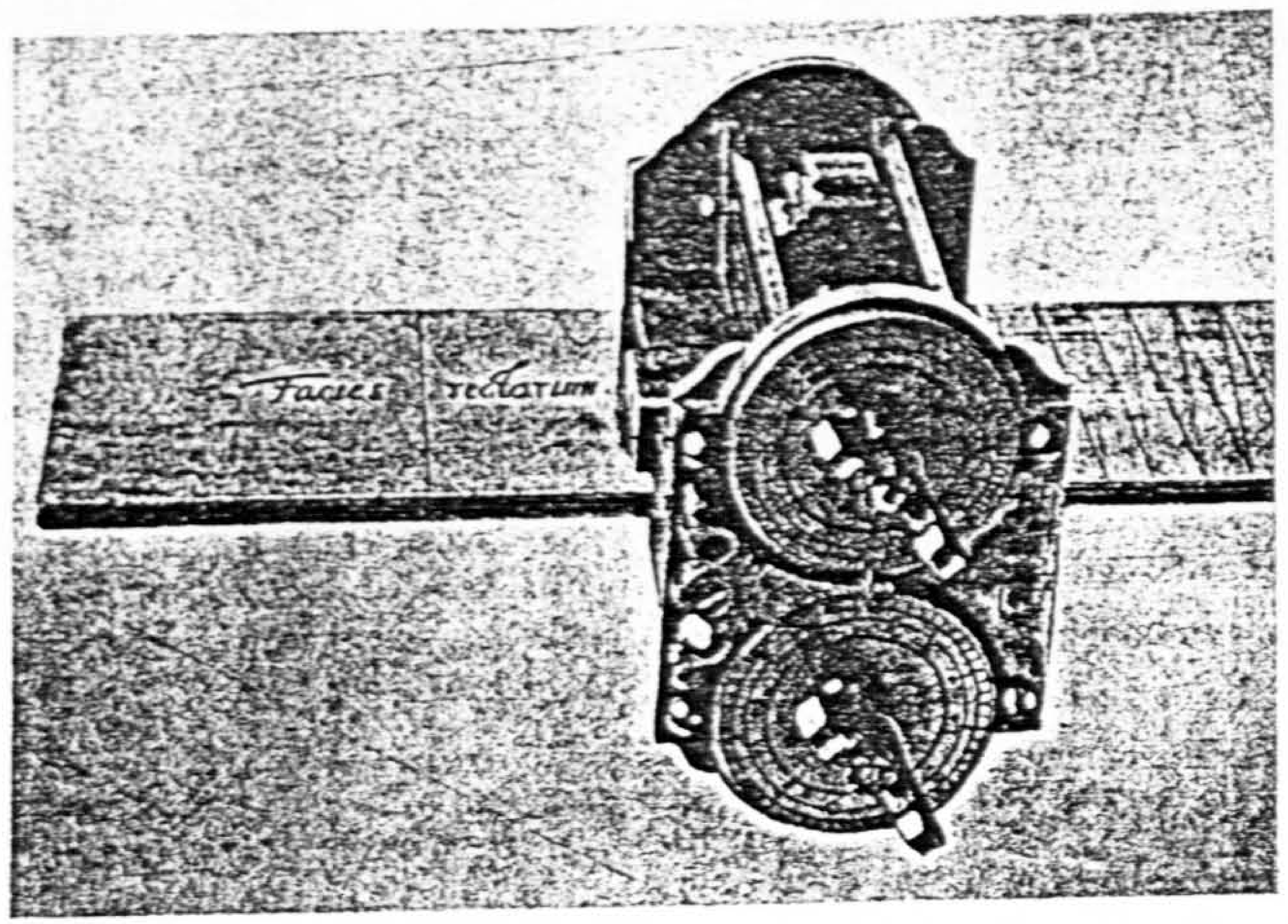
The astronomical micrometer was the invention of a Yorkshireman, William Gascoigne in 1638/9, but it is not generally recognized that other measuring devices dependent on screws had previously been used. Indeed a card in a display on micrometers in the Science Museum states Gascoigne was the first to use a screw for measuring but this is incorrect. A precursor to the measuring application of the screw was its use as an adjusting screw. Regiomontanus, a 15th c Viennese astronomer, used adjusting screws on his instruments. Regiomontanus moved to Nürnberg where a wealthy merchant, Bernard Walther (1430-1504), became his pupil and paid for his instruments. Made in Nürnberg, these were unequalled by any in Europe and only matched or surpassed by those of the Arab astronomers, Nassir Eddin and Ulugh Begh (Berry: 1961, p.88). It might be suggested that the collaboration of Regiomontanus and Walther did much to further the Nürnberg instrument-making trade which was to flourish for more than three centuries. Tycho Brahe employed long screws on his sextant, made ca.1572, to adjust the separation of the arms (Dreyer: pp.39,326-7) and several of his instruments are illustrated with leveling screws on their bases. Tycho's equatorial armillaræ also employed screws (Fig. 3.1.3) to adjust the azimuth and altitude of its polar axis (Dreyer: p.317-9). There is suspect evidence that Tycho Brahe (14/12/1546-24/10/1601) was presented with a screw micrometer to attach to the limb of his instruments (Kellerman & Truege: 1962, pp.111-2,116).[1] Apparently Tycho was not impressed for he never made regular use of the device, preferring his hand divided transversal scales. If this is the case, we can assume that Tycho found his transversal scale at least as precise as the screw and can thereby infer the accuracy of the screw. It is well documented (e.g. Wesley: 1978; Chapman: 1976 I, 1983 I) that Tycho measured consistantly to 1' of arc and with an 8ft or 10ft quadrant this would imply that the divisions were accurate to 0.05-0.07mm. The earliest extant quadrant with an adjusting

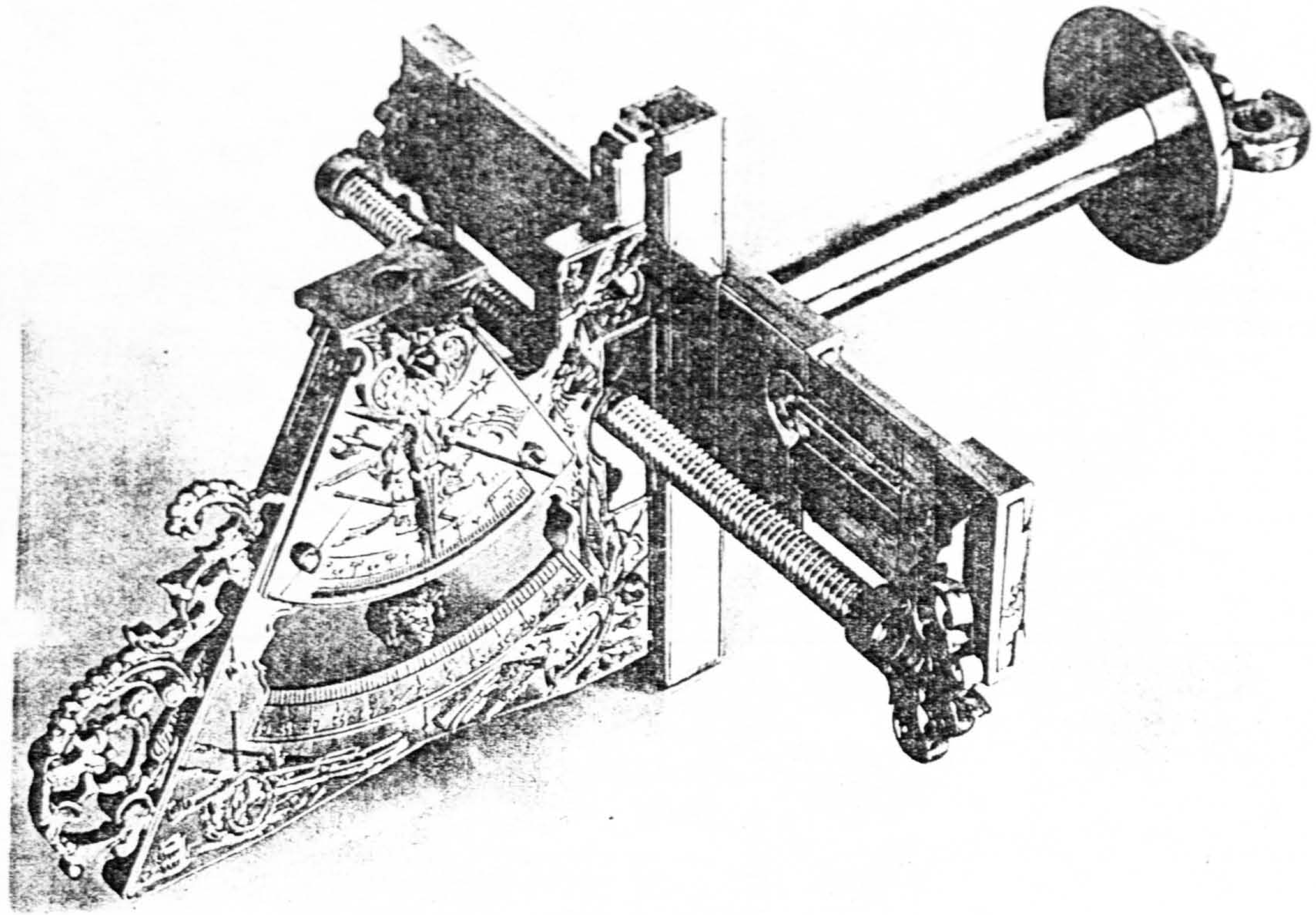
1 Flamsteed also claimed that Emperor Ferdinand had conceived the idea of using screws for measuring as was noted by Tycho in his ***Historia Celestis***, p.112. Ferdinand's instrument is described in Barrettus, p.cxii and in a letter from Flamsteed to Molyneux of 4 November 1686 in the Southampton Record Office (Chapman: 1982 I, fn.133).

Schraubenmikrometer von
Brunn-Trechsler, 1609



Schraubenmikrometer von
Brunn-Trechsler, 1619





3.2.1a (left) The Brunn/Treschler micrometer device of 1609/1619.
3.2.1b (above) An example of Treschler's gun-sights with fine adjustment.

screw is reported by von Makenson[1] to be in Copenhagen but as yet nothing has been learned of its design or maker.

3.2 17th Century Micrometers:

3.2.1 Brunn/Treschler Micrometer (1609/1619):

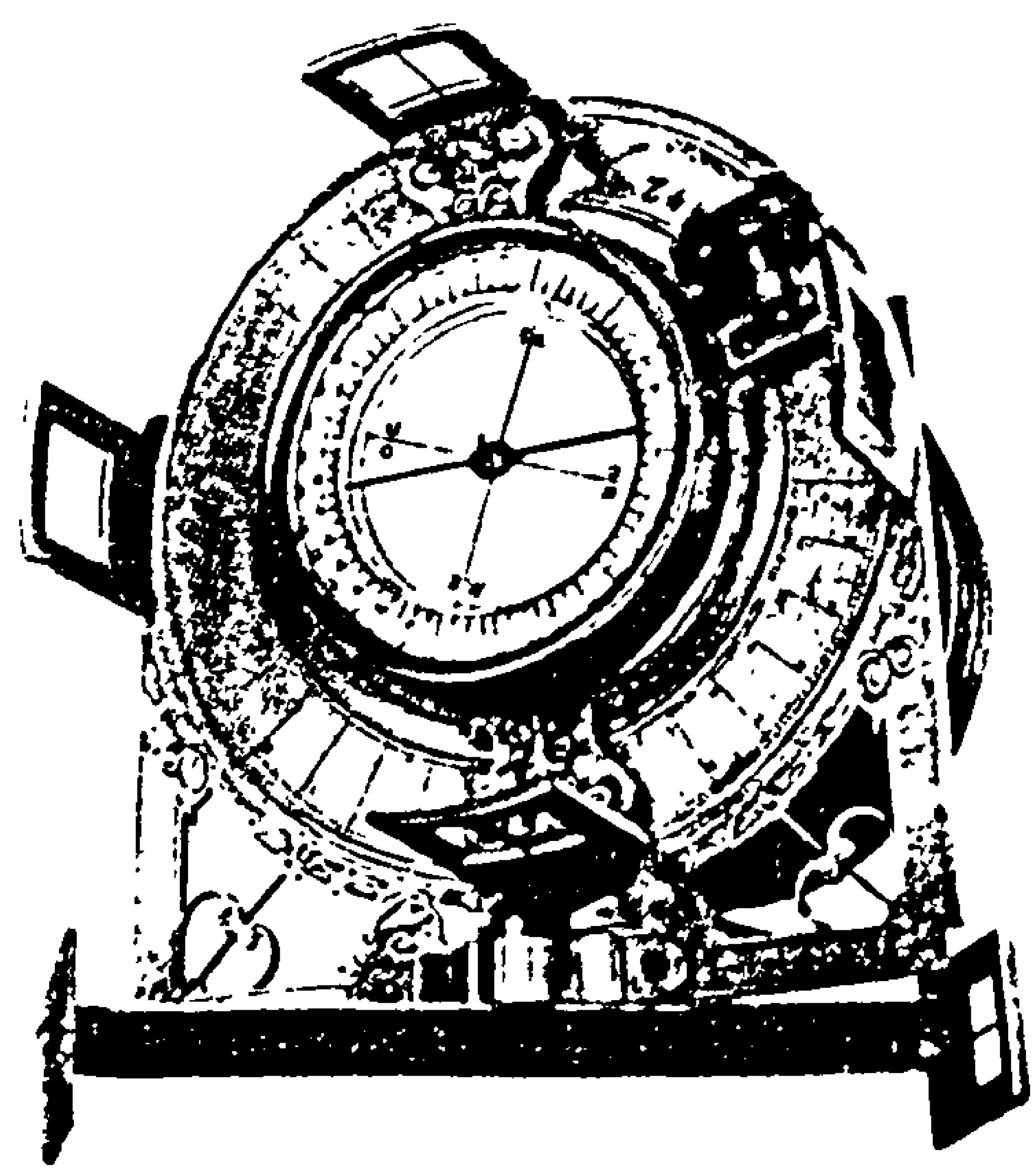
The first successful use of a screw for measurement was the device designed by Lucas Brunn and made by Christof Treschler. Brunn (<1590-1/01/1628) was from Annaberg in Erzgebirge. Brunn received his M.A. from Leipzig in 1601 at which time he began working with Johannes Prætorius at the University of Altdorf (Moran:1981, p.270-1). Brunn became a court mathematician at the Dresden castle in the Kunstkammer where he became director in 1619. His innovative instrument (Fig. 3.2.1a) was designed in 1609 according to the inscription: "+M+LVCAS+BRVN+ANNAEB++INVENT:++C+T+M+F+D++1609++SOLI+DEO+ GLORIA+." It is also signed on the screw frame "+C+T+" and "1609" and signed on the scale "Lucas Brunn inuen: C.T.S.F. 1619 Dresdae". This has been interpreted to mean that Lucas Brunn invented the instrument in 1609 and that it was probably made in 1609 by the Dresden instrument maker Christof Treschler (ca.1540-1624)[2] with some modifications or repairs by Treschler or his son of the same name in 1619. Brunn came into contact with Christof Treschler at the Kunstkammer where the latter was steward between 1602-5.

Treschler's gunsights are very finely made, and one might postulate that having seen Treschler's work and having just studied **A New Geometrical Instrument...** published by the Swiss mathematician, Leonhard Zubler, the use of a screw as a measuring device in a sector came to Brunn's mind. The micrometrical device was the product of both mathematical knowledge and practical craft skills, and was intended for linear and trigonometric measurements. It is presumed that Brunn had use for the micrometer in the castle armouries, where precision fabrication was essential, and that practical experience with the device, sans micrometer screws, suggested that the addition of screws might be advantageous. It is also possible that the device used the screws originally for adjusting purposes and that Brunn or Treschler noted that a carefully made screw with a dial and index might be employed to make measurements. However, this can only be a matter of speculation. As to whether the Elder or Younger Treschler made the screw may be possible to answer since three other signed and dated devices are known: a beam compass with micrometer screw in the Metropolitan Museum of Art (New York), gunner's level in Adler Planetarium (Chicago) and a similar instrument in the Paris

---

1 Comment made by von Makenson at the Scientific Instrument Society Symposium in London, Sept. 1988.

2 See Zinner: 1979, p.266-7 and Engelmann: 1927, p.295-7 and Kellermann and Truege: pp.109-11. Kellerman and Truege's inscriptions for their photos of the instrument indicate they thought that there were in fact two instruments made in 1609 and 1619 but this appears to be incorrect.



3.2.2 The circumferentor of Heintz (1631).

Observatory (#I.A.17.2, Fig. 3.2.1b). Another unsigned gunner's level (#I.A.17.3) with a long horizontal traversing screw is in the Paris Observatory and almost certainly the work of Treschler the Elder. It is also worthy of note that, in addition to the long vertical traversing screw, the signed level in the Paris Observatory carries two dates suggesting alteration or improvements: 1614 on the upper work and 1617 on the base which carried two screws with wing nuts for adjusting purposes.

The gilt micrometer device of Brunn/Treschler employed 2 screws and was 70cm long and 4.5cm wide. Two transversal scales were divided by fiducial lines on a moving plate or carriage to subdivide the transversals in the usual way. This plate moved within inclined ways--one of the first such applications--and carried a frame with two screws which provided a substitute for the fiducial lines. The screws provided finer subdivision of the transversal scales. The screw on the side inscribed "Facies areuum" had a pitch of ≈ 0.75mm and the nut ≈15mm long.[1] Its dial was divided into 60 while the second dial was divided into 100 divisions with each screw working in conjunction with one of the transversal scales. The mode of operation appears to have been to use the screw to subdivide the transversal scale rather than by the divisions on the carriage. This apparently and <u>in theory</u> gave subdivisions to 1/100,000th the spacing rather than the ≈20 divisions one might have expected for Tycho's transversal scales of the same width. The fact that the instrument was engraved with the transversal scale fiducials may fit with the suggestion that the screws for measuring purposes were added at a later time, i.e.1619. This instrument survived until 1945 when it was lost in the destruction of Dresden (Moran: p.271).

3.2.2 Heintz Circumferentor (1631) and Mögling Sundial (1621-7):

Matthaus Heintz (or Haintz), from Zwickau, made a circumferentor (Fig. 3.2.2) for geodetic observations in 1631. This was in the Staatl. Mathematisch-physikalisher Salon Dresden but its current fate is unknown. The instrument was similar to contemporary circumferentors with the exception that Heintz added a screw and dial to subdivide the scale. The screw acted as a tangent screw as Heron had employed on his Dioptra. Divisions were to 1° but Kellermann and Truege (p.111) state that the micrometer dial had 60 divisions and that with the screw was accurate to 5'. This represented a considerable advance for an instrument of small proportions. The circumferentor includes a compass divided to 5° (of 59mm diameter) and has an overall diameter of ≈10.8cm (Zinner: 1979, p.355) There are 2 scales, each divided to 1°, of 7.9cm diameter and of 10cm.[2] It is unclear which scale (if either) the screw matches, but for the inner the pitch would be ≈0.7mm and for the outer ≈0.85mm; it appears to fit approximately mid way between the scales. Using the photos in Engelmann (p.299),

---

1 Measured from Engelmann's, Fig. 1a.

2 Both diameters are estimated from the photo in Kellermann and Truege, p.109.

an estimate of 0.95mm is found for the pitch. The screw was less than a centimeter in length and provided only a few degrees of rotation. It is curious that this micrometer device has not been dealt with in any English work, past or present, so far as can be determined. An instrument which has some similarities and may be related is the horizontal sundial of Daniel Mögling made between 1621-7. According to an unpublished description referred to by Zinner (p.453), it had a micrometer acting on the edge of the horizontal plate and allowed measurement to 1 minute of time. Mögling was a medical doctor and mathematician to the Landgrav Philipp von Hessen-Butzback.

3.2.3 The Gascoigne (1639) and Townley (1667) Screw Micrometers:

The first to apply the micrometer to the telescope for measuring small angles, ca.1638-9 was William Gascoigne (ca.1620[1]-1644)[2]. The precise date is not established although it was definitely in use by 1639 as evidenced by observations published by Flamsteed. It is possible that Gascoigne made or designed it the previous year. Dissemination of his discovery and scientific application were cut off with his untimely death at the Battle of Marston Moor during the Civil War. A small group of acquaintances was aware of the micrometer and of Gascoigne's observations. We know that Jeremiah Horrocks (Horrox) and William Crabtree approved of Gascoigne's micrometer from a letter Horrocks received from Crabtree--a close friend of Gascoigne (**Encyclopedia Britannica**, 1878, see entry 'Micrometer'). William Oughtred was made aware of it in 1641 when he received a letter from Gascoigne which described the instrument and his observations with it. The micrometers ended up in the hands of Richard Townley who was the nephew of Christopher Townley, patron to such scientific luminaries as Jeremiah Horrocks, Jeremiah Shakerly and William Gascoigne (Howse: 1975, p.30).

A factor which made the micrometer feasible was Kepler's discovery (1611) that the Galilean telescope was not the only combination of lenses to form an image. In his **Dioptrice**, Kepler noted that two convex lenses would create a focused and magnified image and this combination soon acquired the name of 'astronomical telescope'. It had the advantage of having a wider field and allowing higher powers to be employed; with the Galilean form employing a concave eye lens, the useful magnification had been limited to about 20x. Another advantage of the Keplerian form, although not recognized immediately, was that it had a positive focus whereby objects in the focal plane are in focus at the same time as the distant object. Keplerian telescopes began to have wide application ca.1630 (van Helden: 1985) and it was to such an instrument that Gascoigne

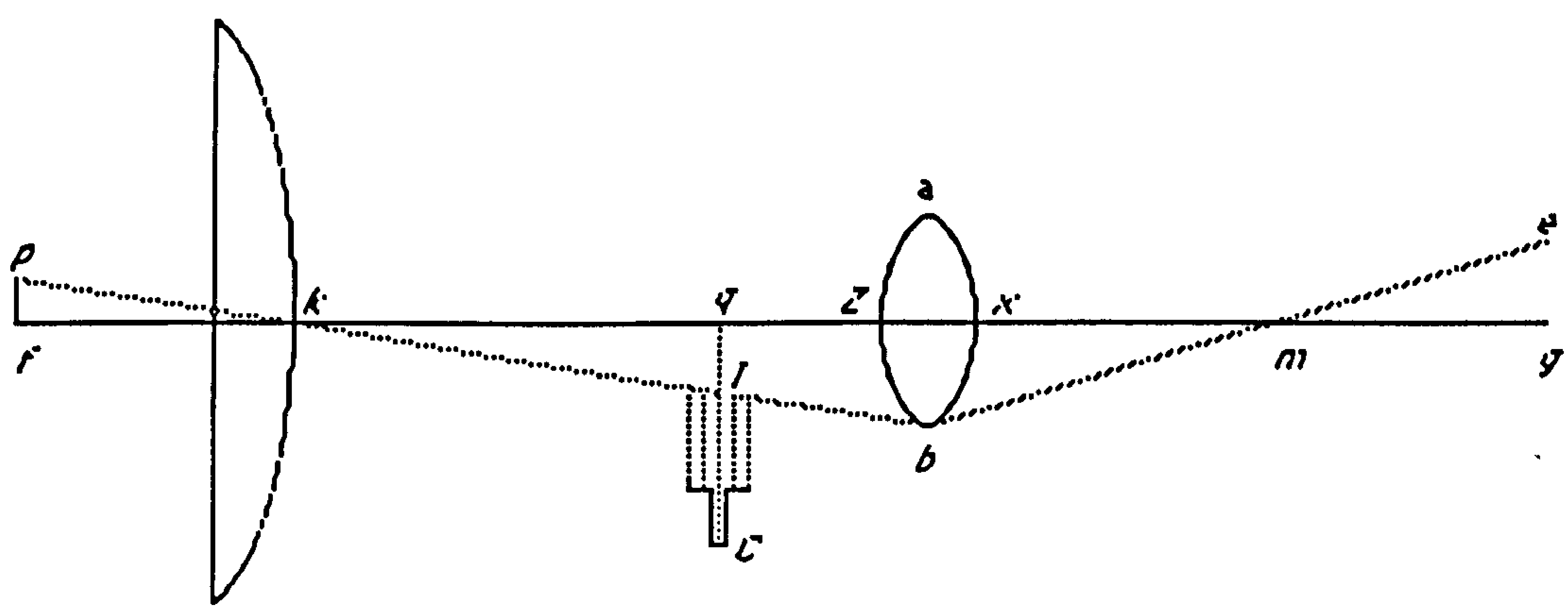
---

1 Gascoigne's date of birth is sometimes erroneously given as ca.1612.

2 David Gill in the 9th edition of the **Encyclopedia Britannica** states that Flamsteed, in his **Historica Cœlistis** included observations by Gascoigne extending from 1638-43 and more were given in Bevis (1753, p.190). Gill's description of Gascoigne's micrometer is actually that given by Hooke of Townley's micrometer.

applied his micrometer. Gascoigne was given the idea for a micrometer at the focus of his open telescopes, or 'case' as he called it, after a spider had made a web there which he noted while observing. In his letter to William Oughtred , ca. Feb 1641, (Rigaud: 1841, p.45-6) Gascoigne stated:

> After the old manner, without a glass, we shall find that there is more show of colour in an obscured room with a larger hole, and more perfection of the diameter's apparition in a less. If it be hard to shew some probability of the reason..., we shall find it readily in the diagram, wherein is comprehended an incredible rarity, *q* here being the same of *C* in the 1st, *ql* of *dl* in the 2nd; the glass *ab* is rightly placed when *lbm* can move rightly here as *Zmbq* in the first: and, as there, the more remote *Z* is from *k*, the nearer is *q* to this, so here if we place an object between *q,k*, the nearer its approach is to *k*, the nearer according to the same reason is its picture in eg to *x*, and contrariwise of the contrary. This is that admirable secret, which, as all other things, appeared when it pleased the All Disposer, at whose direction a spider's line drawn in an opened case could first give me by its apparition, when I was with two convexes trying experiments about



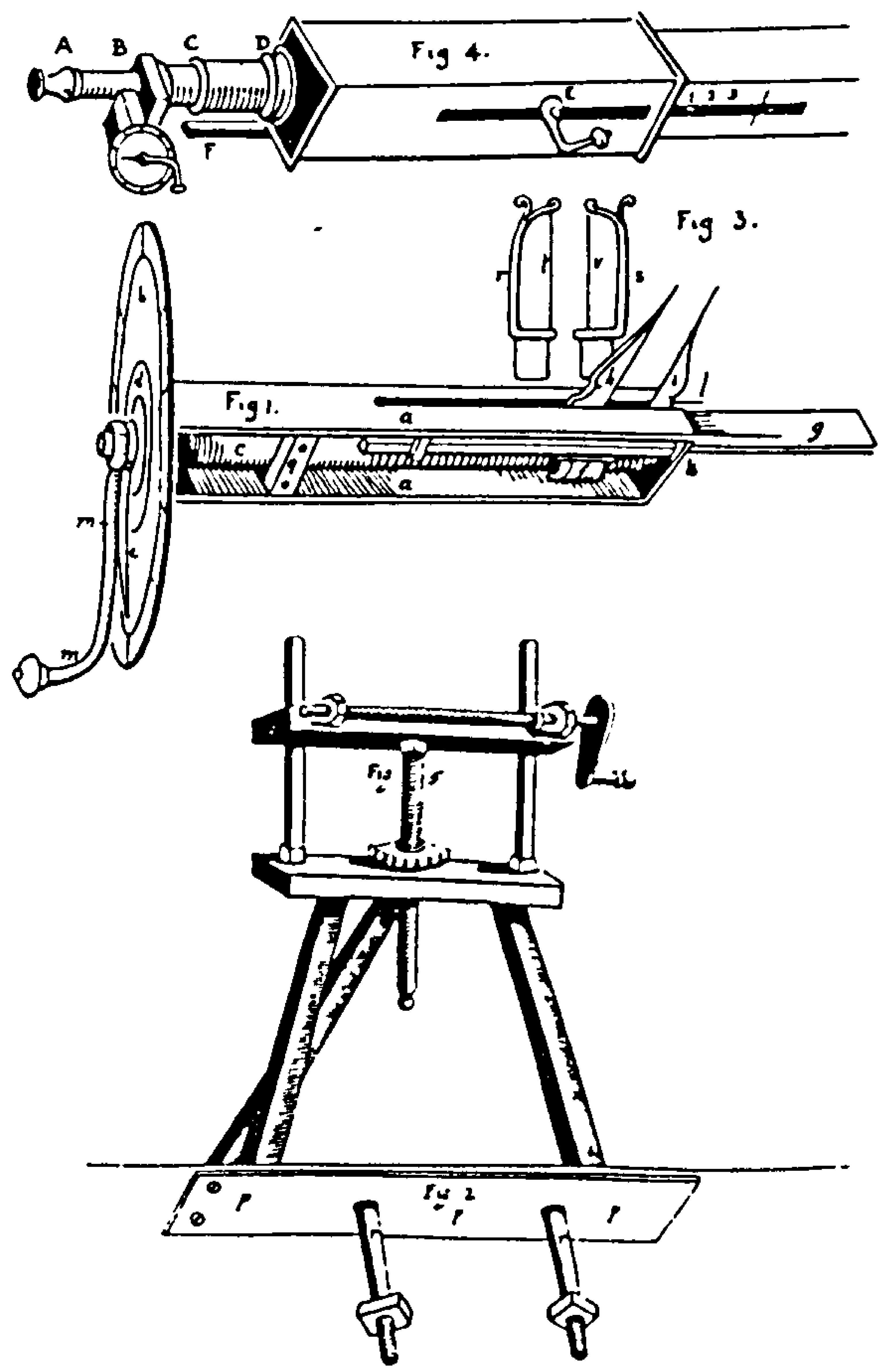
3.2.3 Gascoigne's illustration of the optical path of a telescope with micrometer

> the sun, the unexpected knowledge. Presently, placing my eye some little nearer *x* than *m*, I perceived that the apparition was not so punctual in the eye as on the table, although I had diminished *Zk* answerable to the augmentation by the eye...(it is very possible to prove what convex glass is of equal power with the eye), and therefore resolved that if I tried ab like a spectacle, and placed a thread where that glass would best discern it, and then joining both glasses, and fitting their distance for any object, I should see this at any part that I did direct it to. And so I found it...which the next night's trial confirmed strangely accurate and ready for finding the altitude of any small star.

This probably occurred in late 1638 or early 1639 for Gascoigne was attempting to acquire lenses from London but was having difficulty getting ones of the quality he desired. The idea of employing spider's webs for micrometer fiducials did not occur to anyone else before ca.1755.[1] Gascoigne's

---

1 This is discussed in detail later in this chapter.



3.2.4 Townley's micrometer as illustrated by Hooke (1667).

instruments were of varying quality and the results of his measurements varied accordingly. Gascoigne himself soon noted this.[1]

Outside his small group of scientific correspondents, Gascoigne's micrometer went unknown until after Adrian Auzout published a description of his own micrometer in the *Philosophical Transactions* (1667)[2] Gascoigne's micrometers--"Gascoigne's first and two others perfected by him"--had come into the hands of Richard Townley, a fellow Yorkshireman. According to Townley, Gascoigne's micrometer could measure 40,000 divisions per foot. Townley records how he employed a watch maker (even in the larger centres, the profession of instrument maker was some time in the future) to modify and improve Gascoigne's micrometer. This modified instrument (Fig. 3.2.4) was the one illustrated and described by Hooke (1667) and illustrated by Wolf[3] and Place (Howse: 1975, pl XIIa,b)[4]. Unfortunately Townley was not specific as to the modifications and improvements he had made to the original instrument but from Flamsteed (Baxandall: 1922/3, p.311; Chapman: 1982-2, p.104) we learn that Gascoigne originally used two screws--one left, one right handed--while Townley's had but one.[5] The main elements of the micrometers illustrated by Hooke and Place are similar but differ as to scale of the components. However, we can state that by 1667 the following important mechanical elements were present in the application of the screw to micrometric purposes:

1) a spring plate (≈1in diameter was incorporated to minimize backlash. This was mounted on the exterior between the handle, index and body of the micrometer;

and, 2) a small end-bearing screw was employed to prevent end play of the micrometer screw. This was a common element of the best micrometers for nearly a century.

In his description, Hooke (1667, p.542) says the micrometer screw was "about the bigness of a Goose Quill and of the length of the Box" and was "curiously wrought", i.e.

---

[1] Gaythorpe (1929, p.238-41)has computed the magnification and field of view of Gascoigne's Galilean form telescope (made in Oct. 1640) but nothing is known of the properties of Gascoigne's Keplerian form telescope(s) to which he applied the micrometer. See ref. 7 of van Helden.

[2] Durham (*Philosophical Transactions*, 1717, p.603) also had to put forth the case for Gascoigne having invented the use of telescopic sights.

[3] Wolf: 1950, v.1 has incorrectly labeled the Townley micrometer as that of Gascoigne.

[4] Flamsteed met Townley in 1671 at which time he studied the observations of Gascoigne, Horrocks and Crabtree. According to Howse (1980, p.23) Townley gave Flamsteed one of his micrometers (see note 6). In a letter to Collins, dated 31 Jan. 1671/2 (Rigaud: 1965, p.126-9) Flamsteed states that he had sent plans for his micrometer to Collins and Townley and was waiting a response before divulging his design further. In the next letter dated 10 Feb. 1671/2 (Rigaud: p.129-31), he sent Collins 10 measures of the solar diameter but states that some were too large by virtue of his inexperience with such observations--a problem Chapman (1987, p.362-4) also encountered.

[5] Baily (1835, p.29) notes that Flamsteed's description of Townley's micrometer is in MSS, vol.43 of Flamsteed's papers. He first saw Townley's micrometer in June, 1670 and had received one of Townley's from Sir Jonas Moore by midsummer (Baily: pp.30,109-10).

carefully made. The steel screw was ≈3in long with the third closest to the dial slightly larger in diameter and with a finer thread than the remainder.[1] The remaining threaded portion (≈2in) had 60 threads and was therefore 30 TPI. Rotating the screw carried along a scale with 0-60 divisions. The other sight was fixed to the box, but the genius and elegance of this instrument was that the box was moved with respect to the telescope tube by the finer part of the micrometer screw thereby causing the sights to separate symmetrically from the optic axis. This provided a distinct advantage in making measurements of drifting astronomical bodies--an advantage that contemporary instruments did not possess. It also meant that the two sides of the observed image were equally affected by the aberrations of the lens. Otherwise, if one edge of the object is on the optic axis, it follows that the other must be nearer the edge of the field of view and hence its appearance is liable to be distorted by the coma and defocused by the spherical aberrations of the lens.

From the above information we can deduce that the finer thread was of ≈60 TPI and the coarser ≈30 TPI and were both the same handedness--presumably right-handed on the basis of some deductions and assumptions from Hooke's illustrations. The mode of application of the thrust washer corroborates this: the thread must have been right-handed if the washer was to effectively decrease backlash. The net parting motion of the sights would be equivalent to a 60 TPI screw, and although of relatively fine pitch, a competent watch maker would have been capable of making such a screw on a bow lathe with chasing tools. This pitch and 100 divisions[2] on the 3in diameter dial provides an accuracy of 72,000 div./foot which is very different from the 40,000 div./foot Townley reported (1667, p.468) for Gascoigne's instrument. Perhaps here is the clue that part of Townley's modification was to change the screw, or to supply the Royal Society with a micrometer of his own invention. If this is correct, then Gascoigne's micrometer screw had an effective pitch of ≈0.033in or 33 TPI. If Townley had devised this scheme for moving the sights symmetrically, then he had some mechanical genius and may have also devised the spring loading washer and end bearing screw. This is a tantalizing problem with no resolution without more information. Hooke, in preparing the description and illustrations, also proposed a useful modification of substituting the solid sights with hair sights.

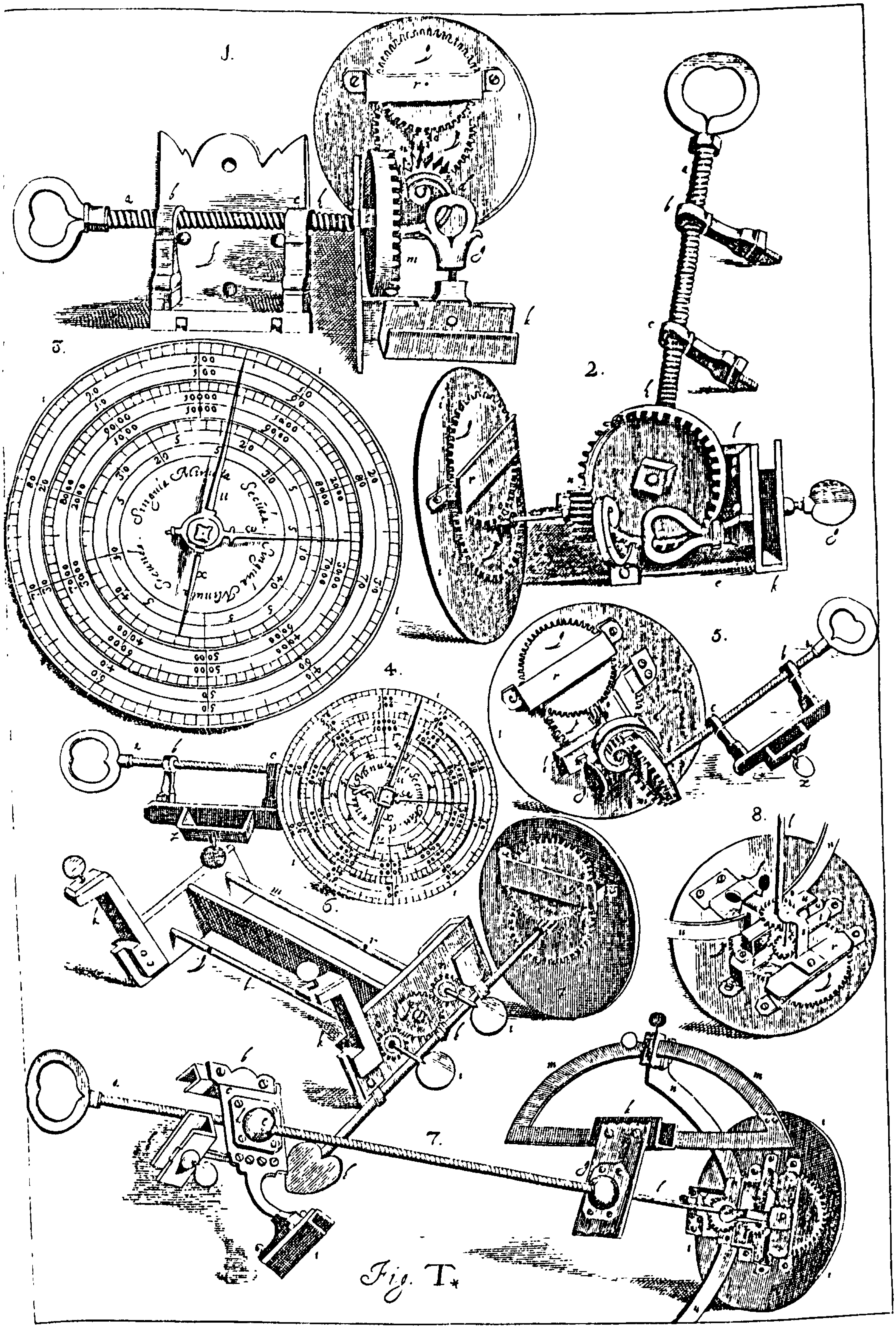
3.2.4 Hevelius Micrometer Devices (1644):

Even more curious is the lack of discussion of the micrometers of Hevelius, the burgomeister of Danzig. His later rivalry with Flamsteed and his even more bitter feud with Robert Hooke over the use of telescopic versus plain sights is well known in the

---

1 Gunter (1923, v.II, p.309) is in error in stating that this screw was made by Townley from a simple screw.

2 Baxandall (1923/4, p.311) states that Gascoigne's micrometer had 100 divisions on the dial.



3.2.5 The components of Hevelius' micrometric devices.

annals of science. As a result, illustrations of his astronomical sextants and quadrants, which were first published in his **Machinæ Cœlestis** (1673) complete with micrometric and adjusting screw devices, appear in several sources (e.g. Zinner: 1979, pl.67; Daumas: 1972, f.56; King: 1979, f.48; Bennett: 1987, f.61). Hooke's **Animadversions upon the first part of the Machina Coelestis...**(1674) certainly brought Hevelius' work to the attention of British scientists, but Hevelius' innovation in scale measurement went without much notice, being overshadowed by the controversy whether Hevelius or Hooke could observe more precisely. Hooke strove to make Hevelius' equipment seem old fashioned and therefore less accurate. The fact that Hevelius did not employ telescopic sights was the dominant point of discussion, and that he did not approve of telescopic sights made Hevelius look reactionary, a position more accepted in response to Hooke's attacks than out of belief[1]. That Hevelius was able to match the measuring precision of Hooke was ascribed to his exceptional eyesight; the suggestion that it may have been assisted by his use of scale micrometers has not been discussed. Chapter 15 of his **Machinæ Cœlestis** titled 'De Instrumentorum Divisionibus' describes his instruments complete with tables for converting micrometer readings to minutes and seconds of arc. The publication date of **Machinæ Cœlestis**, 1673, was several years after the micrometer was brought to the attention of the scientific community, and although Hevelius followed Gascoigne in the use of a micrometer by only a short time, the priority debate had been settled and Hevelius' devices drew little notice. The rivalry between Hevelius, Flamsteed and Hooke over the use of telescopic sights drew great attention as a contest of old versus new technology.

The illustrations in **Machinæ Cœlestis** tend to be somewhat ambiguous as to function, but become clearer from perusal of Fig. 3.2.5. Most of the devices were adjusting screws that could be clamped at any point along the limb (i.e. they were not tangent screws acting on a gear or thread on the limb) but some were modified to transmit their motion through a lantern or crown gear to an index and dial. Daumas briefly mentions the micrometer but rather in the context of an adjusting screw; no mention is made of these devices in his section on micrometers. Daumas (p.49) states "...one questions whether this micrometer was of great practical value, but despite the primitive construction of his instruments Hevelius obtained results as precise as those achieved by his contemporaries using better designed instruments equipped with telescopes". Halley went to Danzig in 1679 to reconcile Hooke and Hevelius, and it became obvious that Hevelius was able to match the observations of those using more modern equipment[2]. Such ability suggests that micrometer devices were a contributing factor. Typically, Hooke was unwilling to accept that the advantage gained from the use of

---

[1] For a discussion of the application of telescopic sights to astronomical instruments see Olmsted: 1949.

[2] For a discussion of the controversy between Hooke and Hevelius see Bennett: 1987, pp.65-69.

telescopic sights was somewhat compromised by the difficulty of aligning the frame and telescopes in the same plane. Although Hevelius, as part of the old guard, lagged behind others in the application of the telescope to his instruments, he was leading the way in another area. The fact that Hevelius incorporated scale micrometers on three important instruments suggests that they were successful despite their apparent frailty and design flaws. Of the many instruments of Hevelius', Zinner (p.380-1) lists three carrying micrometers: the above instrument of 1644, his sextant of 1658 (Hevelius: 1673, fig. M and N) and octant of 1659 (fig. O which is the figure most commonly reproduced). Graham and Bird also successfully employed Hevelius' basic design (i.e. of clamping the device to the limb) on their 18th c instruments. 20th c marine sextants still use a modified form, illustrating the fundamentally sound mechanical principle. To what extent Hevelius described his micrometers and their use to other astronomers prior to 1673 is not documented.

The device illustrated by Hevelius consisted of a screw driving a gear train which turned an index over a dial. If Hevelius' illustration is accurate, the screw drove a lantern (crown) gear of 32 teeth meshing with a 16 tooth pinion gear in turn driving an 8 tooth pinion, 48 tooth spur, 8 tooth pinion and 48 tooth spur gear. However, the purpose of the last pair of gears is ambiguous and, if the ratio is the same as the preceding pair, has no apparent function. A second index would appear to act simply as a marker for the starting position since the device was designed to clamp anywhere on the instrument's limb. The dial has several scales: (reading from outer to inner) 0-100 and 100-0 by 10's, 1-10,000 and 10,000-0 by 1000's, 0-50 and 50-0 by 1's also marked with 5's at the middle of the divisions. These devices had their origins in Hevelius' azimuthal quadrant of 1644 where they acted as a tangent screw or micrometer (Kellermann and Truege: p.109; Zinner: pp. 205,377). Nothing is known of the screws of these devices. However, as illustrated, the screw was held by two nuts without any backlash control. It is also clear from the pairs of scales, that Hevelius operated the screw both in the forward and reverse directions. It was claimed that this quadrant was divided to 5', readable to 1' with transversals, to 5" with Nonius and to 1" with screw micrometer--needless to say optimistically since, without telescopic aid, the eye can only just distinguish objects with a separation of the order of 1 arc minute.

3.2.5 'Ocular' Micrometers:

Notwithstanding Hooke's and Wren's claims for priority (1667) made after Auzout's announcement of his invention of the micrometer, the evidence in their favour is shaky. Hooke was notoriously ready to claim any invention and one is thus suspicious of his claim. The claims of Wren are more substantial though require closer investigation than has thus far been carried out. Some evidence exists to suggest Christopher Wren was using micrometers by ca.1655, for as Bennett points out (1982, p.38-40), Wren was making lunar observations for a Moon globe he was constructing. Sprat (1667, p.314) when discussing the many scientific contributions of Wren says:

> He (Wren) has invented many ways to make *Astronomical Observations* more accurate and easie: He has fitted and hung *Quadrants, Sextants* and *Radii*, more commodiously than formerly: He has made two *Telescopes*, to open with a joynt like a Sector, by which Observers may infallibly take a distance to half minutes, and find no difference in the same Observation reiterated several times; nor can any warping or luxation of the Instrument hinder the truth of it.
>
> He has added many sorts of *Retes, Screws*, and other devices to *Telescopes*, for taking small distances and apparent diameters to Seconds. ....

A couple of points from this passage deserve comment. It should be noted first that Sprat wrote his book shortly after Auzout's letter appeared in the *Philosophical Transactions.* It was entered in Stationer's Hall on 25 July, 1667 and according to Cope and Jackson in the Introduction of the 1966 reprint (p.i) it was printed in the late summer or early autumn. The jointed telescopes must have been used ca.1667 since, as Olmsted (1949: p.223-4) has noted, Picard was the first to employ sights in telescopes and, to measure to half minutes, sights would have been necessary. As for the screws noted by Sprat, this would suggest that micrometers were familiar to Wren, and other evidence exists to connect Wren with the friends and scientific correspondents of Gascoigne. However, the timing of the publication was such that the instruments could have been fabricated after Auzout's announcement. More certain is Christian Huygens' 1659 disclosure (**System Saturnium**) that he employed narrow, tapered strips of metal slipped into the focal plane of a Keplerian telescope. The width of the strip at the point where the object was just covered gave him the angular size of the object in relative terms. Huygens, in this work, gave diameters of the planets in terms of solar diameters. Although we have mentioned several micrometers in use prior to 1659, Huygens' publication must be considered the point from which the concept became widely known and applied. This was due to the wide circulation of **Systema Saturnium.**

The Marquis Cornelio Malvasia, in his **Ephemerides** (1662) described his contrivance of a grid of fine silver wires placed at the telescope focal plane and with it he made observations of the solar diameter. The wide range of diameters (Table 3.1) shows that his device left something to be desired.

Table 3.1

Malvasia's Solar observations*

Date (ca.1661)	Divisions on Micrometer	Semi-Diameter Measured	Semi-Diameter Corrected#	Semi-Diameter Actual†	Notes
16 Sept.	9 div.	15'25"	15'27"	15'58.6"	Horizontal diameter
	8 1/2 div.	14'36.5"	14'38.5"	N/A	Vertical diameter
≈ 25 Jan.		16'48"	16'31"	16'17.5"	Perihelion
≈24 June		15'08"	15'23	15'45.4"	Aphelion

*Taken from Malvasia, **Ephemerides Novissimæ** (1662), p.217.
#Corrected for 1 AU solar distance.
† Diameter for appropriate date taken from the **Astronomical Ephemeris**, 1988

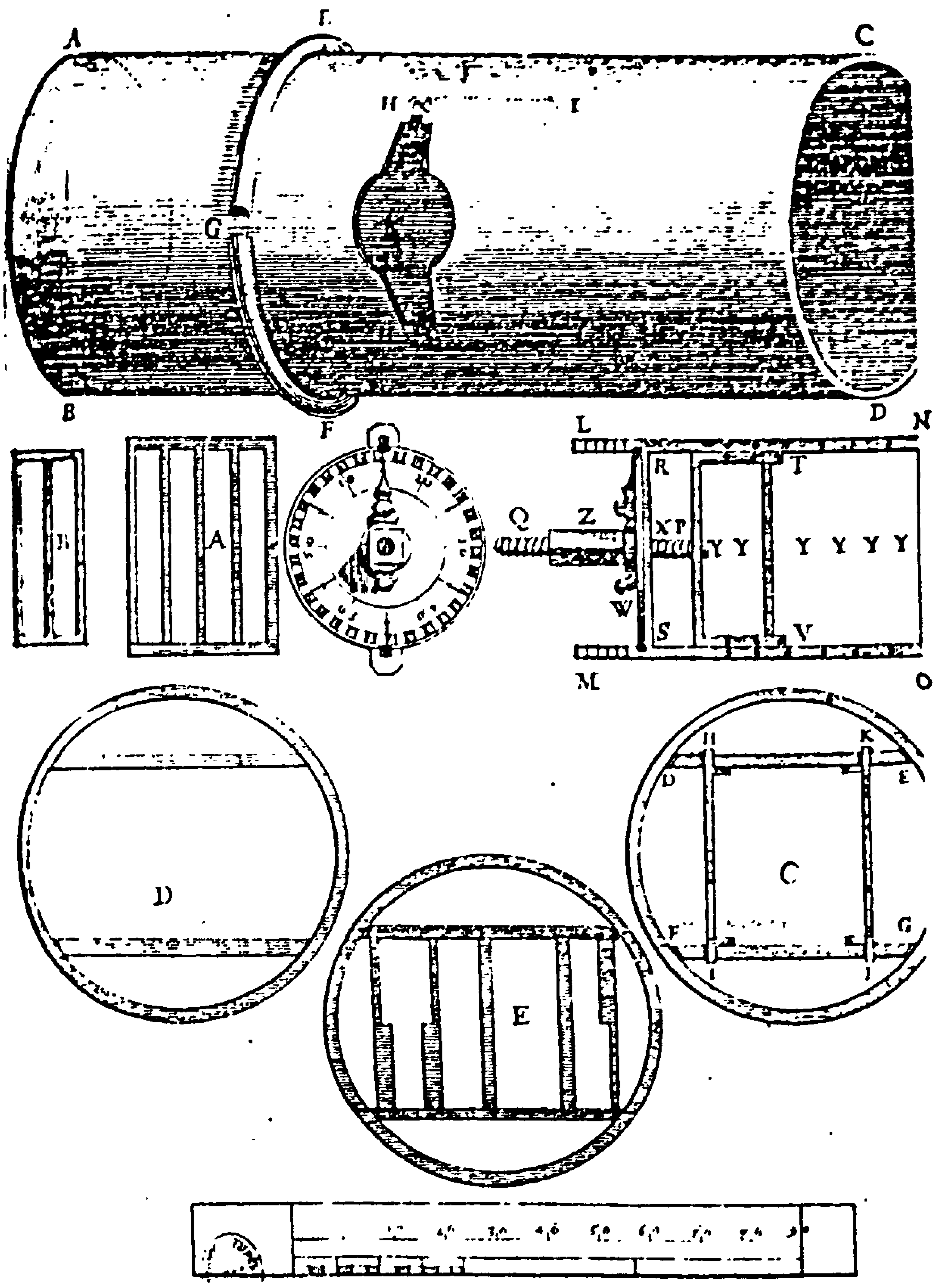
Malvasia died in 1664 but in a 1676 letter to the Duke François II, Geminiano Montanari claimed he himself had designed the instrument in 1661 while a young assistant to the Marquis. Since Malvasia was long dead, there was no means of proving or refuting the claim. Eustachio Divini may have used a similar grid system in 1649. McKeon (1971, p.10-12) reviewed the evidence presented by G. Govi in his "Della Invenzione del micrometro per instrumenti astronomici" (1887) and concluded that Divini may have:

1) discovered the principles of grid and focal plane but did not actually apply them,
2) that Divini had invented the first micrometer as Govi had accepted, or
3) as McKeon preferred (and supported by observations of the Moon depicted in a 1649 engraving with details of the instrument sent to the Grand-duke of Tuscany) that Divini had in fact invented and used the micrometer in 1649.

A curious fact is the description given by Petit (1667, p.103) which states "....faisait par le moyen d'un treillis ou grille des filets très subtil appliqué sur le verre oculaire convexe; j'en fis plusieurs essais." The interpretation of lines applied on the convex glass ocular is a problem since lines drawn on an eyepiece lens would not be in focus. Divini's engraving was made prior to the invention of compound eyepieces by Huygens, though Petit was reporting after the invention. Perhaps he was misinterpreting the engraving. Nonetheless, Divini's invention was the embryonic grid micrometer which was eventually to lead to spectral gratings through the work of such men as G.F. Brander, Fraunhofer and Alfred Nobert.

3.2.6 Auzout's Micrometers:

Use of micrometers for the precise measurement of small bodies became widely known as a result of Auzout's letter (28/12/1666) to Oldenburg, the Secretary of the Royal Society. This letter was published in the *Philosophical Transactions* and brought a flurry of responses claiming priority for English scientists, including Hooke and Wren. Hooke had apparently employed diaphragms and reticles for measuring diameters and star separations, while Wren had constructed devices to take improved measures of longitude



3.2.6 Auzout's micrometer (1666).

(King: 1979, p.99). Though Townley was able to demonstrate Gascoigne's priority in the use of a screw micrometer, Auzout's letter publicized the techniques of screw micrometer measurement to a wide audience, thereby advancing astronomy by a giant leap. With this contrivance lay the means of measuring the lunar and solar parallax to unprecedented accuracy, and even the ever present problem of stellar parallax seemed within grasp.

The first micrometer of Auzout was less elegant than that demonstrated to the Royal Society by Townley, for it had a fixed knife-edge and a single threaded screw moving the other edge. Thus, unlike Townley's, the entire telescope had to be moved to align the two edges on the limbs of the body or on two stars. Auzout claimed the accuracy to be 24 or 30,000 div./foot (One can only speculate whether he was referring to an English foot or Paris pied although the latter is more probable). Little is known of this instrument, for an improved version was made shortly after and was described in Auzout's work **Traite du Micrometre...** (1667).[1]

This more complex micrometer (Fig. 3.2.6) consisted of a fixed frame carrying 6 wires or hairs and a traversing frame carrying 3 wires or hairs moved by a single screw. In Auzout's figure the screw is illustrated as being left-handed. The screw was more than 5 pouce (≈13.6 cm) long and ≈1/2 pouce diameter and the nut was ≈1.5-1.7 pouce long but there is no indication that backlash was otherwise taken into consideration. The dial was divided into 60 divisions and estimated to 0.1 divisions (McKeon: 1971, p.272). This instrument, Auzout claimed, had the same precision as the one referred to in his letter to Oldenburg, i.e. 24-30,000 div./foot or 12.5-9 microns. These numbers lead to the conclusion that the screw had a pitch of 0.75-0.54mm or 34-47 TPI. The maximum separation that could be measured was 4.6cm (McKeon: p.269). Picard examined the screw with a microscope comparing the pitch along its length for possible errors (Auzout: 1667, p.6-8; McKeon: p.276-7).

3.2.6.1 On the calibration errors

Two methods of calibration were employed by Picard when using Auzout's micrometer. One, described by Wolf (1950, vol.1, p.172), was to time the passage of an equatorial star across the wires. Unfortunately this suffers from problems of timing contacts where errors of 1^s or 15" are possible (Brooks and Brooks: 1979, p.12-14). The better method was to place a test card with lines at a distance of some 200-300 toise (400-650m)(as recommended by Bion, 1709) and measure the separation. Geometrical methods gave the angular separation and a table was set up to give the subdivisions. The unrecognized problem was that the telescope's magnification was changed as it was refocused on the closer object. For Picard's 6 pied telescope the error

1 Reprinted in the *Histoire de l'Academie Royal des Sciences depuis 1666 jusqu'à 1699* (1729, v.7 pp.118-30 and in McKeon: 1971, pp.249-254).

was 4.8" for 200 toise target distance and 2.9" for a 300 toise distance. These errors systematically gave enlarged diameters. This phenomenon is demonstrated by the apparently enlarged diameter of the Sun observed in the 17th c (Ribes, et al.: 1987, p.52-55; Brooks : 1988 II). The perceived accuracy of the micrometer in measuring the diameters of the Sun, Moon and planets was mirrored in the transit observations at the Observatoire de Paris but, other than perhaps subconsciously causing observers to modify their timing procedures, no direct link is obvious. For diameters, timing the contact just 0.1-0.2^s early at the leading limb or late at the trailing limb can account for the above errors and bring diameters determined by the two methods into agreement. One should also recall that the pendulum clock was in its infancy and subject to average errors of 5-10^s/day (i.e. 1^s was gained or lost in ≈2.5 to 5hr) as well as random errors of a few seconds over much shorter period (Howse: 1980, p.181). In 1675 Flamsteed stated that he could rectify his two clocks at the Royal Observatory to "scarcely more than 10" [i.e. seconds of time]; but commonly much less" (Baily: 1835, p.45). He also noted that in 1671 "I had no pendulum movement to measure time with: they being not common in the country at that time". Both these declarations reiterate the state of infancy of the pendulum clock and by implication the accuracy one might reasonably expect if attempting to make transit observations.

Flamsteed's description of the method of determining the value of the Townley micrometer[1] is found in a letter he wrote Sir Jonas Moore in 1674 (Baily: p.110). He first attempted (1671) to use a box ruler he had laid off using a diagonal scale. In measuring the Townley micrometer he found the pitch to be 35.15TPI. Townley stated that he had measured his to be 34.65 TPI and that since both screws had been made with the same screw box they should be exactly the same. Repeated measurements by Flamsteed did not permit so small a value so he settled on 34.85 TPI and accordingly set up a new table which he used from August 1672. He

> "was not satisfied with this determination, and therefore resolved on the first opportunity to make a more satisfactory trial, by the method which Mr. Townley had very successfully used and directed me. ....with a surveyor's chain, I measured 908 feet 7 inches, at which distance exactly across to the chain, I placed a very substantial ruler with black marks upon it, at 1,3,6,36,72 and 108 inches distance. I drew the tube to 165 1/2 inches long, where I could best see the object, and then found 108 inches measured within the tube, by 57.55 revolves, but by reason of the wideness of the object, the observation somewhat difficult. Afterwards 72 inches distance by 38.33 much better. Now because the breadth of the distant image projected in the tube is in proportion to its length betwixt the object glass and the place of projection, as the wideness of the visible object to its distance from the object glass...." (Baily: p.110).

Flamsteed then illustrated his calculation (with logs to 6 decimals!) and found the results as: for the 108in spacing, 35.11 and for the 72in separation, 35.07 which was the

---

[1] It was with the Townley micrometer that Flamsteed measured the solar parallax finding it to be <10". This was the first use of the micrometer to measure the parallax (Forbes: 1975, p.27).

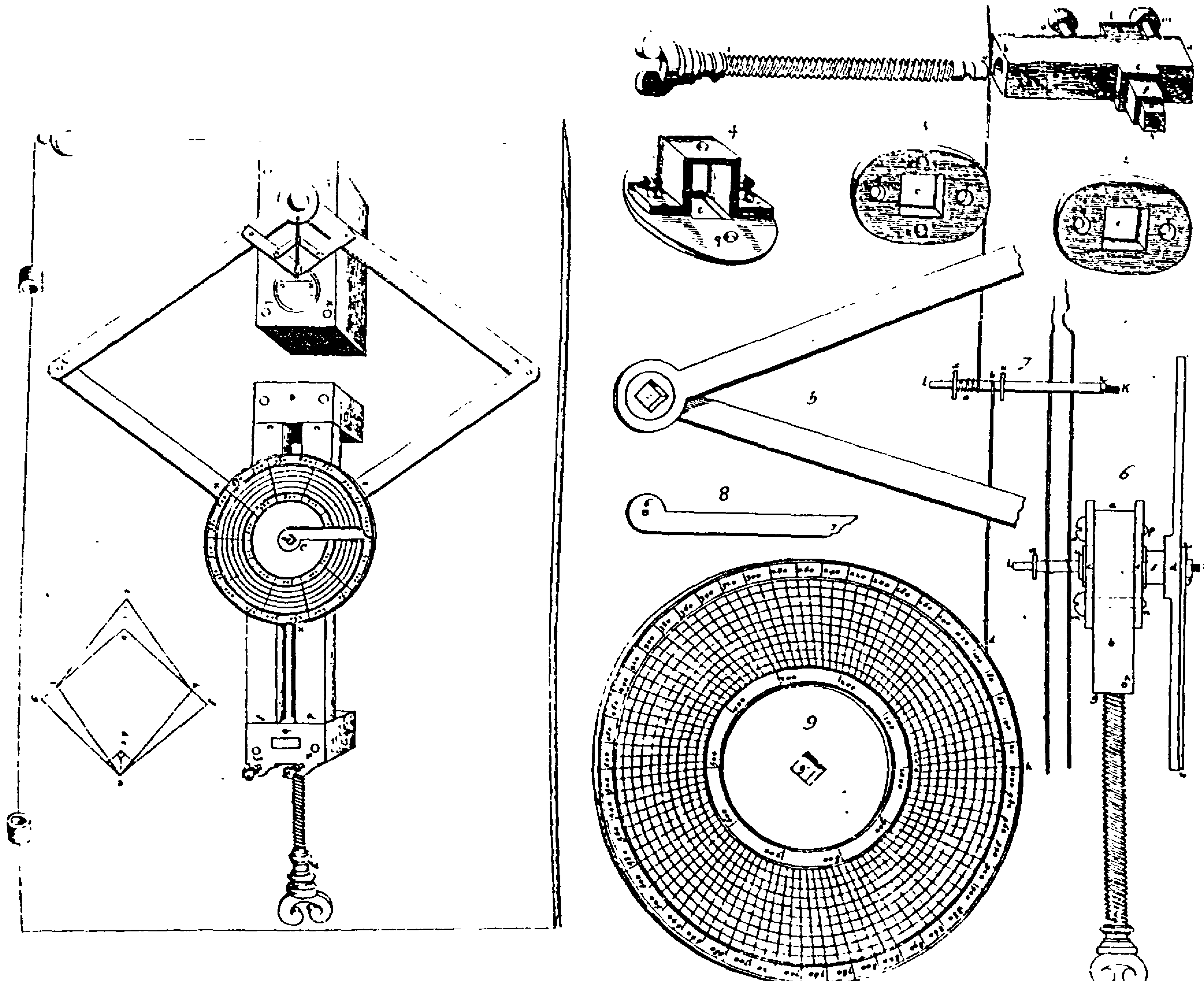
value he had more confidence in because of the relative ease of measuring separation. The focusing error was not considered by Flamsteed and his values are thus enlarged in the same manner as Auzout's. Using the new value, Flamsteed recalculated earlier observations and subsequently used this value of the screw. It also is worth noting the difference between the values of the two screws made with the same screw box and the fact that Flamsteed found the diameters to be different.

Van Helden (1985, p.120) has noted the enlarged diameters of the planets observed prior to the filar micrometer. The diameters observed with the newly invented filar micrometers were also too large, but nevertheless much closer to the truth than earlier measurements. Because of the previous overestimation, errors in the measured size--caused by the calibration technique--went unsuspected until other methods reached an accuracy comparable with the micrometer. Systematic differences only then began to appear. Not until 1717 did LaHire publish a method for correcting this source of error, although his effort seems to have drawn little attention. About 1725 Bradley noted the parallax error in the standard calibration technique and Smith published the first description to appear in English in 1738. This will be discussed in more detail in the section on 18th c micrometers. Recent publications (e.g. Van Helden: 1985, p.127; O'Dell and A. Van Helden: 1987, p.629-631; and Morrison, Stephenson and Parkinson: 1988, pp.421-423) have suggested that the problem was the quality of the optics, but this was not the primary cause given the above information. This is more fully discussed in Brooks: 1988 II.

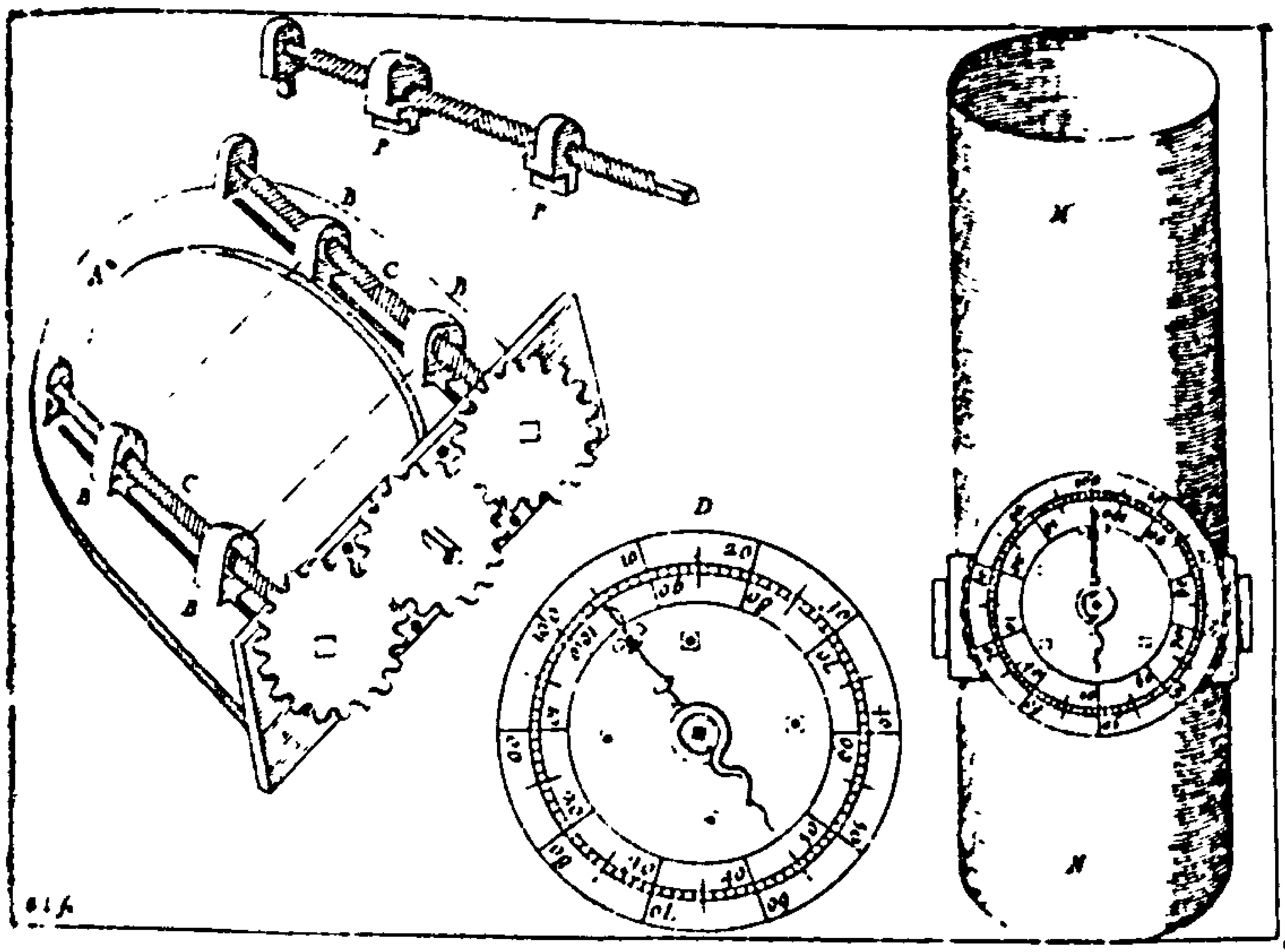
The purpose of having multiple filaments[1] in Auzout's second micrometer was not so much to eliminate errors by multiple observations with different combinations as for convenience. Depending on the diameter or separation of the object(s) being observed, one simply choose the most convenient pair of wires--one fixed and one moveable. This reduced the need to rack the screw back and forth over large separations, thus saving time and reducing wear on the screw and nut. To calibrate a micrometer using a fixed target was simpler and more precise than attempting to set two wires on two objects, or on different limbs of the same object, moving at the sidereal rate. Irradiance, the error caused by observing bright objects against a dark background (or vice versa), causes an enlargement (or shrinkage) of the separation being measured. This effect had been recognized by Galileo and Newton, and the latter had attempted to estimate its size. Errors of the screw, both of runs in pitch and random errors, were prevalent in hand made micrometer screws. The wires of the micrometer were also a source of error on two counts. First, the fixed and moveable wires could not be in the focal plane at the same time thereby causing a small enlargement of the object. Secondly, nonparallel wires cause an error.

---

[1] Cassini was the first having a fixed thread perpendicular to the moveable threads (Maskelyne: 1772, p.46).

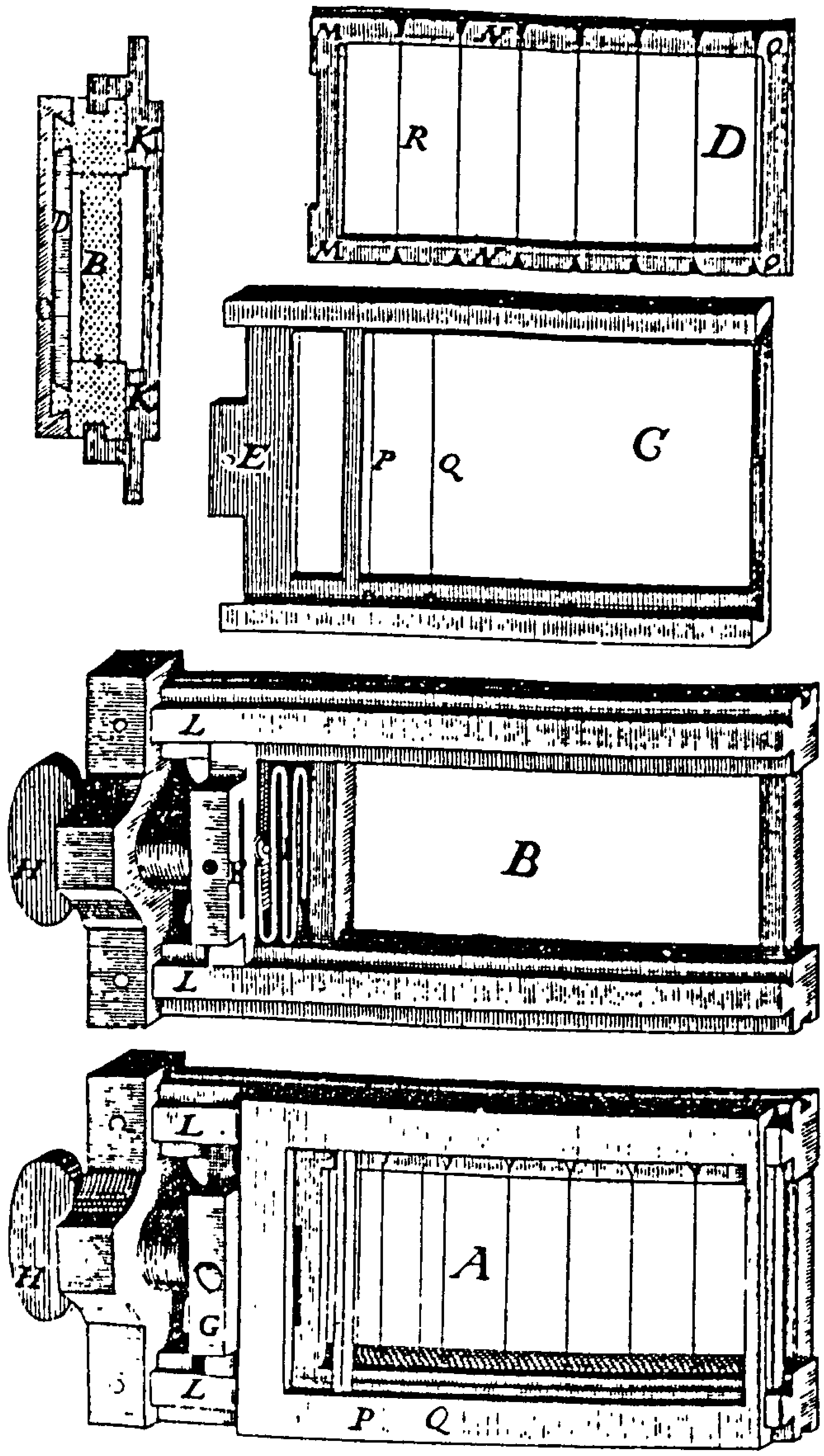


3.2.7 Chérubin d'Orleans' micrometer (1671).



3.2.8 Petit's micrometer (1667).

3.2.9 Romer's micrometer (1672).



LaLande (1792) described the methods of micrometer calibration but by 1829 they had not substantially changed. There were of course changes due to the design of specific instruments but the basic techniques remained. Pearson (1829, pp.99-115) described the following techniques:

1) use of a celestial object of known diameter, e.g. the Sun;
2) measuring the passage of the star between wires set at a specific separation;
3) comparing the separation of two stars preferably in the same field of view;
4) for quadrants, using the focal length of the objective and eyepiece and the TPI of the micrometer screw to determine the ratio to the whole circle; and
5) using the test card technique described above.

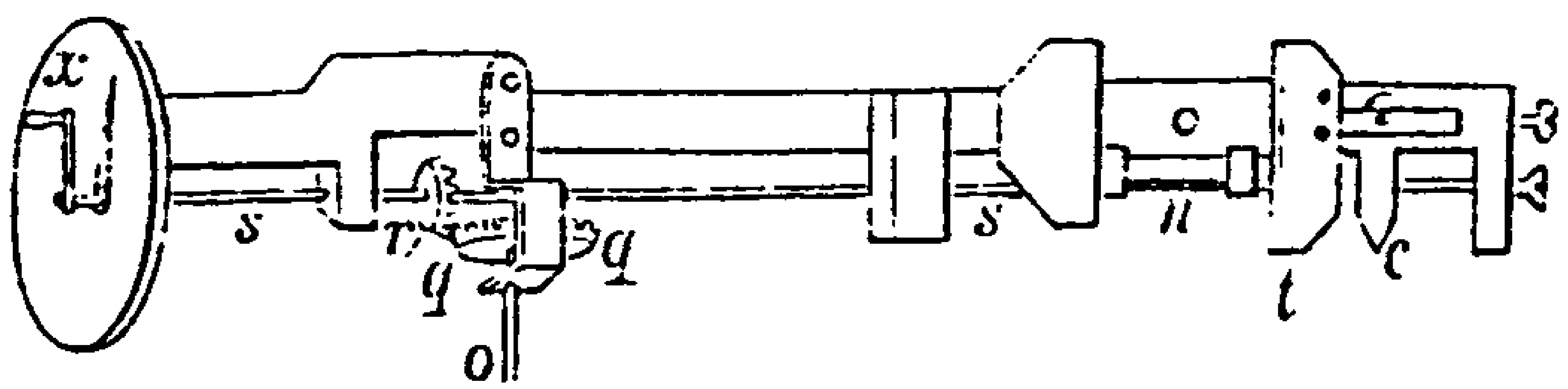
3.2.7 A Proliferation of Micrometers:

Auzout's letter to Oldenburg had the same impact on 17th c astronomy as the CCD camera on astronomical practice in the 1980's. The speed and number of devices which began to emerge demonstrates this. In 1671 Chérubin d'Orleans described and illustrated a device which looks more useful as a bench micrometer than "pour dessiner et mesurer les objets du Ciel qui peuuent estre veus par l'Oculaire dioptrique" (Fig. 3.2.7). The fiducial was screw driven through a parallelogram arrangement which magnified the motion of the screw. The screw's movement was transmitted to the dial by a cord wrapped around a spindle advanced by the screw. As illustrated by Chérubin, the screws in this micrometer are left-handed.[1] The dial was divided to thousands by transversals as shown. The sources of error are so numerous and obvious as not to require further explanation. Chérubin's device never enjoyed the patronage of astronomers.

On the 12 March 1667 Petit wrote Père Jacques de Billy concerning his micrometer, and this letter was subsequently published in the *Journal des Savants* . Petit had been inspired, as had Auzout, by Malvasia's **Ephemerides Novissimæ** (1662). Petit's micrometer is illustrated in Fig. 3.2.8. The dial's diameter was 2 pouce (5.4cm) and carried 100 divisions marked both clockwise and counter-clockwise. The pair of screws were the same length. The innovation Petit introduced was that his screws were both right and left-handed thus allowing both wires to move symmetrically with respect to the optical axis. Motion was transferred through gears of 18 teeth. The most glaring mechanical problems were the lack of backlash controls (confirmed by the obvious intent to measure in both directions as shown by the scale divisions) and, as drawn, the impossibility of finding a zero reading or of measuring very small diameters. Petit was obviously most interested in measuring solar and lunar diameters. The claimed accuracy was 0.75 microns and the pitch 0.75mm (≈34 TPI). The whole arrangement was in a 6 pouce (≈16cm) long tube for mounting on his telescope.

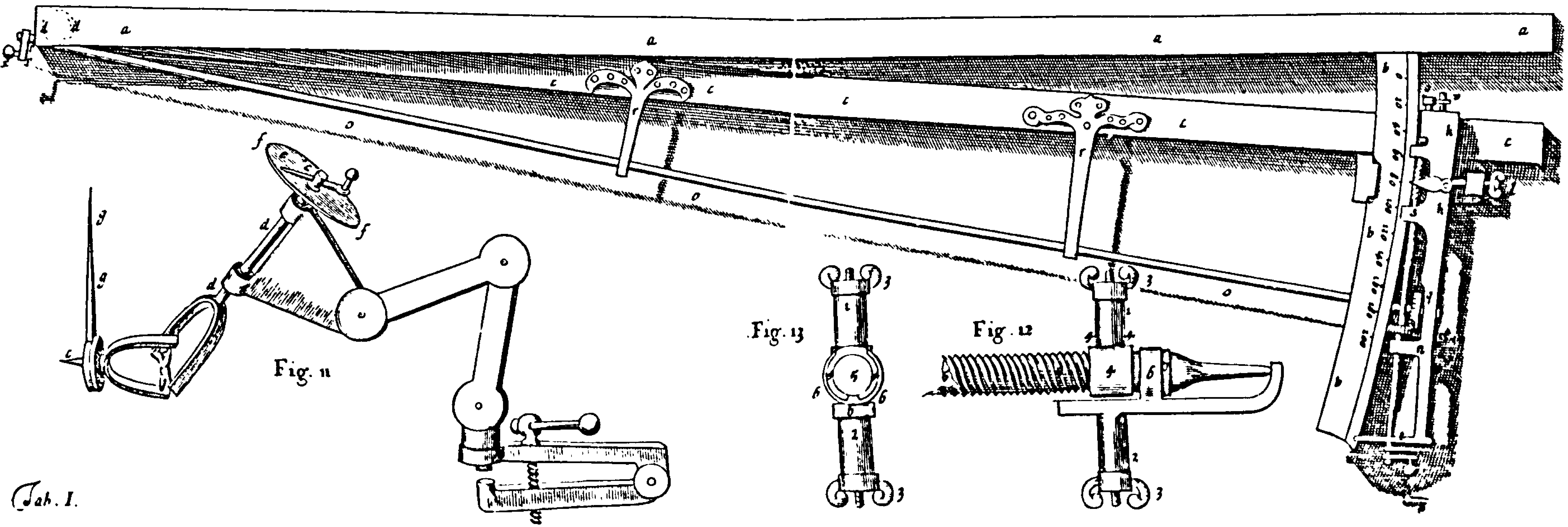
---

1 As pointed out by A.A. Mills this may be due to an inadvertent reversal resulting from the engraving process.



3.2.10a Screw and index mechanism of Hooke's scale micrometer (1676).

3.2.10b Application of the above mechanism to Hooke's zenith sector.



A micrometer which must have held considerable importance for the technical advancement of these instruments was that of Ole Römer. It was apparently invented in 1672 before he met and went to Paris with Picard late in the year. Horrebow, Römer's student and biographer, says Römer invented it independently and without knowledge of Auzout's. From a mechanical perspective, Römer's instrument (Fig. 3.2.9) includes two interesting elements. The frames holding the wires were mounted in dovetailed ways, and there was a double-'S' spring working against the screw to minimize shake between the screw and nut caused by looseness or wear and to reduce backlash. The illustration does not explicitly show a scale although a small scale with 10 div./turn was present. This instrument was designed with the fixed wires separated by a distance equal to 10 times the screw's pitch. The ways carried a scale as a check. The screw itself was relatively short but of comparatively large diameter. This instrument was used by Römer at Paris and after he returned to Copenhagen. Horrebow also used it until its destruction, along with Römer's other instruments and recorded observations, in a fire in 1728.[1]

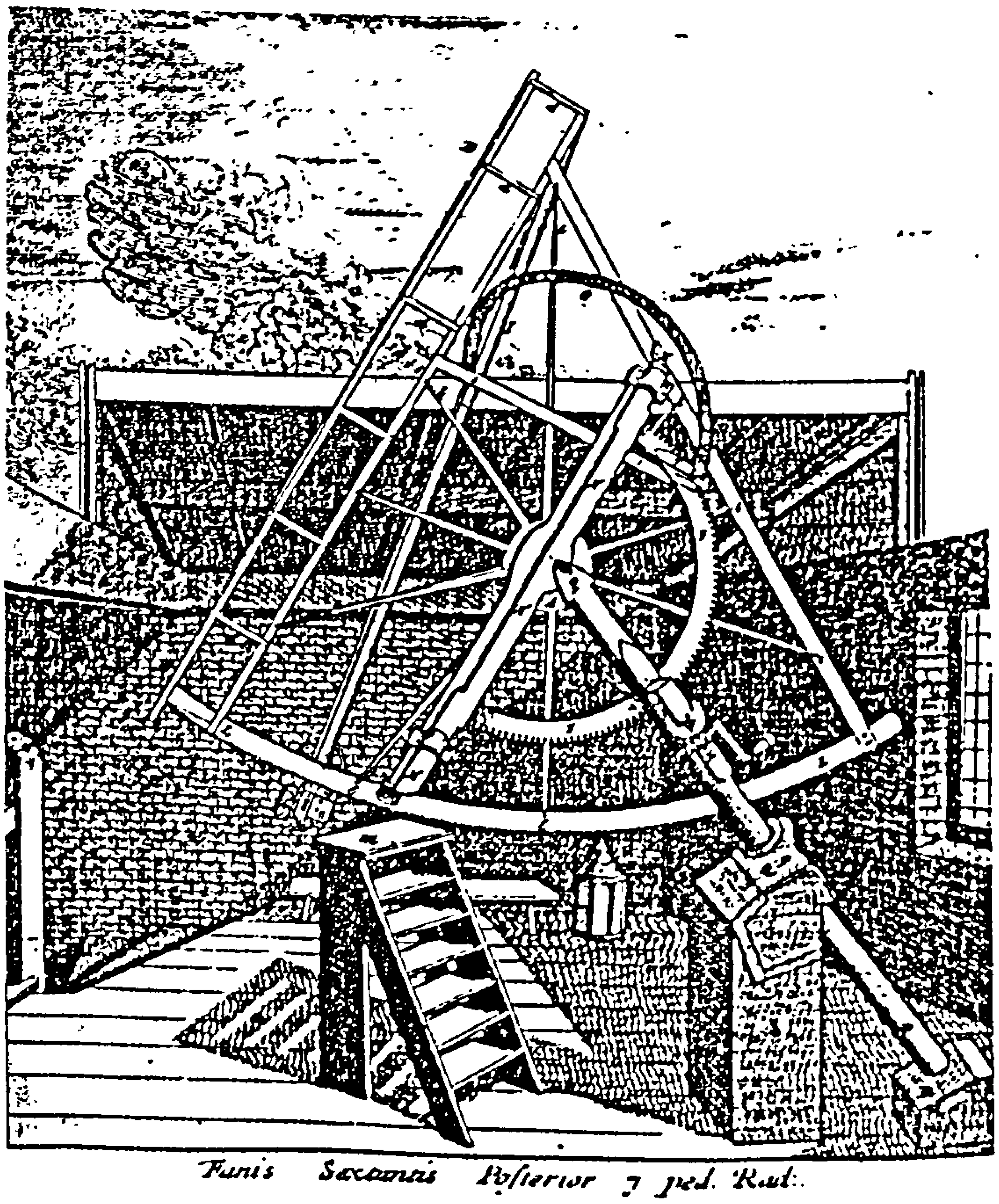
One of the simplest micrometers was that of Kirchius (Athanasius Kircher?, 1602-80). It consisted of a ring with two screws mounted on opposite sides. Measurements were simply made by counting the number of revolutions needed to separate the screws to the diameter or separation of objects being observed (Pearson: 1829, p.97)

3.2.8 Hooke's Scale Micrometer:

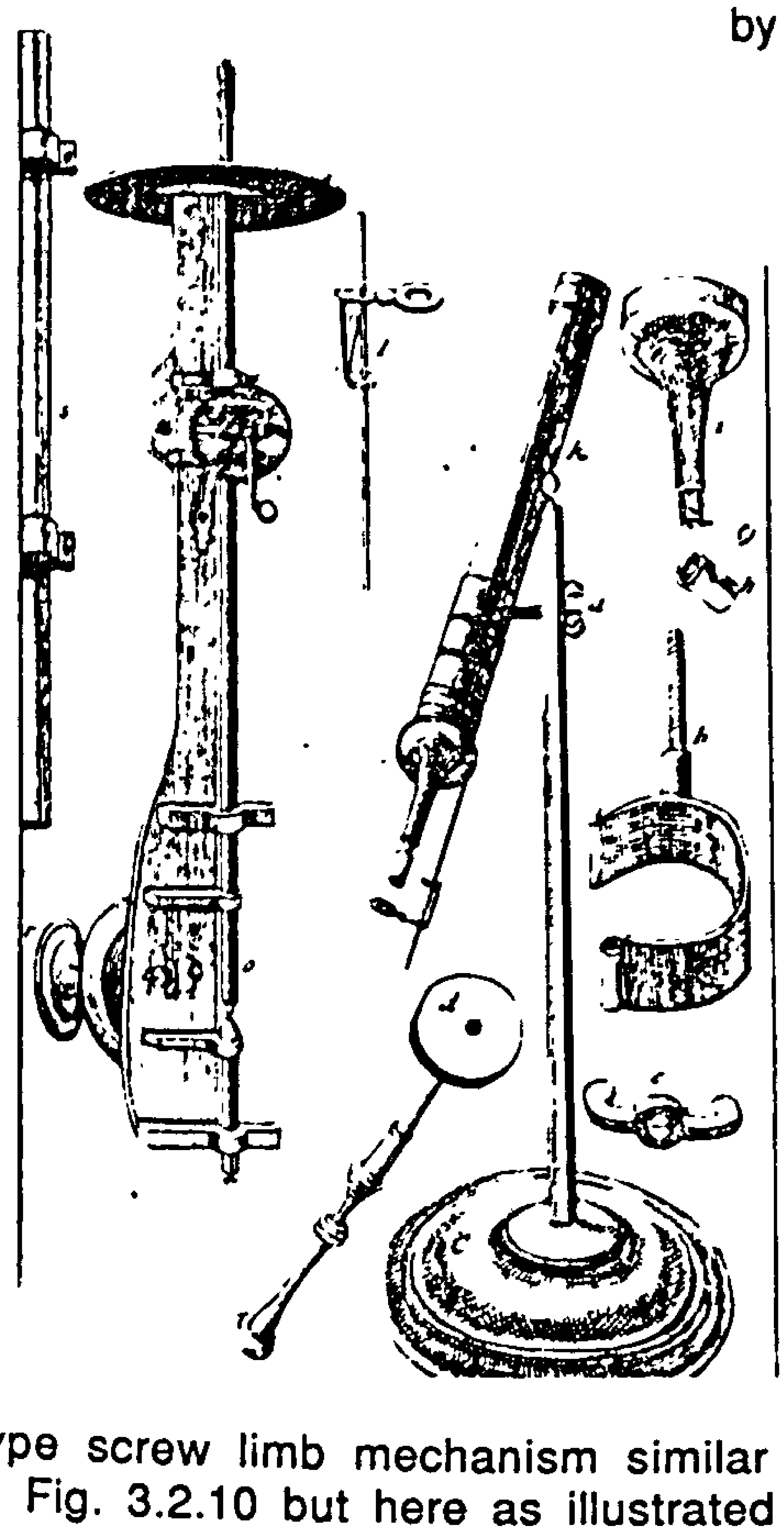
Excepting a poorly documented case where Tycho was given a quadrant with a screw acting on the limb and the apparently little noticed device of Hevelius, Robert Hooke's screw limb quadrant (Figs. 3.2.10, 3.2.11b) was the first to receive wide notice as a result of his **Animadversions** (1674). The device suffered a number of faults, the most critical being the fact that the screw acted continuously on the limb resulting in unnecessary wear of the thread on the screw and limb during the process of racking the screw back and forth. This was also the design of the first instrument made by Tompion for Flamsteed at the Royal Observatory. This instrument was built at Hooke's suggestion but within months it became clear that wear was affecting the accuracy. What is important about this design for the present work is that Hooke described how the screw was made--the first description of the fabrication of a 'precision' screw. The passage is therefore quoted in its entirety.

> 2. Instead of this Screw upon a circular Limb, a Screw may be made to move upon a straight Limb, or Ruler; the end of which must move upon Centres or Rowlers, the centres or axes of which Rowlers must be exactly in the same line, when both the Perspective-sights are adjusted to the same Object, and the divisions began. The same thing may be done by a straight Screw, in the manner of a pair of dividing *Compasses*, where the same care must also be had, that the axes of the Rowlers must be exactly in the same line, and the sides of the Incompassing-screw, being made of steel, must be made to spring

[1] See J.A. Repsold: 1908 and A. Wolf: 1950, v.1, p.173-4.



3.2.11a Flamsteed's 7ft quadrant (1676) with fine mechanism by Tompion.



3.2.11b Hooke type screw limb mechanism similar to that shown in Fig. 3.2.10 but here as illustrated by Place and indicated as unidentified by Howse (1975).

> about the long Straight-screw; this long Screw must be made 18 inches long, and 'twill be best to screw it with a small thred, otherwise it will be apt to be moved out of a *straight* by screwing a large thred; and the thred, whether greater or less, must be made by degrees with a pair of cutting-stocks, that may be set closer every time of screwing.

Given the lack of cutting action of 17th c screw stocks, it is amazing that Hooke thought he could successfully make a screw precise enough for the task. Where the stocks had to be run along the screw blank several times to deepen the thread, the flanks must have been perceptibly flawed. Hooke makes no mention of trying to file the flanks smoother although this soon became common practice. For his 5 foot radius quadrant, Hooke employed a 7 inch diameter index plate and ≈30 TPI screw. On the quadrant, 2 arc minutes equalled 1/30in or one turn of the index and on the index 1 arc second was "not much less than the 5th part of an inch" (Hooke: p.85). The use of this screw for the division of the limb of the quadrant is discussed further in §4.1. After several years use at Greenwich, Hooke demanded the return of this instrument to the Royal Society and it should be noted that in collecting it another instrument was also taken--"the small quadrant of 5 inches with the screw limb".[1]

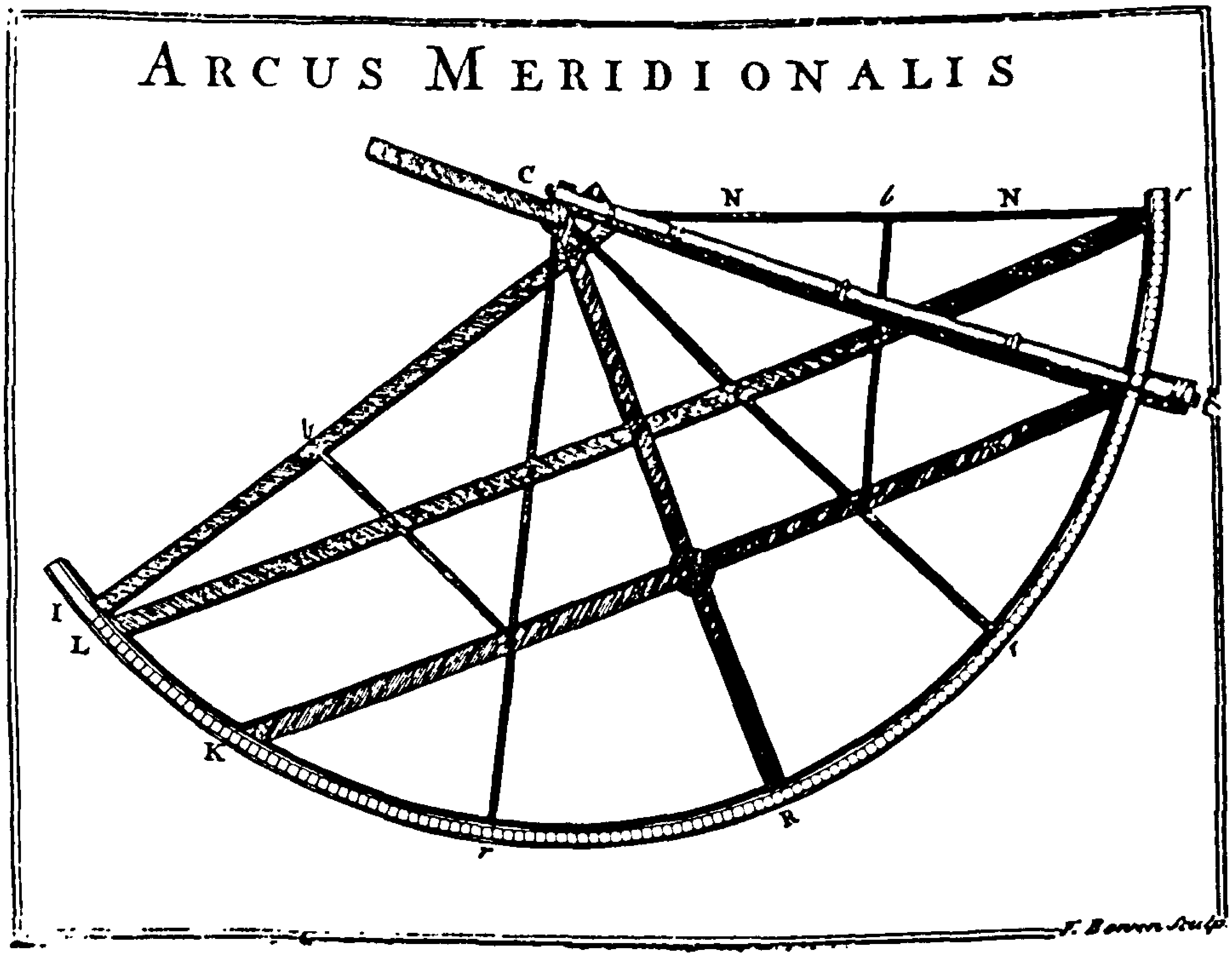
An instrument which incorporated some of the above features was the 10ft quadrant designed by Hooke and made for the Royal Observatory by Thomas Tompion; it was a total failure and was installed at the Observatory only at Hooke's insistence. The 7ft sextant illustrated by Place (Fig. 3.2.11a) was also made by Tompion along similar lines but to Flamsteed's design. Within months of its completion, Flamsteed began to recognize errors due to the constant racking of the screw along the limb. From John Flamsteed's[2] **Historia Cœlestis Britannica** (1725) and John Smeaton (1786) more is learned of quadrants with divided limbs. Smeaton was not convinced by Hooke's statement "[the accuracy] does not at all depend upon the care and diligence of the instrument maker in dividing, graving, or numbering the divisions, for the same screw makes it from end to end" (Smeaton: 1786, p.2). Smeaton noted that the Duc de Chaulnes (1765) had followed a method similar to Hooke's and had found this method of dividing or measuring wanting.[3] In Smeaton's opinion the gross errors were caused by differences in the hardness of the limb causing threads of different depth and shape but Edward Troughton (1830, p.362) thought it was probably caused by wear of the cutting screw from one end of the limb to the other. He speculated that the threads were of different shape from end to end due to this wear. Flamsteed had discovered that the sextant made by Thomas Tompion for the Royal Observatory (delivered 29/10/1676) frequently had errors (as found by Smeaton by referring to Flamsteed: 1725, vol.3, p.104) of half a minute of arc, not infrequently to 40" and for a measurement of the Moon's position (9/06/1687) an error of 55"!

---

1 Baily (1835, 45) quotes this from Flamsteed's **The Brief History of the Observatory**. Nothing more has been found on this instrument.

2 See also Bailey: 1835, p44.

3 Sharp and Rowley also used this technique for making threads on instrument limbs.



3.2.12 Sharp's mural arc (1689) made for Flamsteed for use at the Royal Observatory, Greenwich.

Smeaton calculated the error to be 1/50th inch for a sextant of 6ft 9in radius. Given that the screw of the sextant had a pitch of 1/17th inch (Flamsteed: vol.1, preface), this represents a variation or error equal to 1/3rd of the screw's pitch! However, it should be pointed out that this comparison was made against the diagonals which were later added to the limb and which would have contributed to this error. Nonetheless it demonstrates perfectly the conflict between the two methods. The diagonals were added in August and September, 1677 and the instrument was put back in operation on 11/09/1677. Flamsteed (vol.3, p.106) stated that the screw and limb had worn to the point that he had to put on the diagonal divisions himself. He thereupon set about preparing a second revised table for the conversion of the revolutions of the screw in 1678 but the screw and rack were soon abandoned altogether. A comment by Flamsteed on the divisions is instructive: (Chapman: 1982 II, 116) "Thus the whole of this space is divided into five parts, at the edge of the bronze square which is attached to the index, and each of these partitions or minutes, is divided up into six more, each representing 10 seconds. Therefore, it would not be too hard to measure an angle or a distance in the heavens, to a high degree of accuracy, if we could establish with certainty that an arc of a circle can be divided with sufficient accuracy by human artifice. But there remains doubt as to whether this can be done."

Hooke demanded the return of his 10ft quadrant to the Royal Society and the 7ft sextant was replaced by a 6ft 7.5in mural arc (Fig. 3.2.12) in 1689. This mural arc was made by Abraham Sharp (Bennett: 1987, p.71) whom Flamsteed was able to hire using money left to him in his father's estate (Spencer-Jones: 1946, p.5). This instrument was divided both with diagonals and with a screw and rack in the same manner as that designed by Hooke and made by Tompion. Illustrations of this arc are found in Chapman (1982-1, p.122/4, figs. 22,24) including one which shows the limb-screw mechanism in some detail. Unfortunately, Flamsteed did not describe the method used to create the thread on the limb of the arc although the thread was of the same pitch as the previous instrument, i.e. 17 TPI.[1] The instrument went into operation in September 1689. Smeaton (1787, p.6), analyzing data collated by Flamsteed, found disagreement between the diagonal scale and micrometer readings and concluded that there was a problem with the application of the technique which, as has been stated, proved insurmountable even as late as 1765 with Chaulnes' attempt at using it in a dividing engine. Flamsteed claimed he could obtain measurements to 3" (Baily: 1835, p.45/6).

3.3 18th Century Micrometers:
3.3.1 Early Filar Micrometers:

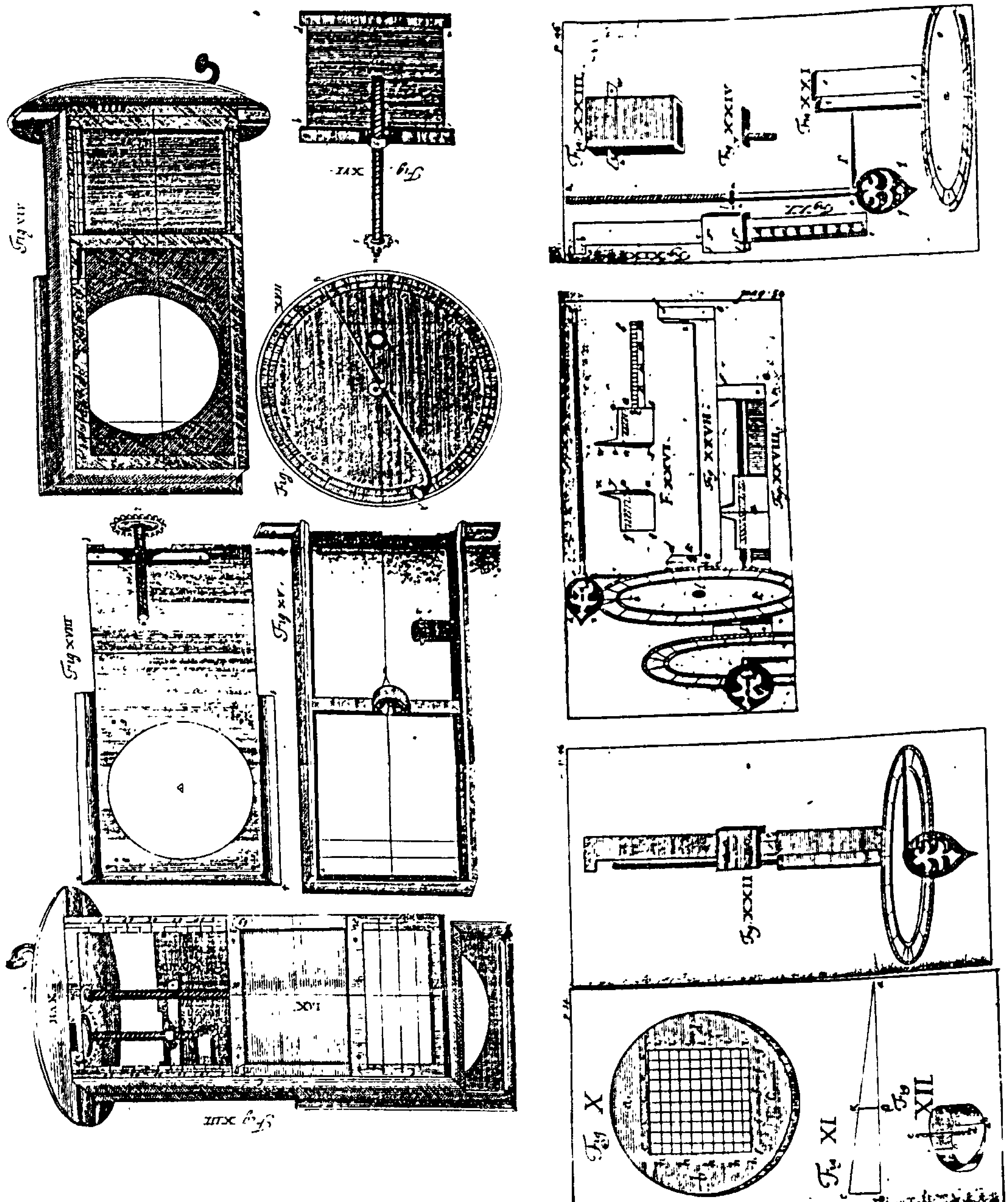
The state of micrometer technology at the beginning of the 18th c is summarized by Theodore Balthasar. In his **Micrometria Siva de Micrometrorum Telescopiis et Microscopiis Applicandorum Varia Structura** (1710) details of four micrometers are given. The simplest is the grid micrometer of the Divini/Malvasia type with a grid of 10 by 10 wires or lines drawn on glass with a diamond.[1] In this paper one encounters a diagram which illustrates the relationship and principle of the inclined plane and helical plane, or screw, for measuring (Fig.3.3.1). This was an introduction to the second micrometer illustrated by Balthasar: a simple version of the Gascoigne/Townley design which employed a screw with a single thread moving a 'box' fiducial over a linear scale of 0-45 divisions. The index indicated the sub-divisions on a dial with 20 large divisions subdivided into 5 subdivisions, i.e.100 divisions per turn of the screw. A more sophisticated version is also illustrated in which the simple screw was replaced with one with both left and right handed threads. In this example the pointers could be drawn together on the optic axis, then separated to measure a separation or diameter. Neither pointer had any spring or other provision for taking up backlash.

The fourth and most sophisticated micrometer illustrated by Balthasar is a filar micrometer incorporating features of Auzout's and Petit's micrometers of some 40 years earlier. The novelty of the design was driving a second screw through gears; Petit had employed two screws each with right and left hand threads whereas Balthasar illustrates two screws of the same handedness, one long and another about half the length. The longer screw, as illustrated, has a 10 tooth spur gear and the shorter a 20 tooth spur gear thus providing similar motions but in opposite directions which were symmetric with respect to the optical axis. The linear scale was divided 0-55 with the 10's divisions numbered and with a 5 marked at the mid-points. The dial was divided to 120 divisions with the 10's numbered. Although not very clear in the engravings, there were end bearing screws acting on the micrometer screws as evidenced by slotted screw heads on the end supports for the micrometer screws. In another part of the engraving, the shorter screw is shown with a dimple into which the end bearing screw could seat[2]. Each moveable frame had two wires plus a wire running parallel to the screws on one of the frames. The overall appearance on this micrometer has much in common with Bradley's micrometer which had great popularity in 18th c Britain. Its greatest deficiency was the lack of a spring to eliminate backlash. The source of this design is questionable. Balthasar does not appear to have been an original designer or instrument maker, his purpose in

---

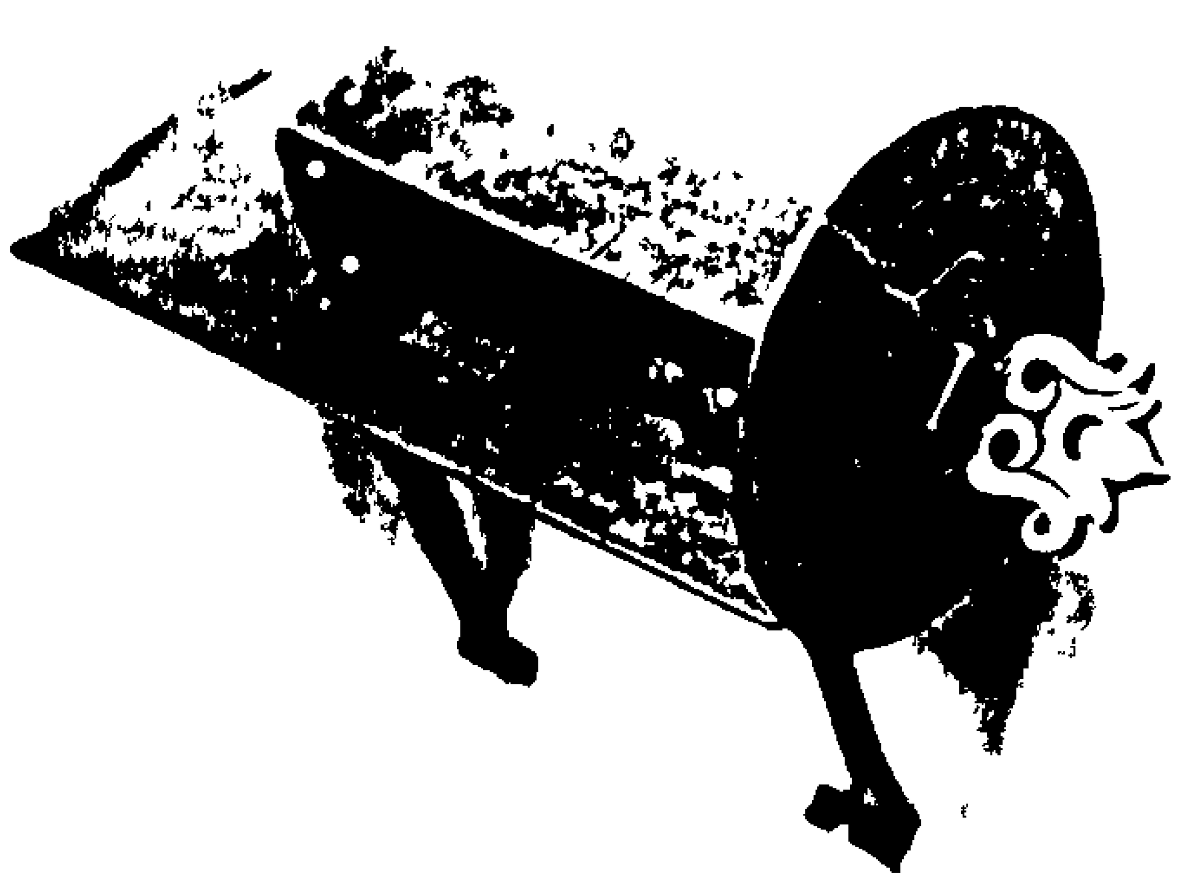
1 Balthasar's use of the diamond to draw lines on glass may be the first such use of the diamond.

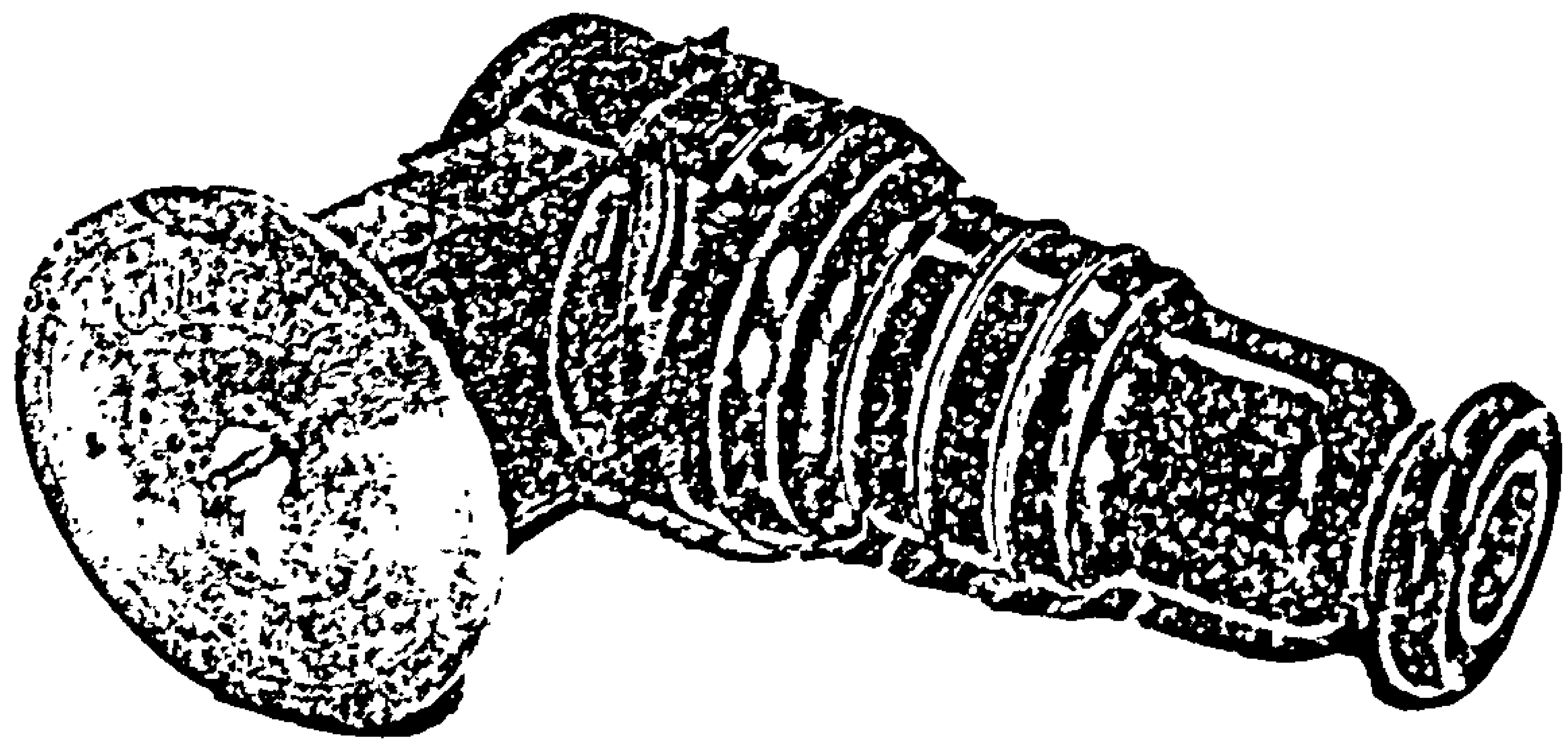
2 Many of the micrometer screws studied had dimples in the end. However, the vast majority were a result of having been made on a screw lathe where the screw blank was supported by a dead centre. This was one of the chief sources of error of eccentricity in micrometer screws.



3.3.1a Micrometers illustrated by Balthasar (1710). The example illustrated in Fig. XXII is similar to an example in the Science Museum (SML-3). That shown in Fig. XIII is similar to Rowley's.

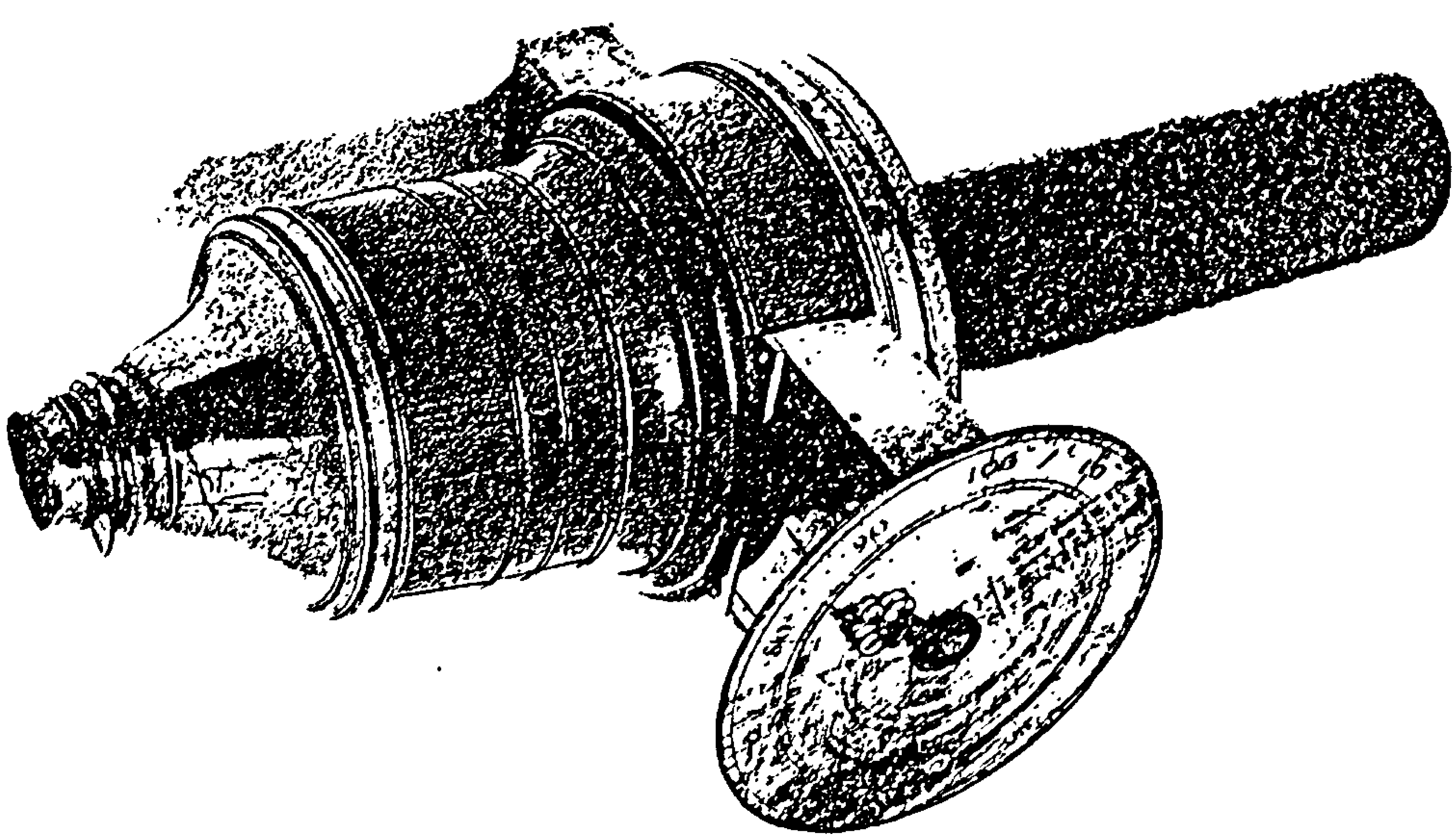
3.3.1b Micrometer (ca.1700) in the Science Museum, London.





3.3.2a Micrometer by Rowley (ca.1703) in the Whipple Museum of the History of Science (WMHS-7).

3.3.2b An unsigned micrometer at Christ Church, Oxford (ca.1700) possibly by Rowley.



providing the descriptions and figures being to provide a manual from which scientists could choose a design compatible with their circumstances.

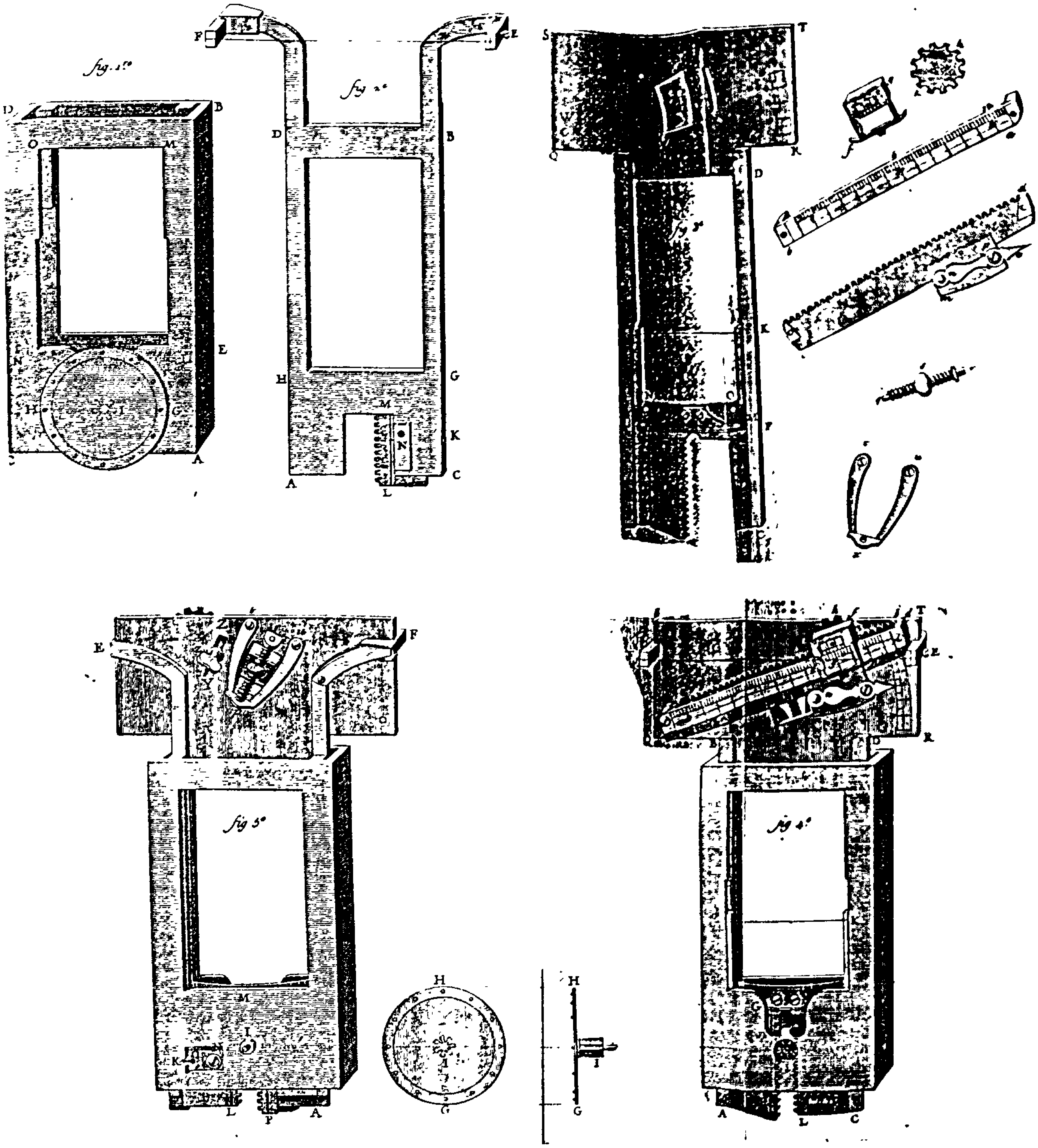
The Rowley micrometer[1] (WMHS-7) in the Whipple Museum of the History of Science (Fig. 3.3.2a) bears more than a little similarity to the fourth micrometer illustrated by Balthasar. According to Price (1952, pp.2-3,12) the Rowley micrometer was acquired by Trinity College Cambridge in 1703. The instrument is a superb example of Rowley's workmanship and may be taken as an example of the state of the mechanical arts of the day. It is somewhat more complex than the one just described and differs slightly in the mounting of the micrometer screws, i.e. the end bearing screw mounts are reversed on longer and shorter screws and there are three gears rather than two thus requiring the screws to be of opposite handedness--a step backwards considering the mode of fabrication of screws at the time. One flaw, besides the lack of backlash spring, is that the micrometer hairs cannot be closed closer than 1/8-3/16 inch. The dial is divided to 100 divisions. A micrometer, unsigned, of ca.1700 was in Christ Church, Oxford and is item #172 of the Orrery Collection (now in MHS) (Fig. 3.3.2b). The outward appearance and quality may be sufficient to suggest Rowley's hand.

The micrometer of LeFèvre (1735), designed and described to the Academie des Sciences in 1705, is certainly the most complex encountered to this time (Fig. 3.3.3). The theoretical basis was the method of subdividing and reading scales described by Perè Tacquet in his **Géometric Practique.**[2] Although LeFèvre's micrometer does not employ screws, it was described as being superior to the ordinary micrometers. Motion of the wires was effected by a pinion gear causing two opposing racks to move with respect to each other thereby moving the wires and a glass plate with parallel lines engraved on it. A scale attached to one of the racks gave the primary divisions while subdivision was effected by a pivoted scale with vernier. The angle of the secondary scale (divided from -5° to 65°) was apparently preset according to the size of the object to be observed and was read by a peculiar system of a fiducial wire intersecting the pivoted scale and attached to the plate carrying the wire measuring the object. The vernier was moved along the scale with a rack and pinion arrangement so that its zero corresponded to the intersection point of the fiducial wire and the scale; the unit divisions on this scale were thus subdivided to 1/4 of a division. The instrument had a number of problems to overcome but the most inconvenient must have been the inequality of the sub-divisions effected by the pivoted secondary scale. Thus this micrometer drew little attention and did not have its features copied although, according to Daumas (1972, p.77-8), several examples were made. Two were in the collections of the Academie des Sciences but their present whereabouts is not known.

---

1 The instrument is actually signed 'John Ronley' but there is little doubt that it was made by Rowley (Bennett: 1987, f.58).

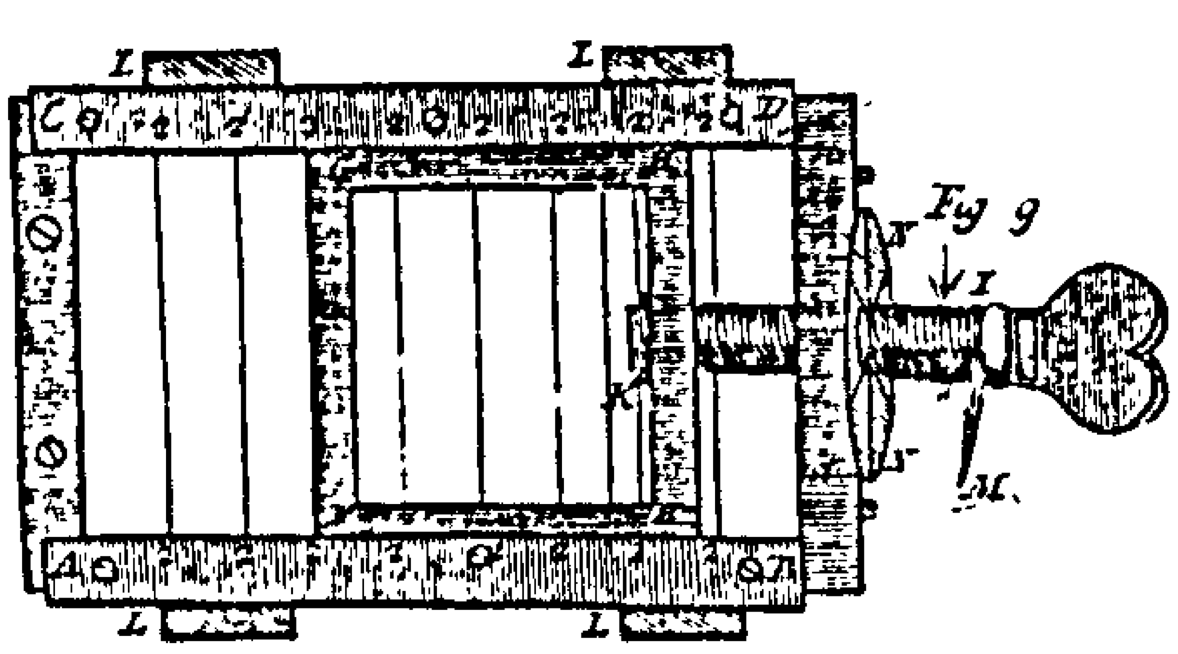
2 Peré André Tacquet published his **Opera Mathematica** in 1668 with Geòmetric Practique as the third part. A second edition appeared in 1707.

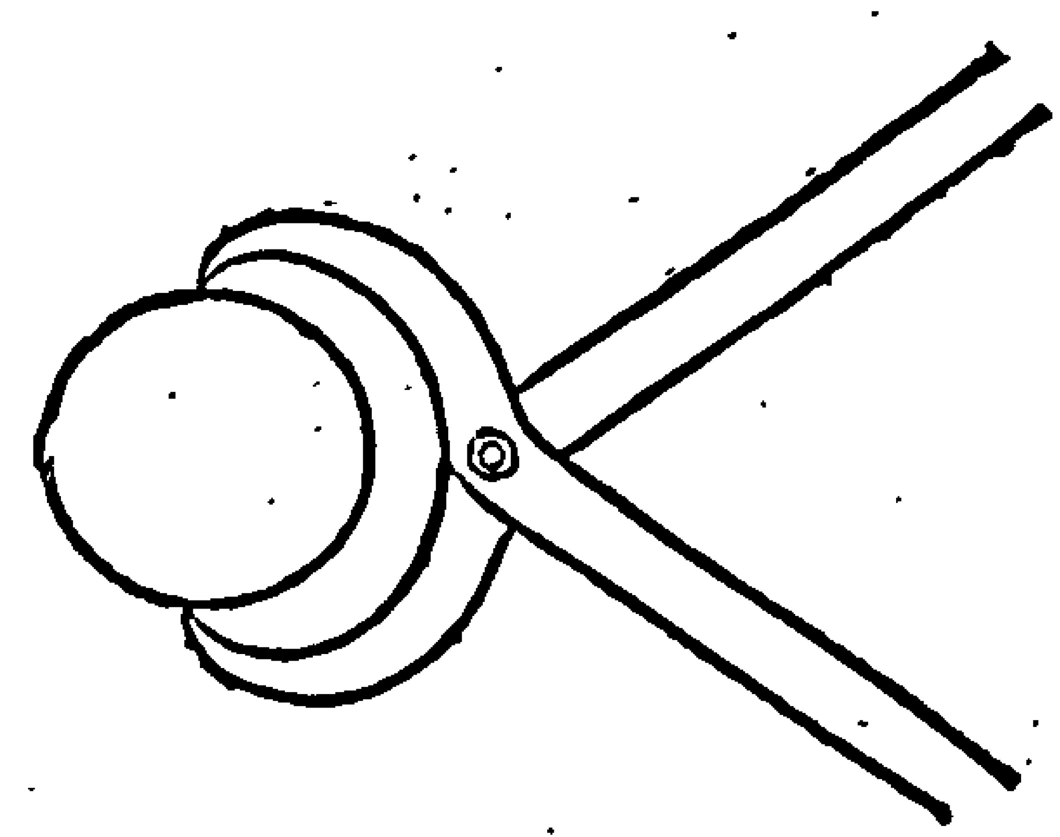


3.3.3 LeFevre's micrometer (1705).

3.3.4 Bion's micrometer (1709)

3.3.5a LaHire's proportional compasses for micrometric observations.





Nicolas Bion's **Traité de la Construction et Principaux Usages des Instruments de Mathematique** is well known because of Edmund Stone's translations of 1723 and 1758. The 1723 translation was of the 1709 edition although Bion had revised it in 1716.[1] Stone's 1758 edition was based on Bion's of 1709 but includes an appendix providing updated information on British instruments and instrument making practice of the mid-18th c. The micrometer illustrated by Bion (Fig. 3.3.4) is rather crude and incomplete. The description (Bion/Stone: p.155-6), however, fills in some of the details. The frame was to be ≈6.3mm by 3.8mm, with several wires (actually human hair) placed about 4 lines[2] apart depending on the pitch of the screw. The screw was 4-5 lines (8.4-10.5mm) in diameter and ≈3.7cm long. Its end was made to fit through a hole in the middle of the frame, being free to rotate although held in place by a pin through the end of the screw. The screw also carried the index indicating the fractions of turns on a dial, ≈2.5cm in diameter, divided into either 20 or 60 divisions. Because of this arrangement, reading parallax would have been severe. The linear measurement was effected by a scale on the frame. Bion suggested that the threads should be 4 lines apart and that 10 times the pitch should equal the 4 lines. Therefore we can deduce that the pitch was ≈ 0.85mm (or 30 TPI). Bion suggested La Hire's glass plate with finely engraved lines was preferable to human hairs due to the latter's susceptibility to heat and moisture. It should be noted that Bion's calibration technique was identical to that described by Auzout and Picard (Auzout: 1667, p.6-10) but as we shall see shortly, its deficiency was about to be discovered and corrected.

3.3.2 Discovery of Calibration Errors:
3.3.2.1 The parallax effect:

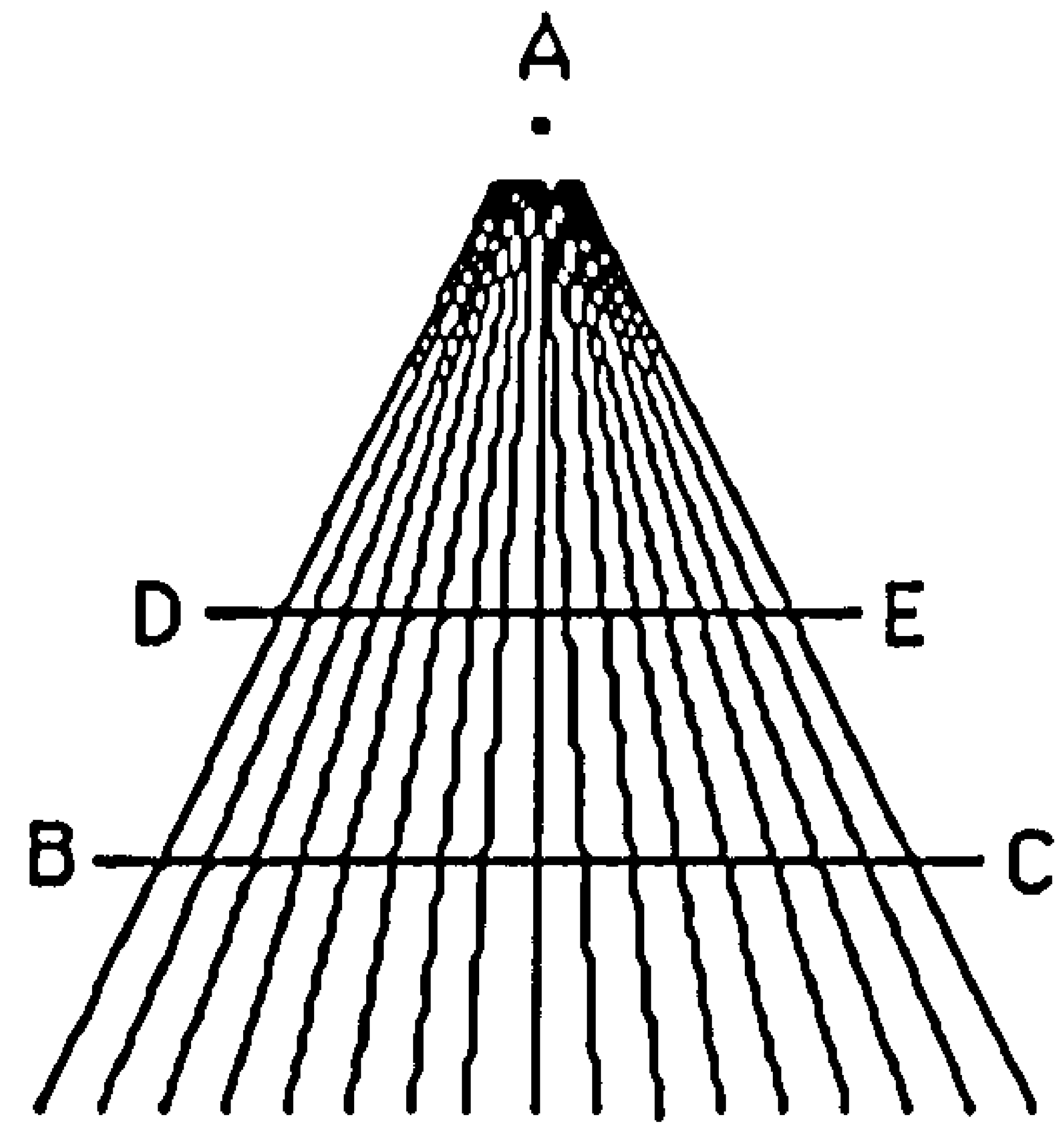
On first glance, LaHire's description (1717 II) of a 'universal' micrometer looks superficial because the micrometer is simply a proportional compass with one set of points being reshaped so that the compass assumed the appearance of a pair of ice picks as illustrated in Fig. 3.3.5a. The design and use is so simple as not to require description. The primary flaw was to determine when one was exactly measuring the greatest diameter of the disc of the Sun, Moon or planet. However, what was far more important in La Hire's paper is the procedure for calibration; the basic procedure was that advocated by Auzout, Picard and Bion but LaHire (p.62-3) had come to recognize a fundamental flaw in the method. He observed that a telescope focused on a nearby target--even if 200 or 300 toise (400-650m)--has a different magnification or 'plate scale' than when focused at infinity. LaHire did not give the formulae per se but gave the necessary factors: distance between the lines on the target, target distance, focal length of the telescope and tangent of the angle made by the telescope objective for the chosen target

---

1 This work went through 5 French versions to 1751, 5 German editions to 1752 and Stone's two editions. Thus the impact of the work was very extensive.

2 1 line = 0.17473 inches ≈ 4.44mm but Bion used 1 line = 1/12 inch ≈ 2.1mm

distance. He proposed that the target could be redesigned as illustrated here.



3.3.5b LaHire's calibration card pattern.

He drew 24 lines emanating from a point A, and at right angles to the central line, a line BC was drawn. The points BC represent the spacing of the lines on a standard target which, if it could be measured at a much greater distance than 300 toise, would yield a correct calibration. Between BC and A, LaHire drew another line DE parallel to BC which was chosen for the focal length and target distance to be used and which then provided the correct calibration without further calculation. If one prepared the test target with a number of lines parallel to BC, one could calculate combinations of focal lengths and/or target distances for each line. This provided little practical advantage since the calculations still had to be carried out, but at least by 1717 this serious source of systematic error was recognized. LaHire noted the desirability of measuring the separation of several of the line pairs as a means of comparing different parts of the screw with one calculation, but the calibration curve was not yet a recognized concept.

An example of the result of this source of error was that the solar diameter, as measured at Paris, shows a systematic enlargement from the first adoption of the filar micrometer (1666) until LaHire's discovery (qv. Ribes, et al.: 1987, p.52-5) and Brooks: 1988, II). It is curious that LaLande, in his **Astronomie** (1792, p.673-4) believed James Bradley (third Astronomer Royal) had discovered the error ca.1725. The first published description in English appears to have been that written by Robert Smith in his **Optics** (1738, p.348-9). Perhaps LaLande's belief was influenced by Bradley's handwritten note on micrometer usage which was later found and published by the fifth Astronomer Royal, Maskelyne (1772, pp.46-53). Another possibility was the appearance of the French edition of Smith's **Optics** in 1767, just a few years before LaLande published the second and much expanded version of his **Astronomie** in 4 volumes between 1771-81. Since LaLande devoted several paragraphs in his 3rd edition of **Astronomie** to this method of micrometer calibration we can assume that it was still a popular and useful method to determine the value of the screw.

In mathematical terms this enlargement is explained as follows. The focal length and distances to the object and image are related by:

$$\frac{1}{F} = \frac{1}{S} + \frac{1}{S'}$$ Where: F = the focal length of the objective
S = object distance
S' = image distance

For an object at infinity: $F = S'$; and the image height is $h = S'\alpha = F\alpha$

For an object at S: $S' = \frac{FS}{S-F}$ and image height is $h' = S'\alpha$

Hence the change in height is: $\Delta h = (S' - F)\alpha = \frac{F^2}{S-F}\alpha$

∴, the fractional correction to the image is: a) $\frac{\Delta h}{h'} = -\frac{F^2}{(S-F)}\alpha\frac{(S-F)}{FS\alpha} = -\frac{F}{S}$

or, the fractional error in an observation: b) $\frac{\Delta h}{h} = +\frac{F^2}{(S-F)\alpha}\frac{1}{F\alpha} = +\frac{F}{(S-F)}$

In practical terms for 17^{th}-18^{th} c observations, this meant that by not correcting for the difference in S', the calibration target image's size was slightly larger on the micrometer scale than an object of the same angular size at infinity. Thus, the resulting calibration of the micrometer scale was systematically large and objects measured with it were overestimated. For an object at 400m[1] (≈200 toise): S = 2.010m or for an object at 650m (≈300 toise): S = 2.006m. For Picard's telescope, the image size of the Sun was ≈ 2cm and taking the Sun's diameter as ≈ 32' (1920") we can determine the image size, h', for an object presenting the same angular size to the telescope objective Substituting the values of S, S" and h known or determined in the formula given in a):

$$h' = 1929.6''$$

Thus the difference in the size of diameter of the solar image and the test image caused by refocusing the telescope on an object at 400m is 9.6" or 4.8" in difference in the semi-diameter. For an object at 650m the difference is 5.8" in diameter or 2.9" in semi-diameter.

3.3.2.2 Focal plane error:

An error in micrometer measurements result from the fact that the wires cannot be in the focal plane simultaneously as is illustrated by the following figure.

[1] The values used for this example are for the solar observations taken by Jean Picard between 1666-1680 as given by Ribes, et al. (1987, pp.52-55).

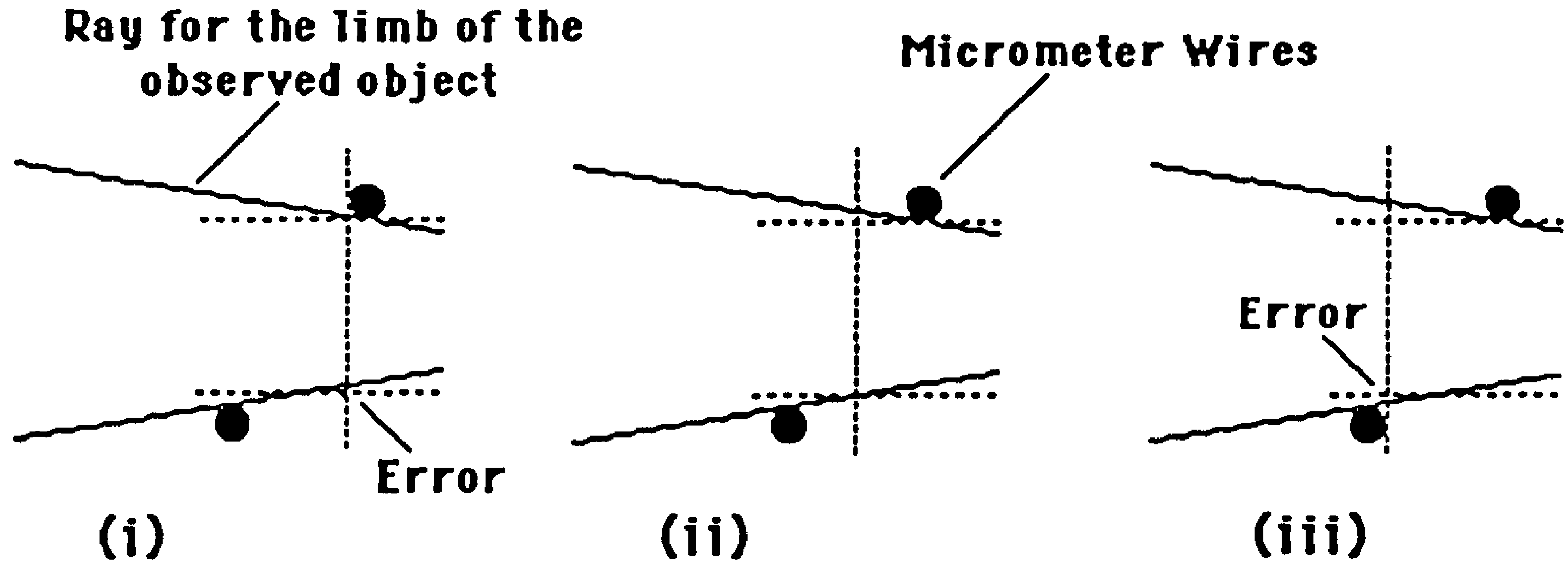


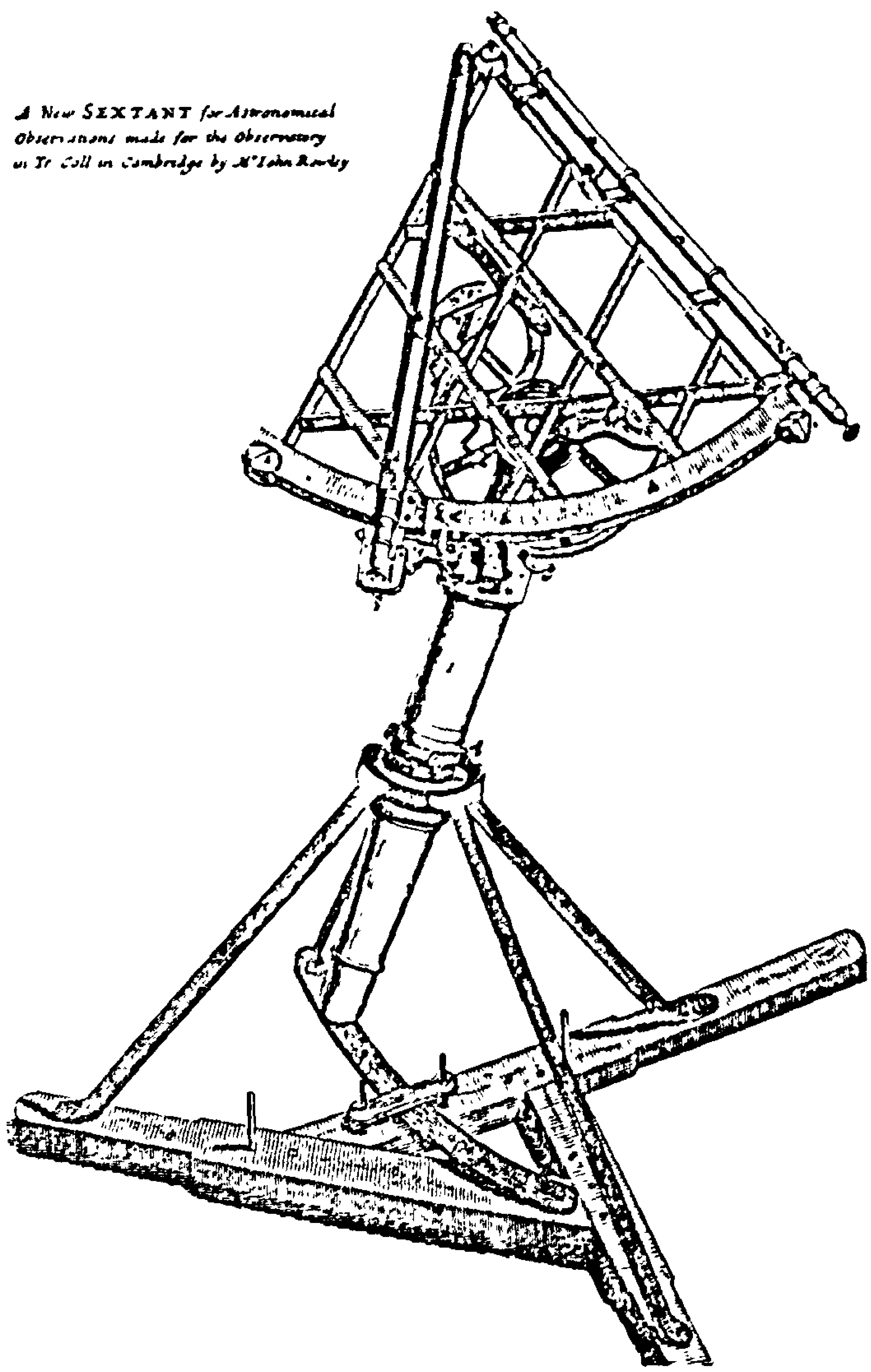
Fig. 3.3.6 Focal plane errors in filar micrometers

The value of the error is dependent on the focal ratio of the telescope, the diameter of the wires and their separation along the optic axis. The small size of the Ramsden and Troughton micrometers made this error insignificant in comparison with the other errors encountered at that time, but by the mid-19th c, Burton and Grubb (1880/1, p.59) were concerned enough about this source of error to design a micrometer to eliminate it.

3.3.3 LaHire's Glass Grid Micrometer:

LaHire had made a micrometer, which he described before the Academie des Sciences on 16 July 1700 (1701, p.118), composed of a piece of glass engraved with a grid of lines or 6 concentric circles. The lines or circles were drawn with a sharp diamond. The circles were of such a size that he could easily distinguish changes in the size of the Sun. Such micrometers were intended to be used with telescopes of 40-60 pied. The concept was similar to that used by Römer of whom LaHire was well aware but, as LaHire pointed out, his glass reticules did not suffer the problems inherent with grid micrometers with hairs or wires, e.g. slack tension due to temperature or humidity changes. It is not inconceivable that LaHire was then beginning to get a hint of the refocusing error which was plaguing filar micrometer readings--though still unrecognized. With the same telescope and same test card for calibration he may have discovered that the value for the solar, lunar or planetary diameters varied with the distance to the card during the calibration procedure. However, if he did note anything suspicious, it was not conveyed to the astronomical community until his paper of 1717.

A matter for further speculation, since there is no documentary evidence, is that a device at the IMSS in Florence may have been devised to engrave lines (though not circles) on glass. The purpose of the instrument is unknown and, as it is unsigned, the date of fabrication and maker are also a mystery. The museum dates it late 18th c and French. However, LaHire described the technique of applying the lines with a large



3.3.7 Rowley's sextant made for Trinity College (ca.1707). The micrometer mechanism was based on Hooke's (Fig. 3.2.10).

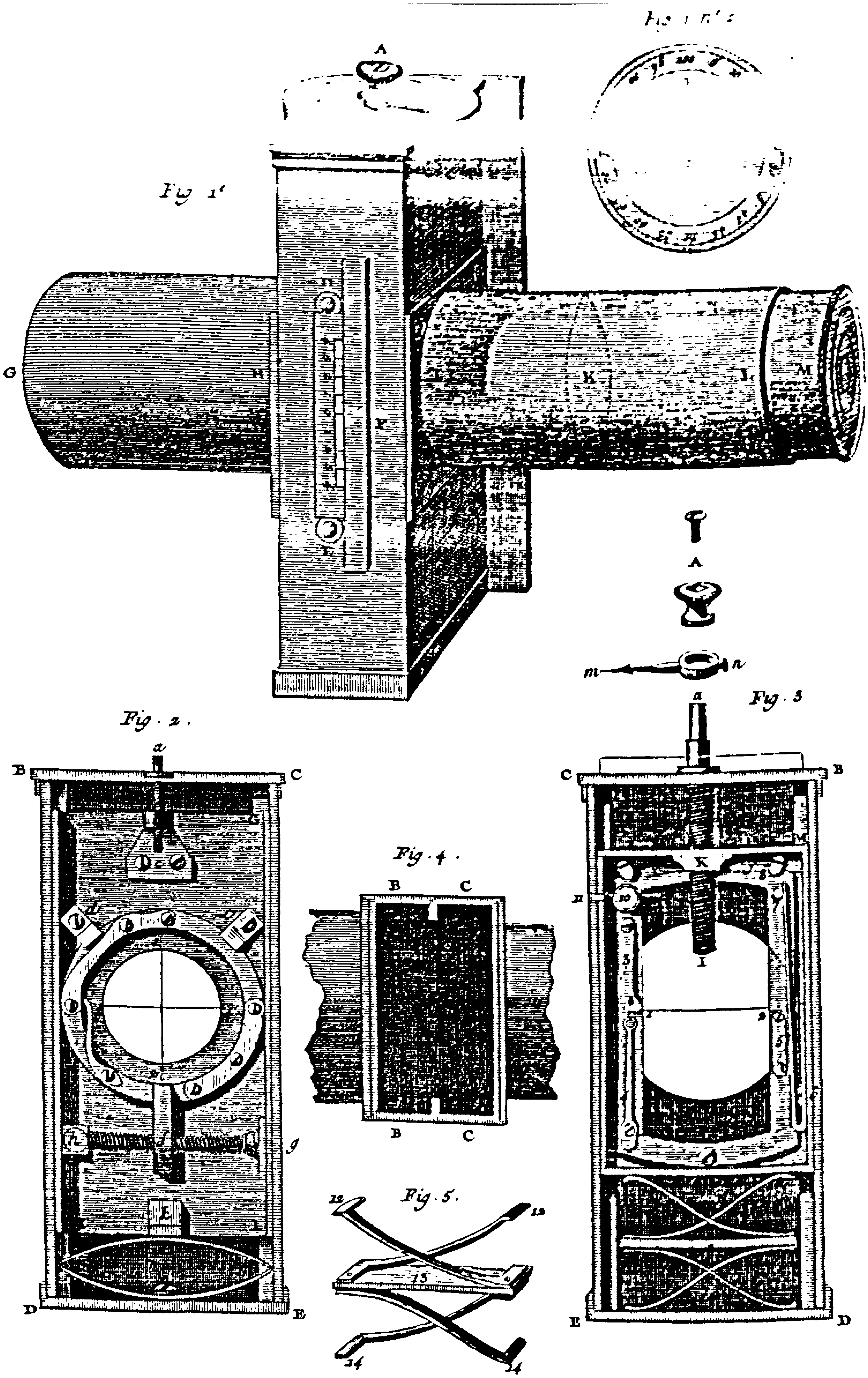
compass and this surviving instrument (IMSS-4) is essentially a large beam compass with the beam being ≈1.7m in length. The pivoted wooden beam is adjustable in length by a micrometric screw, the whole apparatus being mounted on granite with an ornamental carved base of Louis XV or XVI style. The screw is of good precision and is unlikely to be of early 18th c origin, but it is not at all inconceivable that the Duc de Chaulnes was the designer of the device and that its purpose was similar to that conceived by LaHire, i.e. to draw lines on glass for reticule micrometers. If this was used by Chaulnes, then he would have been falling behind Georg Brander in the optimal method of engraving reticules, since from about the 3rd quarter of the 18th c Brander was using what would be classed as a ruling engine, though relatively crude by later standards. With this machine Brander was capable of making quite finely drawn scales (Brachner: pp.307-16). The IMMS instrument is not in very good condition but even when new would not have been capable of matching the results of Brander. The fact that it works on a compass principle means that any lines drawn with it will be small arcs, but given the aberrations of 18th c telescopes this may have been a small problem. A weak point in the design is the joint between the long wooden arm and the brass pivot and micrometer screw arrangement which varied the length of the arm. The use of wood would, however, limit the instrument's susceptibility to changes in temperature although not of humidity.

3.3.4 Application of Micrometers to Scale Reading:

Equally important to the eyepiece micrometer were those micrometers devised to sub-divide the primary division of scales. These had their origins in the adjusting screws used by Tycho as described previously. As shown, Hevelius took a further step by actually using screws to make measurements. Hooke's scale micrometers were ill-conceived but, with Sharp's improvements, served Flamsteed better. John Rowley made a quadrant for Trinity College Cambridge along the same lines as Sharp's in 1703 (Fig. 3.3.7). In France, Louville developed a useful design which is described below. Of more interest, because of the scientific discoveries made with them, are the scale micrometers of George Graham. A series of improvements began with the zenith sector made for Samuel Molyneaux and quadrant made for Halley in 1725 and zenith sector made for Bradley (1727). The style of Graham's micrometers employed on these instruments was used effectively by Bird. LaCondamine used a 12in zenith sector in his meausre of a degree of latitude in Peru but in his instrument the micrometer was a standard filar micrometer. Unlike Graham's where the micrometer measured the scale, LaCondamine's was set by having a plumb line correspond to a scale division and the micrometer measured the subdivision.[1] The application of microscopes to scale reading by Chaulnes and Ramsden toward the end of the century allowed visual resolution to keep up with the accuracy achieved in the division of scales with dividing engines.

---

1 See Lalande, *Astronomie*, 1771-81 ed., v.2, pp781ff.)



3.3.8 Style of micrometer developed for quadrants by Louville (illustration from Diderot and d'Alembert, 1765).

3.3.4.1 Louville's scale micrometers:

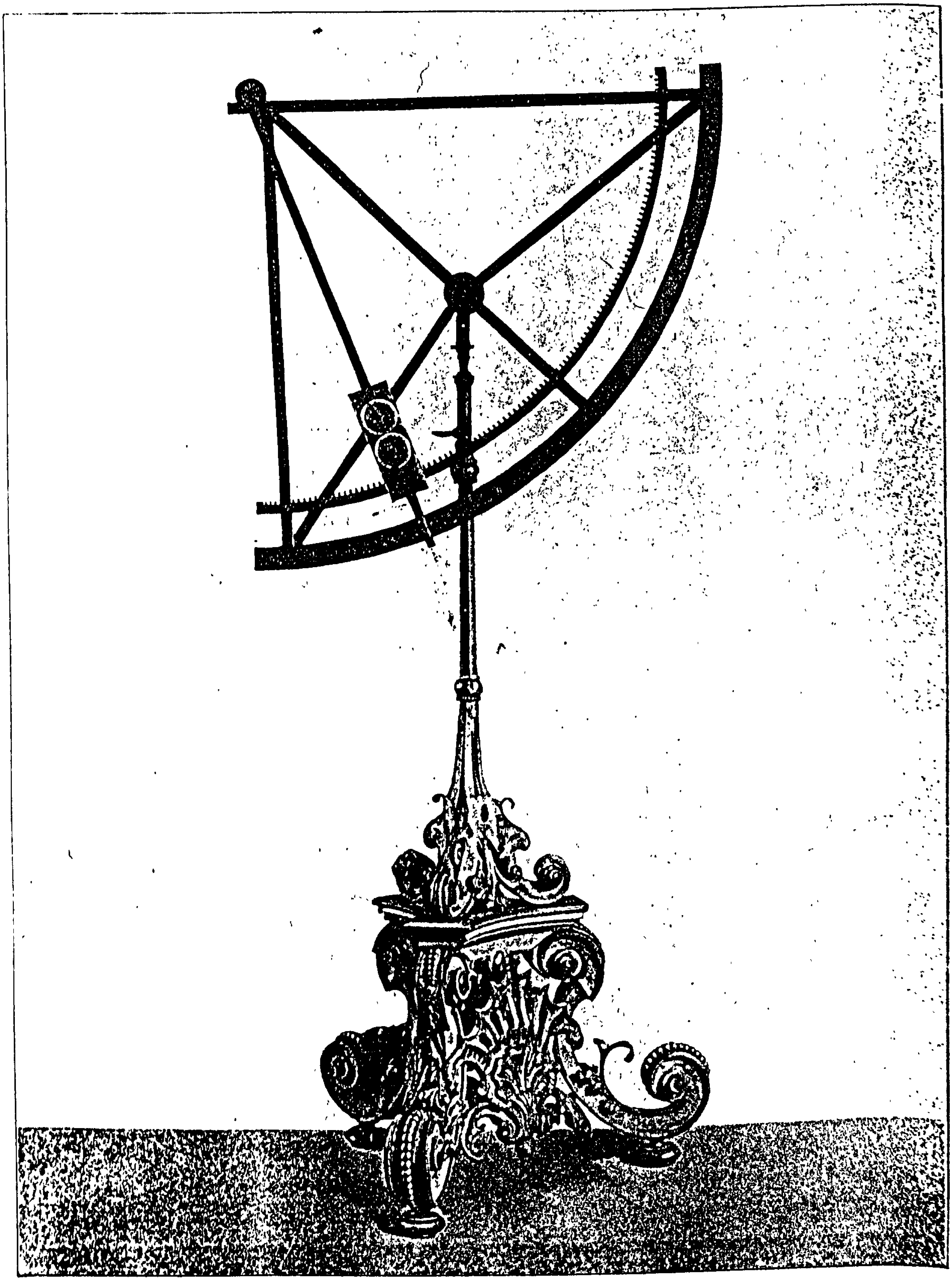
In 1714 Le Chevalier de Louville published a paper on the application of the micrometer to quadrants and similar instruments (Louville: 1714, pp.73-5). In principle there was little difference from that employed by Hevelius: the design was similar to the filar micrometers which had been developed in France and was superior to the fragile design of Hevelius. By 1721 two micrometers were being used on Louville's quadrants--one to read the scale and the other with four wires oriented at 15° intervals in the field of the telescope (Daumas: 1972, p.293) (Fig. 3.3.8). LaLande claimed a 3 pied radius quadrant could be read to 3" (Louville: p.67). Although important in its own right for advocating this 'new' use of the micrometer and for the advancement in reading angles greater than ≈1/2°, Louville's paper is also an important and little recognized precursor to the better known description of scale division as practiced in the 18th c by John Bird (1767).

The method employed by Louville was to measure the position of the cursor from one of the primary division points of the scale. The delineation of these points was thus crucial and his technique is described in detail--complete with use of carbon and water to polish the burrs off the dots made in the scale with his compass in order that the dots should appear exactly the same--a problem that makers of dividing engines were still wrestling with in the 19th c[1]. Louville noted six advantages of this scheme of scale reading over transversals: the first was the facility and ease with which one could measure angles much more easily than with transversals--this of course assumes the instrument maker had accurately matched the screw with the limb division size; 2nd, use of transversals assumed the scale fell on one of the dots and most often ignored the fact that the line of transversal dots should be slightly curved rather than straight as was normally drawn; 3rd, the micrometer gave the proportional parts with facility; 4th, the ease of measuring the height of the Moon and of finding its centre as it passes the meridian; 5th, that one can have more than one scale on the limb of the quadrant as a check of one against the other as was so usefully employed by Graham and Bird half a century later; and 6th, helped overcome the problem of making the limb truely flat (one of the principle difficulties of making quadrants) and overcame the parallax observed with the transversal index.

Louville was the premier designer of astronomical quadrants in the first quarter of the 18th c, relinquishing that distinction to Langlois in the 1730's. During this period Louville ordered and supervised the construction of many quadrants, using de l'Isle to oversee the actual work which was normally carried out by Lebas, Chapotot II and LeFèvre (1712-20). In verifying the division of quadrants, Louville employed a technique that was later adopted by others including Graham and Bird. Using the radius of

---

1 See also Louville's order for a quadrant from Chapotot II in Daumas: p.292-4.



3.3.9 Klein's quadrant with micrometer employing gears (ca.1746) in the Prague Observatory.

the scale, he would check the 60° point finding the 30° point by bisection. Then starting from the 90° mark, he would check the 30° point against the the previously laid off point and if correct, the 30°-90° arc was bisected to check the 60° point. This confirmed the correctness of the 30,60 and 90° points. It is noted that this paper was also the first to advocate that points should be made with the compass as a guide for the engraving which was to be carried out as a second independent procedure. Points were utilized from the time of Bird throughout the 19th c as the most accurate means of dividing astronomical scales. A result of this paper was that Louville's influence was felt in French micrometer design for half a century and scale dividing of the highest quality for a century and a half[1]. This contrivance must have made the use of the portable quadrant and its micrometers significantly easier.

The micrometer incorporated on an extant portable astronomical quadrant of P. Johann Klein (25/07/1684-15/01/1762) follows the principle of Hooke's version of 1676. It has a combination of features derived from Hooke and Hevelius. Klein placed an arc interior to the limb which had its inner radius filed to form a gear or rack (Fig. 3.3.9). Each tooth equals slightly less than 1°. The alidade carries a gear box which has a gear meshing with the toothed arc. This gear box has two dials, one to read off the degrees and the other to read fractions of degrees to ≈1' of arc. The instrument is in the Prague Observatory but is not dated[2]. Brander's quadrant (1760-61)(Fig. 3.3.19a) also employed a geared limb but apparently simply as a means of moving and supporting the index (q.v. §3.3.6.3).

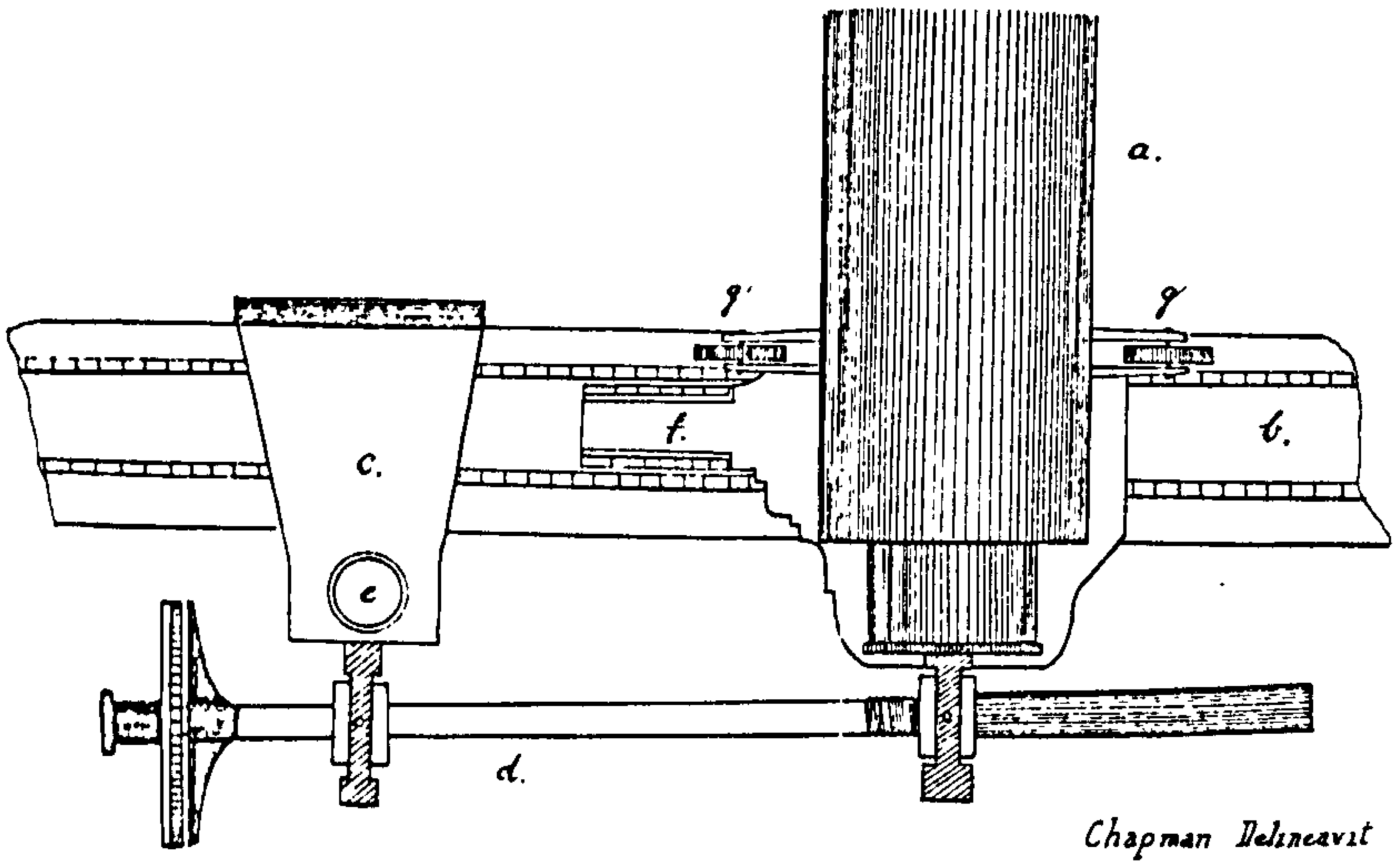
3.3.4.2 Graham's scale micrometers:

The origin of Graham's scale micrometers was the zenith sector made for Molyneaux in 1725. The concept of the zenith sector was not new, one having been made by Hooke at Gresham College in 1669 (Forbes: 1975, p.92). This 36 foot instrument was so unstable that Hooke claimed to have found an annual parallax of the stars of 27"-30"--a value which was generally thought unreasonable. Molyneaux's sector was soon found to be stable to ±0.5" but variations of 3.5" were found in two or three weeks and prompted Bradley to order a zenith sector for the Royal Observatory. It was with this instrument that Bradley discovered both aberration and nutation in the Moon's motion which required a high degree of stability of the sector and micrometer over a period of weeks or a year respectively. The idea of two scales, i.e. 90 and 96 division scales (Fig.3.3.10), occurred to Graham when constructing the 1725 quadrant for Halley, which was claimed

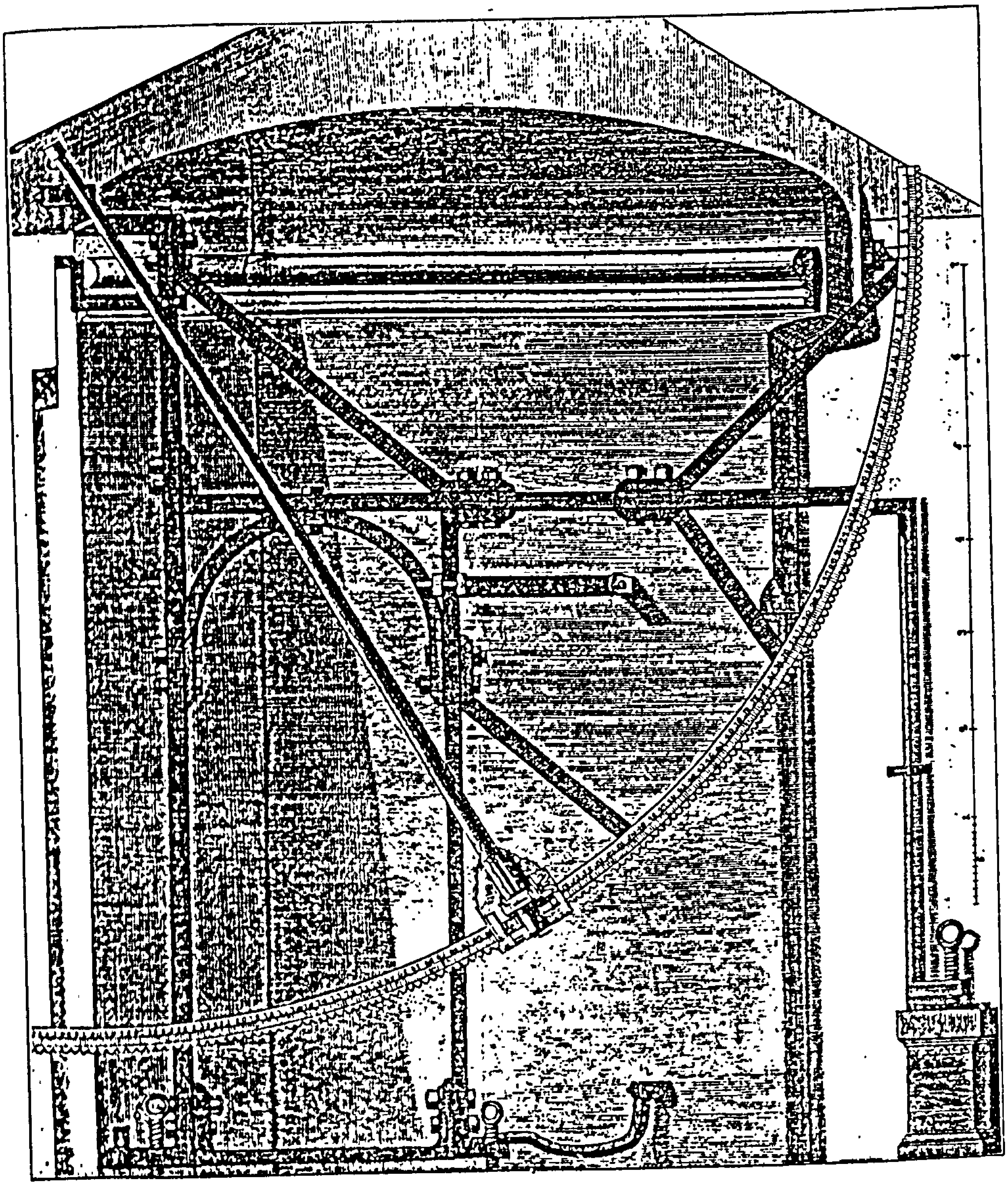
---

1 Grandjean de Fouchy devised the adjusting screw and steadying arm found on French quadrants from 1735.

2 Zinner (1979) lists 5 instruments by Klein--4 sundials and this quadrant. 3 dials are dated 1738, 1751 and 1752. The frame of the quadrant is similar to the style and stiffness of French quadrants of the mid-18th c and we may speculate that the quadrant was probably made ca.1750's.



3.3.10 Chapman's (1976) illustration of the relation of scales and micrometers on Graham and Bird quadrants of the 18th c.



3.3.11 Marinoni's scale micrometer (ca.1740).

to have a discrepancy of a few seconds between the scales according to Smith (1738, p.334). The 96 division scale was the more reliable proving the advantage of the bisection division technique of Graham and was thus adopted on quadrants until they became obsolete. This quadrant was not originally equipped with a micrometer but had a screw for fine adjustment. Twenty years later Bird was contracted to replace the adjusting screw with a micrometer which employed a screw of 391/4 TPI and was of the same design as that found on Molyneaux's zenith sector (Chapman: 1976 II, 148-9). It is worth noting that errors appeared in Graham's quadrant which Bird attributed to buckling of the frame due to differential expansion in the brass and iron parts. Bradley thought that part of the error was due to the fact that the pivot was 1/191th inch off the centre of the limb (Rigaud: 1832, p.lv).

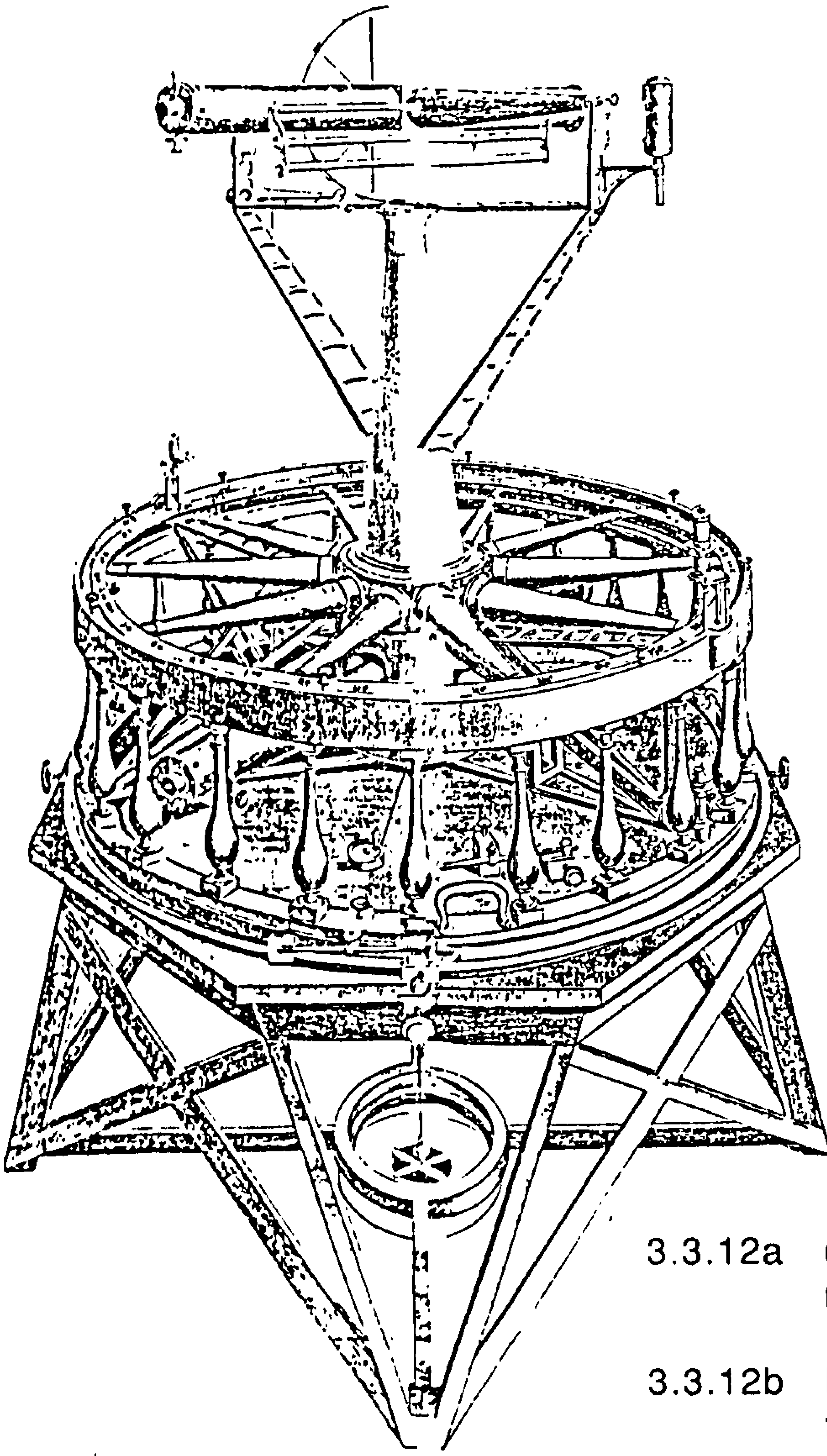
3.3.4.3 Marinoni's scale micrometer:

Johann Jakob Marinoni[1] built a private observatory in Vienna in 1740 and equipped it with a variety of instruments of his own design (Fig. 3.3.11). He described these in 1746 and after his death the instruments were given to the University Observatory. However, the current descriptions and illustrations come from Repsold (1908, p.62ff.). His fixed mural quadrant of 1740 carried a micrometer which outwardly looked something like those on French sextants of the period. The quadrant design itself was quite original with a number of features (not necessarily desirable) including adjustment screws for positioning the scale. The 9ft frame was bolted together but not symmetrically laid out, which must have led to unequal expansion/contraction with changing temperature. The scale was divided from -2 to 95° and sub-divided to 10'. Details of the scale micrometer are wanting although the micrometer, described later, could well have been that used on the eyepiece of the quadrant. The limb of the quadrant is notched as if it were intended to have a screw. Speculation would suggest that Marinoni's method was to set an index on the alidade in one of the notches then adjust the 'fixed' wires to one of the divisions on the scale followed by adjustment of the movable wires on the observed object. The micrometer scale was then read to give the subdivision of the quadrant scale. This is not very different from Graham's method of clamping the alidade to the scale.

3.3.4.4 Ramsden's scale micrometers:

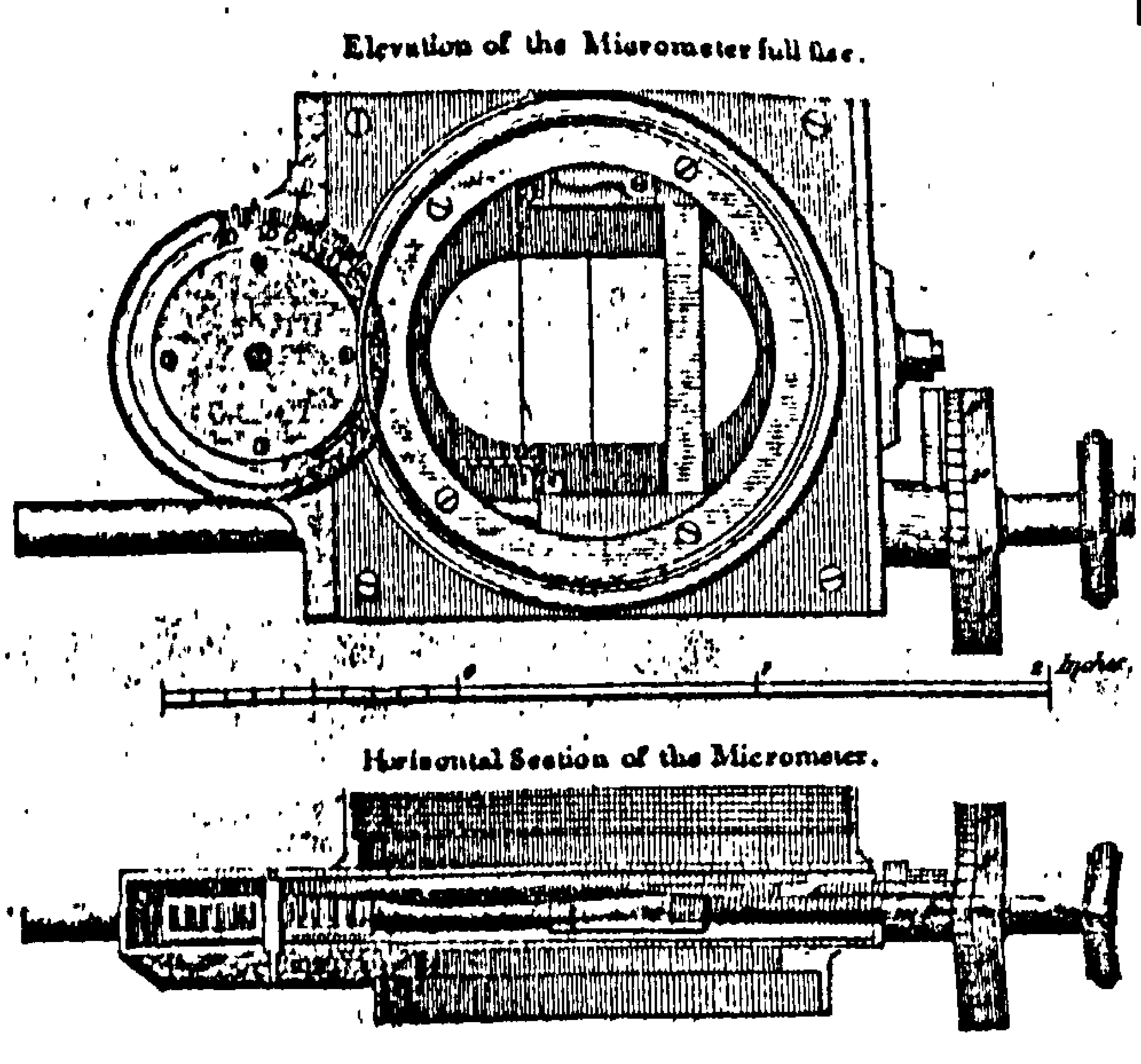
Although both Römer and Chaulnes had employed microscope micrometers for reading scales, this particular style of micrometer did not achieve wide application in scientific instruments until Ramsden designed and made the baseline (Roy: 1785) and the great theodolite (1787) for General Roy's trigonometric survey to connect the longitudes of

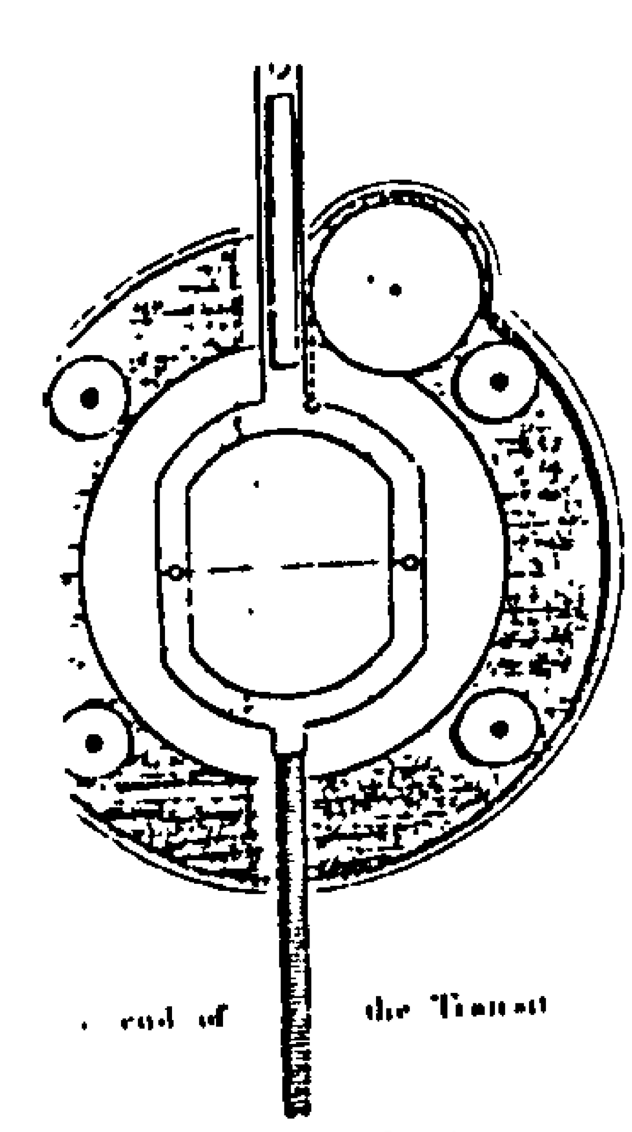
1 Born Udine, 1676; died Vienna, 1755. When he died he was Director of the Akademie der Kriegswissenschaften in Vienna.



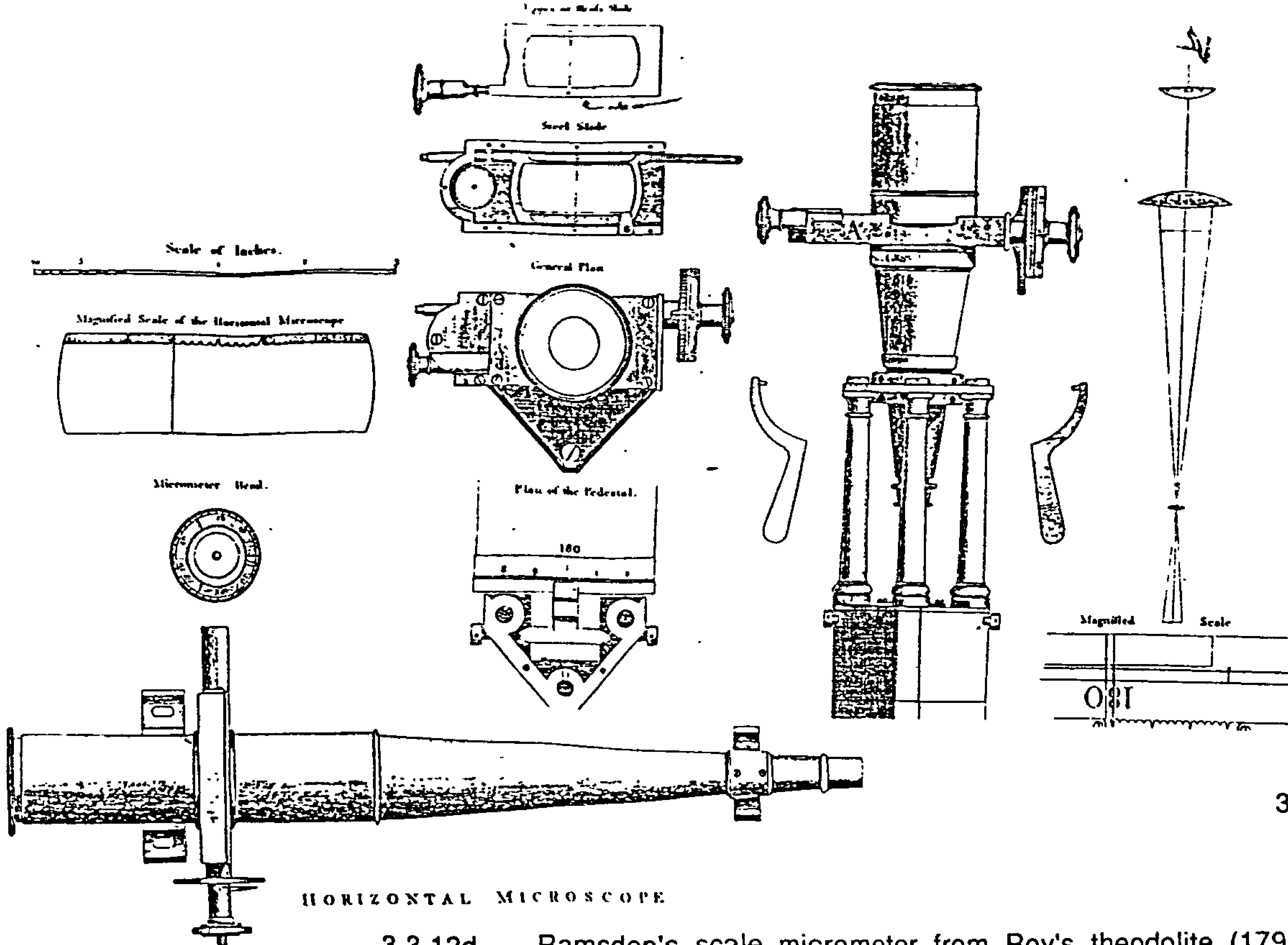
3.3.12a (right) Ramsden's large theodolite made for General Roy (1790).

3.3.12b Ramsden's scale micrometer for the baseline standard made for General Roy (1785).

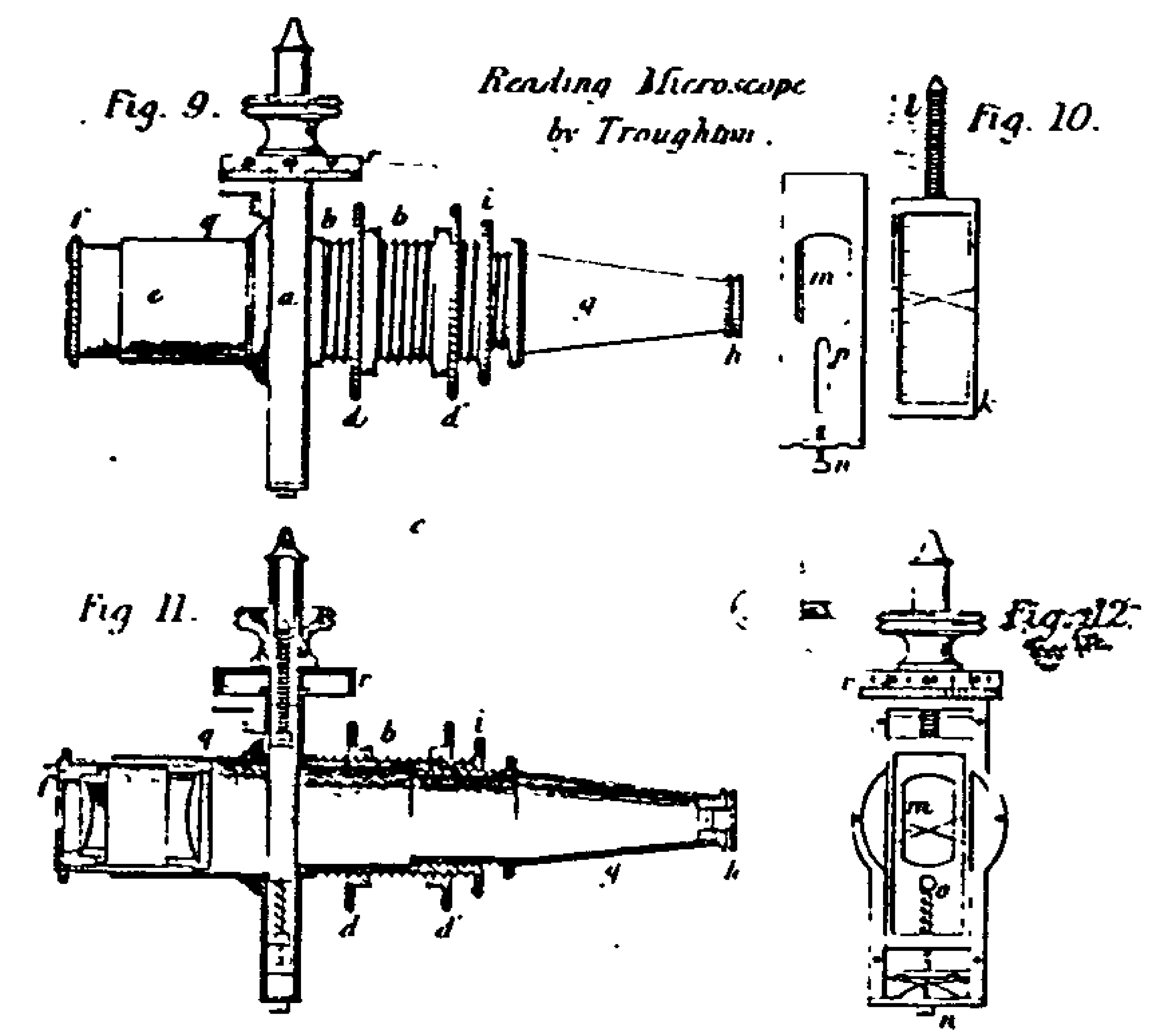




3.3.12c Eyepiece micrometer of Roy's Geodetic theodolite. Note the chain around the wheel to the right of the upper shaft.



3.3.12d Ramsden's scale micrometer from Roy's theodolite (1790).



3.3.12e Troughton's scale micrometer was evolved from Ramsden's scale and filar micrometers.

Greenwich and Paris. This is not entirely surprising since graduation had been done by hand so the errors in the graduations were larger or about the same size as the resolution of the human eye. But once Ramsden had successfully mastered the dividing engine, the quality of graduation began to exceed the resolution of the eye, and to take advantage of this, higher magnification was desirable. Of course, errors due to other mechanical defects had to be simultaneously overcome, but in the hands of the mechanically astute Ramsden many defects were identified and measures taken to eliminate them. These new scale micrometers by Ramsden were compact due to his use of ≈100 TPI screws and showed refinements over the small filar micrometer made in 1775 (see §3.3.6.5).

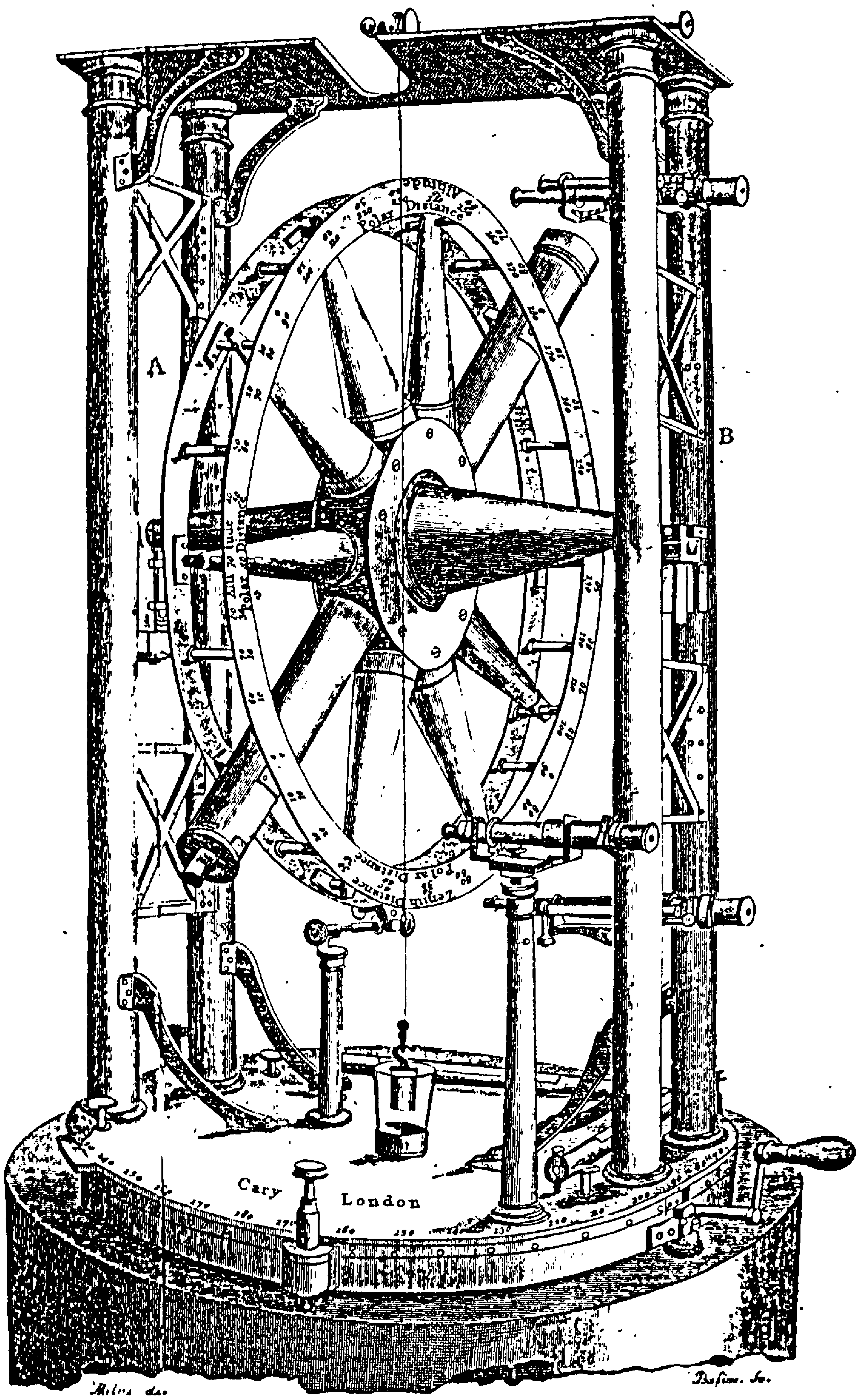
Roy's 3ft theodolite (1787)(Fig. 3.3.12a) incorporated micrometers with several innovative features (q.v. Roy: 1790) some of which had appeared on his baseline apparatus also made for Roy two years before (Fig. 3.3.12b). These micrometers are much smaller than those of Bradley's design made by Graham, Bird and Sisson, and defined the style and standard size for the next century. The screws were up to 100 TPI and were thus, by necessity, fabricated on a screw lathe[1]. Backlash of the screws was controlled by a wound spring (à la watch springs) contained within a small barrel (indicated by arrow in Fig. 3.3.12c) and acting on the moveable frame through a 'fusee' type chain (Roy: 1790, p.146).[2] This feature did not survive in later examples. The eyepiece micrometer of the transit also incorporated the coil spring arrangement, but opposite the micrometer screw was a guide rod moving within a cylinder. It must have occurred to Ramsden fairly quickly that a simpler solution to the backlash problem was to place a helical spring around the plunger and this was soon adopted on subsequent models (e.g. micrometers of the Shuckburgh equatorial, 1791, and the transit instrument described by Roy: 1795, pp.421,445-6). Either on one of the micrometer slides or on the fixed frame--depending on the particular application--a set of lines was filed or engraved. This 'comb', as it became known, was simply a row of fine 'V's' with their separation equal to the pitch of the micrometer screw. Every fifth 'V' was deepened to facilitate reading the scale in low light.

There were three basic types of micrometers on the theodolite (Fig. 3.3.12d): the eyepiece micrometer, two vertically mounted micrometers for reading the azimuth and a horizontally mounted micrometer for reading the angles of elevation or depression. The vertical micrometers have two frames--one to carry the fixed wire (which is adjustable to position it on one of the primary dots of the divided scale) and the other to carry the moveable wire via the micrometer screw and head to measure the angle indicated by the theodolite's telescope. The screws of the vertical micrometers were 72 TPI and the

---

[1] The micrometer screws on the companion instrument, which is in the Science Museum, have dimples in the end of the screw where the dead centre supported the screw while it was machined in the lathe.

[2] A similar barrel on the baseline micrometer contained gears and an index to indicate the number of revolutions.



3.3.13 Cary's transit circle (1793) made for Wollaston.

micrometer head was divided to 60 divisions which was to correspond to 1". The scale on the limb was divided to 1/4°. However, trials in 1787/8 (Roy: 1790, p.147) showed micrometer A varied from 896" to 900" in measuring the 1/4° and B varied from an average of 901" in 1787 to 894" the following year. These differences, of course, had to be taken into consideration in the reduction of the data. Having two diametrically opposing micrometers eliminated the error due to eccentricity[1] of the scale but Ramsden did not yet use additional micrometers in order to drive down the scale division error. A near duplicate theodolite, begun for the East India Company but purchased by the Board of Ordnance (1790), had four micrometers to this end (Bennett: 1987, p.144). The single horizontal micrometer design was similar to the vertical micrometers, although of longer focal length. It was to measure a scale divided to 30' and therefore the micrometer head had to be divided differently. The comb had 10 divisions with each equal to 3'. The head was divided into three intervals and subdivided into 12 divisions with each then equivalent to 5". Hence there were 36 divisions rather than the 72 divisions found on the vertical micrometers (Roy: p.150). This reflects the relative importance of the horizontal and vertical measures--the former being of much greater importance for the objectives of the trigonometric survey.

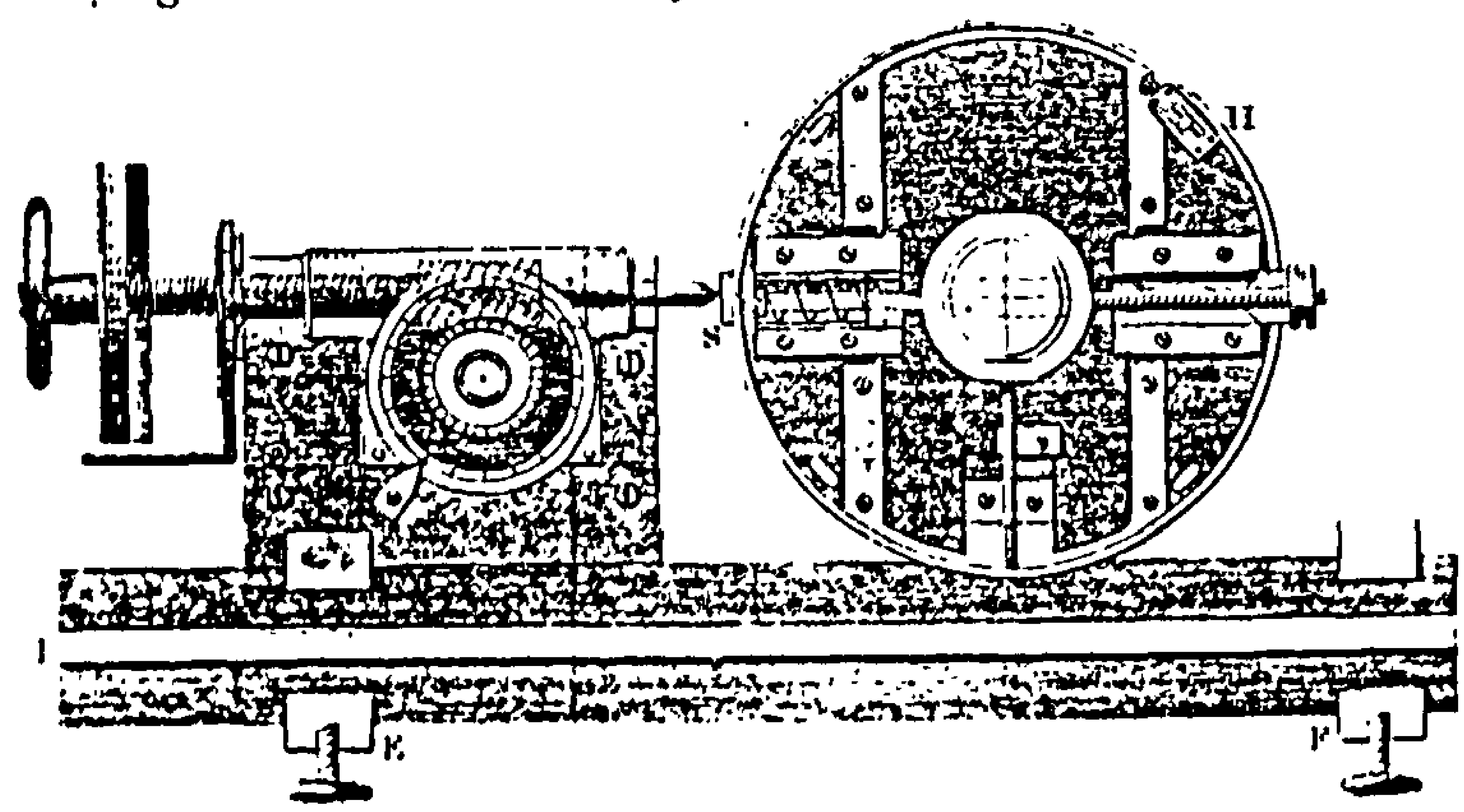
The eyepiece micrometer incorporated a screw with 100 TPI thread and a head divided into 100 divisions (Roy: p.154). By comparing observations of an object made with it and with the horizontal micrometer its scale was determined to be equal to 10'59" (659") for 7.77 revolutions of the micrometer head. Therefore, quoting Roy, one revolution equals 1'24.8314" (!) or 84.83" and 1 division ≈0.85". Orientation of the wires of this micrometer (three fixed horizontal and two cross wires, plus one moved by the micrometer head) was permitted by four adjusting screws. The means of adjusting is given by Roy (pp.154/5) but, not being directly relevant, will not be described here.

This general design for scale micrometers was adopted by Rev. Francis Wollaston for his transit circle and described by him in 1793 (Fig. 3.3.13). These were designed to read to 1" and to take measurements of both right ascension (RA) and declination. Both magnified 24 times. The fixed wire was adjusted by means of an offset plumb line which could be read on either side of the vertical axis. The micrometers were 5 1/2in long with the objective lens 3in from the limb to be read. The moveable wire was adjusted in a manner similar to Ramsden's but the nut rather than the screw was incorporated as part of the micrometer head. This was a design adopted and maintained by the Troughtons (Fig. 3.3.12e) and by William Cary, the maker of Wollaston's instrument (Bennett: 1987, pp.165/6,174). Five vertical wires for measuring RA were separated by spaces requiring 35 seconds for the passage of a star between successive wires. There were also

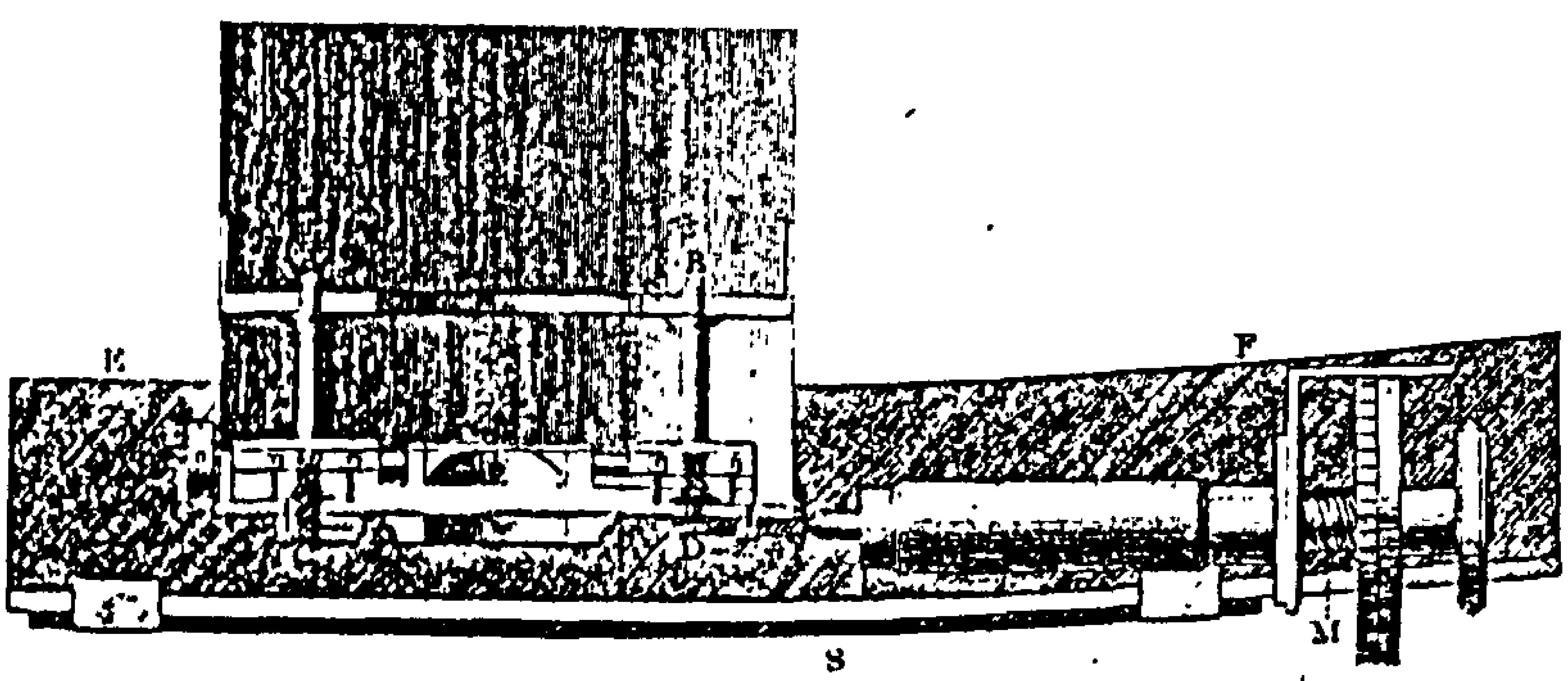
---

[1] The idea of using two readings of a scale taken on opposite sides was Römer's for he incorporated such an arrangement in his meridional instrument of 1702 (see Horrebow: 1734, V.3 or Repsold: 1908, p.50 and f.64). Römer used simple microscopes for reading the scale.

Horizontal View of the End of the Telescope, with the Apparatus carrying the Wires, and also a view of its Micrometer Screw.



Section of the Bottom of the Telescope, with its Micrometer Screw.



3.3.14 Ramsden's micrometer arrangement for the zenith sector used by Mudge (1803). Note the screw bearing against a steel plate.

three horizontal wires with a 15' separation chosen so that the Sun could be viewed with minimal adjustment of the vertical height (Wollaston: 1793, p.142). The instrument's azimuth scale was divided by hand to 10' by dots and on another smaller radius was divided to 10' by strokes. The two micrometers were designed to be adjusted with the right hand and to have the moveable wire approach the fixed wire from the right hand side as seen through the telescope although this was in actuality the reverse since the optics reversed the field. Edward Troughton made but one transit circle (1806 for Groombridge) which was very successful, but the form of instrument soon evolved into the mural circle[1] which achieved greater stability.

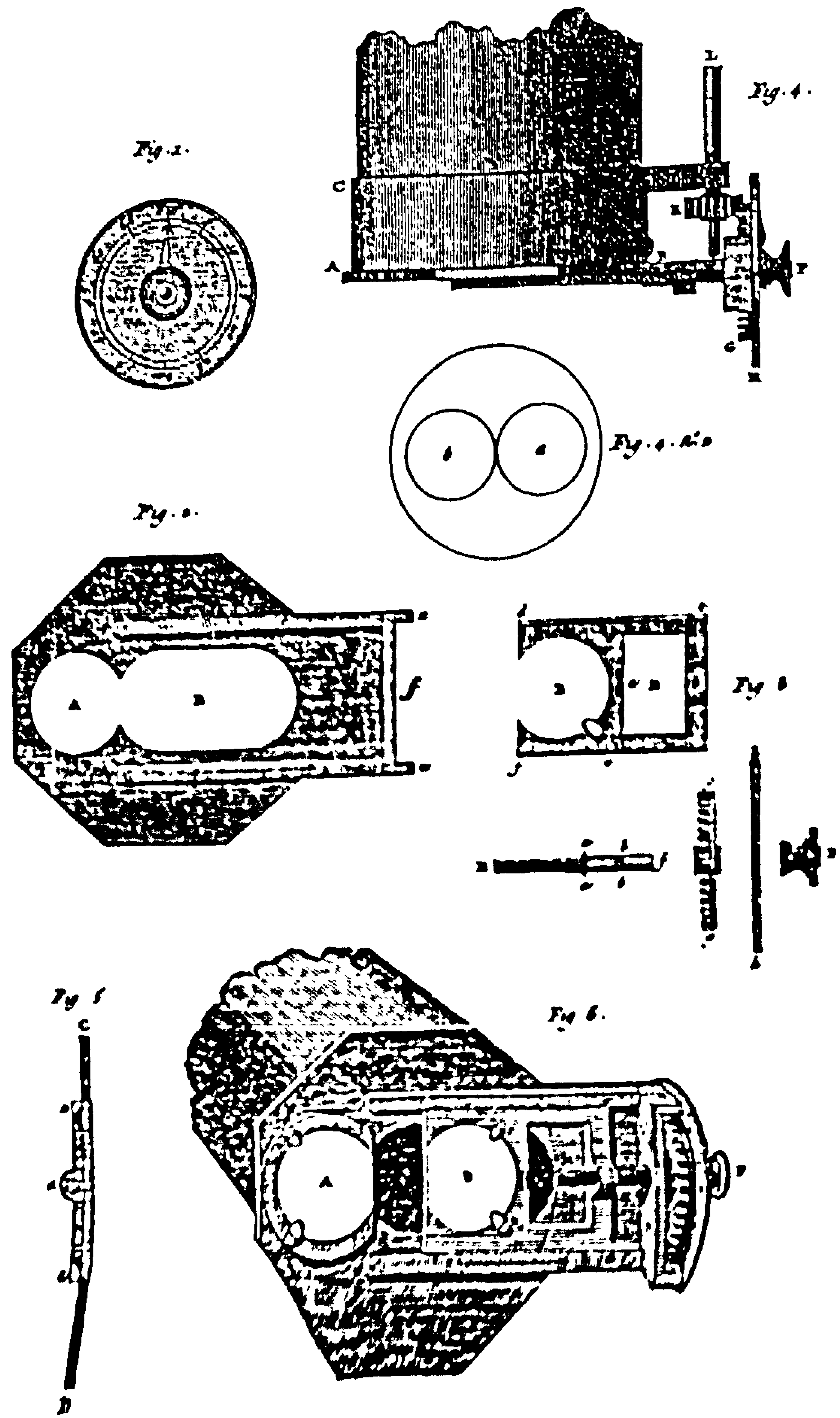
Mural circles generally had 4 or 6 scale micrometers as a means of detecting errors in the scale and to even out the errors of the micrometers themselves--these being partially due to the screws, but primarily due to the adjustment of the micrometer's distance from the scale (i.e. the effective magnification). On the Washington mural circle, 5 revolutions of the micrometer screw were to exactly measure 5' but if the lens of the scale micrometer was too close or too far from the scale this condition was not met. Loomis (1870, p.86-7) described the simple method used to correct 'errors of run' caused by this misadjustment, temperature changes, etc. One division of the scale was measured by each of the scale micrometers and usually for four divisions on different parts of the scale. The mean for each division for all micrometers was obtained and the mean of these designated the error of runs, R. The mean for each division for individual micrometers, M, was determined. Since these errors are proportional to the size of the division measured and dependent on the size of the division measured, the correction applied was:

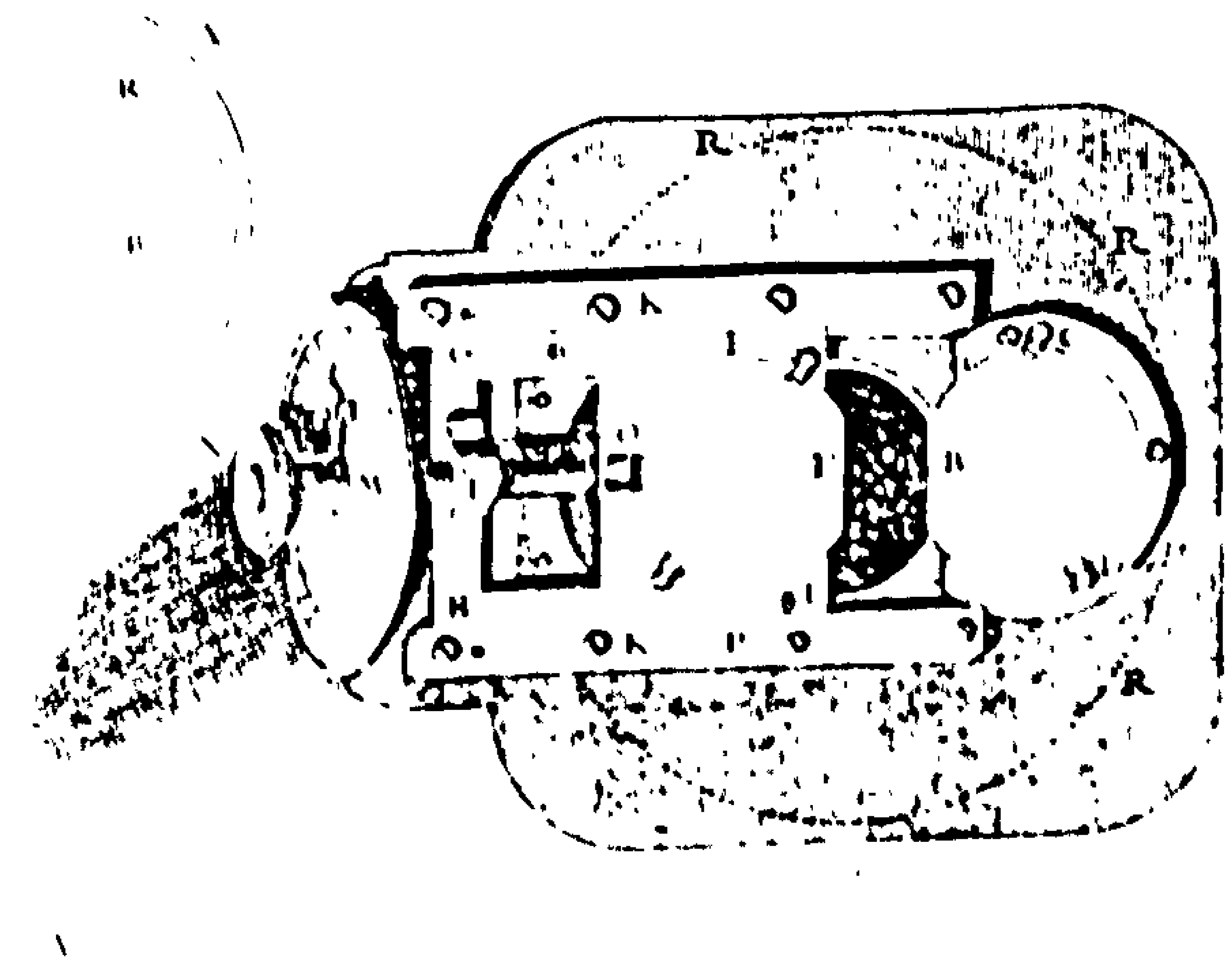
$$-\frac{M\ R}{5'}$$

Similar techniques were used to correct errors on transit telescopes and any other circular scaled instrument.

Another instrument made by Ramsden for the survey of Britain was the zenith sector used by William Mudge between the Isle of Wight and Yorkshire (Mudge: 1803). The 15° scale division was done by Mathew Berge, Ramsden's senior assistant, to 5' with major divisions marked on inset gold pins as recommended by the Astronomer Royal. The micrometer screw was designed to act on a polished steel head on the alidade of the sector rather than in the usual mode as devised by Graham, i.e. the micrometer screw was moved and clamped independently of the alidade. There were also screws to adjust the parallelism of the micrometer screw with respect to the limb of the instrument. This arrangement is illustrated in Fig. 3.3.14 (Mudge: pl XII). It should also be noted that the

[1] As Dewhurst notes (1985, p.151) the mural circle was primarily employed in Britain with transit circles based on the design of Römer ca.1689 used on the Continent. Gambey made some mural circles in France.





3.3 15 Illustrations of Bouguer's heliometer (1748).

wires in the field of view of the telescope could be positioned by an adjusting screw not unlike the principle which was adopted by Repsold in the 2nd quarter of the 19th c.

3.3.5 Heliometers:

Pearson (1829) claimed that Rõmer had suggested using two lenses to form two images of the same object for the purpose of measuring the separation or diameter. Gill (1878, p.249) also noted Rõmer's suggestion for the use of double images but nothing is found in Horrebow's **Basis Astronomiæ** (1734) which described Rõmer's instruments in detail. Rõmer's papers were all destroyed in a fire so the source of this claim is not known.

3.3.5.1 Bouguer's heliometer:

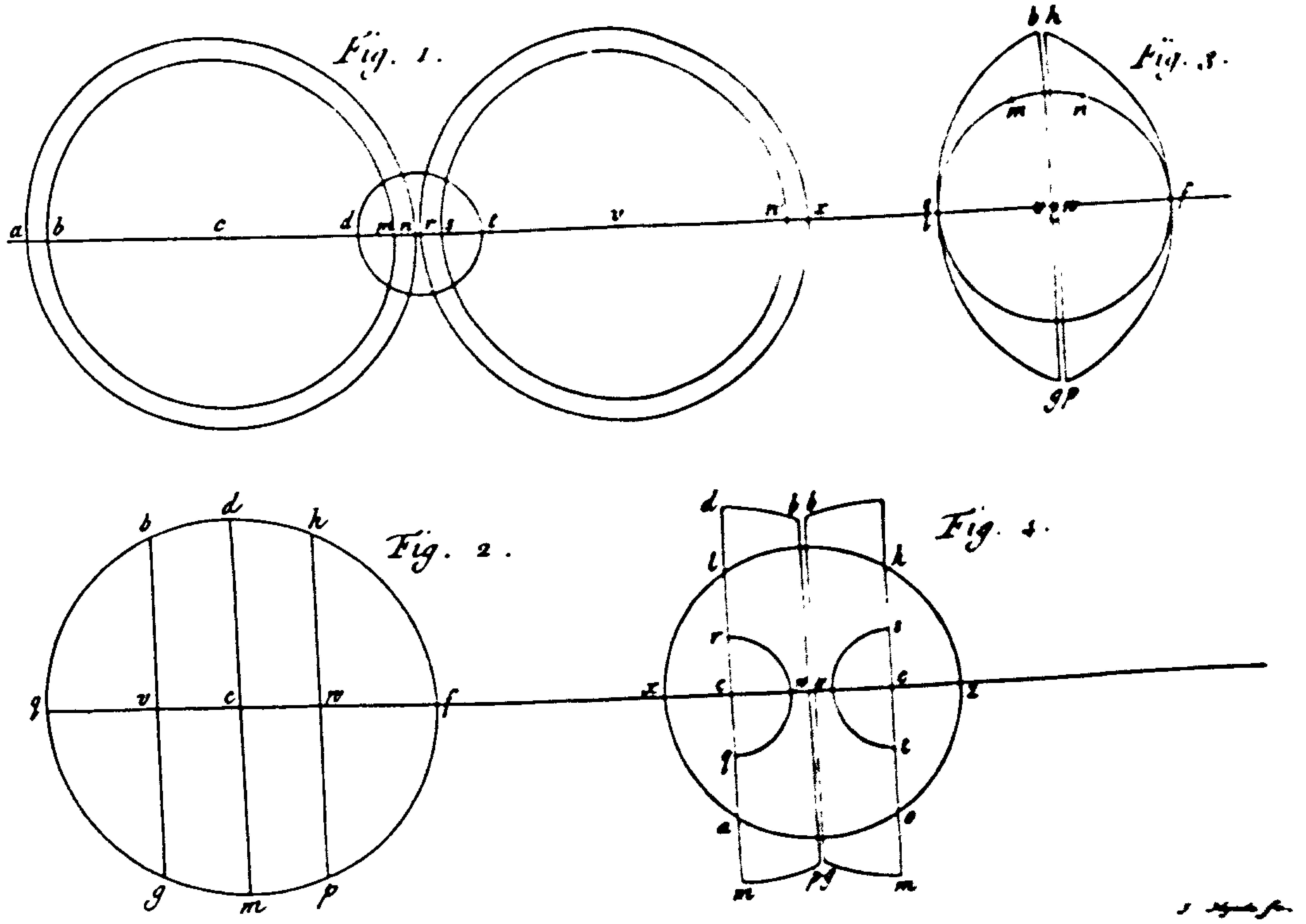
The next major breakthrough in micrometer design was Bouguer's[1] heliometer of 1748 (pp.11-34; LaLande: 1792, p.639ff). An example is in the Conservatoire des Arts et Mètiers in Paris). The 'Heliomètre' or 'Astromètre' was of an entirely different principle employing two identical lenses mounted side by side (Fig. 3.3.15). These were separated by means of a screw.[2] The frame and dial were essentially identical to a filar micrometer and indeed some were, like filar micrometers, made with one screw and only one moving lens or with both halves moving symmetrically with respect to the axis by means of two screws. The separation was measured on a linear scale on the frame with sub-division made by an index moving over a dial. Parallax of the index (which adversely affected the micrometer illustrated by Bion) was overcome by redesigning the mounting of the screw and index.

Bouguer's use of two almost complete lenses prevented measurement of small or close objects since the two images could not then be made to exactly superimpose. However, for larger objects (i.e. Sun or Moon or for stars or planets separated by a sufficiently large angle) Bouguer found his instrument to be far superior. It permitted telescopes of much shorter focal length to be used--i.e. it was particularly applicable to Gregorians though he also used it on refracting telescopes of 18 or 20 pied focal length. With his new instrument Bouguer attempted to measure both refraction and irradiance, the latter being the effect of enlargement of a bright object observed against a dark background (or vice versa). Because the limbs of both images were equally affected by irradiance, it was easier to align the limbs and so more precisely measure the diameter of a bright object. The heliometer also eliminated the problem of obscuration of faint stars by the hairs of filar micrometers. Calibration was usually carried out by observation of the passage of a

---

1 Bouguer was with the Académie des Sciences' 1735 expedition to Peru to measure the shape of the Earth by measuring a degree of longitude. His group was headed by LaCondamine and was complimentary to Maupertius' expedition to Lapland.

2 On longer instruments the screw was driven from the eyepiece end by a shaft with pinion gear turning a crown gear attached to the screw and dial.



3.3.16 Savery's heliometers as presented to the Royal Society in 1743.

star or the Sun. The design was particularly useful for measuring angles equal to those of the Sun and Moon or separations somewhat larger. Chappe took a Charnière 'megameter' to California for the transit of Venus in 1769. Four or five examples were made by Carochez by 1766 or 1767 (Daumas: 1972, p.128 quoting Charnière's **Expériences sur les Longitudes**, 1768). Unfortunately, further details of this particular French instrument have not been located.

3.3.5.2 The English contenders:

On the 10 May 1753 two papers were read before the Royal Society on the topic of heliometers. The first was a letter by James Short (1753/4, pp.165-177). He had received a letter the previous year from Rev. F. Pézenas[1], which had described Bouguer's heliometer. This had brought to mind a paper read before the Royal Society by Servington Savery of Exeter, and although the paper had not been published in the *Philosophical Transactions*, it had been recorded in the Society's minute book for 27 Oct. 1743 and was appended to Short's contribution. Savery had invented devices to measure the difference of the Sun's diameter at aphelion and perihelion. He used two lenses of the same focal length (the first instruments had lenses of 12-13in focal length and the second lenses of 3ft focal length). The first heliometer described by Savery was made by cutting a lens of 104.96in focal length (chosen to give the desired separation of the images at moderate power) into four parts as illustrated in Fig. 3.3.16. The pieces **bgq** and **hpf** were cemented with 'barm' along the cuts **bg/hp**. This cemented lens was mounted in a tube whose diameter equaled the width **qf**. The two halves each created images of the Sun which were separated by a small amount when the Sun was at perihelion. A standard micrometer was then employed to measure the separation. Because the separation was small--even at aphelion--the errors due to the screw were much reduced since only a small length of thread was required. This thus reduced the importance of errors of runs in the pitch of the micrometer screw.

A second model was attempted which employed the other pieces of the original lens, **bgmd** and **dmph**. These were cemented together along the cuts **bg/hp**. The width of these parts was ≈1/2in. However, they were masked off except for two small semi-circular apertures **rwq/svt** of ≈1/3in radius. These apertures each created a solar image though on the opposite side. Since the lenses were non-achromatic, Savery thought that the property of having the red images next to each other was an advantage in taking the measures. As in the other model, the separations were measured with a standard filar micrometer.

---

1 Pézenas, a professor of hydrography at Marseilles, designed a heliometer type micrometer and one was made in London (by Dollond?) ca.1755 for the Observatoire de marine de Marseille and was of two pied focus and mounted on a telescope of 40 pied focus. A second example was made for Pézenas in 1760 by Dollond but was of only one foot focus. (Pézenas: 1755, p.93 (not seen) and LaLande: 1792, p.644)

Yet a third version was conceived which consisted of two small lenses of 104.9in focal length. These were mounted in short tubes with inner diameters closely matching those of the lenses and these tubes were mounted on a disc of 2.5in diameter. The centres of the lenses were separated by precisely one inch with care taken to rotate the lenses so that the solar images were separated by a very small amount as before. The instrument maker had the problem of matching the focal lengths of the two lenses with sufficient accuracy; a second problem was the centering and alignment of the two lenses[1] which required great care. A slight disturbance to the position of the lenses would also have thrown off the calibration. A single eyepiece was required and as in the two previous models, measurement was with a filar micrometer.

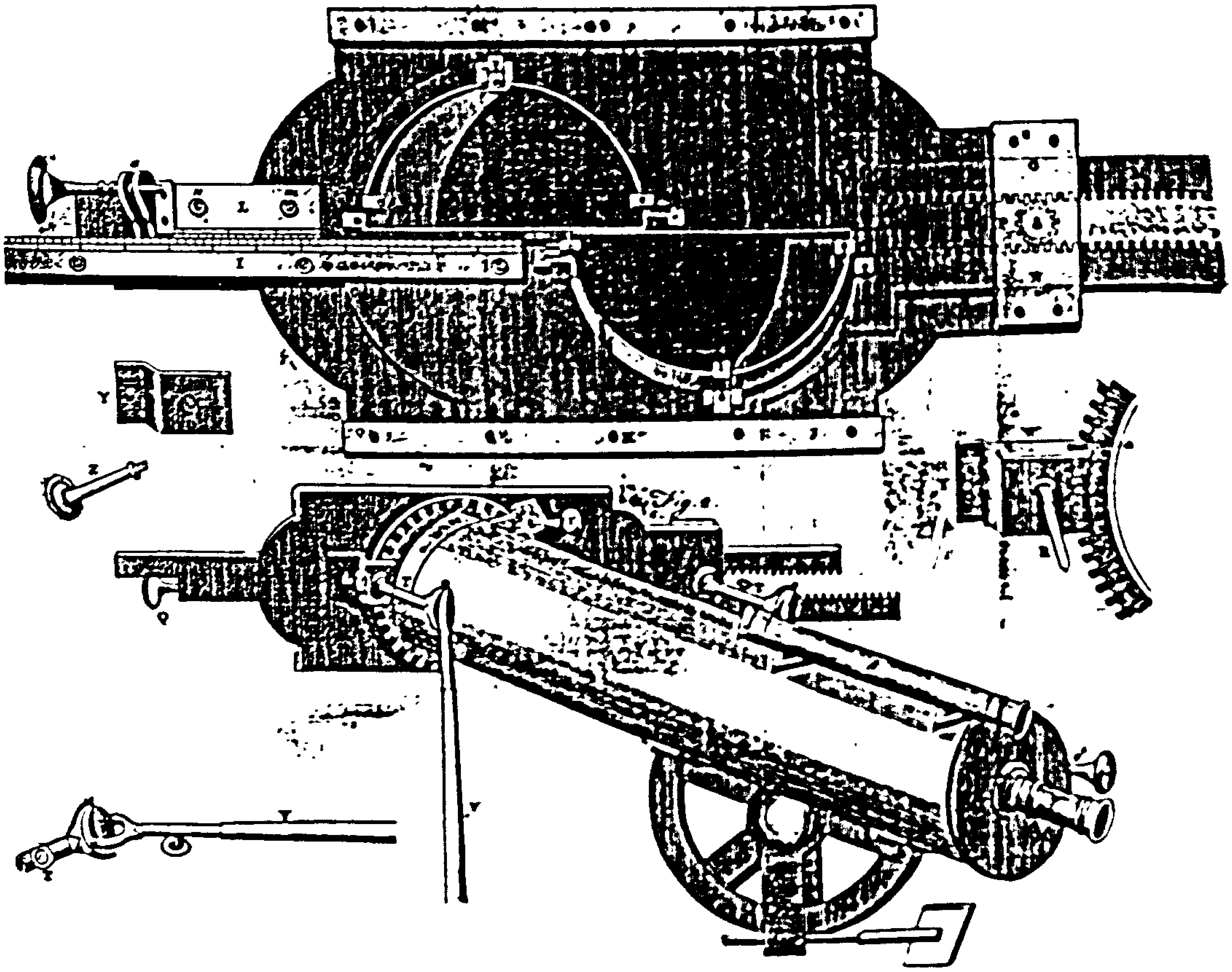
His second form of heliometer--and this is where Short's interest was piqued--employed a speculum mirror with the mirror cut in half. Savery recognized that a slight tilting motion about this cut would form two images and having been cut from the same mirror, the two halves had very similar focal lengths. The two halves were mounted on a thick brass plate and were separated by two pins whose diameters were equal to the kerf of the saw used to cut the speculum.[2] Two screws--one for each half--were inserted through the plate to push the outer edge against springs. The tilt caused the two images to appear separated by an amount dependent on the tilt effected by the screws. The amount the screws were advanced was the required measure which was determined by an attached dial as on a modern spherometer. One problem anticipated by Savery was the flexure of the brass plate and the speculum halves. Thus he chose both to be thick. Viewing was as one normally expects with a Gregorian telescope. Nothing further is known about the screws. Gill (1878) described the models constructed with lenses, but did not mention the catoptic version.

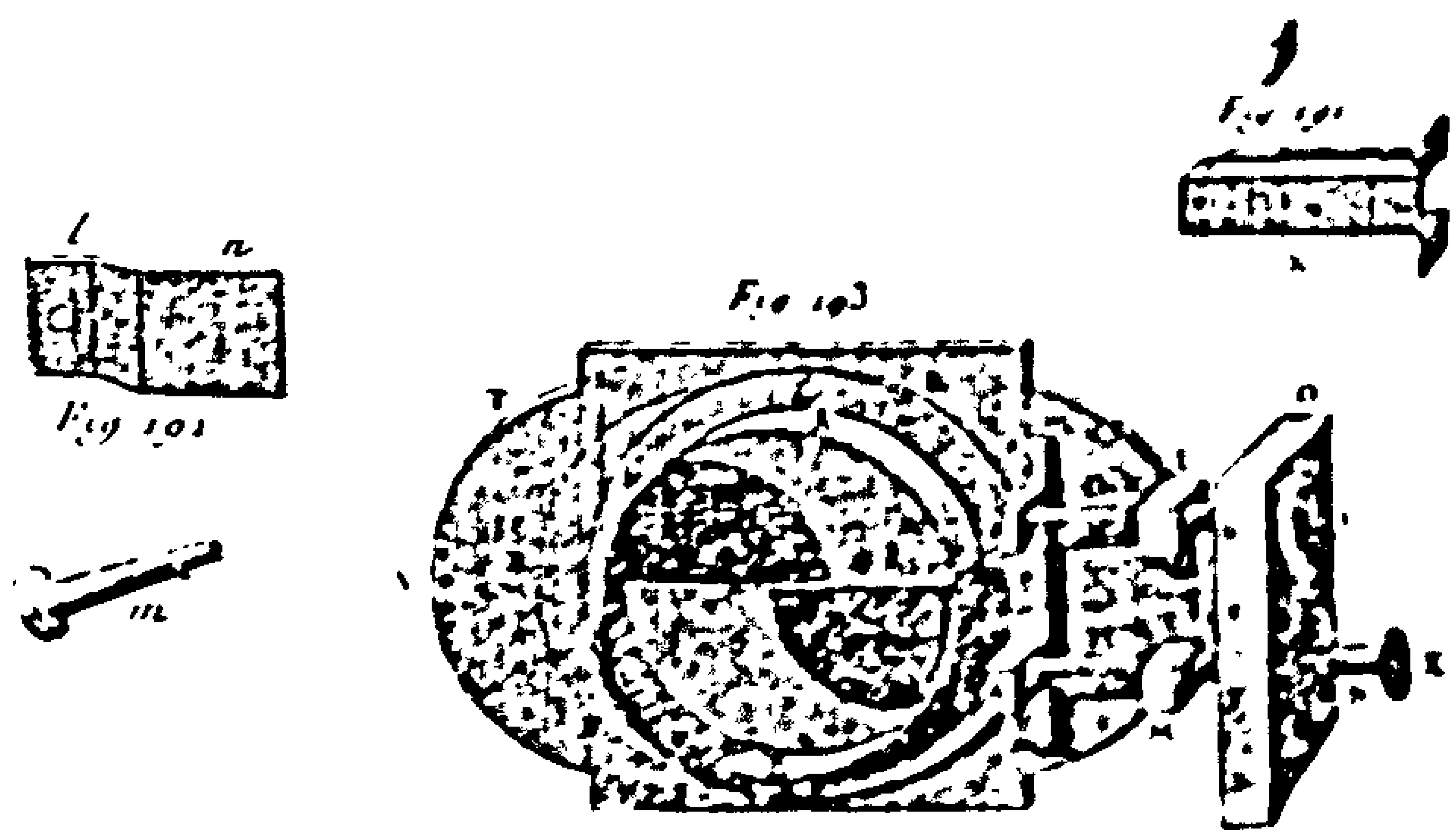
The fact that Servington Savery had designed these instruments specifically for solar observations may have been the reason others did not follow up the concepts. The application was so specialized that, on first consideration, the officers of the Royal Society did not publish the paper in 1743. Reminiscent of Gascoigne's case, Savery's priority was not promoted until the French laid claim to the discovery of the concept. The application envisioned by Savery was adequately accomplished with standard micrometers and transit observations. In the latter, Bradley's implementation of his 'ear and eye' method of timing transits had brought about a considerable improvement in the application of that technique. Thus there was no pressing need for the technology proposed by Savery.

---

1 For discussions on the centering of telescope optics see Harris, 1704 under "Optics". Smith, 1738 also described George Graham's method but it was Harris' which Savery had used.

2 Short specifically uses this term although saws of the day must have had difficulty cutting the hard speculum metal and it is possible that rotating cutting discs charged with emery were used.





3.3.17 Two forms of heliometer made by Dollond. The first used screws (examples signed by Short are extant). The second form used a vernier to determine the separation of the lens segments.

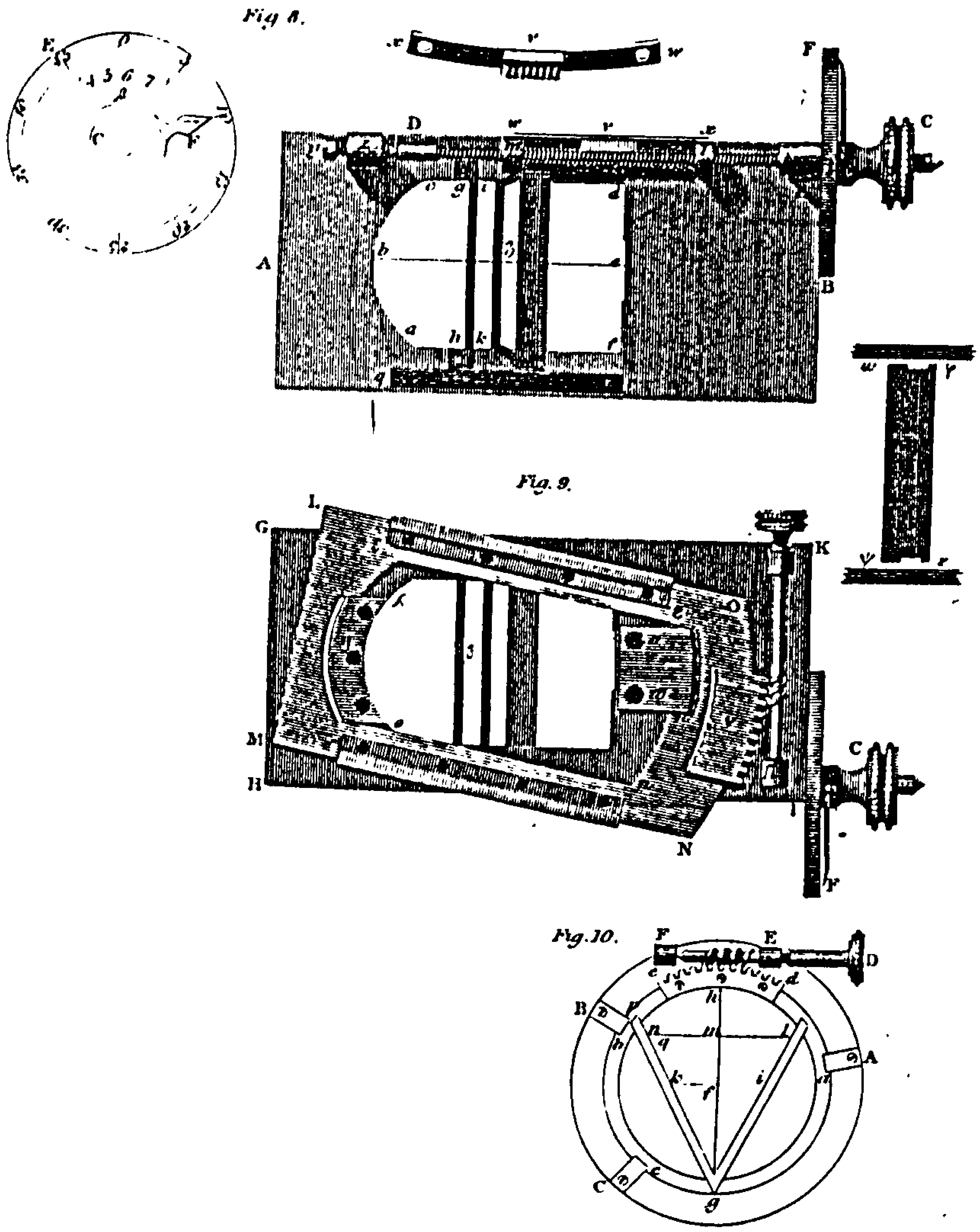
The paper read immediately following Short's was by John Dollond (1706-1761). His concept was a combination of Bouguer's and Savery's and was a more elegant solution. Dollond employed a single lens cut in half; each segment was mounted in a frame which moved back and forth by means of two screws and gears as in Bradley's filar micrometer (Fig.3.3.17). However, instead of separating the halves away from the optic axis, he made them slide along the cut. The following year Dollond (1754, p.551) expanded on the concept and showed how such a divided lens could be used in front of a refracting telescope (the type of heliometer which became popular in the 19^{th} c after Fraunhofer's Königsberg heliometer), or in the tube before the eyepiece (not too different from Airy's) and was the model he recommended to be used with a reflecting telescope. The versions he made for reflectors employed screws as the measuring device as in filar micrometers. The screws were right handed and of equal pitch with one driven by the other through gears with an equal number of teeth. Motion was indicated by a linear scale with subdivision read by an index and dial. Models with the screw mechanism became an instant success, gauging from the number of extant instruments. Examples survive at the Science Museum, Royal Observatory, Observatoire de Paris and Dollond and Aitchison Museum in Birmingham (q.v. Barty-King: 1986, p.25).

Within six or seven years, the screw arrangement was replaced by one having motion provided through a handle turning (through a Hooke's or universal joint) a pinion mounted between two racks. This arrangement was made necessary because longer fócal length heliometers were desired and with the screw arrangement, the length of the telescope was limited to arm's length so that the screw could be manipulated by the observer. Thus the extant screw versions are all found on Short or Dollond Gregorians of ≈1 foot length. Reading of the new style of instrument was via a linear scale subdivided by a vernier. Models with achromatic lenses soon followed John Dollond's re-invention of the achromatic telescope lens in 1758[1] but the third problem of vignetting was not solved until the 19^{th} c. George Dollond's solution to this problem (caused by separation of the lenses) was to make elongated lenses (Pearson: 1829, p.180-1). Other versions along similar lines soon appeared, including one by Pézenas (1755). However, since the screw operated version was short lived, little further will be said of this particular type of heliometer.

3.3.6 Filar Micrometers:
3.3.6.1 Bradley/Graham design and Bradley's observing techniques:

In Britain the most widely used filar micrometer from ca.1725-1775 was the improved design of James Bradley (1692-1762). It was relatively simple, having but

1 The achromatic lens was invented ca.1733 by Chester Moore Hall.



3.3.18 General form of filar micrometer made by Graham (from ca.1725) and Bird (from ca.1742).

one screw moving one wire.[1] This micrometer (Fig. 3.3.18) incorporated an end bearing screw to lessen end play of the micrometer screw, the latter being 0.3 inches in diameter and 5.5 inches in length. One improvement was the use of a half-nut about 1/2 inch long mounted on a spring plate between the two nuts which were 3 inches apart. This was Bradley's attempt to overcome backlash. However, the chief innovation was his incorporation of a toothed arc which permitted turning the wires around the optical axis about ±10° by means of an endless screw meshing with the arc. The wires were interchangeable with solid brass sights if desired. Smith (1738, p.347) provided the dimensions of the main components and it is from these that we find the recommended screw pitch of 40 TPI. The index plate was first divided into 40 divisions as Smith described but later versions had 60 divisions. Three examples of this style of micrometer have been found: two by Bird (MHS-3) and one by Jeremiah Sisson (SML-26). These follow Smith's dimensions fairly closely though made many years after the original design was developed[2]. The collaboration between Bradley and George Graham in building the Greenwich zenith sector in 1727[3] may have been the impetus for Bradley's development of this micrometer. The two would have had numerous discussions on mechanical design for that instrument (including the scale micrometer) and the design of the filar micrometer may have followed from that project.

Mid-18th c practices of micrometer usage are summarized by Bradley[4]. After a few historical notes and the observation that the first micrometers could only be used to measure the diameter or separation of objects in the field of view, he shows how later micrometers and techniques extended this range. From the directions given by Bradley it is clear that he is describing the use of the above type of micrometer. Success, as he pointed out, was dependent upon the care with which the wires were mounted and checked. The worm and arc, which permitted accurate and easy adjustment of the attitude of the wires, was probably one of the features which made this micrometer so successful. Bradley described how the moveable wire and its fixed parallel wire could be separated by an amount equal to the change of declination and then how the difference in right ascension could be measured by timing the passage of a star across the fixed wire mounted perpendicular to the moveable wire. The need to take into consideration the semi-

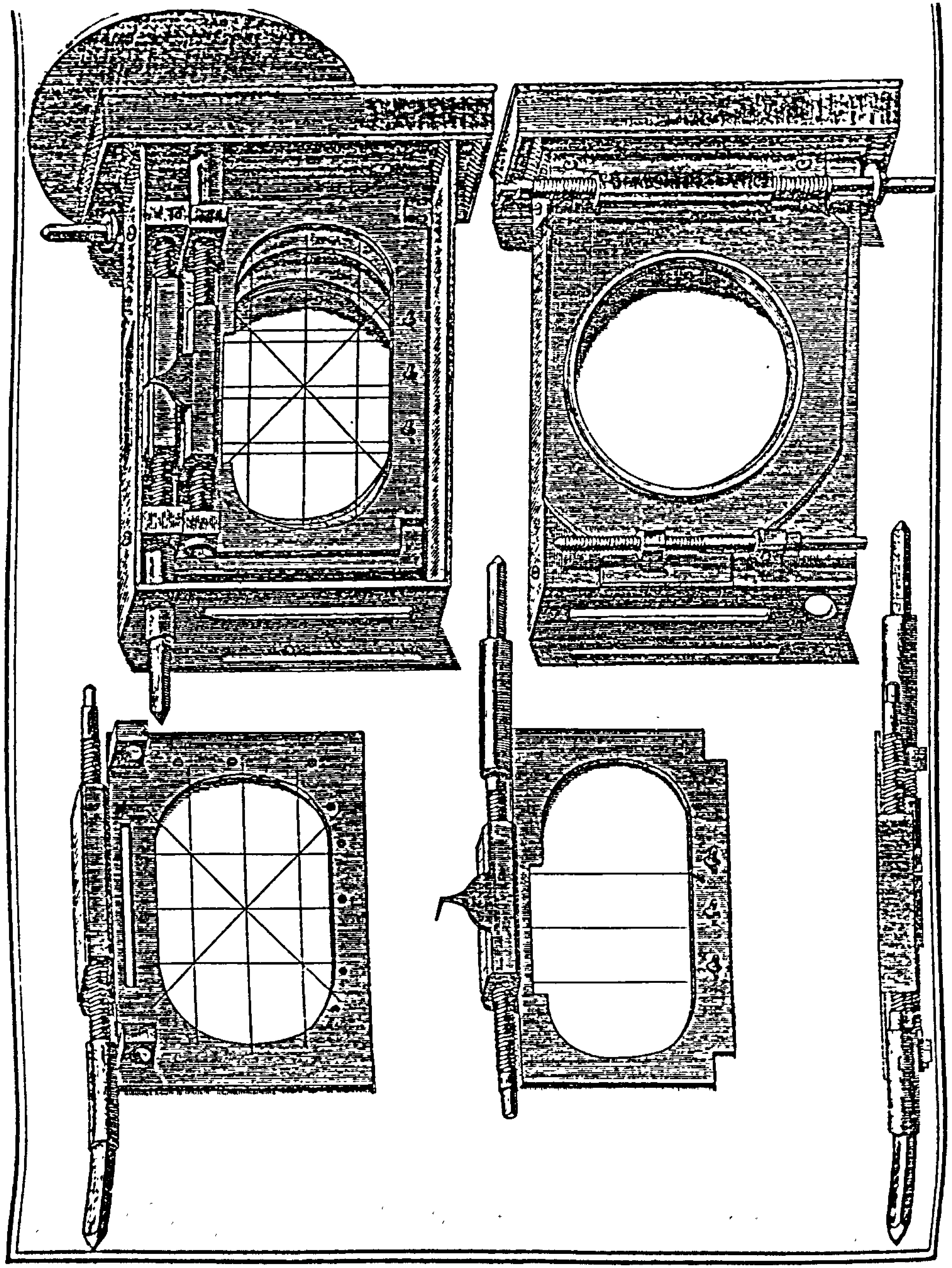
---

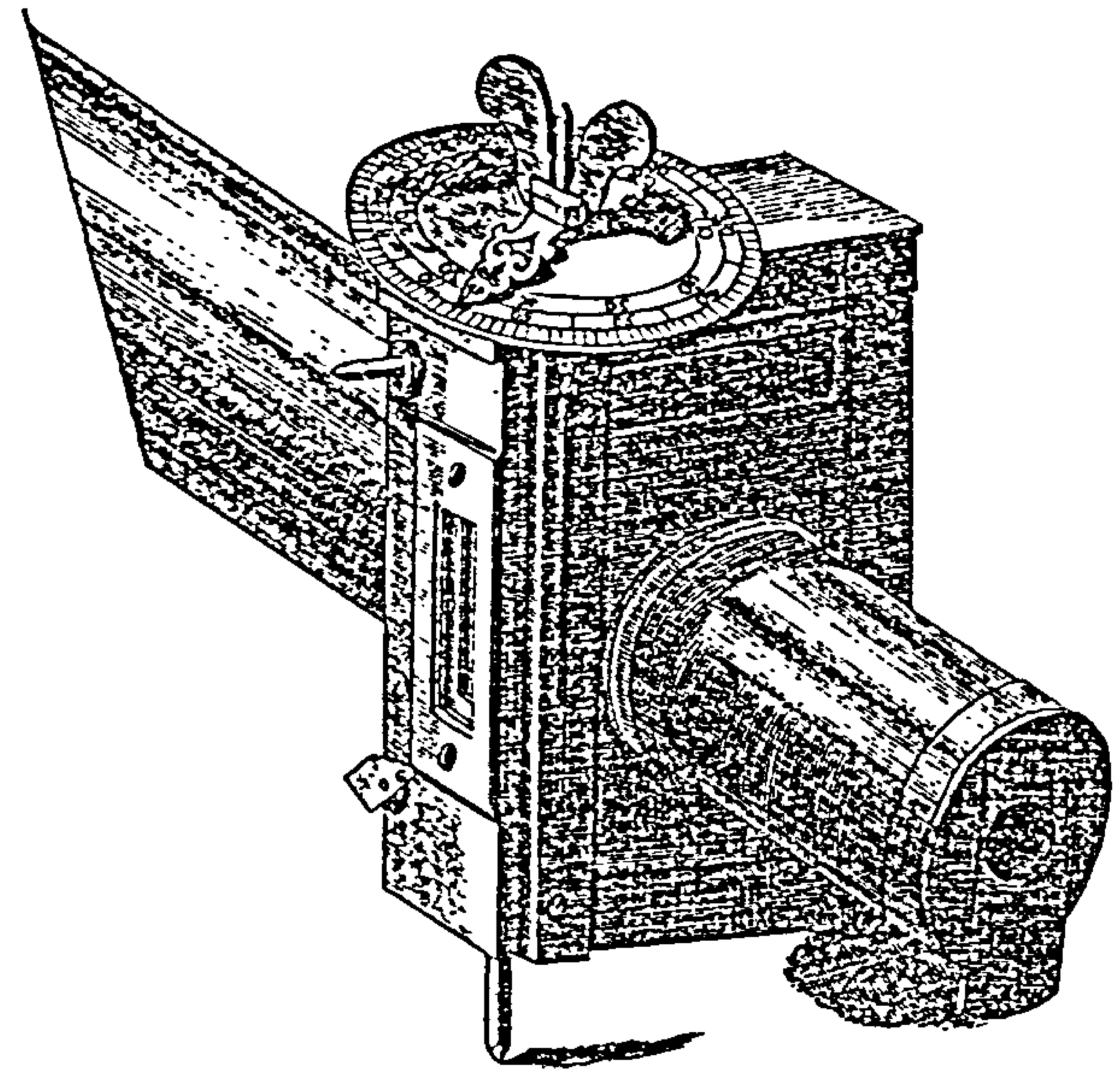
1 Halley had used a micrometer with two sets of wires crossed at right angles in 1720-21 to make observations of the relative right ascensions and declinations of stars. The procedure was to orientate one star so that it ran along one of the wires and to determine the time between the passage of one star and a following star. The declination was found by determining the difference in time for the star to cross from one diagonal thread to the other (See Forbes: 1975, p.81).

2 Smith and Bradley had worked together before becoming, respectively, Plumian and Savilian Professors of Astronomy and of course Bradley became Astronomer Royal following Halley's death in 1742.

3 See Bennett: 1987, p.118.

4 Maskelyne was Bradley's successor, but one, as Astronomer Royal and apparently found these directions in Bradley's handwriting and submitted them to the *Philosophical Transactions* for publication (1772).





3.3.19a Marinoni's large micrometer.

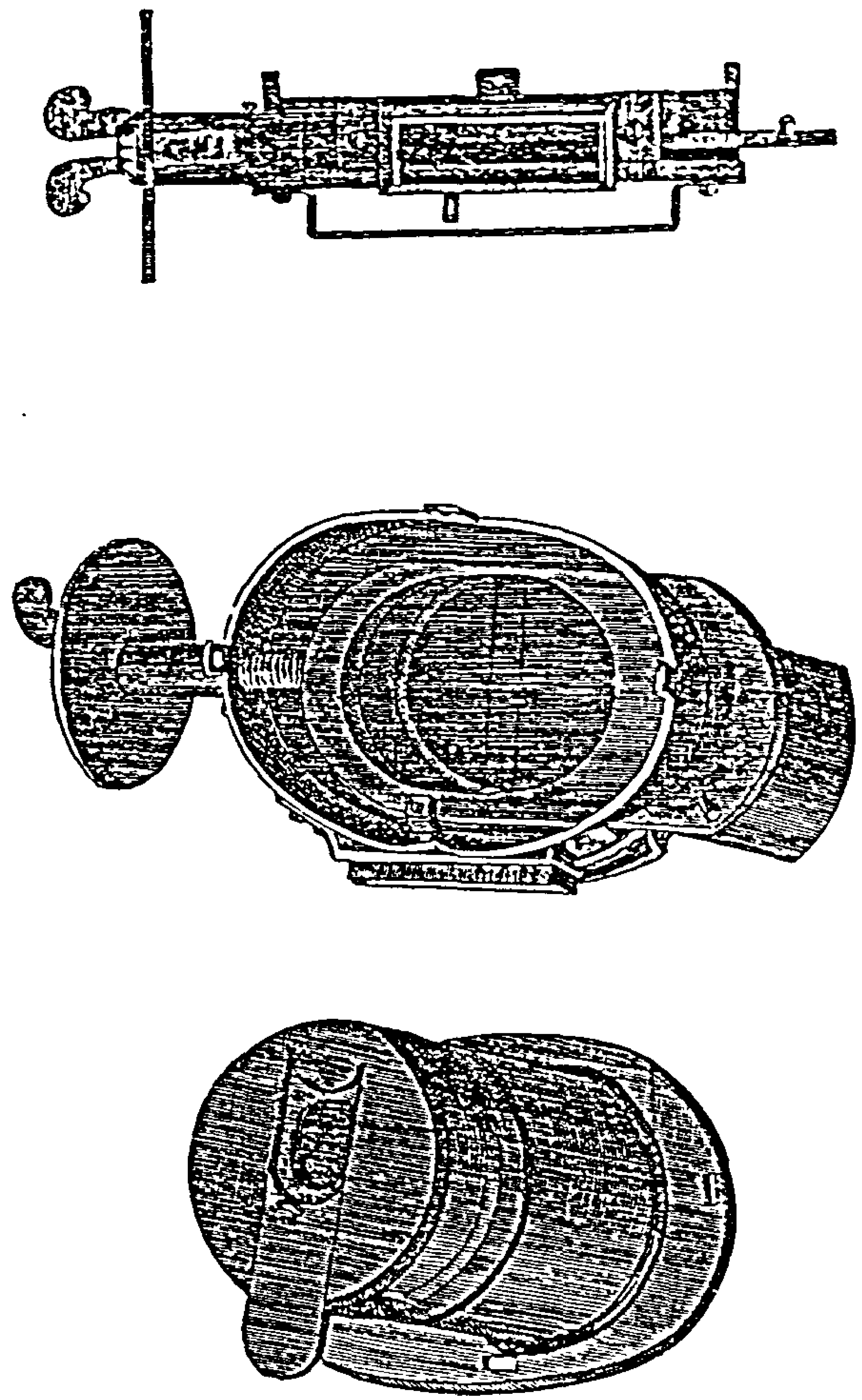
diameter of the wires is also noted for the calculation and subsequent use of the micrometer.

Bradley described the technique for calibrating the micrometer for each telescope. First he described in detail the method of ensuring that the wires are at the mutual focus of both the object and eyepiece, since the calibration depends on the wires always being at the same point on the optical axis. Bradley's preferred method of calibration was to measure: 1) the distance of the object-glass from the wires, and 2) the distance equal to 100 revolutions of the screws. The scale was determined by proportions by taking the object-glass distance as the radius and then the distance required for 100 threads as the sine or tangent of the angle as a close approximation since the angle is small. Other angles were determined by proportion. Thus there was still no attempt to determine the progressive errors of the screw. However, Bradley noted that the object-glass distance should include a factor approximately equal to one third of the thickness of the object-glass when the object-glass is a double convex non-achromat. The other two methods for calibration were the test card and timing methods already discussed but without further refinement.

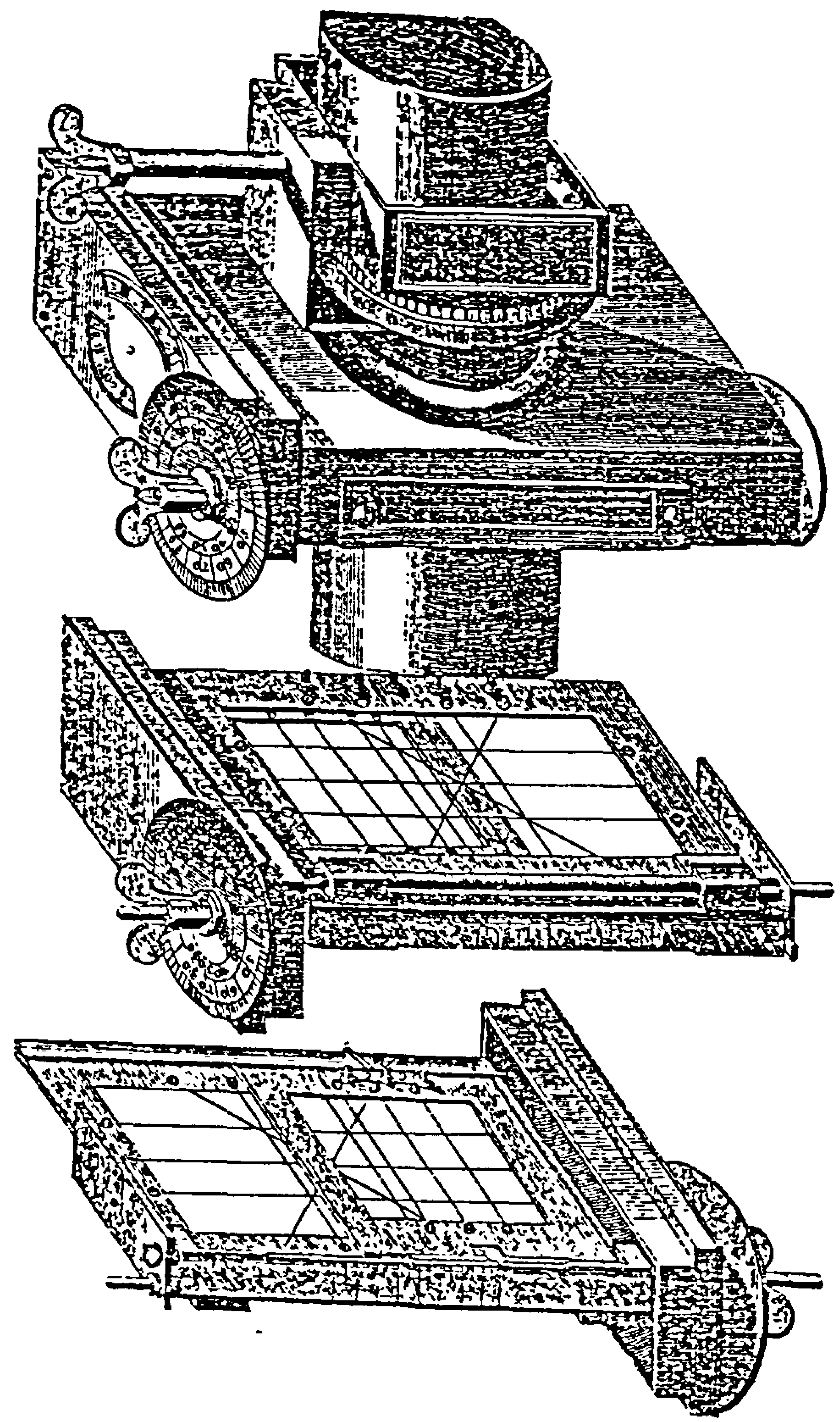
3.3.6.2 Marinoni's filar micrometers:

Marinoni's large filar micrometer (Fig. 3.3.19a) outwardly looked similar to French scale micrometers but had provision for adjustment of a number of degrees of freedom of the wires. In all there were four screws on Marinoni's micrometer. Not only could the wires be adjusted longitudinally but they could be adjusted tangentially and rotationally. The 'fixed' wires could also be adjusted longitudinally. The majority, if not all, of other maker's micrometers had a fixed scale on the case of the instrument. However, Marinoni's arrangement with the 'fixed' wires adjustable required that the scale be carried on the screw for adjusting the three parallel moveable wires. This arrangement was presumably to eliminate errors caused by driving a second micrometer screw through gears in order to impart opposite motions to the wires and in that he succeeded but at the cost of ease of use. The scale was divided 0-100, 100-0 with the tens divisions indicated, and as was common was intended to be read when the screw approached the limb of an object or star from either direction. No springs were employed for backlash though the nuts were very long in order to average out errors of pitch. If the speculation concerning the use of this micrometer on his 9ft quadrant is correct, we can say that the pitch of the screw must have been ≈24 TPI.

Marinoni's position micrometer (Fig. 3.19b) was more conventional in appearance. It had provision for rotation of the micrometer head with a crown gear attached to the telescope tube which was turned by a geared 'key'. The whole turns of the micrometer screw were, however, read either from a linear scale (in the traditional fashion) or with a dial which was driven through gears by the micrometer screw 'key'. The linear scale



3.3.19b Marinoni's small micrometer.



3.3.19c Marinoni's position micrometer.
(All illustrations from Repsold: 1909)

read 40-0-40; the micrometer dial 0-100 and 100-0. This micrometer's moveable frame carried 4 parallel wires while the fixed frame appears to have had three parallel wires with a pair of crossed wires intersecting on the centre wire. As in the previous scale micrometer, there are no springs to control backlash and the nut is rather shorter though still appears to be many times longer that the screw's pitch.

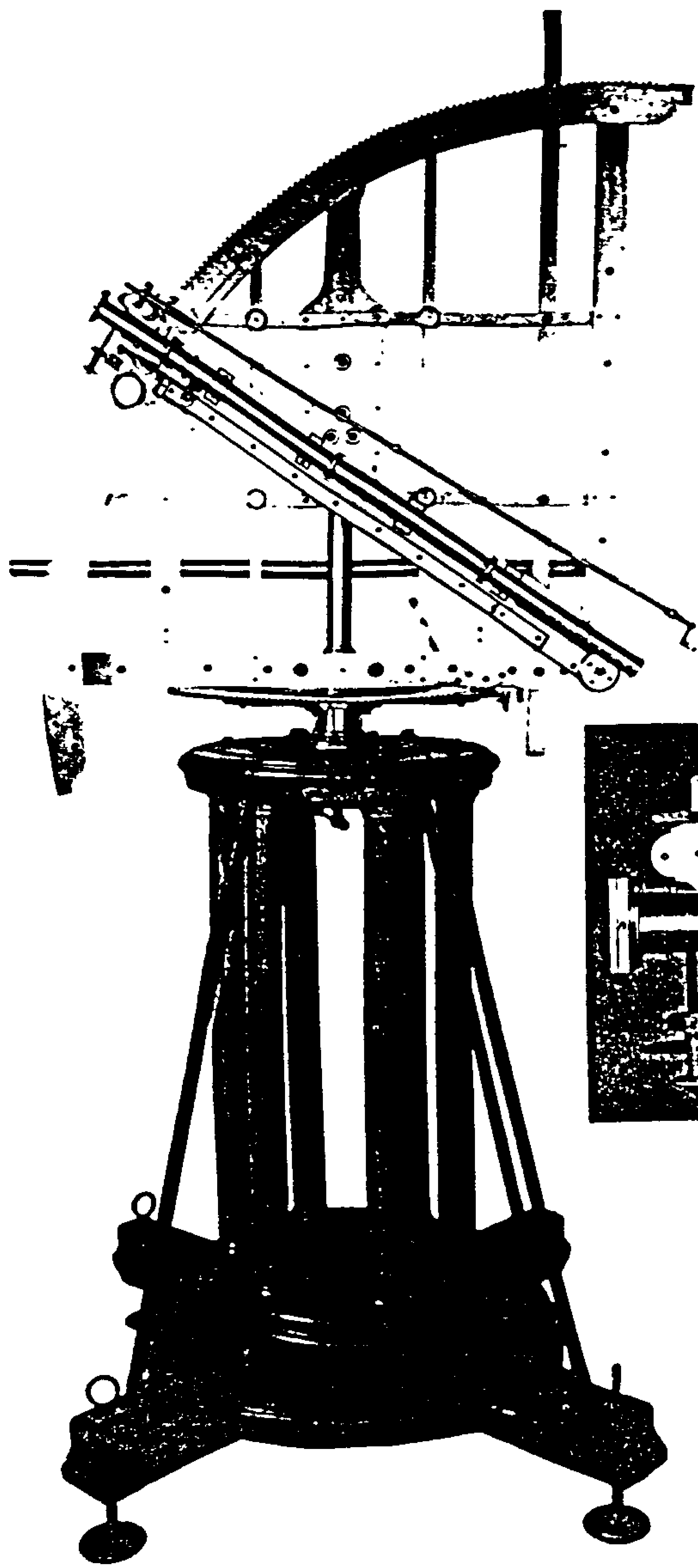
Yet another, smaller micrometer (Fig. 3.3.19c) of Marinoni is illustrated by Repsold. It had two fixed wires and one movable wire. To keep the size small, the moveable frame had rounded ends to match the outer oval case which was made from shaped sheet metal with small tabs over which a cover carrying the lens was fitted. Whether the screw was threaded in the moveable frame or in the tube illustrated attached to the sheet metal case is not clear. One may draw some conclusions by assuming that the dial was attached to the tube just mentioned. The index, not shown, would then have been attached to the screw and the screw threaded into the moveable frame. This frame carried an index projecting over the linear scale. The eyepiece also incorporated a small sliding cover as is found on many 19th c nautical telescopes. This micrometer would appear to be a precursor to the small divided eyelens micrometer of Ramsden (1779) and, although the size is not directly indicated, is the smallest micrometer to that time, i.e. to the early 1740's.

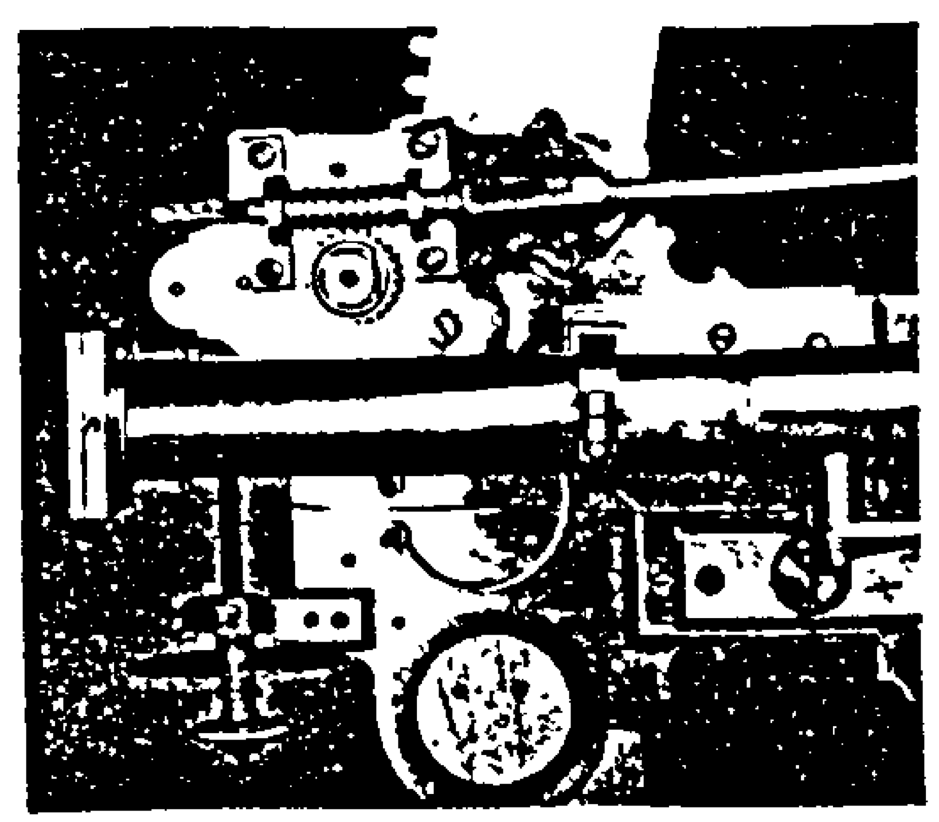
3.3.6.3 Brander's Micrometers:

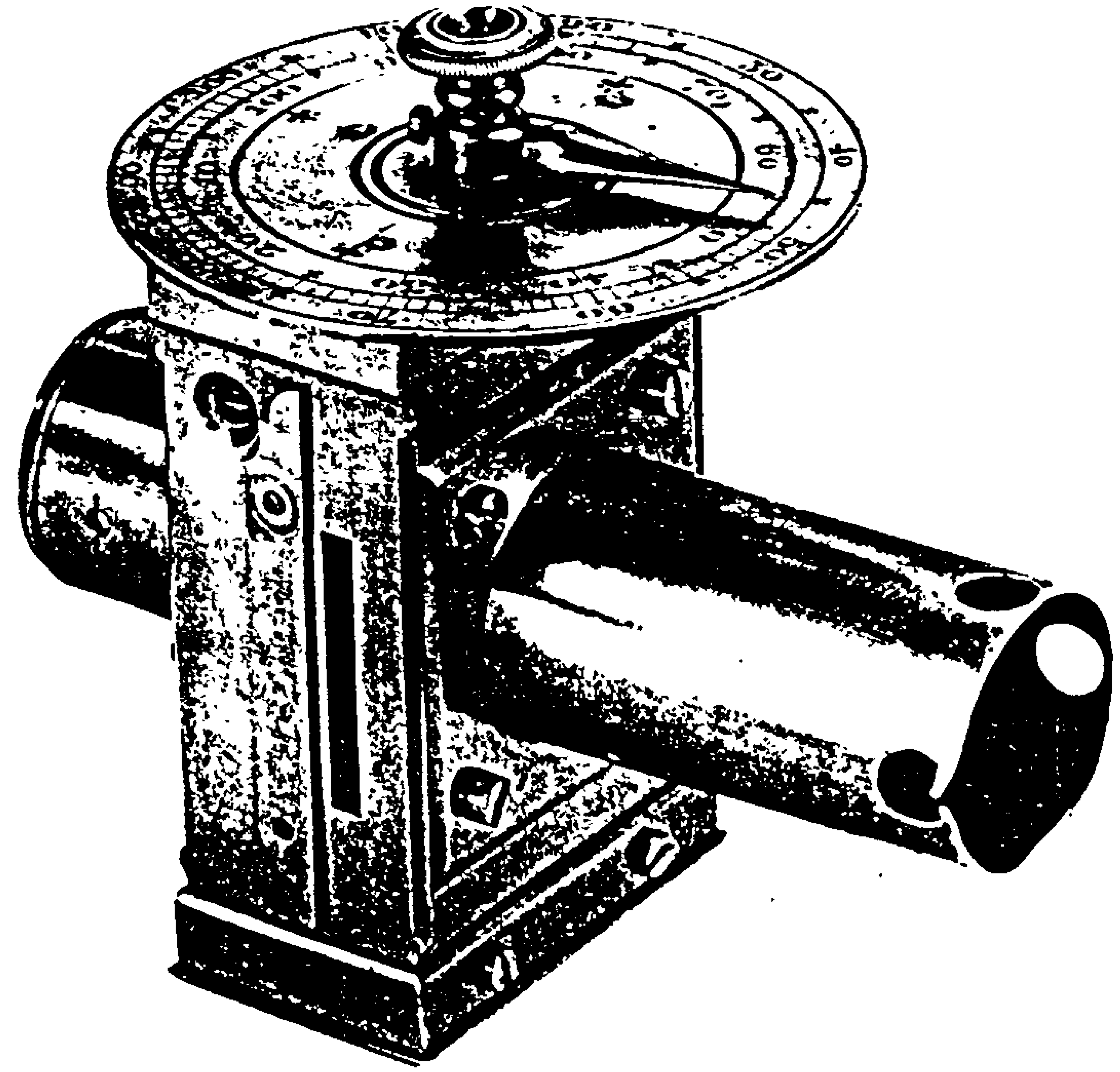
The most important German instrument maker of the 18th c was certainly Georg Friedrich Brander (1713-1783) working in Augsburg. The range of his production was very wide, approaching that of the largest London firms. Brander was in partnership with his son-in-law and successor, C.K. Hoschel, from 1775 and was contemporary to the Dollonds, Bird and Ramsden in London and with Nollet, Canivet and Lenoir in Paris. A perusal of the Brander instruments preserved in the Deutches Museum and illustrated in their **Katalog** (1983) shows that Brander was not particularly original in developing new concepts[1] but was exceptional in his workmanship and the details of his instruments' construction. Unfortunately, the **Katalog** does not deal with the detail of the instruments to a degree which will allow us to make anything more than general observations on Brander's micrometers.

A couple of unusual quadrants are illustrated in the **Katalog**; the first is a large azimuthal quadrant (Fig. 3.3.20a) of 0.95m radius mounted on an elegant base. The altitude of the telescope was adjustable from the eyepiece end via a shaft with hand crank operating a worm wheel and pinion gear meshing with teeth cut in the exterior of the quadrant limb not unlike the scheme employed by Hooke 90 years earlier. Fine

[1] Indeed it may be argued that even the British makers were largely producing instruments which were requested by scientists, of which there were many more in London than in Germany.







3.3.20b Brander's filar micrometer (ca.1770) which is similar in outward appearance to French quadrant micrometers from ca.1730's.

3.3.20a Examples of Brander's scale micrometers.

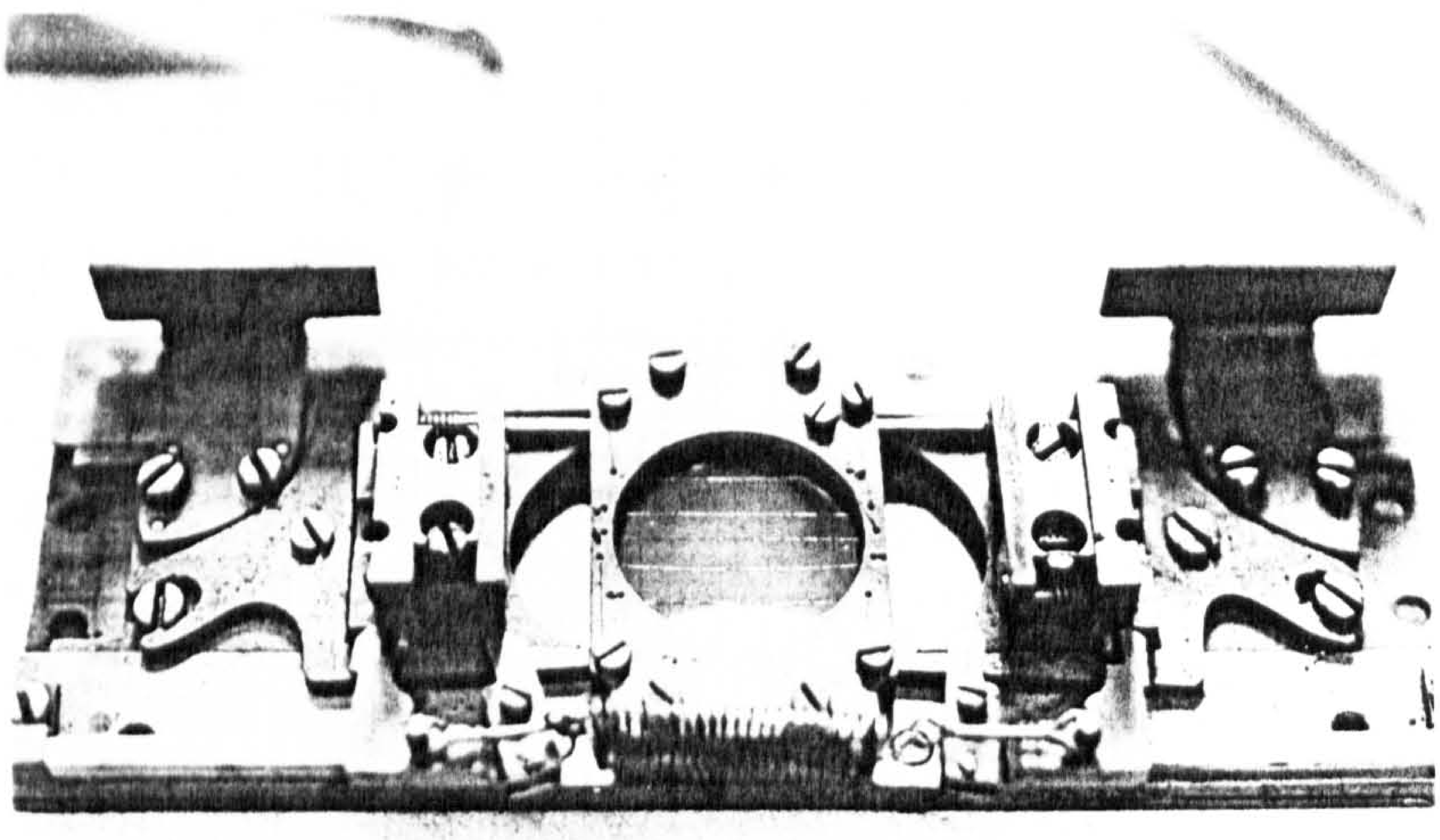
adjustment was accomplished with a micrometer screw which separated a split alidade. This would have had to have been operated by an assistant while the observer gave directions from the telescope eyepiece. A circular spring (shaped like an 'Ω') attached to the two segments of the divided alidade worked against the micrometer screw. This scheme was also adapted on a small portable quadrant of 38cm radius (Brachner: p.150-1). For both, the mode of operation was to adjust the telescope to the approximate angle, then to adjust a fiducial over a division of the scale and to take the angle by adjusting the micrometer screw to the object. On the small version, the observer could easily observe and adjust the micrometer but, as noted, the larger instrument required an assistant which must have seriously affected the precision achievable.

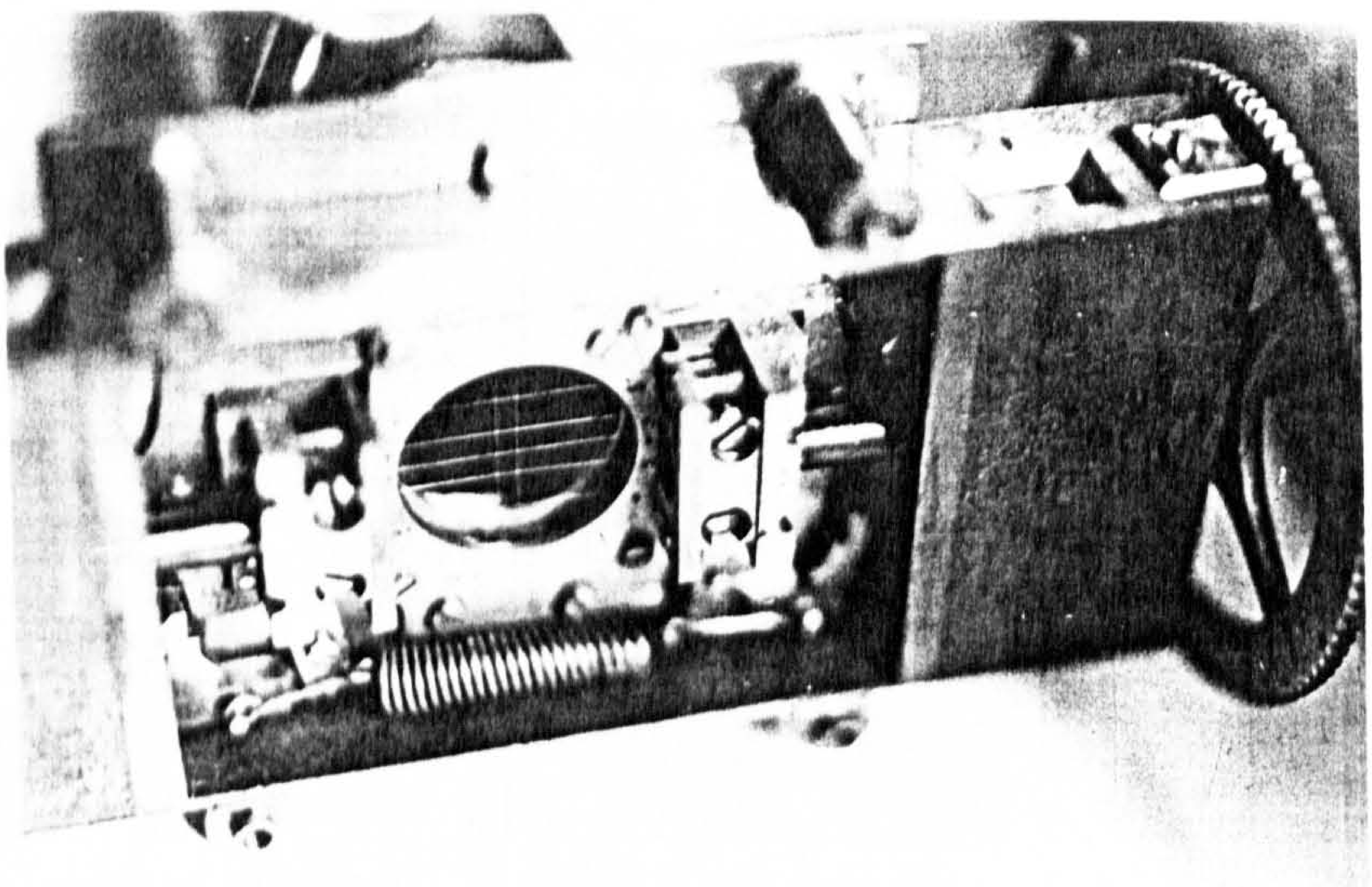
Brander (p.154-6) also made quadrants with eyepiece filar micrometers and three of these are illustrated. In exterior appearance (Fig. 3.3.20b) these are very similar to those made by Langlois, examples of which have been studied at the Observatoire de Paris. These employ a single micrometer screw and given the almost identical outward appearance, probably work against a double split leaf spring. The drums are divided 0-100 and 100-0 indicating the continued lack of concern for errors due to backlash when rotating the micrometer screw away from the spring. One of the three illustrated is dated 1761 and the others are provisionally dated ca.1760 by the Museum. (q.v. §3.3.7.1 on Optical Micrometers for a discussion of Brander's glass grid micrometers and their applications.)

3.3.6.4 Smeaton's astronomical micrometer:

The involvement of John Smeaton with micrometers began when he was a young man. He met his fellow Yorkshireman, Henry Hindley, whom we have already met as the inventor of a precision screw lathe, in the autumn of 1741. Hindley was a clockmaker in Halifax and maker of an engine to divide circular scales discussed later. The contact with Hindley must have been stimulating and a valuable education for Smeaton. He must have impressed Hindley as he took him into his confidence divulging secrets of his dividing engine that were not known to his own brother (Smeaton: 1786, p.27 or Scott: 1919, p.10). Smeaton's admiration for the master resulted in the most complete account of the life and achievements of Hindley. After an initial period of training, Smeaton began his career as an instrument maker in London in 1748. Hindley sent an equatorial telescope to Smeaton to try to sell in his London shop but apparently without success since it was returned to Hindley sometime later.[1] Smeaton's interests were evolving and he increasingly turned to engineering pursuits and has become recognized as the 'father of civil engineering'.

1 See Smeaton (1786, p.20n).





3.3.21 Two views of Smeaton's micrometer (ca.1770). This instrument is in the Science Museum (SML-8).

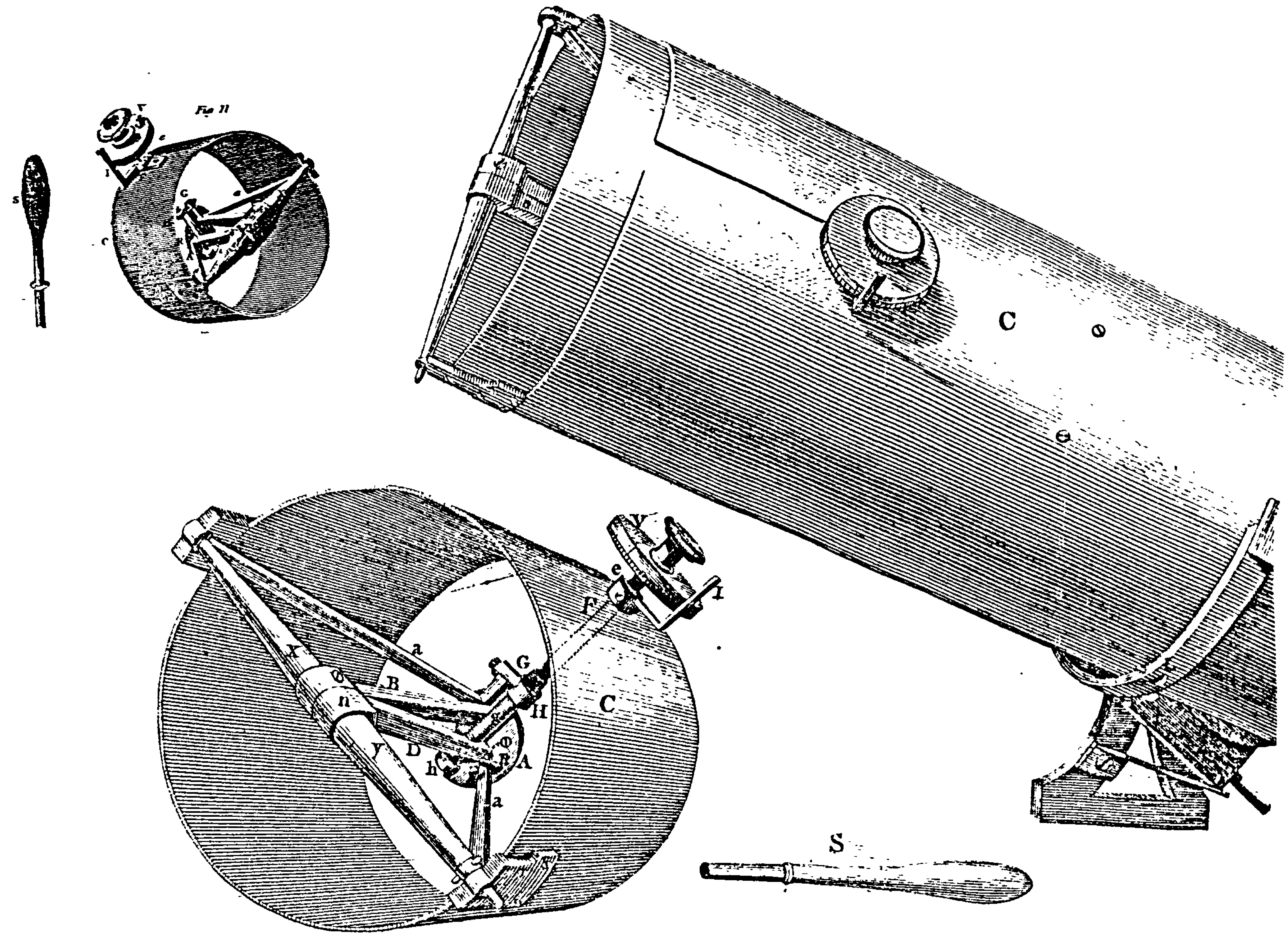
However, before going astray, Smeaton constructed a micrometer (Fig. 3.3.21) which was apparently begun prior to his departure from Yorkshire and was probably inspired by Hindley's use of a precision screw for dividing purposes. The micrometer is in the Science Museum and has been studied (SML-8) in the experimental section of this investigation. It is by far the most complex micrometer of any made before ca.1850 demonstrating Smeaton's understanding of mechanical principles. Although somewhat crude by later standards, it reflects the availability of machines and materials of the mid-18th c. It is interesting to note that he recycled materials since a date, 1748, was found on the inside of one plate comprising the micrometer enclosure. The piece was clearly cut from a piece of brass belonging to another instrument (or an earlier version) and helps to confirm the origin of the design and to connect it with the micrometer described by Smeaton in 1786.

Smeaton used his micrometer to observe an elongation of Mercury in Sept.-Oct., 1786, the results being published in the *Philosophical Transactions* (1787, pp.318-343). In this paper he states:

> I judged, therefore, that it might be of some utility to astronomy, if, by *any means*, a good observation of Mercury could be got; and also, that it would be a proper subject whereon to make trial of an instrument for such purposes, the idea of which I had conceived, and begun to construct, above forty years before but which from various avocations, I did not perfect to my satisfaction till the year 1770: since which time it has lain by, in hopes that something might happen, by which a full and effectual trial might be made thereof.

This instrument then was begun ca.1745 and worked on until 1770, after which it was apparently not much used. The complexity is such that the average instrument maker would have had great difficulty fabricating and assembling its many components into a proper functional instrument. Smeaton states he sent some observations made with it to Alexander Aubert, who then had one constructed for his cometary and similar observations. The instrument has two wires each operated by a separate screw. The screws have coil springs under tension to prevent backlash and long nuts (≈0.5in--long by contemporary standards) and work very smoothly. Smeaton estimated the accuracy of the micrometer to be 1/2300in which was far below that achieved on his pyrometer but not surprising given the differences in design. His skill in producing screws may have been gleaned from Hindley's practices. The two wires were most often used to determine differences in declination since there were five 'hororary' wires for timing the passages of stars.

Smeaton's procedure for timing the passage of a star was similar to Bradley's 'ear and eye' method of timing transits. Smeaton employed a Hindley journeyman clock beating half-seconds and took up the beat at 15, 30, 45 or 60 seconds, counting 30 beats repeatedly until the star arrived at the middle of the wire. The beats, or intervals between beats, were remembered and by looking at the clock, the time recorded was to a



3.3.22a Ramsden's micrometer (1777) for a reflecting telescope.

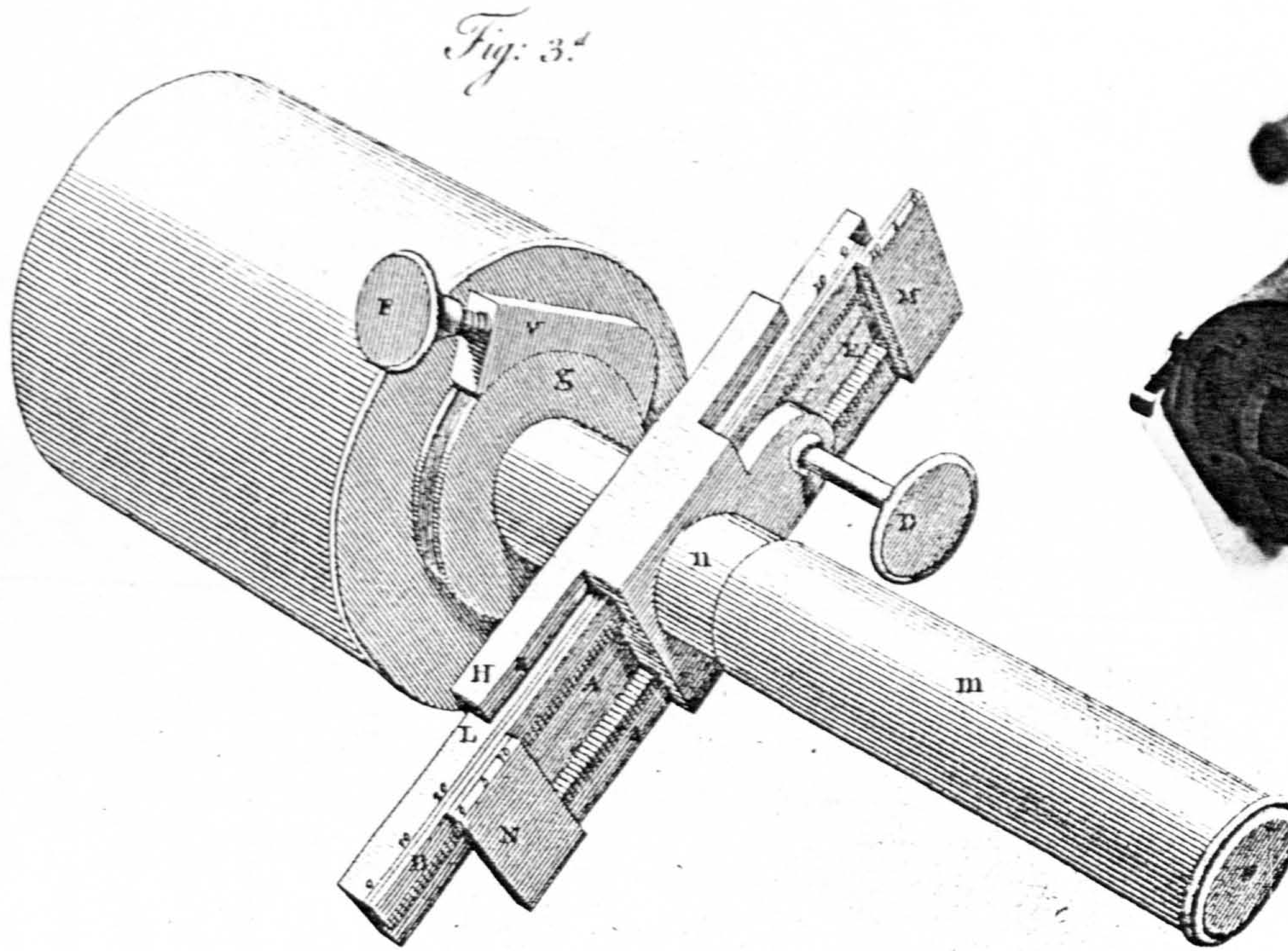
quarter second being recorded as 0.2 or 0.3, 0.5 and 0.6 or 0.7[1]. Smeaton claimed that he could take measures to 2 1/2", which corresponds to ≈1/2300th part of an inch (p.311). The drawn brass wires of the surviving micrometer in the Science Museum are very coarse, (≈1/50in) even by 18th c standards. Even with a magnification of sightly under 20x the wires must have appeared quite large in the field making it difficult to determine exactly when the star bisected the wires. The telescope is also preserved with the micrometer and incorporates a Dollond achromatic objective of 34 2/3 inch focus and an achromatic eyepiece of 1 3/4 inch focus (p.311). In order to have a sufficiently large field for his purposes, the magnification was low compared with that normally used with micrometers. In attempting to measure the passage of the planet, it was necessary to set the telescope pointing to the declination of Mercury and to time the passage of stars some time prior to the passage of Mercury. This was necessary since the sky was not sufficiently dark to see stars in the required declination when Mercury's passage itself was timed in the morning twilight. The telescope remained in exactly the same position for almost a month of observations which helps explain why the field of view was necessarily large.

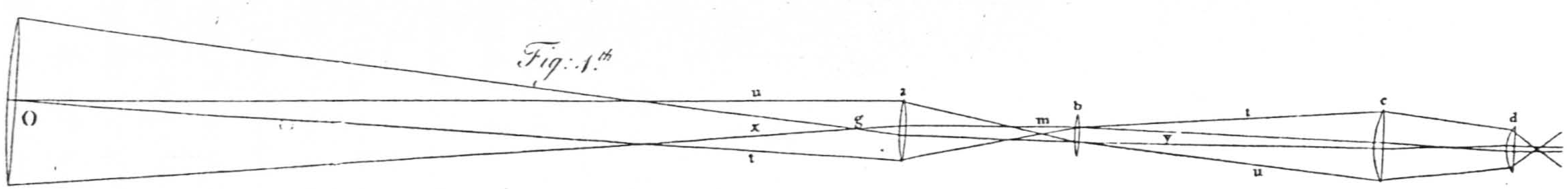
3.3.6.5 Ramsden's astronomical micrometers:

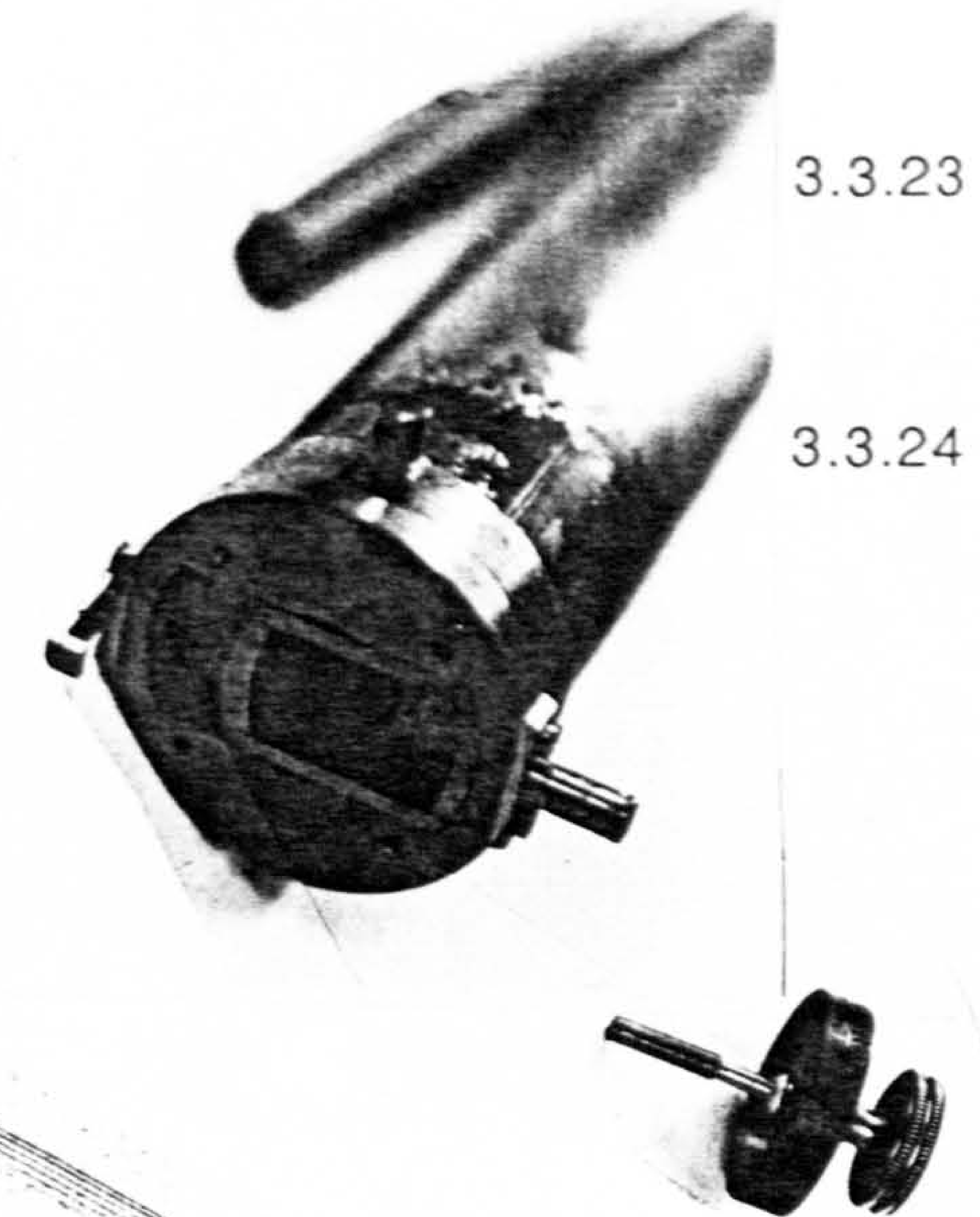
By the early 1770's Jesse Ramsden (1731-1800) briefly turned his interest to consideration of astronomical micrometers. This interest was partly stimulated by the new prism micrometers of Rochon and Maskelyne. On reflection, he concluded that the divided object-glass micrometer could never overcome a certain level of error because of its design, i.e. that **any** imperfection of the divided object-glass was magnified by the telescope's eyepiece or secondary mirror. In fact he described how, without changing the micrometer, an observer could see the images in the telescope fluctuating, sometimes overlapping, and sometimes separated. This was due to atmospheric seeing and to temperature gradients in the telescope itself. Further, the divided object-glass lens introduced an aberration which altered the angle measured by the micrometer, produced vignetting as the separation increased, and was expensive to manufacture.

Ramsden's solution was first to divide the secondary speculum of a reflecting telescope or alternatively to divide the eye-lens of a telescope. His first attempt with the divided speculum was a modification of Savery's concept. Ramsden divided the speculum through the middle then inclined the halves along the cut (Fig. 3.3.22a). However, it became immediately obvious that an index to measure very small angles would have to be intolerably long. Therefore on rethinking the situation, Ramsden settled on moving the halves longitudinally along the cut. This was effected by producing a screw within a screw, one being of twice the pitch of the other. The screws he employed were of 50 and

1 Brooks and Brooks (1979) provide a discussion of the 'ear and eye' method's accuracy.

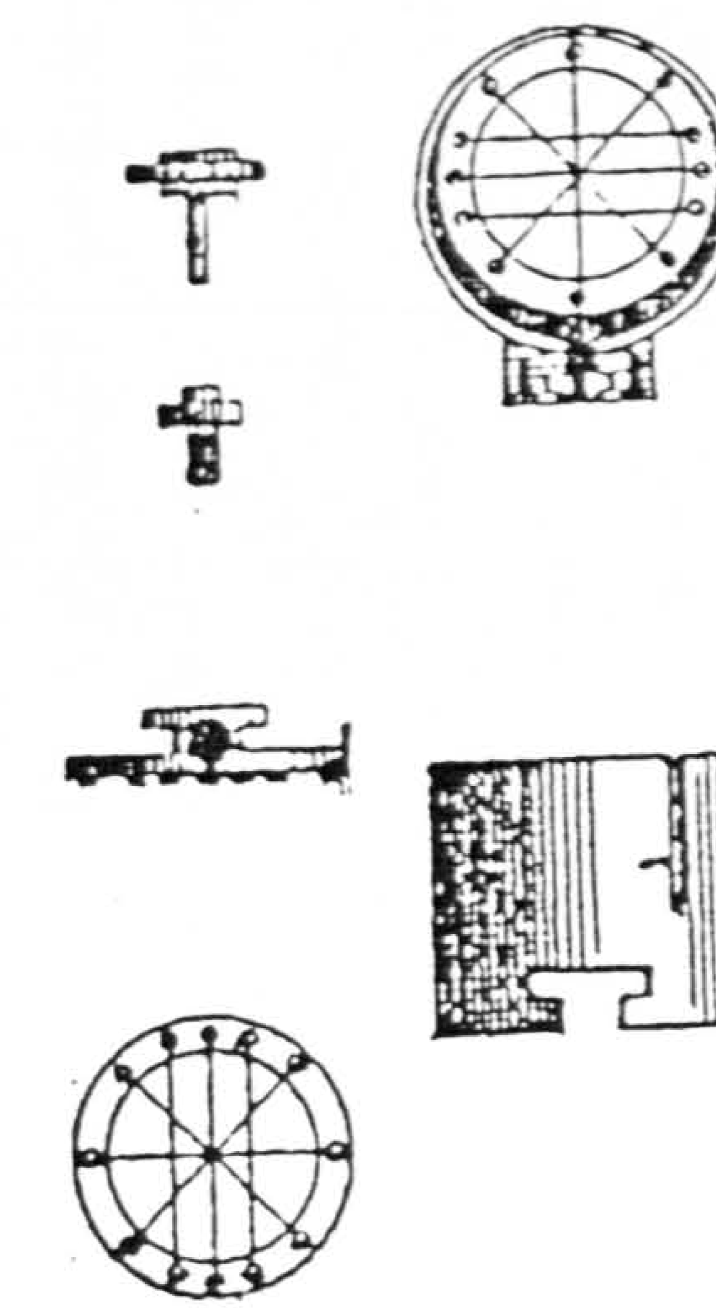






3.3.23 Ramsden's filar micrometer for an equatorial refractor in the Science Museum (SML-9).

3.3.24 LeMonnier's filar micrometer for his transit telescope (ca.1740). The arrangement of the filaments is very similar to that used by Ramsden for the large theodolite scale micrometers.

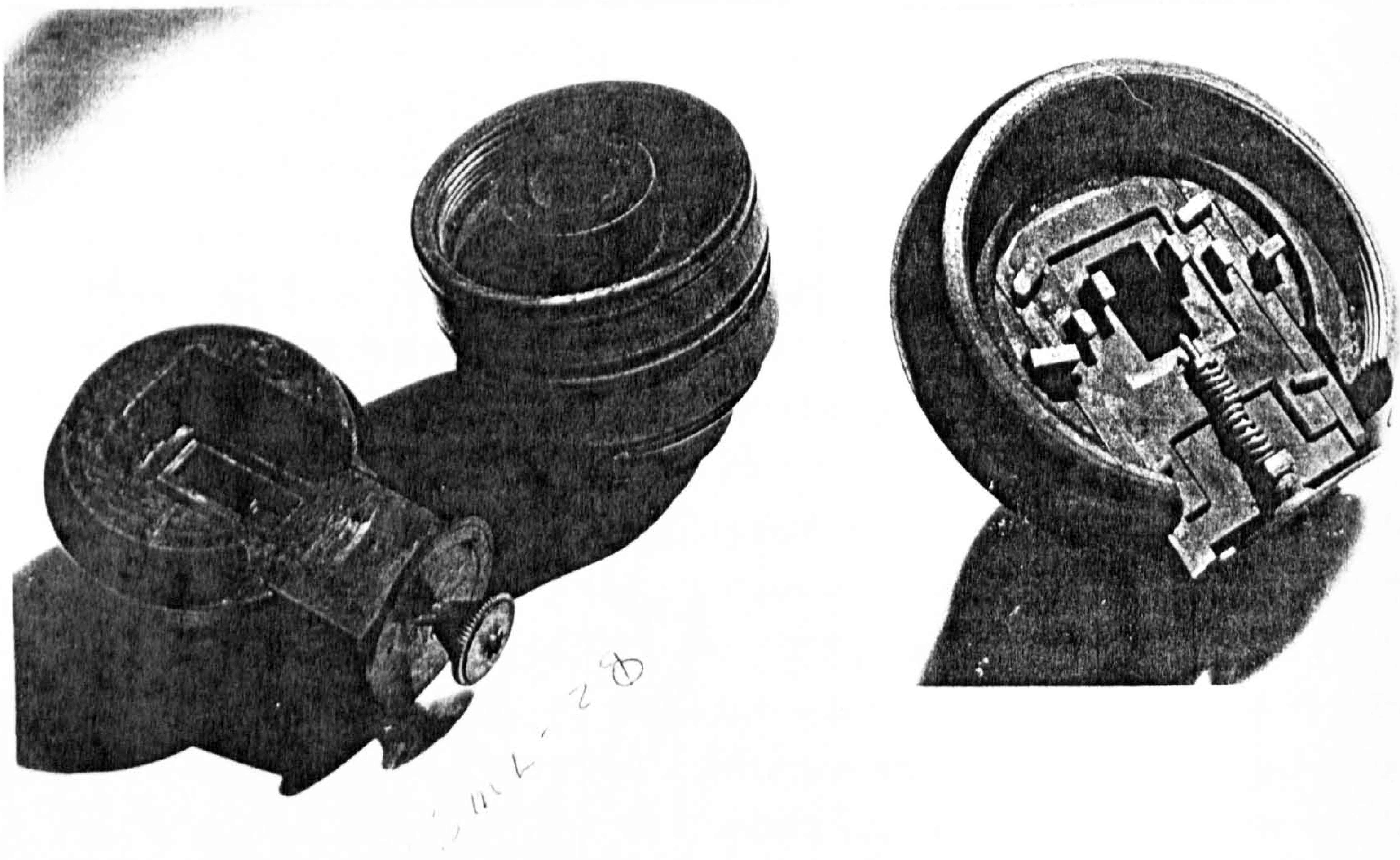


3.3.22b Ramsden's micrometer (1777) with divided eye-lens.

100 TPI and represent one of the first applications of the screw lathe to making micrometer screws. Ramsden had made the lathe to produce the screw of his dividing machine, but the design was flexible enough to produce small screws of fine pitch through the gearing. By inference from the drawings and Ramsden's description of the micrometer's use, the 100 TPI screw must have been left-handed. The mechanism to support the secondary and allow the required motion was necessarily complex and would have caused considerable shadowing of the primary with the resulting diffraction. With reference to Fig. 3.3.22a, a spiral spring was incorporated in component 'n' on the cross support 'XY' to prevent shake and backlash in the nut 'H'. The other nut, 'F', was on the side of the telescope. The inclination of the secondary was adjustable with the small steel screw 'R' and handle 'S'. The micrometer was read from a micrometer head divided to 100 divisions and an index which indicated the whole number of revolutions. A table of separations of the halves of the secondary was set up to correspond with objects of various separations. In doing so, it was found that a small error was caused by the fact that each half effectively approached the primary very minutely for large separations--this being due to the curvature of the primary. The error could not be neglected for angles greater than 10'. Ramsden also discussed the aberrations and properties of specula with parabolic, hyperbolic and spherical mirrors and why the Cassegrain forms were to be preferred for this micrometer design and for general use. It should be recorded that Ramsden mounted the above micrometer in the tube of a 5 1/2in Cassegrain of 22in focus.

The second micrometer described by Ramsden was a divided eye-lens micrometer (Fig. 3.3.22b). It had some distinct advantages. First, it was much cheaper to make, requiring that the optician polish only a small lens with a saving of time and, secondly, the images in such a micrometer appear equally bright regardless of the separation of the segments. This is desirable in observing faint stars of wide separation. The optical system is shown in Fig. 3.3.22b. The rays from the telescope's objective are focused by a lens at 'a'. The micrometer is placed at 'm' which is the focus of the lens, a, while lenses at 'b','c' and 'd' refocus the beam for viewing. It might be noted that 'c' and 'd' are in the configuration of what is known as a Ramsden eyepiece. Ramsden examined the size of the error caused by this micrometer and found it proportional to the magnifying power of the objective/micrometer lens combination.

The mechanical principle of this micrometer was not too different from the standard divided object-glass micrometer in that the two halves were separated by a rack and pinion arrangement. Readings were taken by two verniers--one for each half--on either side of the zero point. Both were read for the most precise measurements but ideally would have been identical. No springs are visible to control backlash. Rotation of the micrometer body for alignment of the objects on a line perpendicular to the motion of the lens halves was also possible with what appears to have been a worm and wheel



3.3.25 Two of the micrometers used by Herschel and probably made by his brother, Alexander. These are in the Science Museum. (SML-28,29).

arrangement. Why Ramsden did not use the double screw arrangement here is a matter of speculation. The screw arrangement would have provided greater resolution but would have added to the complexity of the frame with attendant cost. Perhaps Ramsden's purpose was to make available to the less wealthy amateur, a micrometer of reasonable precision which was easily mounted on any telescope. Whatever his reasons, this instrument was the progenitor of several other divided eye-lens micrometers. It was with such a device that Ramsden discovered that he could determine the magnifying power of a telescope with ease and hence in a slightly modified form was to become the dynameter. Later versions of the micrometer and dynameter were invariably screw operated to compensate for the lower resolution of the field lens and to provide the degree of precision desired. Where the divided object-glass micrometer had begun with screw micrometer adjustment and evolved to rack and pinion with verniers, the divided eye-lens micrometer began with rack and pinion and verniers and evolved to screw micrometer adjustment.

A filar micrometer not described by Ramsden but which survives on an equatorial telescope of 1775 in the Science Museum (SML-9) is illustrated in Fig. 3.3.23. Curiously it has some similarities to the adjustable crossed wires for a transit instrument (Fig. 3.3.24) illustrated by LeMonnier (1741 in his **Histoire Céleste**) (note this is not a micrometer). Repsold speculated that LeMonnier's instrument had been made by Graham and this is quite possible since LeMonnier was well known to be communicating with Graham in an attempt to modernize the instrumentation of French astronomers (Brooks: 1979, p.336-7). On LeMonnier's instrument the wires were fixed to a circular frame within a tube which was slightly larger in diameter. A screw was attached to the side of the frame in order to adjust the lateral position of the entire frame. The frame carried three parallel wires with two more in an 'X' pattern crossing the centre wire and a wire at right angles to the three parallel wires. Ramsden's micrometer used a very similar setup in that he moved a frame with parallel sides joined with circular segments past fixed wires in an 'X' pattern. The screw, of only 0.104in diameter (≈102 TPI) was divided into 100 divisions. Backlash was controlled by a coil spring housed in a cylinder opposite the screw. The design is very compact and must be considered to have been one of Ramsden's earliest attempts at miniature micrometer design. Between the device on LeMonnier's transit instrument and Ramsden's small filar micrometer, we can begin to see the origins of the collimating arrangements common on 19^{th} c surveying instruments.

3.3.6.6 Herschel's micrometers:

A number of micrometers are extant (SML-28,29 (Fig.3.3.25), ROG-1,2 among others) which are attributed to or are known to have belonged to William Herschel. They are associated with eyepiece sets belonging to him and are of the same materials and general appearance. The primary characteristic of the screws of these micrometers is the very small diameter relative to others of the period. The threads are poorly cut and one has the distinct impression that they were made with screw plates. Dates are unknown for these, but deducing from several bits of information, probably date from ca.1775-85[1]. It may be further speculated that these were made by Alexander Herschel, William's brother[2]. Lubbock (1933, e.g. pp.118-9) includes a number of letters from William which indicate that Alexander was still making parts for William after he moved to Datchet. Of course, it may be assumed that Alexander was assisting prior to William's move, but living close at hand in Bath there would not have been need for written communication. Bennett (1976, p.84) also notes that Alexander played an important role in the mechanical achievements of William's telescopes. He was in part responsible for the mounting of the 20ft telescope of 1783 which was to become William's favorite and the one with which he did most of his important work. The large 10ft telescope mirror was cast by Alexander in his home (in Bath) in the first half of 1799 so the relationship was lengthy, and indeed Caroline, William's younger sister, acknowledged that she and Alexander were merely 'William's tools'.

Steavenson (1924/5, p.210) provides "A Peep into Herschel's Workshop" and states:

> But, when we come to enquire more closely into the technical details of his optical work (such as the methods used by him in grinding and polishing mirrors,....., and the exact optical and mechanical construction adopted by him for his eyepieces and micrometers), it is by no means easy to obtain much definite information from any published sources. No doubt this is partly due to the fact that Herschel himself was not a little reticent in regard to these matters, so far as actual publication was concerned. We must remember that these things were to him in the nature of trade secrets.

Some details may be gleaned from the Herschel manuscripts in the Royal Astronomical Society. But on the micrometers Steavenson also states (1924/5, p.215):

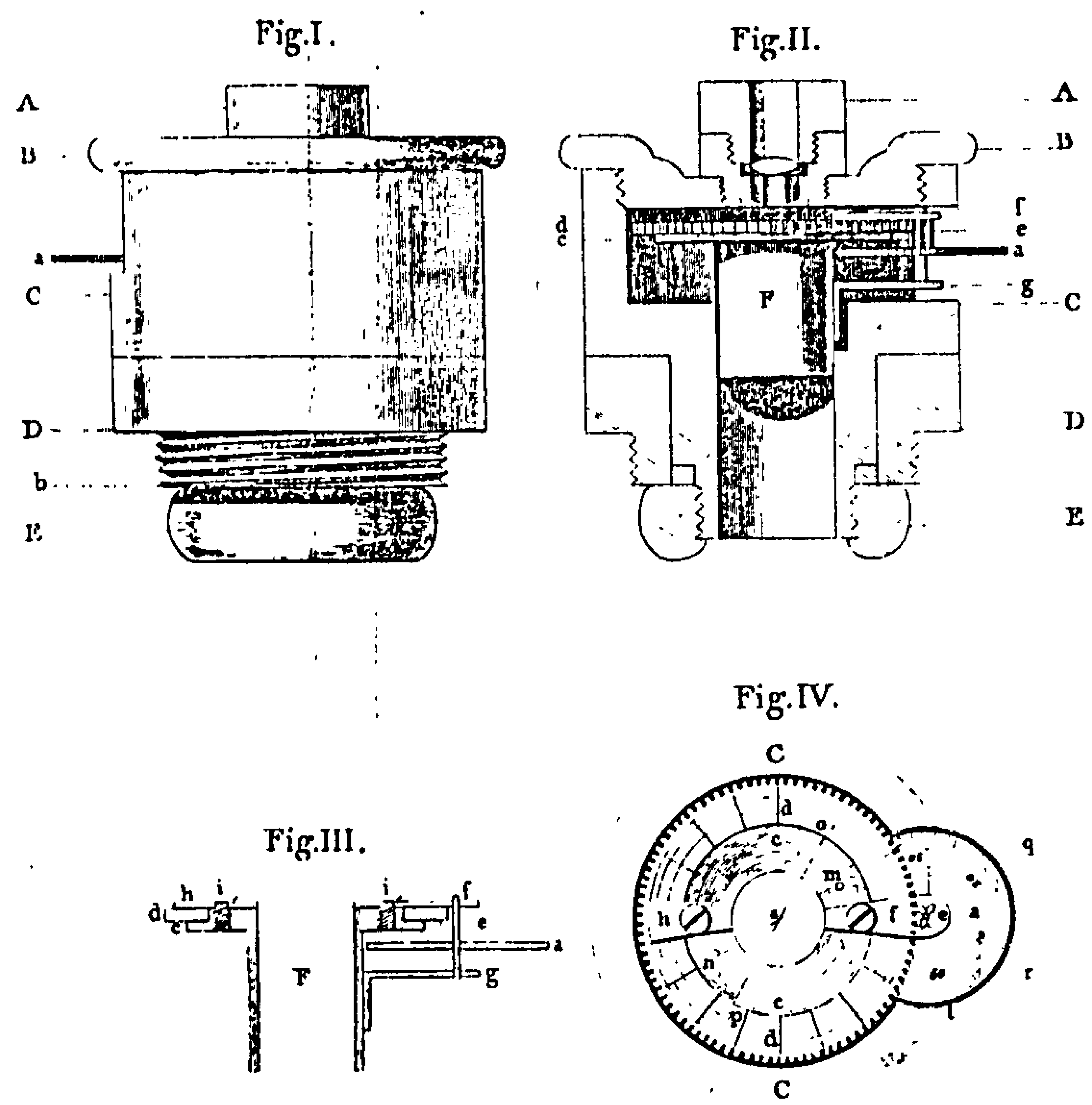
> There are 48 of these (i.e. eyepieces) in a complete condition, and about half a dozen more in various finders and micrometers. Some are in brass and others in wooden mounts, these being probably the work of Herschel's brother Alexander, who appears to have done much of the purely mechanical work for the telescopes made at Slough. The lathe which was used is preserved in good condition, and is actually still in working order (ill. in Steavenson: fig. 12 facing p.221).

This lathe is a wood turning lathe and unsuitable for screw making of the size used in the micrometers.

---

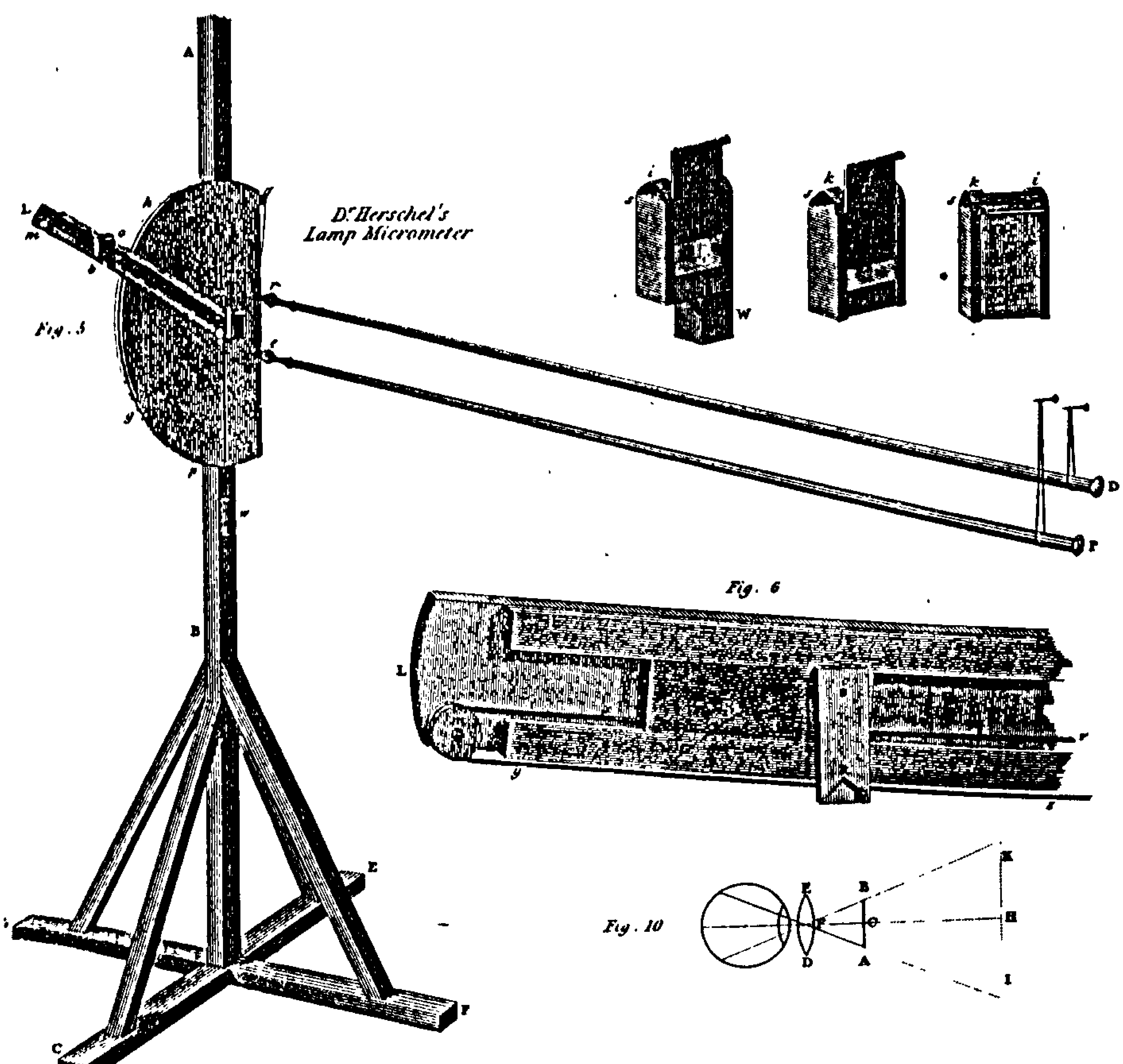
[1] William himself noted that he was experimenting with the designs for a number of micrometers and his correspondence with Alexander Aubert of 9 Jan 1782 suggests that Aubert was able to help solve the problem he had with coarse wires for his filar micrometers since Aubert sent him some 'fine silver wire' (see Lubbock 1933: 102-4).

[2] Alexander was the second oldest son, William the third oldest son and fourth oldest of the family.



3.3.26a Herschel's position angle micrometer (1781) which was made by Nairne and illustrated as Nairne's by Rees (1819).

3.3.26b Herschel's lamp micrometer. The long arms were 10ft in length.



Only two of Herschel's designs for micrometers were published--his position angle micrometer and his lamp micrometer (Fig. 3.3.26a/b)--both of which were used in his double star work to obtain position angles and separations for double stars. The description of the first micrometer was published by Herschel (1781, pp.500-1 and pl.XXVI); it was intended only to determine position angles and with it Herschel became the first astronomer to regularly measure position angle. Two wires were viewed with one being rotated by a small index dial or thumb dial which transmitted the rotational motion through gears. In 1785 Herschel mentioned this as the micrometer he used to make measurements for his Catalogue of Double Stars (Herschel: 1785, p.40) and there also stated that his instrument had been made by Nairne and Blunt. Thus we can see the attribution made with this micrometer by Rees (1819) in his plates on micrometers; the design was Herschel's though executed by Nairne. In a letter of 1782, Herschel also stated with respect to this micrometer: "Tell Alex. I have got a micrometer made by Mr Nairne for my Cross-wire. I have had a great deal of trouble to make them do it well, and have been no less than ten or a dozen times backwards and forwards 2 or three miles to look after it; the last time I saw it there were still 4 capital blunders in it but I am determined not to say that it is to my liking till it really is so" (Lubbock: 1933, p.118-9). This not only explains Herschel's relationship with those contractors making his instruments but suggests also the way designers worked with their machinists to perfect an instrument. Hooke had gone through much the same process with Tompion with some of his inventions.[1]

In 1782 William was apparently frustrated by his filar micrometers in two aspects: the quality of the screws was not to his liking, and faint stars were hidden by the wires thus not permitting accurate measurements. Herschel has provided a unique description of the errors encountered with his filar micrometers; considering his stature as an observer and that this was almost the height of filar micrometers' importance as an observational tool, his criticisms are quoted in full (1782, p.164/5).

> The next imperfection, which is none of the smallest, is that every micrometer that has hitherto been in use requires either a screw or a divided bar and pinion to measure the distance of the wires or divided image. Those who are acquainted with works of this kind are but too sensible how difficult it is to have screws that shall be perfectly equal in every thread or revolution of each thread; or pinions and bars that shall be so evenly divided as perfectly to be depended upon in every leaf and tooth to perhaps the two, three, or four thousandth part of an inch; and yet, on account of the small scale of those micrometers, these quantities are of the greatest consequence; an error of a single thousandth part introducing in most instruments a mistake of several seconds. The last and greatest imperfection of all is, that these wire micrometers require a pretty strong light in the field of view and when I had double stars to measure, one of which was very obscure, I was obliged to be content with less light than is necessary to make the wires perfectly distinct;

---

1 See Robinson and Adams (1935) for some of Hooke's descriptions of his dealings with Tompion.

> and several stars on this account could not be measured at all, though otherwise not too close for the micrometer.

His contrivance to overcome these flaws was his lamp micrometer illustrated in Fig. 3.3.26b. It was placed 10 feet in front of the telescope with lamps in two small housings with pinholes. The semicircular board was moveable vertically according to the height of the stars being observed while the position angle and separation were controlled by the long handles PD. These were controlled by Herschel as he observed--one eye at the telescope and one eye observing the lamp micrometer and adjusted until the lamps' separation and position angle corresponded with the double stars. This micrometer was used for pairs where the separation was greater than could be measured with the above position angle micrometer.

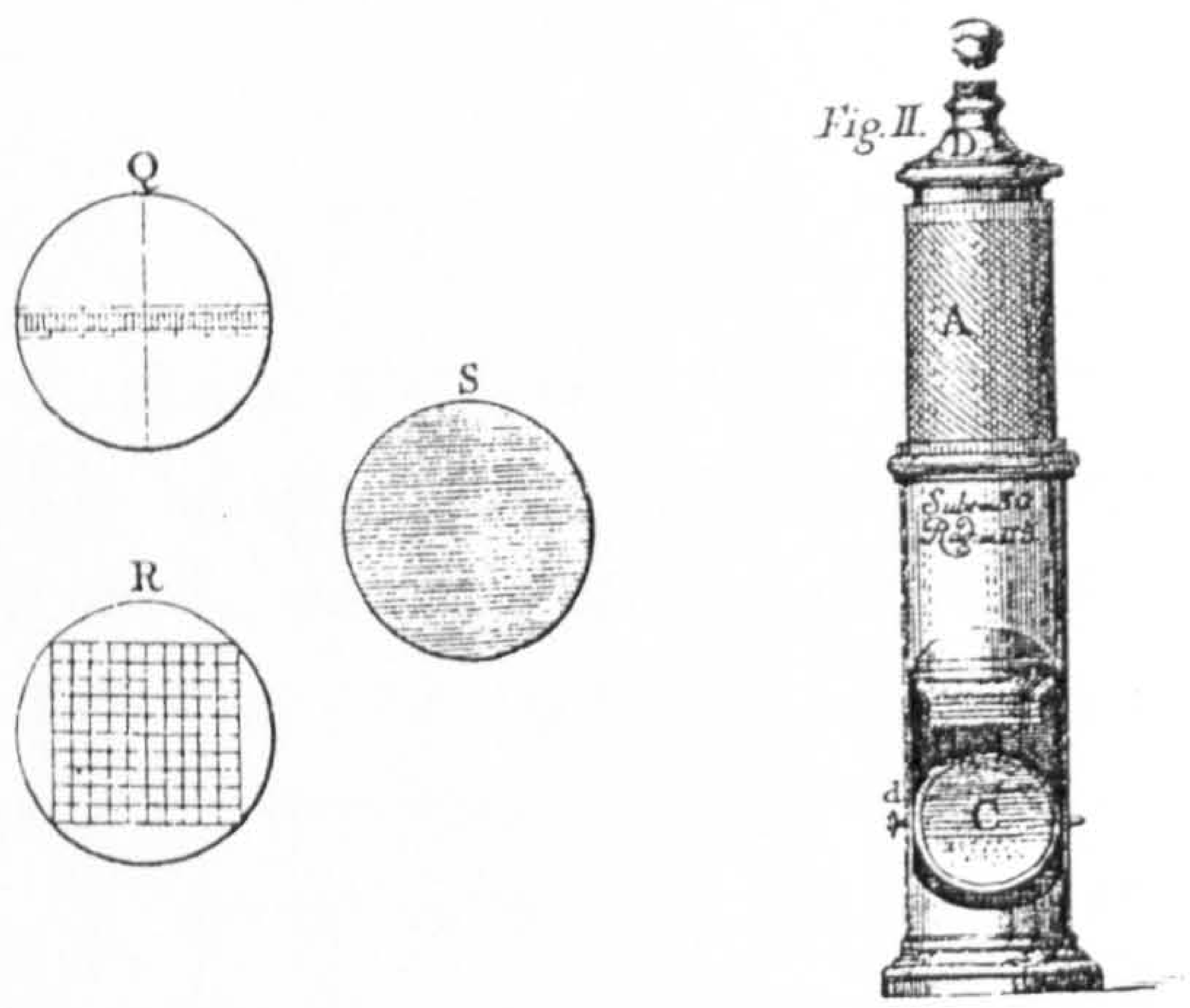
Somewhat related was the binocular micrometer invented ca.1820 by Thomas Jones. This consisted of a tube to screw (q.v. Pearson: 1822 II, f.5/6) into the telescope's eyepiece adaptor and which carried the tube for an eyepiece and another which carried either a glass grid micrometer or a spider's line micrometer. The separation could be adjusted in the same manner as modern binoculars. To observe, one viewed the object through the telescope with one eye while comparing the image with the grid or line micrometer with the other eye. In essence this was similar to Herschel's lamp micrometer except that the comparator was now moved to a position very close to the eye. Its advantages were that faint stars were not obstructed by the grid lines or spiders web and secondly a variety of magnifications could be used to alter the scale size although, of course, the magnification of each eyepiece had to be accurately known so that the value of the screw could be determined for each eyepiece.

3.3.7 Optical micrometers:

Optical micrometers are those micrometers which rely upon a 'glass' element of some form, e.g. a flat piece of glass ruled with lines, a crystal of particular shape, etc. Among the earliest were those of Balthasar mentioned in §3.3.1 and Martin in §3.5. The heliometers of Rochon and Flamsteed do not fall within the terms of this research.

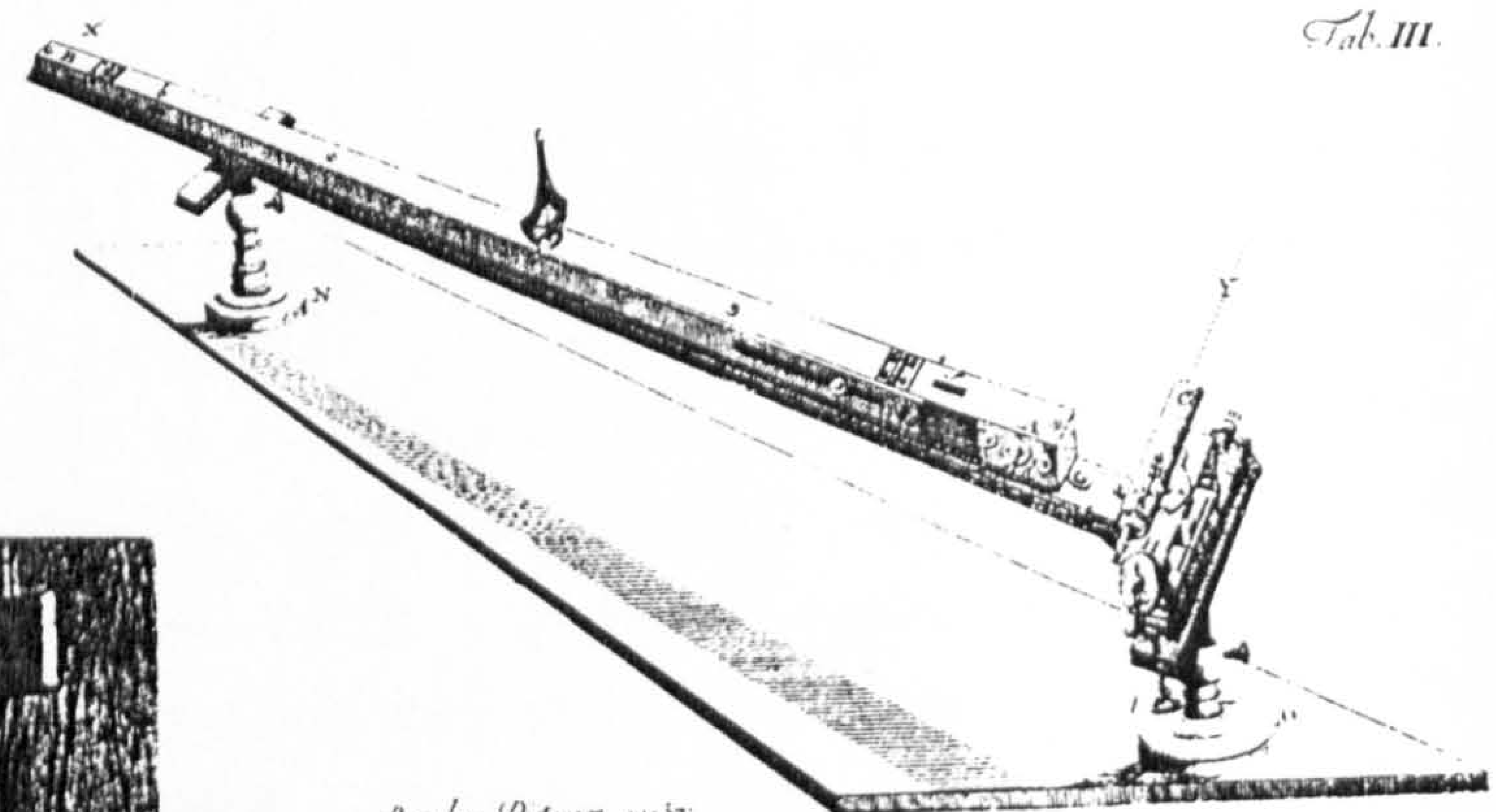
3.3.7.1 Brander's Grid Micrometers:

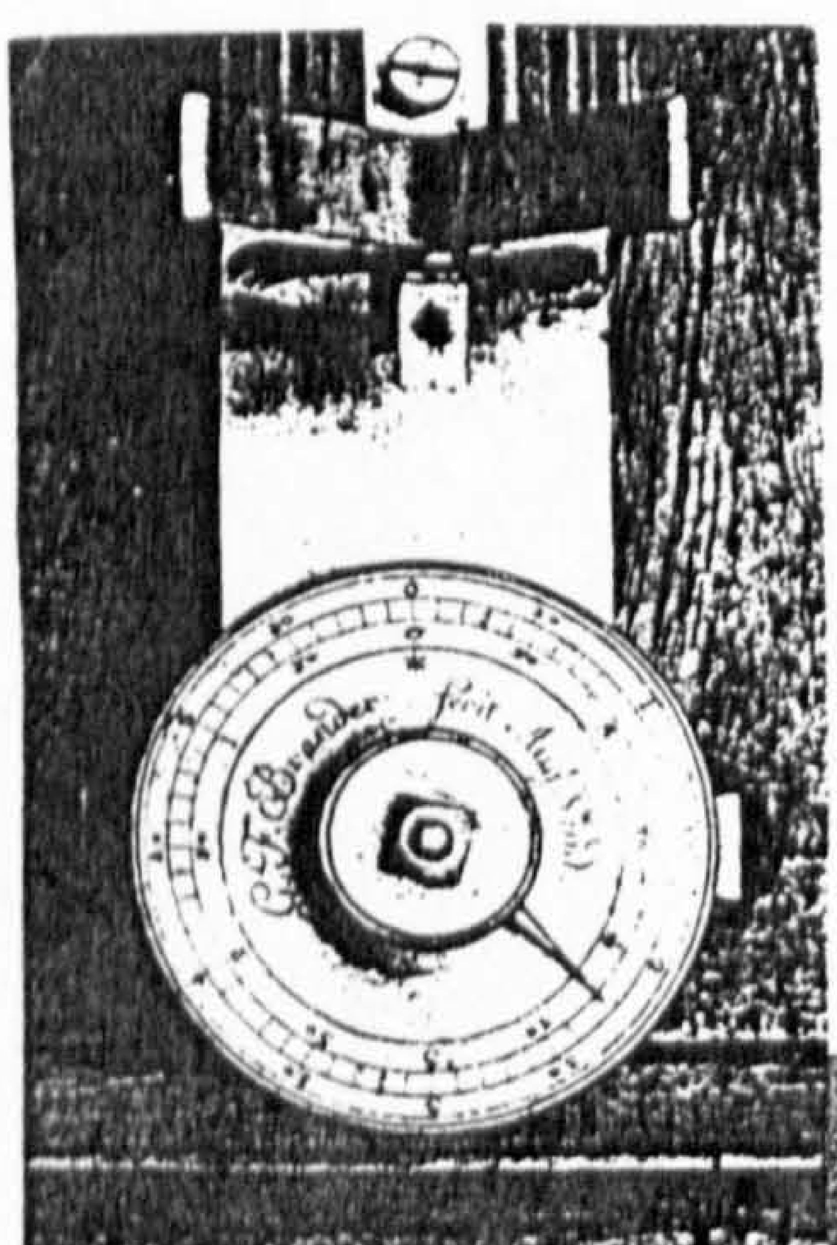
The glass micrometers of Brander are probably those for which he is best known. A large number of instruments by Brander contain a glass grid micrometer with the glass discs engraved with a variety of patterns. Some are quite finely graduated and could only have been made with a ruling engine. The patterns ranged from simple cross, to 3 parallel lines cut by 3 others perpendicular to them to the rhomboidal pattern of Bradley, to a 4th pattern which appears



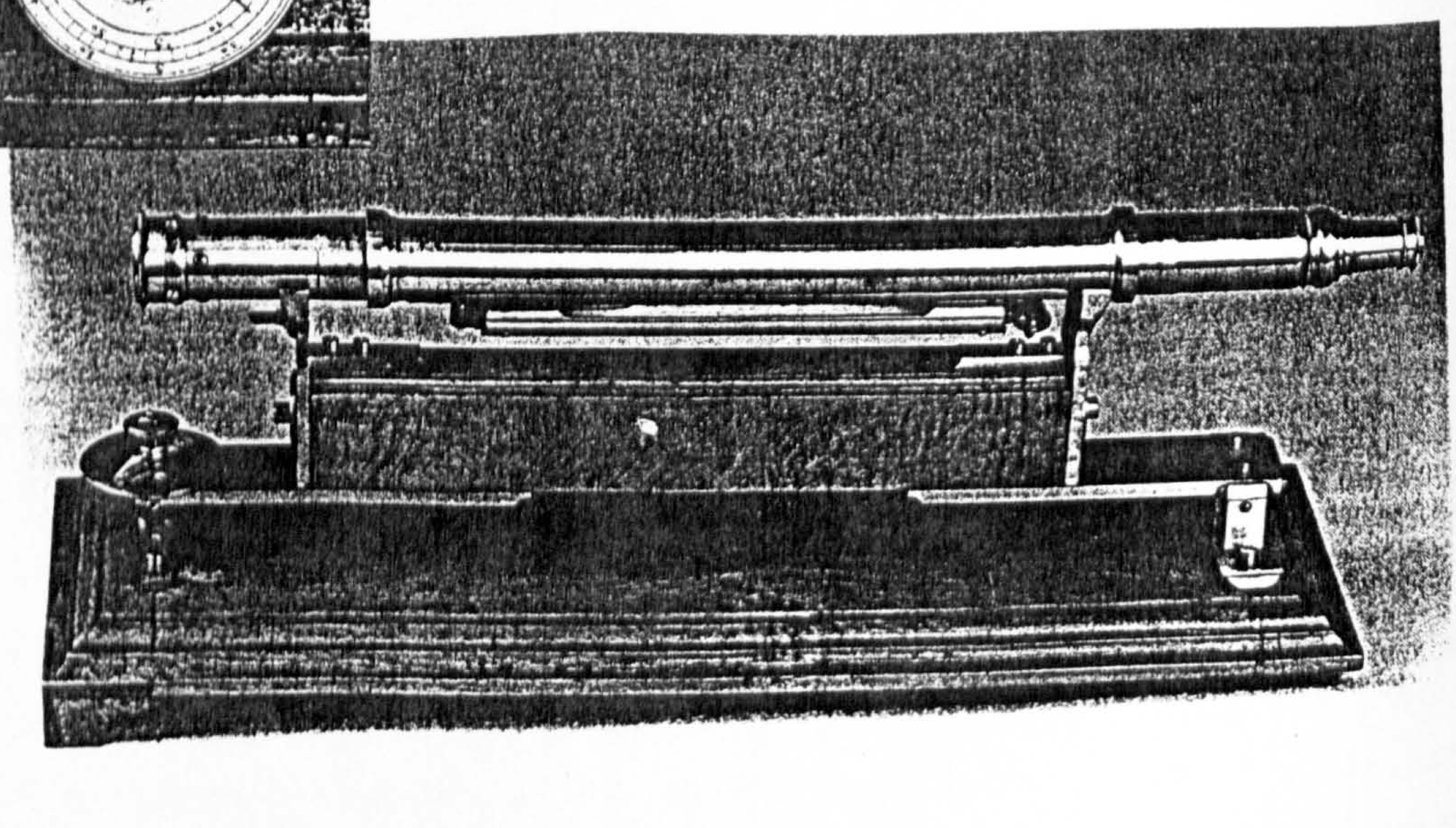
3.3.28a Brander's distance measurer (ca.1750).

3.3.28b Brander's 'rangefinder' with micrometer on the base of the telescope.





3.3.28c Brander's level with micrometer for adjustment of the telescope's elevation (ca.1780).



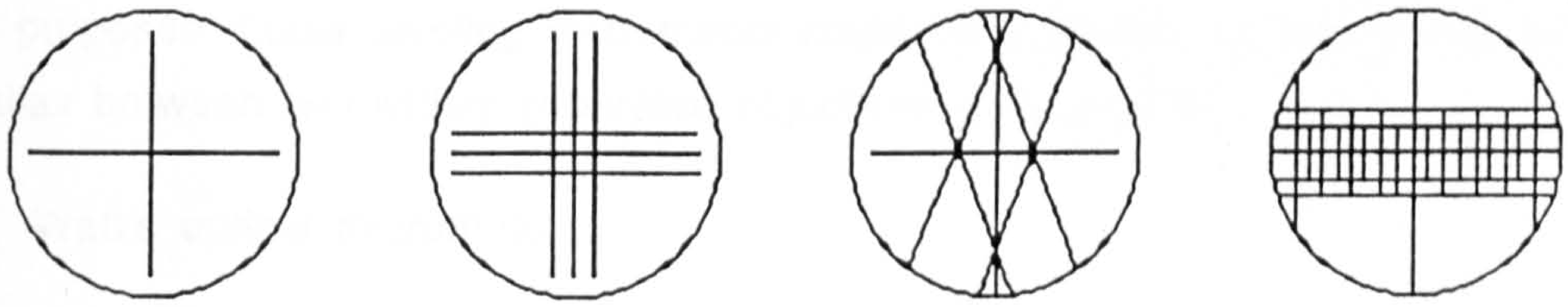


Fig. 3.3.27 Patterns of grid lines used by Brander

as the last of the above patterns. The spacing of the lines on this micrometer is somewhat variable as illustrated by Fig. 4.2.3 which was measured from the 5X and 10X reproductions in Brachner (1983, p.313). The lines are about 0.02mm wide and under a magnification of 500X and 2000X show striations from the cutting tool which was undoubtedly an unfinished diamond.[1] The striations are 0.002-0.004 mm wide and 0.001-0.002mm deep (p.310-1). These glass micrometers were often made in sets and were used on telescopes, microscopes, level instruments and distance finders (q.v. pp.169-178, 226, 234-5). The ruling engines designed and used by Brander do not appear to have survived, but a description and illustrations may be found in the **Katalog** (p.349ff., ill. p.379-382) and are discussed here in Chapter 6.

In 1764 Brander published **Polymetroscopium Dioptricum** wherein he illustrated a simple distance measuring instrument which employed his engraved glass discs. The first design (Fig. 3.3.28a) was similar to Benjamin Martin's drum micrometer, but other models were developed that appear more similar to the telescopes of tachymeters. The principle of Brander's distance measurer was to measure the angular size of an object or target of known size. The latter instruments had a scale engraved on the tube for direct conversion of scale size to distance; since users might not have been trained in mathematics this direct measurement instrument was useful. An application, also for surveying purposes, was the leveling instruments of which several are illustrated in the **Katalog**. Brander described and illustrated this instrument in 1769 in **Beschreibung der ganz neu verfertigten Libel oder Nivelirwage.** These consisted of a telescope tube mounted, with a bubble level, on a pivoted frame. This frame was adjusted by a micrometer screw while a glass grid micrometer in the field of view was used to orientate the telescope. The disc was engraved with a scale of ±>40 divisions and was placed in the focal plane to assist in the leveling. The vertical range was small and the mounting not very suitable for surveyors. Actual measurements for difference in level were made with the micrometer screw. However, an example (Fig. 3.3.28b), not unlike a 19th c transit, shows that his design evolved to make it more functional and was clearly intended for surveyors. Brander also illustrated how, for

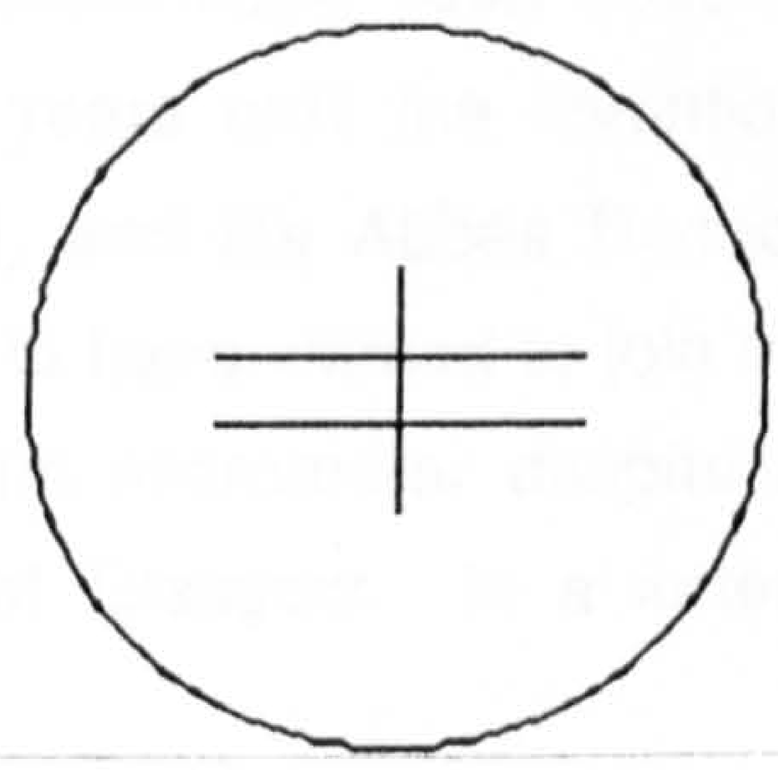
---

1 The idea of using a diamond was apparently old since LaHire (1717 I, p.57-67) had the idea of using a diamond to engrave concentric circles on glass and Balthasar (1710) had previously advocated the use of diamonds for preparing a grid micrometer.

military purposes, these leveling instruments could be combined to determine distance by parallax between two widely separated objectives (Fig. 3.3.28c).

3.3.7.2 Watt's optical micrometers:

James Watt invented several micrometers about this time in addition to the one already discussed, and although technically they do not fall within the limits of this thesis, they were precursors of important and relevant innovations. In a letter to Thomas Bolton (with whom Watt was later to become a partner in the construction of his steam engines) dated 5 Feb. 1769 Watt mentions a micrometer with lines engraved on a piece of glass in the form below (Muirhead: 1854, v.1, p.cxxxii-iii and also 1858, p.229-30).



3.3.29 Form of the fiducials in Watt's tachymeter.

This was essentially the first tachymeter, since it was intended for surveying purposes. It was to be used with a graduated rod with lines marked to correspond with the separation of the lines on the glass calibrated for specific distances separated by 1 chain intervals. The parallel lines on the glass were ≈0.01in apart. The calibration of the rod was done empirically; the telescope was refocused for the nearer distances and the lines on the rod thus took this adjustment into consideration. According to Strang (1926, p.685-6) the accuracy of Watt's tacheometer was about one percent.

This adjustment for distance suggested another use for the micrometer to Watt. His new range-finder had a long focus object-glass mounted in a moveable tube before a field lens and eye lens. The calibration was also carried out empirically and consisted of marking the position of the object-glass tube for specific distances. As with the former instrument this was limited to determining the distances of nearby objects and was useful for Watt's surveying work. The principal is that employed by LaHire (1701 p.119ff.). Muirhead (1854, vol.1, p.cxxxix and 1858, p.232-3) says Römer had suggested the use of a moveable object-glass for a micrometer, but no further account has been found. LaHire found this micrometer to be somewhat inconvenient and dropped it in favour of the one he described in 1717 which has already been discussed. Brewster patented his 'pancratic' telescope in 1815 which worked on this principal although the aging Watt was the only one who recalled his earlier application.

A third Watt micrometer, also designed ca.1771, employed a prism of 1-2° angle (Muirhead: 1854, vol.1, p.cxxxv and 1858, p.231-2). The prism was cut laterally half way along the wedge and mounted with a hinge. Two images were formed with the separation dependent on the angle

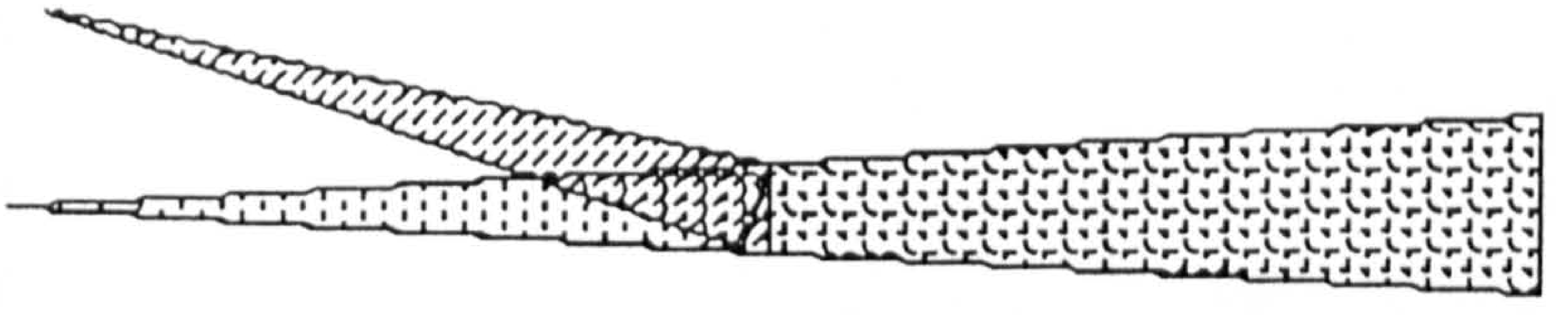
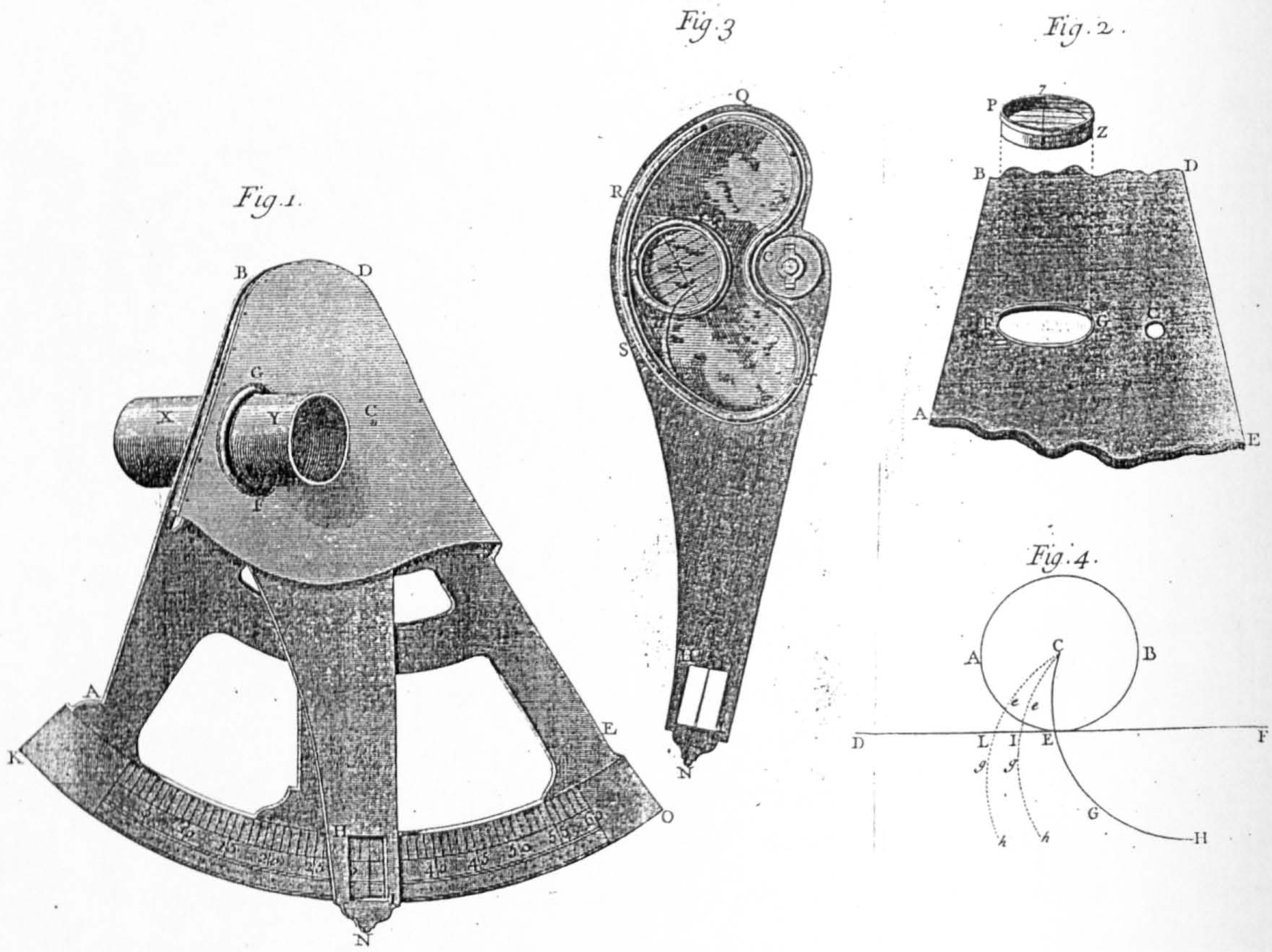


Fig.3.3.30 Watt's prism micrometer.

between the two halves since the thicker piece refracted the image more. An index attached to the rotating segment was in the form of a divided sector of a circle. In principal this type of micrometer could have been used for astronomical work, but this application had to wait for a few years until the invention of the prism micrometers of Rev. Nevil Maskelyne (Aug. 1776), and the Abbés Rochon (Jan./Feb. 1777), Boscovich and Fontana. Watt does not seem to have wanted to join the fray during the debate on the priority of the invention of the prism micrometer despite being encouraged to do so by his correspondent, Dr. W. Irvine of Glasgow. In a letter dated 2 July 1778 the latter writes:

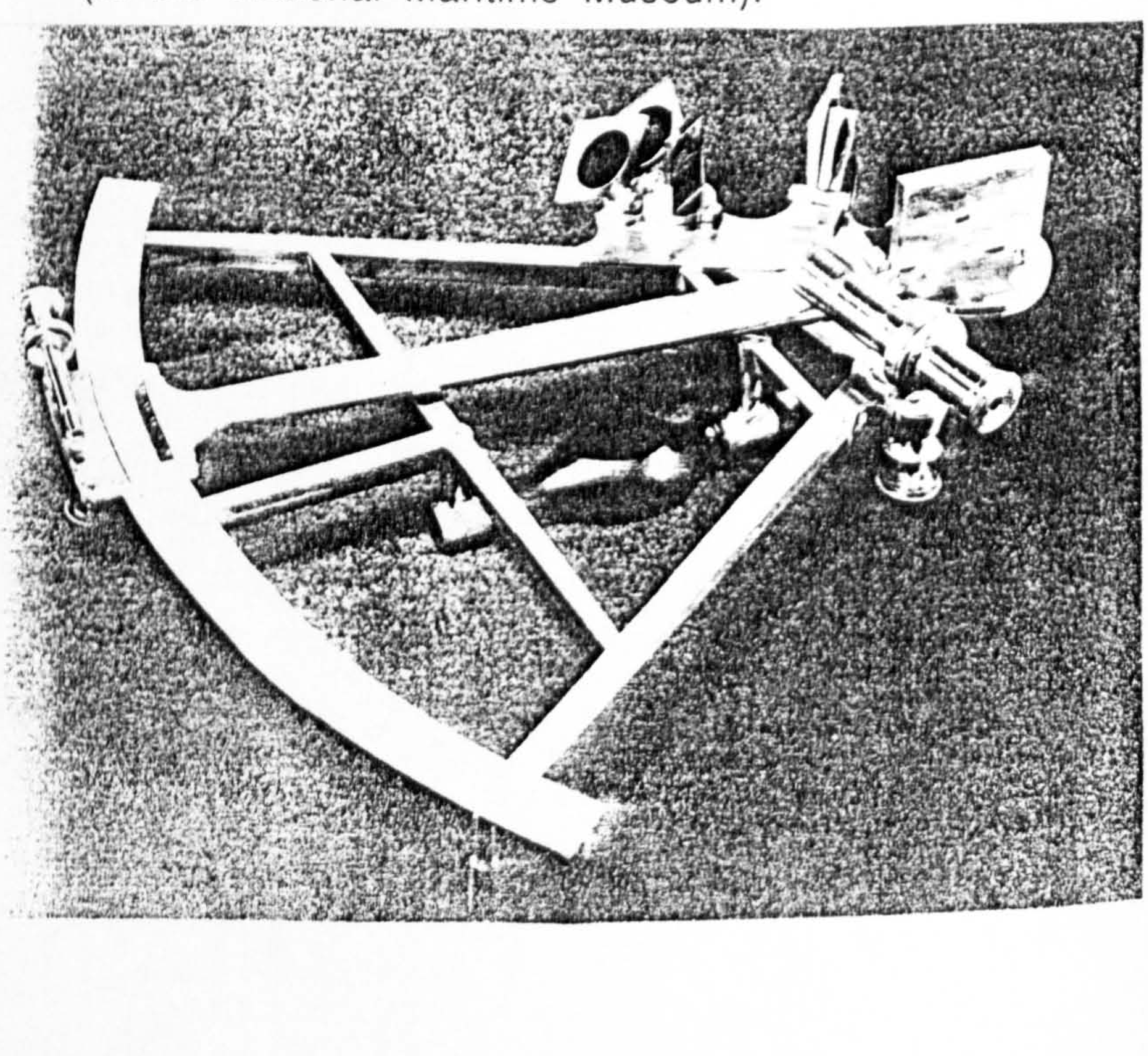
> Pray have you seen the last volume of the (Philosophical) Transactions? You must surely know that it contains the description of a certain micrometer, that shall be nameless, made by one J. Watt six or eight years ago, and which has been in Macfarlane's Observatory in Glasgow for several years past. Would you not think it proper that the said J. Watt should claim this discovery? And as the authors of these papers in the Transactions have brought witnesses, he might bring Dr. Reid, Dr. Wilson, Pat. Wilson, G. Hamilton, &c., who are ready and willing to attest the same, and who are surely as respectable as Pat. (sic) Dollond and -- Aubert (i.e. Alexander); and to make the whole still stronger, I should imagine you could have no objection to join in the attestation. You perhaps despise such unprofitable inventions; but to others they will procure fame, and perhaps fortune. (Muirhead: 1854, vol.2, 108)

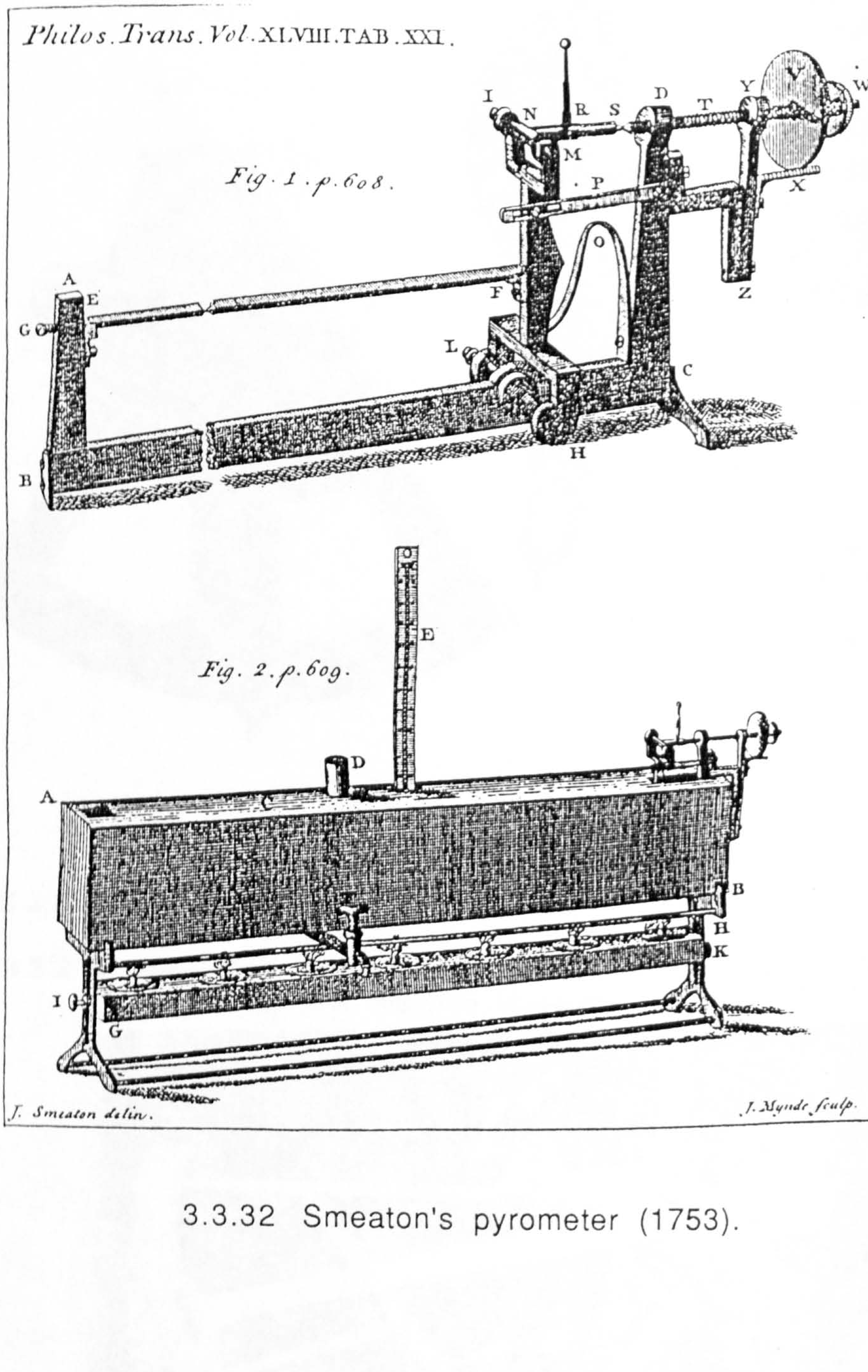
Since nothing, save personal letters, has been found mentioning Watt's micrometers prior to his description in the memoirs published (ca.1820) late in his life, we can assume that he did not wish to attest to his invention. Indeed, he was busy advocating the benefits of his more important technical achievement--the steam engine. This type of micrometer perhaps does not deserve the attention devoted here as it does not employ a precision screw, but it was the starting point for a new class of optical micrometer which was to be important in the 19th c, i.e. the divided object glass micrometer and dynameter.



3.3.31a Fouchy's octant (1723) with curved fiducial.

3.3.31b Ramsden's sextant (ca.1783) with screw micrometer (in the National Maritime Museum).





3.3.32 Smeaton's pyrometer (1753).

3.3.8 Miscellaneous micrometers and instruments employing micrometers:
3.3.8.1 Micrometers on nautical instruments:

About 1723 Grandjean de Fouchy (1735, p.45-7) described a small octant (Fig. 3.3.31a) with sub-division of the 60° scale effected by a curved cursor over which the alidade moved, with a frame of wires or engraved glass disc sub-divided to 10'. The intersection of the curved cursor and lines on the disc gave the reading to 1' or 2' by estimation. The difficulty would have been in drawing the curved cursor. This instrument predated the reflecting octants of Hadley and Godfrey, though not that of Newton. A micrometer did not appear on a nautical sextant (or similar instrument) until ca.1783 when Ramsden used a drum micrometer (Fig. 3.3.31b) on one which is preserved in the National Maritime Museum (NMM#S.27, ser. no.727), Greenwich (Stimson: 1976, p.128). Late in the 19th c, the drum micrometer was again adopted, being much easier to read. Tests of a couple of World War II vintage sextants by Husun[1] and Hughes revealed that the accuracy was not appreciably better. The pivots of these two specimens are scored from misuse; this is probably responsible for much of the error.

3.3.8.2 Smeaton's pyrometer:

Hindley's success in employing a screw for measuring purposes also prompted the invention of Smeaton's pyrometer (Fig.3.3.32). This was described to the Royal Society in 1754 (pp. 598-609)[2]. According to Smeaton (p.601n), George Graham made a device to measure the expansion of metal bars by determining the change in length between a fixed stop and a micrometer screw. This was in James Short's shop after Graham's death and was accurate (Smeaton's estimate) to 3-4,000^{ths} of an inch. However, Smeaton's micrometer was much more sophisticated and incorporated several innovations. Not only did it incorporate a flame to heat water in a cistern into which the rods were submerged, but it also used a system of levers to amplify the expansion. It is interesting to note that this paper may well have been the origin of the term 'feeler' (though its meaning has evolved) since this is the word Smeaton coined to describe the piece against which the micrometer screw bore. The instrument was made of brass as it had one of the smallest coefficients of expansion of metals then used.[3] The crucial dimensions are as follows (Smeaton, p.605):

	Inches
From the fulcrum of the lever to the feeler	5.875
From the fulcrum to the plane of contact	2.895
Length of 70 threads of the screw	2.455 (≈28.51 TPI)
Divisions in the circumference of the index-plate	100

---

1 Trade mark for H. Hughes & Son.

2 See also *Gentleman's Magazine*, **25** (1755), p.400-1.

3 Presumably, brass was used in favour of iron, which has a smaller coefficient of expansion, because of its ease of machining and freedom from rusting.

These dimensions give "10/57863 inch" for one division. Smeaton stated that repeated reading to 1/4 division was possible thereby giving an error of less than 1/20,000th of an inch (a printer's error gives it as '1/2345 part of an inch'). As the micrometer screw was the only piece requiring any degree of precision, Smeaton went to considerable pains to verify its accuracy. It is worth quoting the technique and its introduction (p.605-7).

> There is one thing still remains to be spoke of, and that is, the verification of the micrometer-screw which is the only part of this instrument that requires exactness in the execution; and how difficult these are to make, perfectly good, as is well known to every person of experience in these matters; that is that the threads of the screw may not be equidistant, in different places, but that the threads shall be equally inclin'd to the axis in every part of the circumference.
>
> As nearly the same part of the screw is made use of in these experiments, the latter circumstance is what principally needs enquiry. For this purpose, let a thin slip of steel, or other metal, be prepar'd, whose thickness is about 1/8 of the distance of the threads: Let the edges of this thin plate be cut into such a shape, as exactly to fit into the fix'd notch in which one end of the bar is laid: Let a screw pass thro' the standard of brass, on which that notch is supported, in such a manner, that the end of the bar to be measured that is farthest from the lever, may take its bearing against the point (or rather the small hemispherical end) of this screw: Let one of the brass bars, us'd in the other experiments, be apply'd to the instrument, and a measure be taken; then let the thin plate be put in between the end of the bar and the point of the screw last mention'd, and again take the measure; but first observe, that the plate is put down to the notch, so that the same place of the plate may always agree with the point of the screw, and, consequently, no error may arise from a different thickness in different places of the plate: Observe also, that the whole comes to a true bearing; then advance the same screw till the micrometer-screw is push'd backward 1/4 of a revolution; again repeat the measure with and without the thin plate; again advance the former screw, so as to make that of the micrometer recede another quarter of a turn, and repeat the measures with and without the thin plate. This method being pursu'd as far as necessary, it is evident, that, the thickness of the plate being always the same, if the difference of measures, taken with and without it, are not always the same in the different parts of a revolution of the micrometer-screw, that this screw is not equiangular; but from the differences of the measures corresponding to the thickness of the same plate, in the different parts of a revolution, the errors thereof may be nearly assign'd. For greater certainty in this examination, lest the heat of the observer's body should affect the bar or instrument during the observation, let the whole be immerg'd in the cistern of water, which ought to stand a sufficient time before the observation is begun, to acquire the same temper as the air, which also ought to be in a settled state.
>
> In this manner I examin'd such threads of this screw as were made use of in the following experiments, but did not find any material errors.

This technique is important on two counts; first it introduces a technique expanded and refined by Johannson in the 20th c--i.e. that of using slip gauges to measure precise distances and secondly, it would appear that this is the first attempt at defining a calibration curve for a micrometer screw.

The whole apparatus suffered a number of problems, e.g. the inevitable expansion of the whole mechanism as the water in the cistern warmed up. However, Smeaton used a number of schemes to minimize other problems. A curved leaf spring kept the measured rod in constant contact with the bearing points. The two nuts holding the micrometer screw were mounted in such a way that one was mounted on a bracket deliberately sprung out so that it "endeavours to pull the screw backwards from the hole at D (see Fig. 3.3.28); of consequence keeps the micrometer-screw constantly bearing against its threads the same way, and thereby renders the motion thereof perfectly steady and gentle" (p.609). All in all, this pyrometer and his astronomical micrometer amply demonstrate the mechanical genius of Smeaton. Had he continued in instrument making, one suspects that he would have matched or outshone even the great Ramsden.

3.4 19th Century Micrometers:

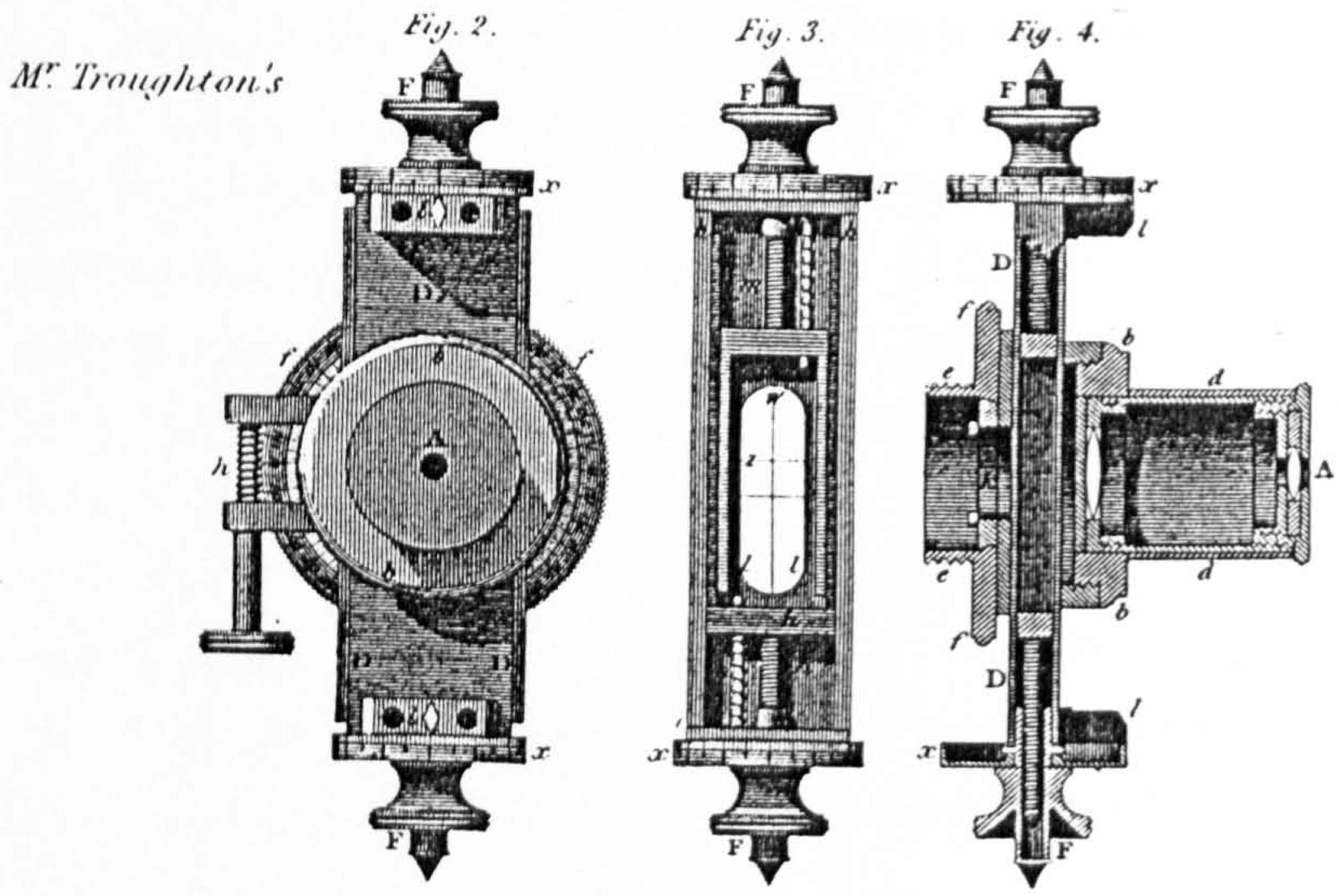
The problem of stellar parallax remained one of the most important problems to which micrometers were directed in the early 19th c. There were many false discoveries of parallax--which for the nearest stars, Alpha and Proxima Centauri, amounts to just 0.75". This suggests the lower limit of instruments in use until the 1830's was ≥0.5", although measurement of parallax requires that the instrument as a whole must remain stable for several months. Some instruments were able to exceed this accuracy for individual measures, but the objective was to consistently reach this precision over a long period so as to make this crucial determination. At Greenwich (1816) two 10ft telescopes with micrometers were erected on stone piers specifically for the purpose of measuring the positions of alpha Aquilae and alpha Cygni, after Brinkley in Ireland had detected several stars he thought exhibited parallax. Not long after this, trouble erupted over the quality of the observations being made at Greenwich. Steven Lee, assistant secretary to the Royal Society, complained that Pond's work was faulty and noted 8 problems with the 1821 observations; one problem was the fact that the wires in the transit instrument (7 in all by this time) were not equally spaced. The following year Lee also noted that the scale microscopes appeared to have been poorly adjusted and some micrometer screws were defective (Forbes: 1975, p.167-8).

3.4.1 Astronomical Micrometers:

Two references stand out as sources of information on 19th c micrometers: William Pearson's **A Treatise on Practical Astronomy** (1824,1829) and David Gill's entry on the micrometer for the 9th edition of the **Encyclopedia Britannica** (1878)[1] This latter article was reprinted and updated in the acclaimed 11th edition of the **Encyclopedia Britannica** (1910/1); it also became the basis of a number of later

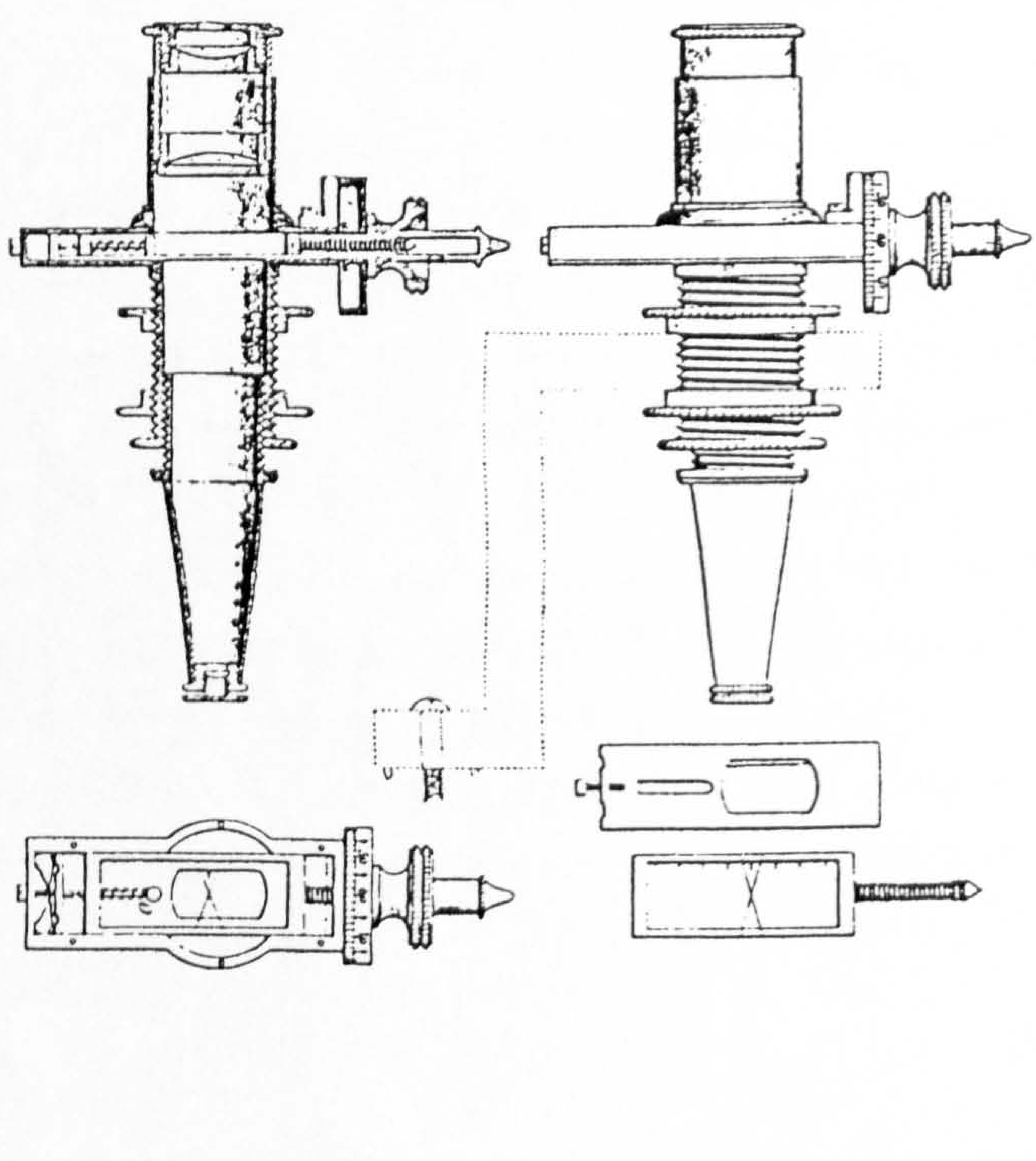
---

[1] Gill's contribution to the **Encyclopedia Britannica**, "Micrometer", appears in vol. 16 which carries a publication date of 1878. However, Gill's article makes reference to a paper by Stone in the Dec. 1879 number of the *Memoirs of the RAS.*



3.4.1a Troughton's design for a bifilar micrometer (late 1790's) and used, with modifications, through most of the 19th c.

3.4.1b Troughton's scale micrometer (ca.1820).



encyclopedia entries (e.g. **Universal Ilustrada** in Spanish). By the 19th c, the forms of filar micrometer could be classified by a few recognizable categories[1]. Gill (p.243) provided the following divisions:

> Type A: Micrometers in which there are two webs, each movable by a fine screw with a divided head. This is the usual English form of filar micrometer.
> Type B: Micrometers by which one web is movable by means of a fine screw with a divided head, and the other by means of a screw without a divided head. The latter screw, in ordinary use, is only employed to change the coincidence reading of the two webs, for eliminating the errors of the micrometer screw. This is the ordinary German form of micrometer as originally made by Fraunhofer and since by Merz, and employed by the Struves and other principal Continental astronomers down to the present day.
> Type C: A similar type of micrometer to B, except that the coincidence point cannot be changed--there being no second screw to alter the position of the fixed web.
> Type D: A micrometer somewhat similar in general construction to form B, except that, in addition to means of changing the zero point, there is a screw head by which a fine movement can be given to the whole micrometer box, in the direction of the axis of the micrometer screw. This is the modern form of micrometer as constructed by Repsold.
> Type E: Micrometers fitted with two eye-pieces for measuring angles larger than the field of view of an ordinary eyepiece.

3.4.1.1 Troughton's biflar micrometer (and some subsequent improvements):

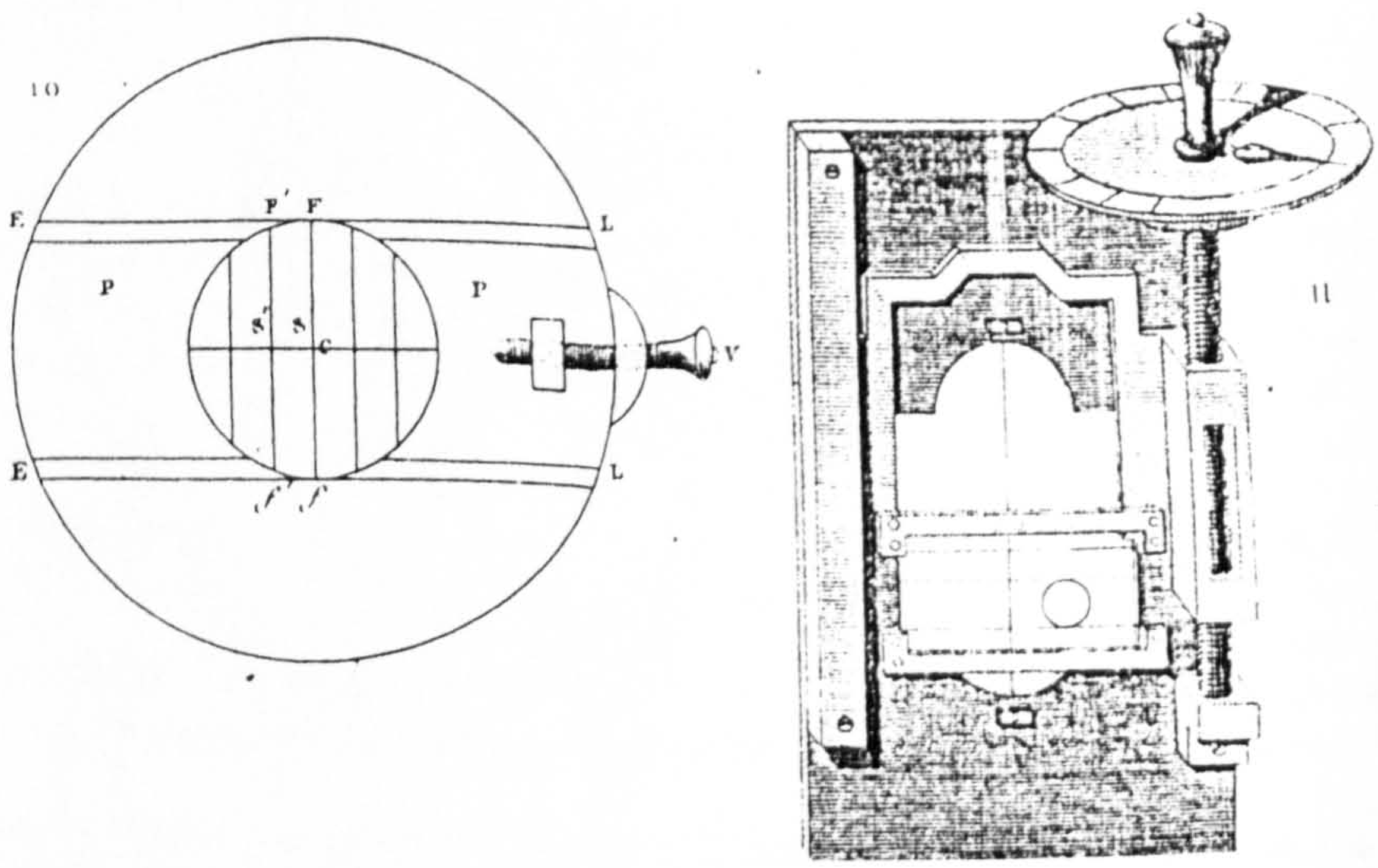
The Troughton form of micrometer (Gill's type A)(Fig. 3.4.1) was developed by Edward Troughton in the late 1790's and with modifications and improvements was made by him and other English makers--e.g. Dollond, Simms, etc.--for most of the 19th c[2] and was a considerable advance over those illustrated by Biot (1803,1810)(Fig. 3.4.2). Brewster (1813, p.7) stated that Troughton's biflar micrometer was the first to be able to measure 1". The two screws moved a frame with web[3] and each of the drums was normally divided into 100 divisions. The screws were rigidly attached to the frames and threaded into the knurled knob. This was not a particularly desirable solution since the length of the female screw engaged with the screw varied with every turn thereby changing the force required to turn the knob and also affecting the errors of the screw. The internal thread was usually ≈5/8in in length. This arrangement was changed about 1820 from which time the screw was part of the knob and threaded into the frame with the web or wires. This not only provided more constant force and backlash, but also permitted a greater range of separations of the threads. Forms with one screw were also

---

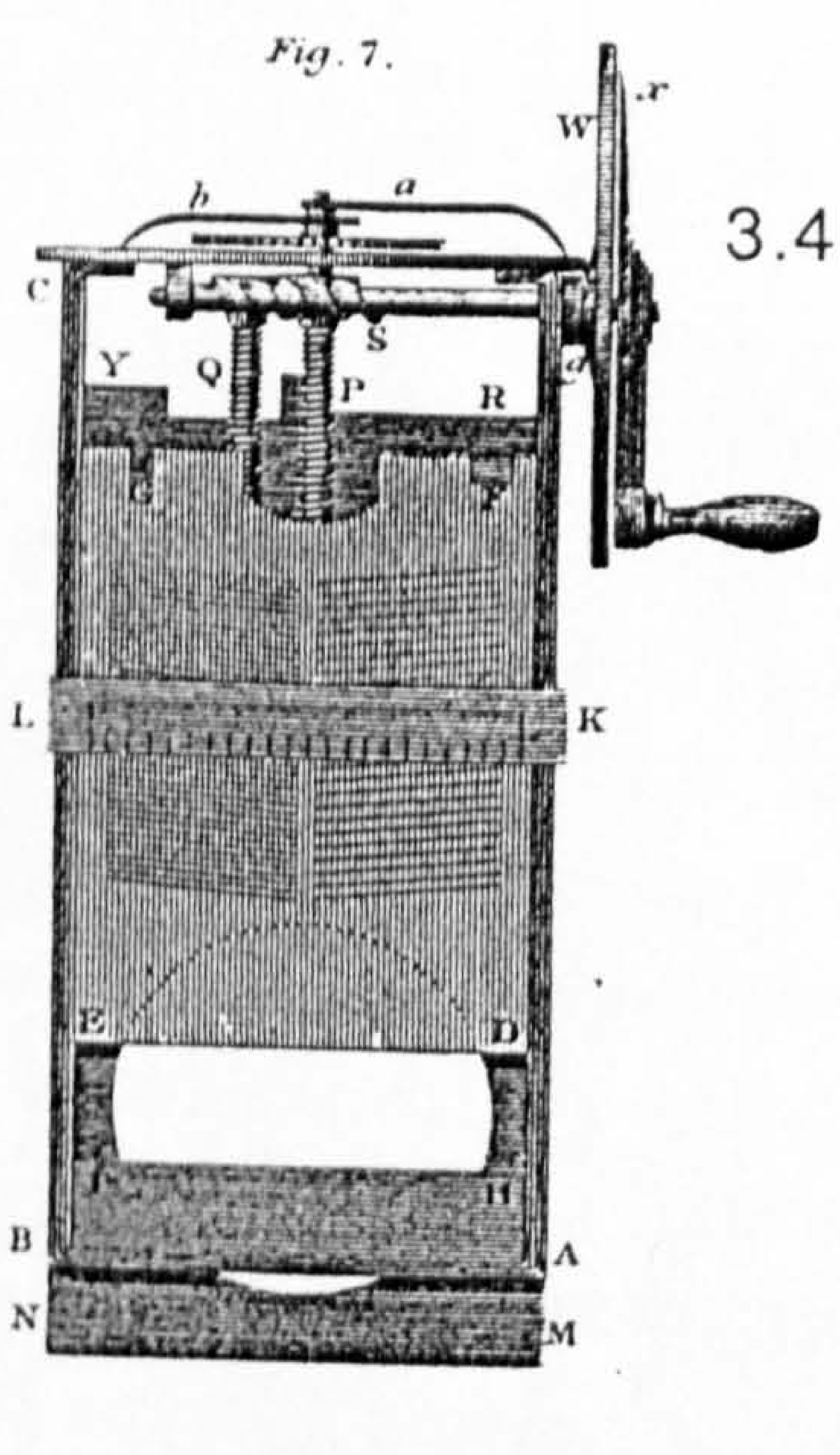
1 These categories were removed from the 11th ed.

2 Troughton used an open ended **U**-frame to carry the webs while Dollond used a closed frame. The open frame was intended to keep slight tension on the web but the better closed design gradually won favour and was still being made in the US after World War I by the J.B. Lippincott Co. (see Ball: 1922, p.172).

3 The wires of 18th c micrometers were replaced by spider's webs ca.1800-10 and micrometers with these were referred to as spider's line or Troughton's micrometers.



3.4.2a Biot's filar micrometer (1803).

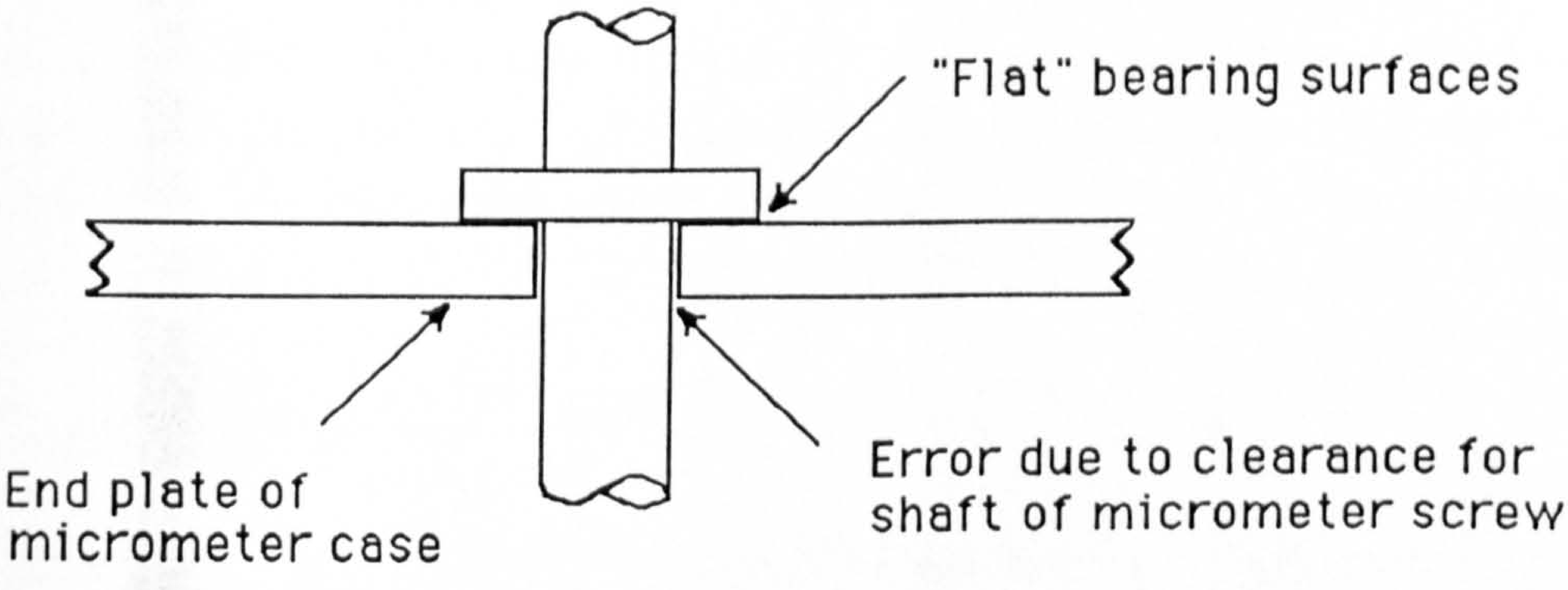


3.4.2b Biot's micrometer of 1810. The measurement was made between two plates moved in opposite directions by the screw mechanism. The scale was engraved on one plate and read off like a transversal scale.

made; these had a number of fixed webs, the choice of which depended on the telescope and the size of the object to be measured.

A feature of the Troughton micrometer was that a number of positive lenses were supplied with the micrometer in order to change the magnification to suit the particular telescope. This permitted adapting the micrometer and telescope to the object being observed to best advantage. But this required that each combination be calibrated and if a terrestrial eyepiece was used (i.e. one with two pairs of lenses with variable distance between the pairs), the combination had to be calibrated for the specific separation of the terrestrial eyepiece lens pair. For this calibration Pearson (1829, p.101) recommended the use of the summer Sun using the vertical diameter which was least affected by refraction. By the 1820's values of refraction were reasonably well determined (except for low altitudes[1]) and the value for the solar diameter was only a few seconds of arc. Once the scale of the micrometer was determined for one telescope, it could be calculated for others simply by taking the ratio of the focal lengths. One is referred to Pearson (pp.101-110) for a description of what he referred to as polymetric telescopes and micrometers.

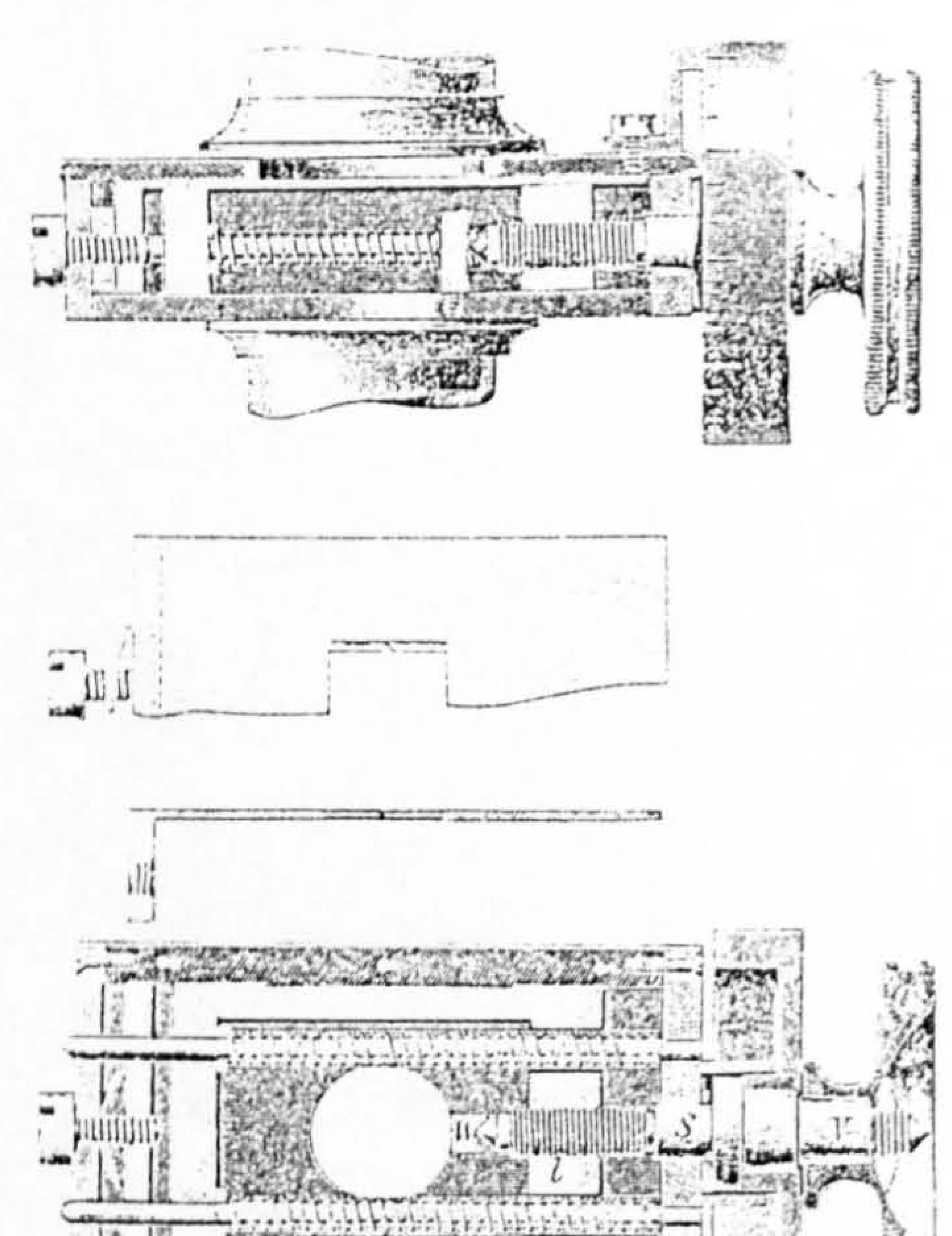
A point of some weakness in Troughton's micrometer was the bearing surface between the screw and micrometer case. Until the mid-century this was flat--or nominally so. However, an error of flatness causes a periodic error with each turn. Even if manufactured without this error, a blow to the knob--such as might occur if the micrometer fell to the floor--could cause the screw to become bent at this point thus introducing a periodic error. More than one micrometer inspected had sustained such damage with one by Bird (MHS-2) bent to the point that it could not function at all.



3.4.3a Troughton's form of bearing surface for a micrometer screw.

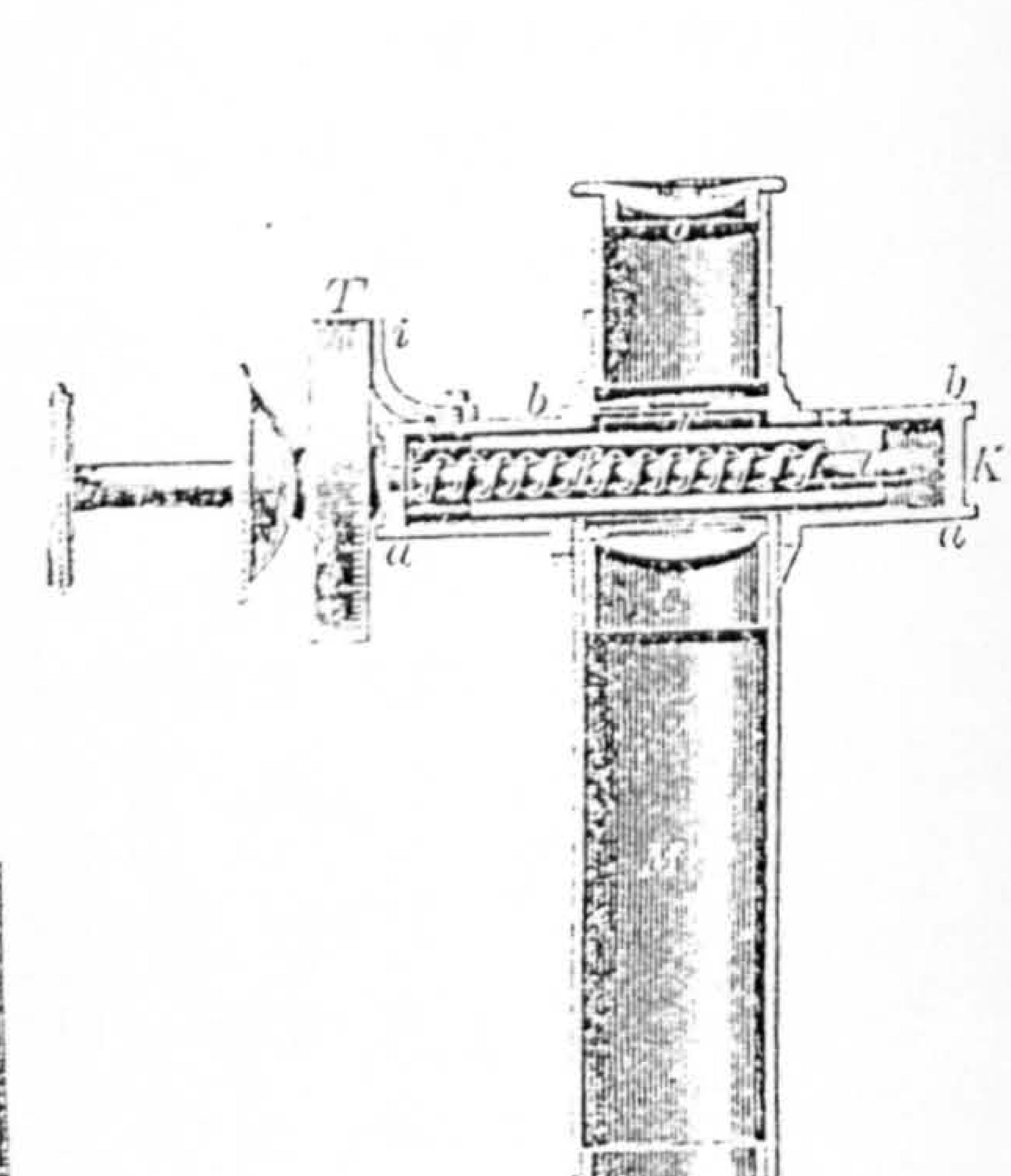
To alleviate this type of problem, Repsold introduced a bearing surface on the screw which was spherical and mated with a conical depression in the case of the micrometer.

[1] Q.v. Ivory: 1838, pp.169-229 (Bakerian Lecture).



3.4.4a Vogler's micrometer with double springs for backlash control.

3.4.4b Huneaus' micrometer with single coil spring for backlash control.



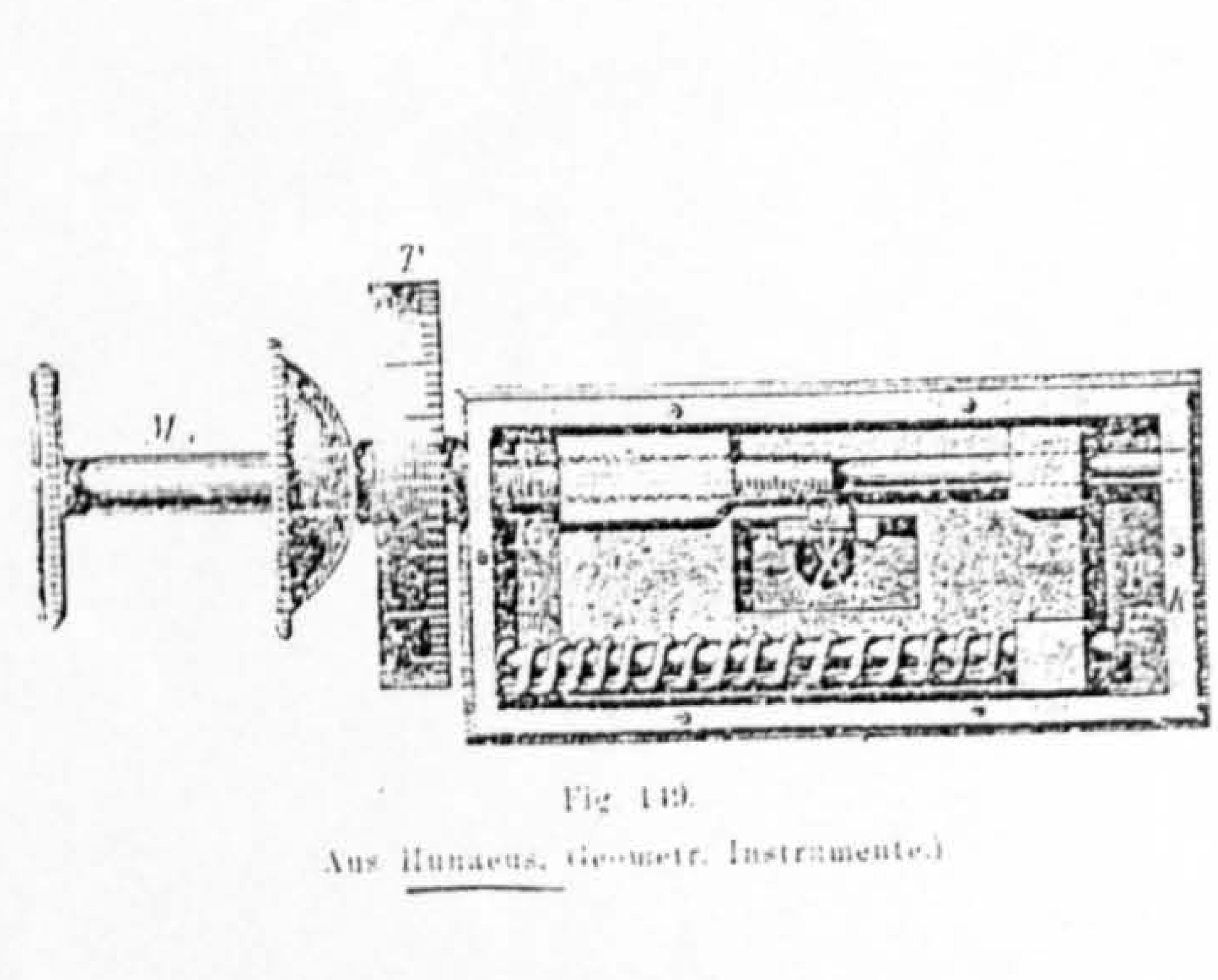


Fig. 149.

(Aus Hunaeus, Geometr. Instrumente.)

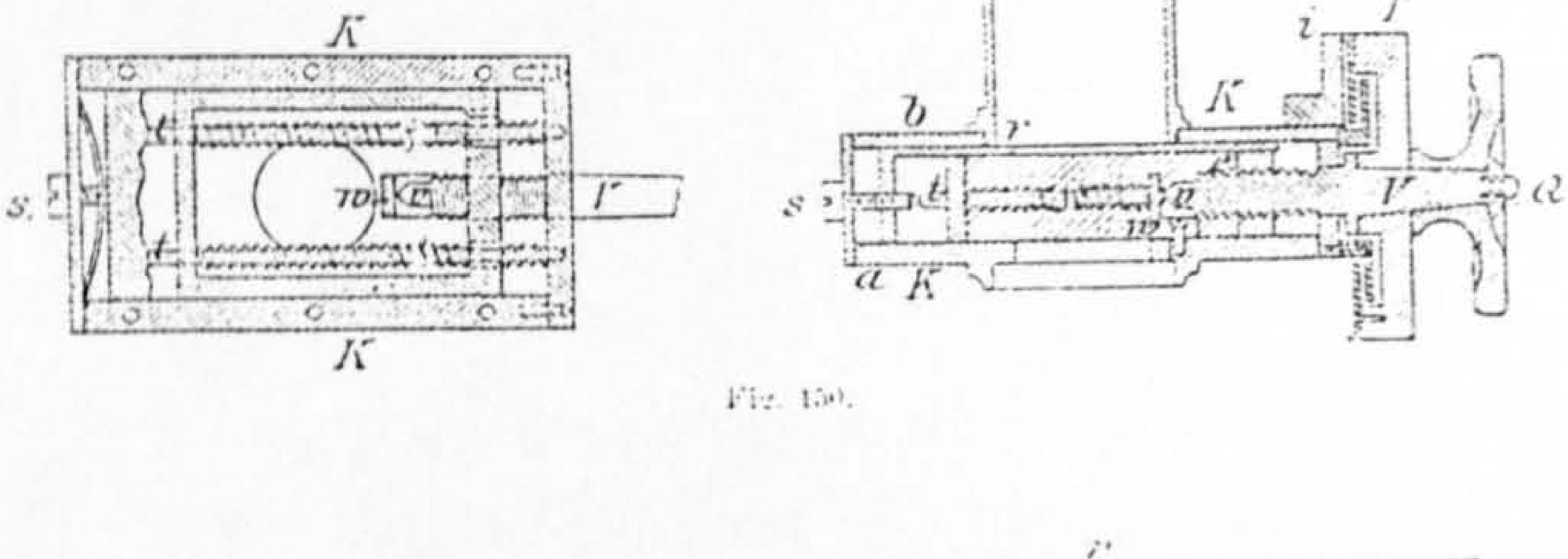


Fig. 150.

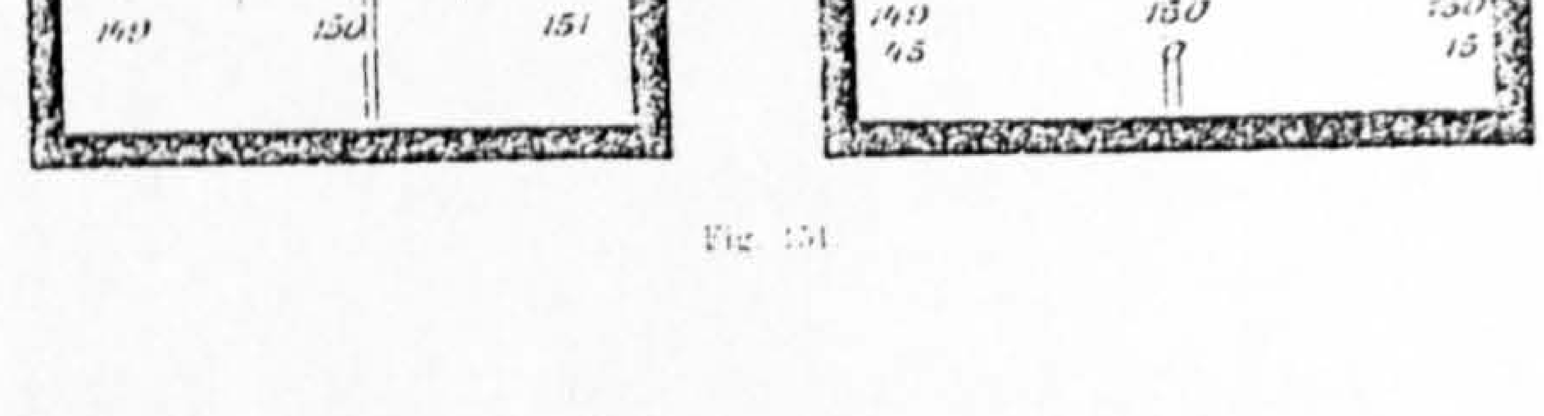
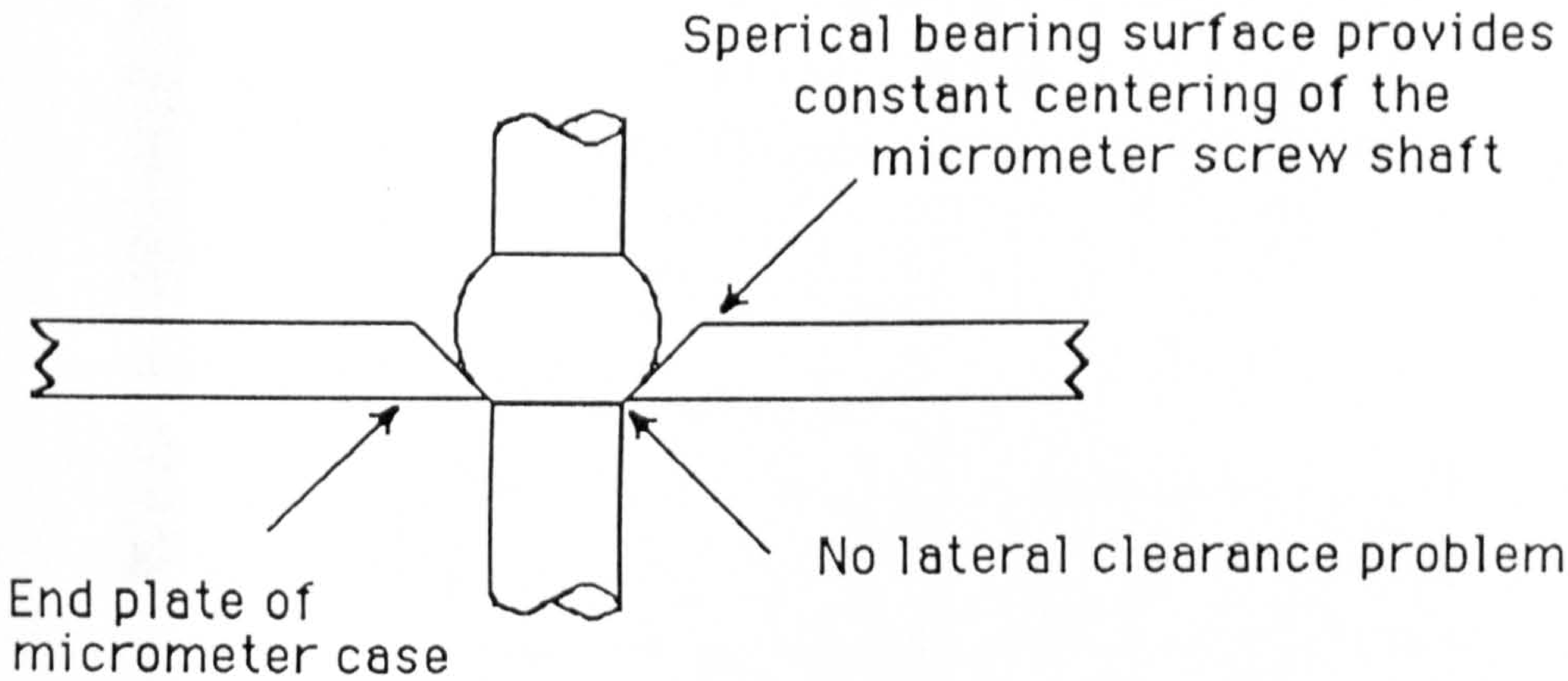


Fig. 151.

This solved the problem of parallel mating surfaces while also eliminating the error caused by the tolerance required for the screw shaft to pass through the body of the micrometer.



3.4.3b Repsold's form of bearing surface for a micrometer screw.

The backlash--or as it was referred to by astronomers, the 'loss of time'[1]--was controlled by means of a spiral spring wound around a pin attached to each frame. However, this caused the frames to twist with respect to each other causing friction and loss of parallelism of the wires. The makers Simms (Troughton's successor) and Cooke of York employed two pins and springs on each frame but French makers retained the single spring construction.[2] Grubb of Dublin further modified the backlash control because he found the varying tension objectionable. He thus adopted a scheme similar to Reichenbach's[3], i.e. the spiral spring was replaced by a flat spring incorporating a nut which forced the screw away from the nut in the frame. The tension was thus constant and could be varied by small screws and springs which were used to attach the main spring to the frame (Fig. 3.4.4a/b). To also ensure that the micrometer screw head was in constant contact with the conical bearing, Grubb attached a sprung conical bearing on the micrometer drum.

3.4.1.2 Scale micrometers in the 19th century:

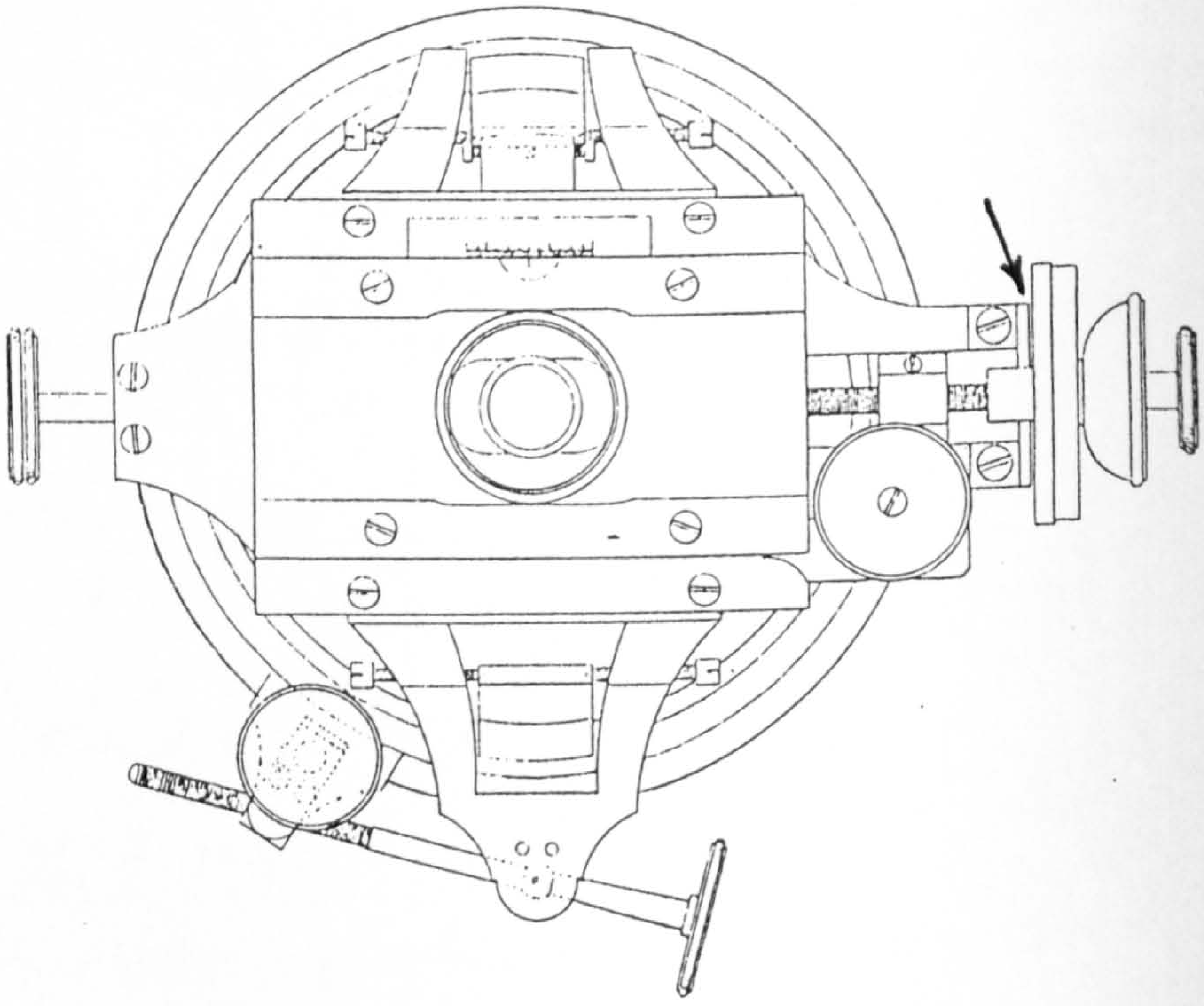
Scale micrometers (Gill's type C) were invariably single screw instruments which were mounted on reading microscopes. They were mechanically very similar in detail to biflar

---

[1] The origin of this term is fairly obvious since micrometers were often used to measure the differences of right ascension of stars and slack in the screw resulted in errors in right ascention and hence in the time.

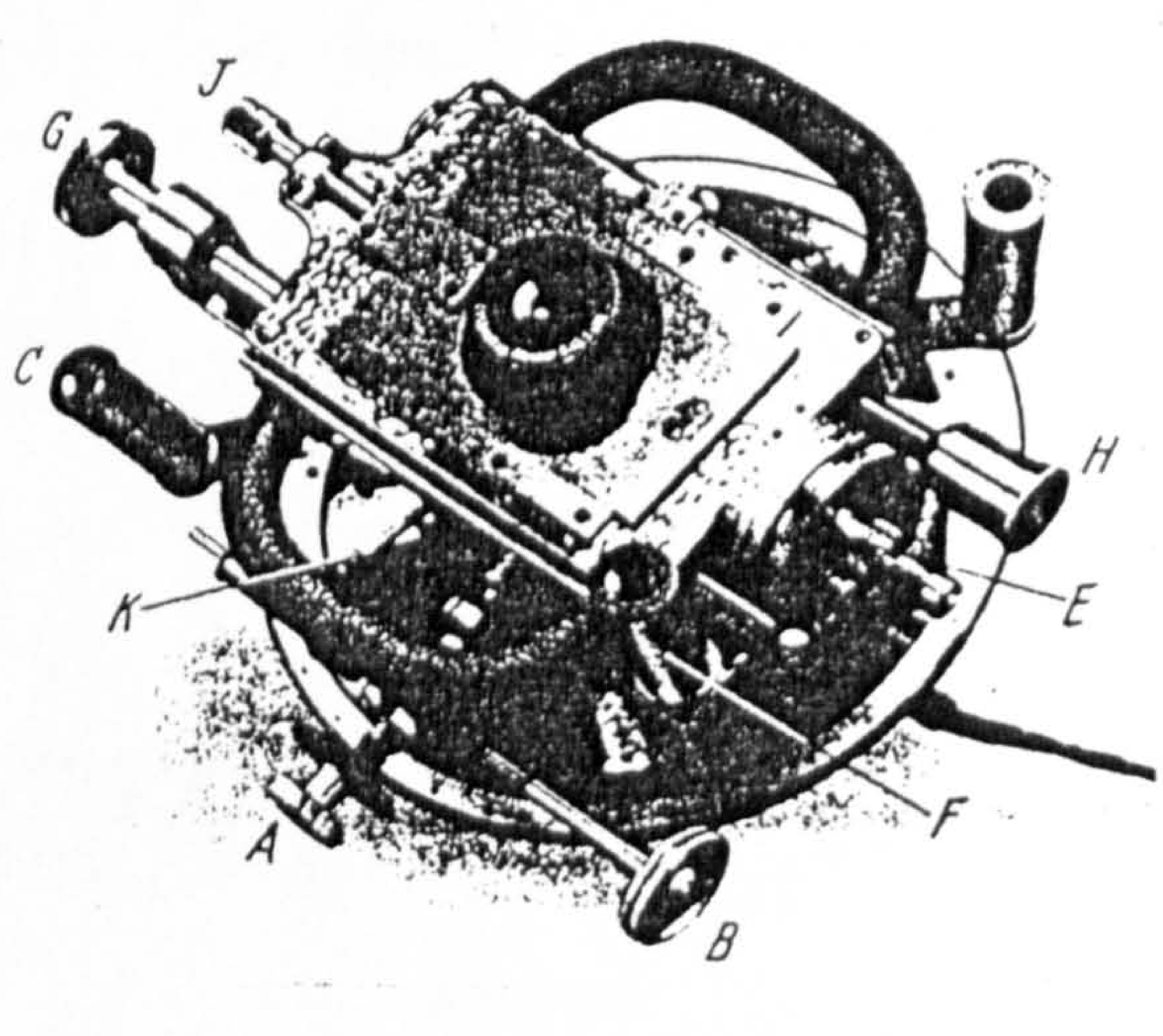
[2] German makers were also split as to which design to use. As illustrated by Carl (1867), Vogler used a double spring while Hunaeus used a single spring (see Fig. 3.4.4a/b).

[3] The micrometer of Reichenbach's repeating circle at the Paris Obs. (ca. 1811) is the earliest instrument which has been found with this type of anti-backlash spring.



3.4.5a Fraunhofer's filar micrometer (ca.1820). The arrow points to the sprung element which controls screw backlash.

3.4.5b The most advanced of Fraunhofer's micrometers and one which was the model for features found on later examples by Repsold.



micrometers by the same makers; the basic design can be traced to Troughton's biflar micrometer. The screws were generally of coarser pitch and chosen to match the divisions of the scale being measured. The chosen pitch was often 1/5th or 1/10th the length of the scale divisions[1]. From Ramsden's time, the webs were crossed and whole divisions indicated by a 'comb'. By the mid 19th c, the crossed webs were replaced by two parallel webs separated by the width of the engraved scale divisions. This feature required that the two adjacent scale divisions had to be measured at least once and preferably for every observation.

3.4.1.3 Fraunhofer's position micrometer:

The micrometer illustrated in Fig. 3.4.5a (taken from Repsold and shown at half scale) was designed by Joseph Fraunhofer (6/03/1787-7/06/1826) and would appear to have been from the early 1820's. It illustrates his well known mechanical genius though one feature which is not very desirable is the exposed micrometer screw. This is the same arrangement as on the Reichenbach micrometer found on the Paris Observatory's repeating circle (PO-3) of ca.1810. The connection is fairly obvious since Fraunhofer worked with and was a partner of Utzschneider and Reichenbach in the Munich Institute from 1806. Reichenbach had built his first dividing engine in 1796 and a second larger one in 1804. It is thus not surprising to see the Fraunhofer micrometer carring a circular scale similar to ones found on surveying instruments, complete with two verniers. This, of course, was to facilitate measuring precise position angles of double stars and represents a vast improvement over previous position angle micrometers. What is somewhat unusual, and not very desirable, are the verniers carried on pivot screws to allow them to be flipped up and to be laterally adjusted. Rotation of the micrometer head was by a fine adjustment screw similar to those commonly found on surveying instruments of a later period.

The micrometer screw itself is not illustrated with the anti-backlash spring that Reichenbach installed on the repeating circle in the Paris Observatory, though this may simply be a matter of drafting practice. Reichenbach's spring was a curved piece of steel held at the end of the fork carrying the micrometer screw.[2] Repsold's illustration shows this piece as flat but it is clear from Gill's description (1878, p.245) that this piece was also a strong spring in Fraunhofer's micrometers. Two features are worth noting in Fraunhofer's instrument. The micrometer was intended to be screwed directly onto the telescope and was one of the earliest instruments with this feature; micrometers, like

---

1 The space between scale marks, the run, had to be determined for each micrometer screw and for the distance of the microscope objective from the scale, i.e.. for the magnification.

2 A vertical circle in the Royal Observatory, Brussels, made in 1855 by Ertel, employs an eyepiece micrometer of this design. The scale micrometers on this and a companion vertical circle are of standard design and all have drums with 60 divisions.

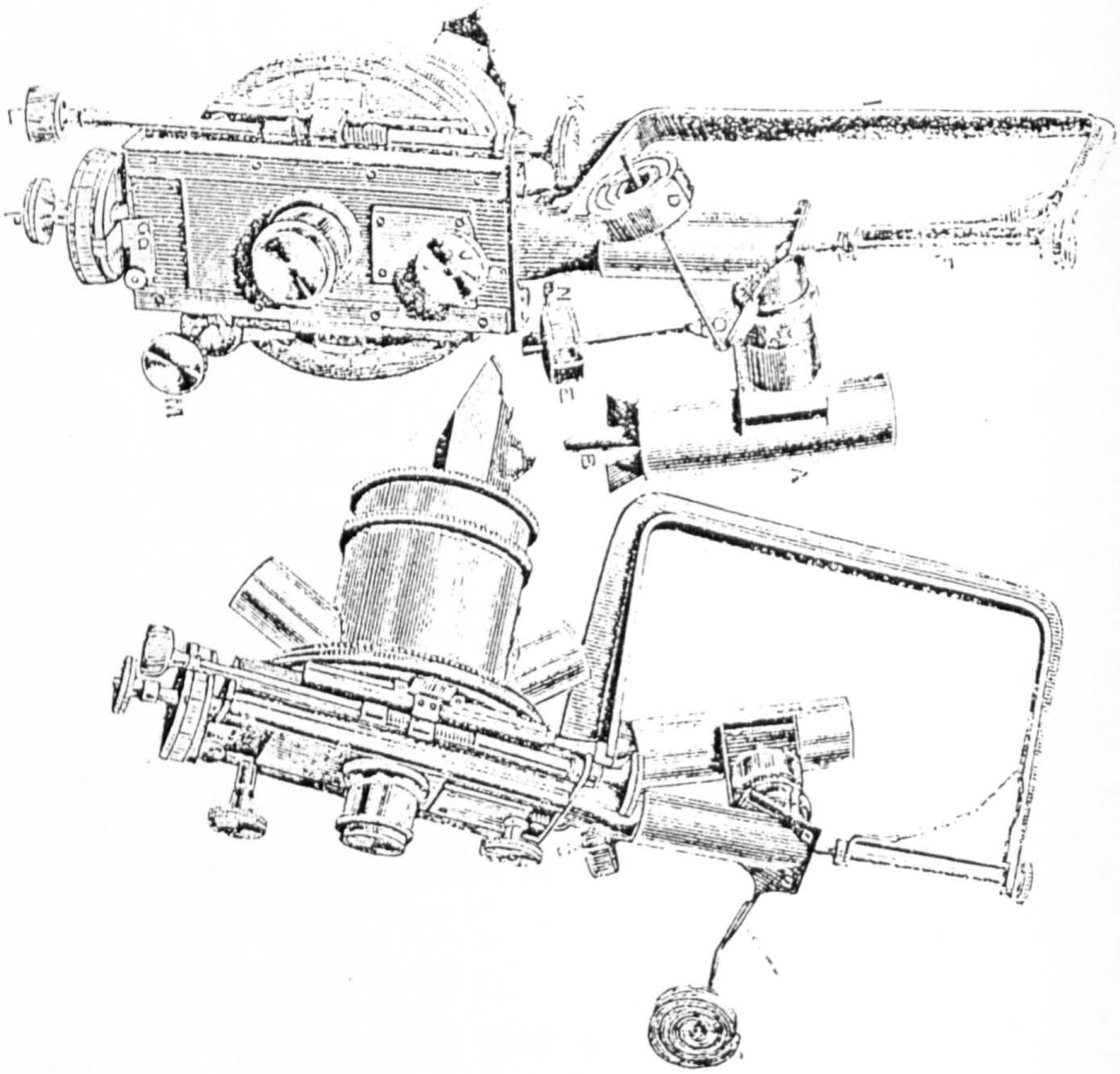
eyepieces, were normally mounted by means of a sliding tube. On his more complex filar micrometers, Fraunhofer added a screw that could be used to position one of the wires independent of the micrometer screw. This idea, although differently applied, was adopted by Repsold and became the means of eliminating errors of run in the micrometer screw thread. The basic features of Fraunhofer were copied by the German manufacturers Merz on a micrometer for the Cape Observatory and by Pistor & Martins in one made for the Dunsink Observatory. Indeed Gill noted that three-quarters of the micrometer observations made between 1825-75 had been carried out using Fraunhofer or Merz micrometers by such well known observers as the Struves, Dembowski, Secchi, Wm. and George Bond, Maclear and most continental astronomers. Thus the illustrated micrometer by Fraunhofer was the successor to the Troughton/Dollond form which continued in use through most of the 19th c in Britain. According to König (1937, p.141), Fraunhofer was also the originator of the two-coordinate position micrometer (Fig. 3.4.5b) which later reached a high degree of perfection in the micrometers of Repsold, with the latter's impersonal micrometer reflecting the pinnacle of 19th c micrometer technology.

3.4.1.4 Measuring Position Angles with Filar or Biflar Micrometers:

After Herschel's pioneering work on double stars, the measurement of position angle became increasingly important. Troughton's micrometer provided for rotation with a screw working on a thread cut on the limb of a circular plate to which the micrometer case was attached. Original models did not have this plate divided but this innovation was a simple addition. This mechanism was relatively slow to move with a standard single threaded screw but multiple-threaded screw versions (e.g. MCML-1) improved the convenience. Likewise, a pinion working on a toothed wheel speeded up the rotation further, but the best method was similar to Graham's method of moving the alidade of a quadrant. A clamp combined with slow motion screw allowed the micrometer case to be turned to the approximate position angle and then the wires rotated by the fine adjusting screw. Cooke and Grubb attached a position circle directly to the end of the telescope tube which meant that <u>any</u> instrument could be rotated with the same mechanism--a matter of some convenience and monetary saving since any micrometer, reticulated diaphragm or the slit of a spectroscope could be accommodated. The constant use of this arrangement made it necessary to monitor the device for wear and resultant slack.

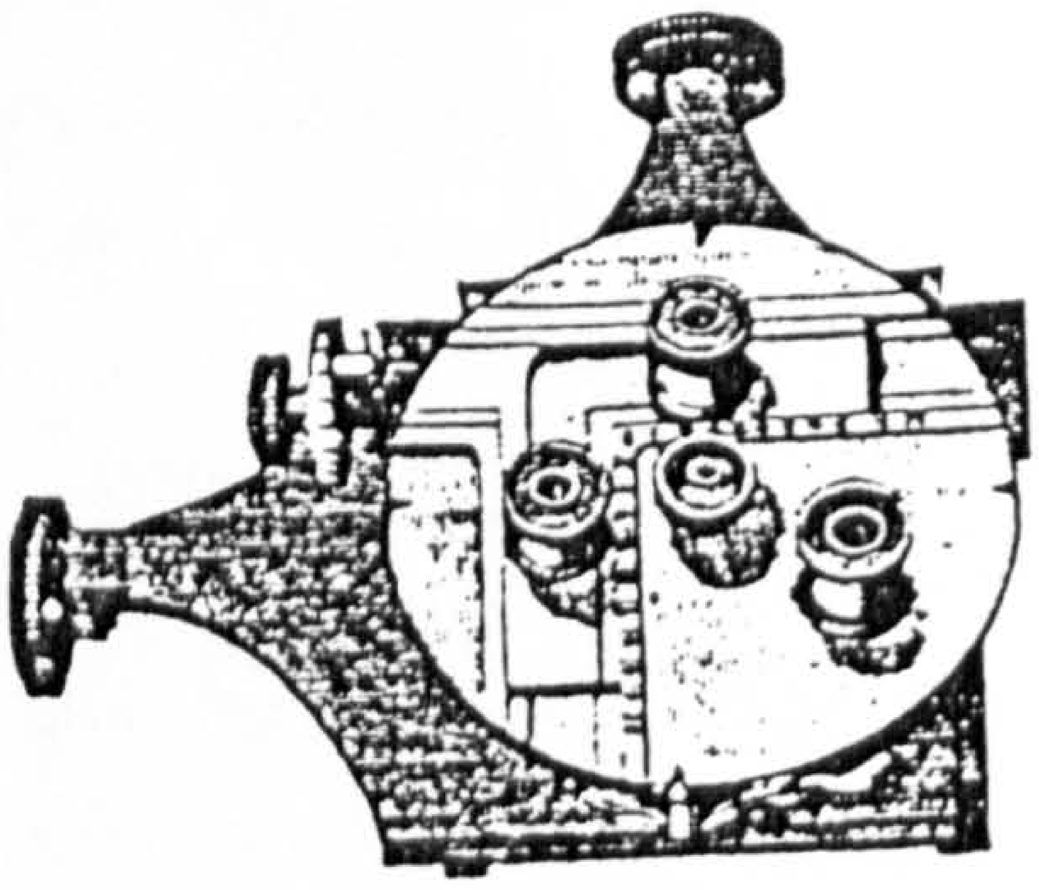
3.4.1.5 Micrometers for Measuring Large Separations:

Herschel had found it impossible to measure the separations of wide doubles with standard micrometers and this problem persisted into the 19th c. Herschel's lamp micrometer required immense patience to use and was never widely adopted. Chevalier (1843, p.111-2) was reported to have a micrometer with a scale on a piece of glass



3.4.6 Clark's filar micrometer made for the Washburn Observatory (ca.1880) complete with illumination and counter-balance mechanisms.

3.4.7 Grubb's 'Duplex' micrometer (ca.1870).

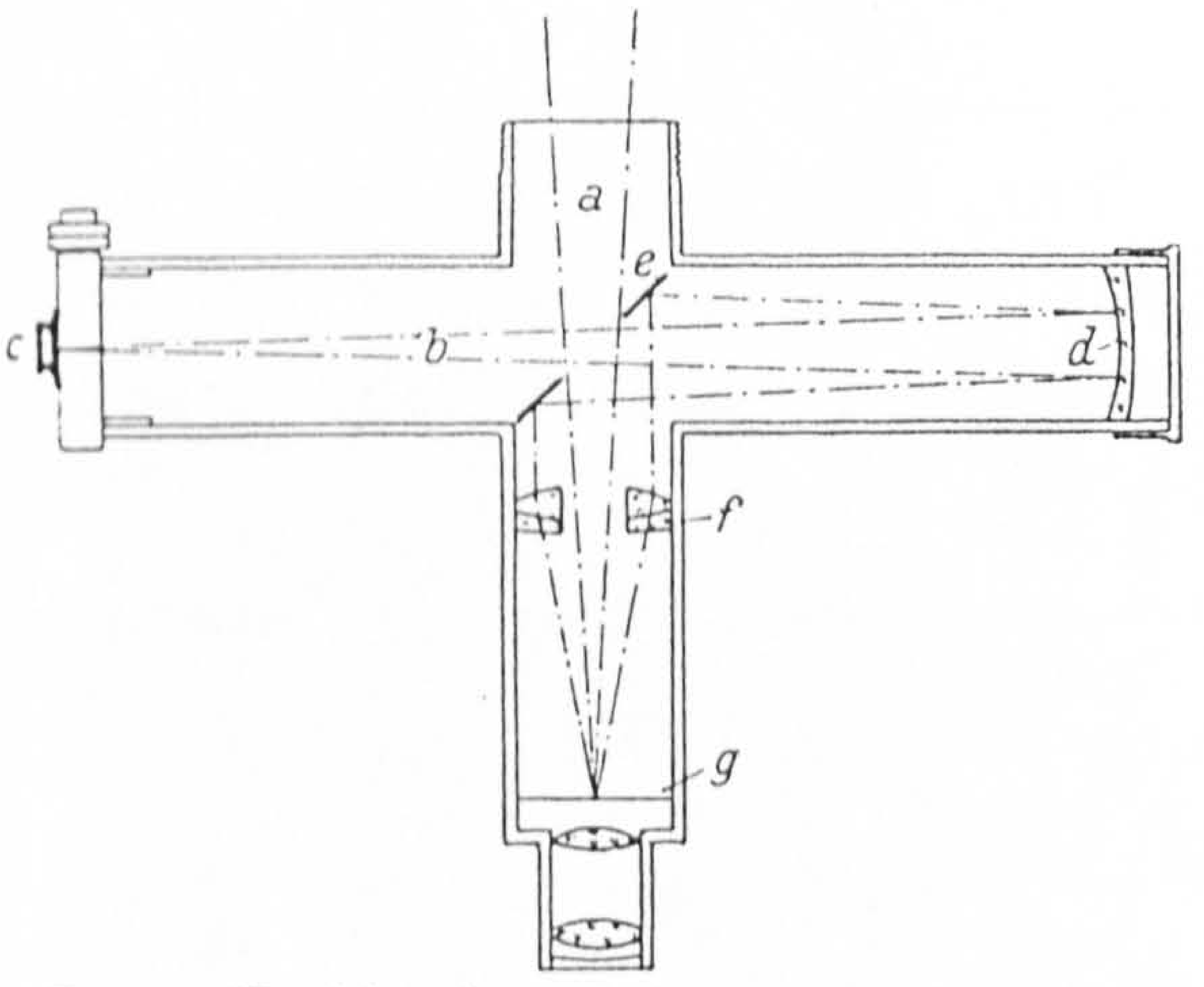


which was observed simultaneously with the object. A similar solution was found by Alvin Clark of Cambridge, Mass. and by Grubb in Dublin. Clark's micrometer was exhibited at the June 1859 meeting of the Royal Astronomical Society and could measure angles up to 1°. A brief description was given in the *M.N.R.A.S.* (Clark: 1858/9, p.324) but Gill (1878, p.247) described this instrument thus:

> It is "furnished with two eyepieces, composed of small single lenses, mounted in separate frames, which slide in a groove and can be separated to the required distance. A frame carrying two parallel spider lines, each mounted separately with its own micrometer screw, slides in a dovetailed groove in front of the eye-pieces; and by a free motion in this frame each web can be brought opposite its own eye-lens. In using this micrometer, the first step is to set the position-vernier to the approximate position of the objects to be measured. Then the eye-lenses are separated till each is opposite its own object. The frame containing the webs and their micrometer screws is then slid into it own place; and the webs, having been separated nearly to their proper distance by their free motion in the frame, are placed precisely on the objects by their fine screws, the observer's eye being carried rapidly from one eye-lens to the other a few times, till he is satisfied of the bisection of each of the objects by its own web. The frame is then removed for reading off the measure by means of an achromatic microscope, on the stage of which it is placed." The advantages which Clark claims are these:--
> "1. Distances can be observed with great accuracy up to about one degree, and the angles of position also.
> "2. The webs, being in the same plane, are perfectly free from parallax, and both are equally distinct, however high the magnifying power may be.
> "3. The webs are also free from distortion and from colour.
> "4. A different magnifying power may be used on each of the objects,--which may be advantageous in comparing a faint comet with a star."
>
> It appears to us that the method of removing a slide in order to measure the interval between the webs is liable to objection, not only because of the risk to the webs, but because the taking of measurements of such a different character with a different instrument is inconvenient and troublesome.

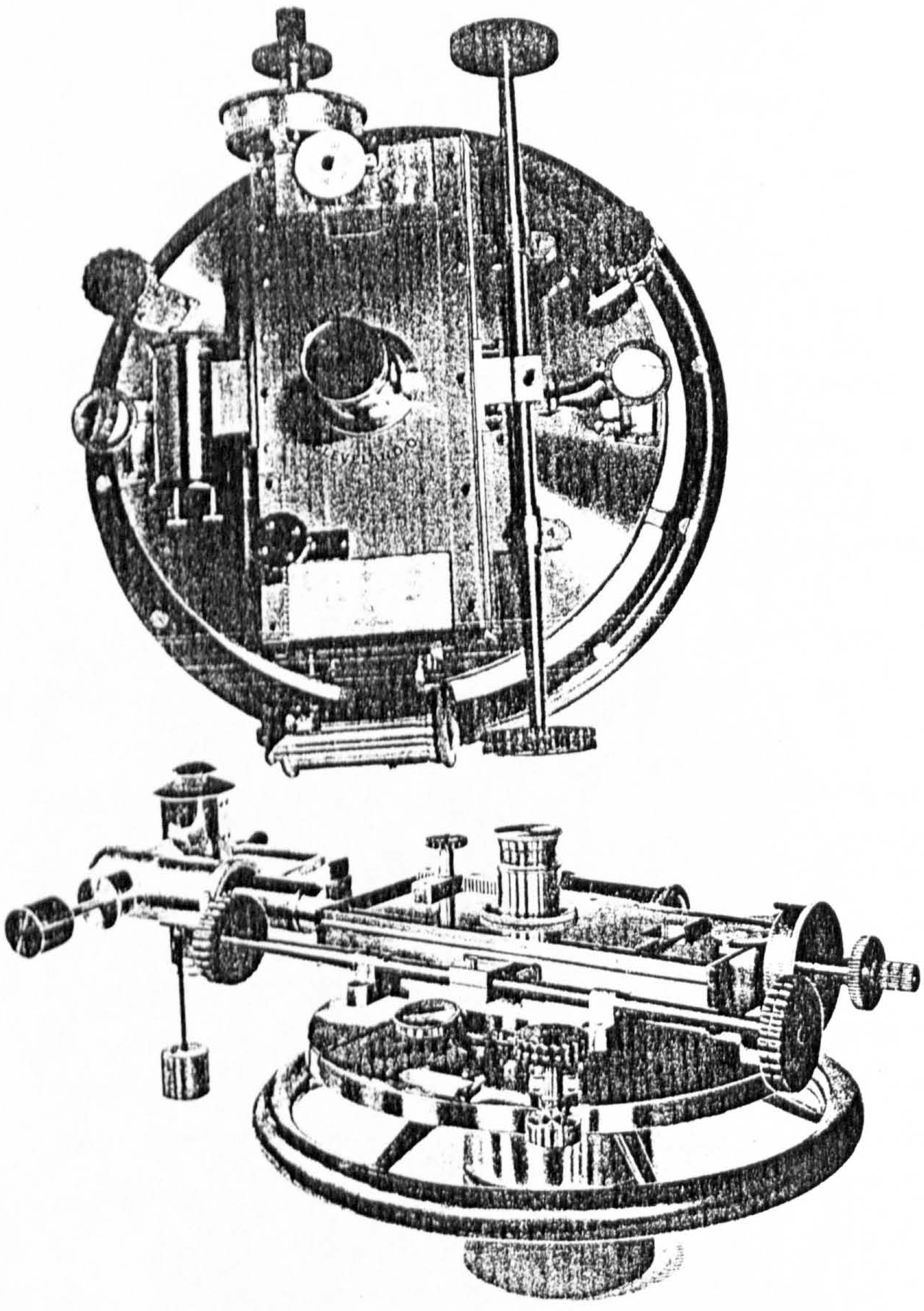
A description of Clark's micrometer for the Washburn Observatory (Fig. 3.4.6) may be found in Burnham (1881, pp.39-40). It incorporated numerous changes but these were mainly in the illumination of the wires. It was a single screw micrometer with an adjustable 'bisecting-screw' as Repsold used. The head was rotatable with scale and vernier for position angle measures. The whole instrument weighed just 26oz.

Grubb's 'duplex micrometer' (Fig. 3.4.7) was more desirable since the measurements were carried out directly on the instrument thereby bypassing Gill's objection to Clark's design. The main innovative feature was the use of a piece of glass with lines ruled to form a 2in square grid with line separations of 0.1in. A micrometer screw of 100 TPI moved a frame in front of the glass grid. This frame had a scale with lines ruled to correspond with every second line on the glass plate. The third element of the duplex micrometer was a plate with two eyepieces--one to move vertically, one horizontally. To use the instrument, two stars were placed on a horizontal line of the glass grid. The distance was measured by counting the number of lines in the glass plate and the residual was measured by the micrometer screw. Thus the micrometer screw



3.4.8 Burton/Grubb ghost micrometer (1880). The principle is still used for projecting grid lines into the field of telescopes.

3.4.9a Warner & Swasey's micrometer for the 40in Yerkes refractor (1893/4).



was only required to measure separations of less than 0.1in thereby reducing screw errors and temperature effects. To determine differences in right ascension, the telescope drive was stopped and the micrometer rotated until one of the stars ran along one of the horizontal lines. Once adjusted, the drive was started and the other eyepiece adjusted vertically until its web bisected the other star; the measure was taken with the second micrometer screw. One therefore had two sides of a right angled triangle and all elements could be determined. The accuracy of the duplex micrometer depended largely on the glass plate being engraved with lines which form perfect squares. To check this a third eyepiece was incorporated by which transits of stars could be observed across the diagonal of the squares. Although the observations made with this micrometer did not reach the accuracy[1] of the best heliometers of the late 19th c, it did permit measurement of stars too faint to be observed with the latter.

A related instrument was the ghost micrometer illustrated in Fig. 3.4.8. This was similar in concept to one Steinheil had made in 1827, both using a system of lenses to simultaneously focus the sky field and a glass plate with grid. Following papers on ghost micrometers by J. von Lamont[2] and by K.L. von Littrow[3], C.E. Burton and Howard Grubb (1880/1, p.59 and König: 1937, p.140) described their ghost micrometer. This consisted of lines scratched in silver deposited on a glass disc. The disc was projected and focused onto the field, and when illuminated from behind produced a grid for measuring purposes. This scheme is still used for some applications. This idea originated, according to König (1937, 140) with C.A. Steinheil in 1827. Burton and Grubb described how such a device could be used with both filar micrometers and split prisms. John Browning (1869/70, p.71-2) used the same idea of projecting an image of crossed wires into the field of view for his micrometer for measuring spectra. The wires were those of a standard micrometer used with microscopes. Having the lines in one plane eliminated the parallax error caused when the wires were in different planes. Their motive (Burton, Grubb: 1880/1, p.59) for designing it was that filar micrometers were not well suited for measurement of very close double stars or for planetary discs. The ghost micrometer was the stepping stone to Grubb's duplex micrometer which was of wider (no pun intended!) application. It is not known whether Grubb was aware of Steinheil's ghost micrometer, but as no detailed description of the latter has been found it is suggested Grubb discovered the principle independantly.

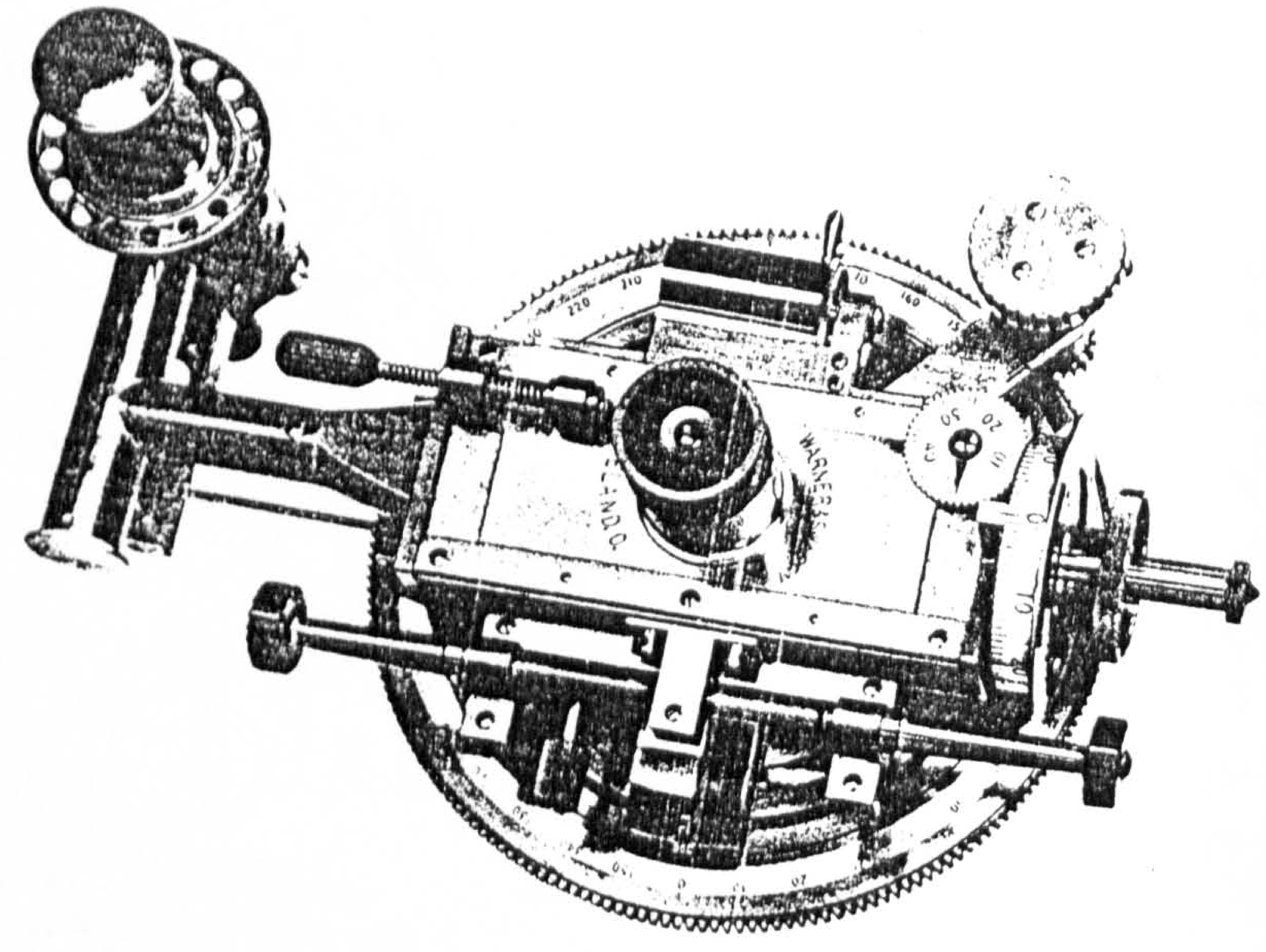
Waren De la Rue made a 'macro-micrometer' for measuring photographs which had a 2in range in both **X** and **Y** directions. In his description, Pritchard (1882/3, p.7) said its accuracy was 0.0001in. He gave the diameter of the drums as 3in (X) and 2in (Y) but did not give either the diameter or pitch of the screws.

---

1 Gill noted C. Pritchard's observations made at the Radcliffe Observatory, Oxford and published in *Memoirs of the RAS*, **47** (1882-3), pp.5-12.

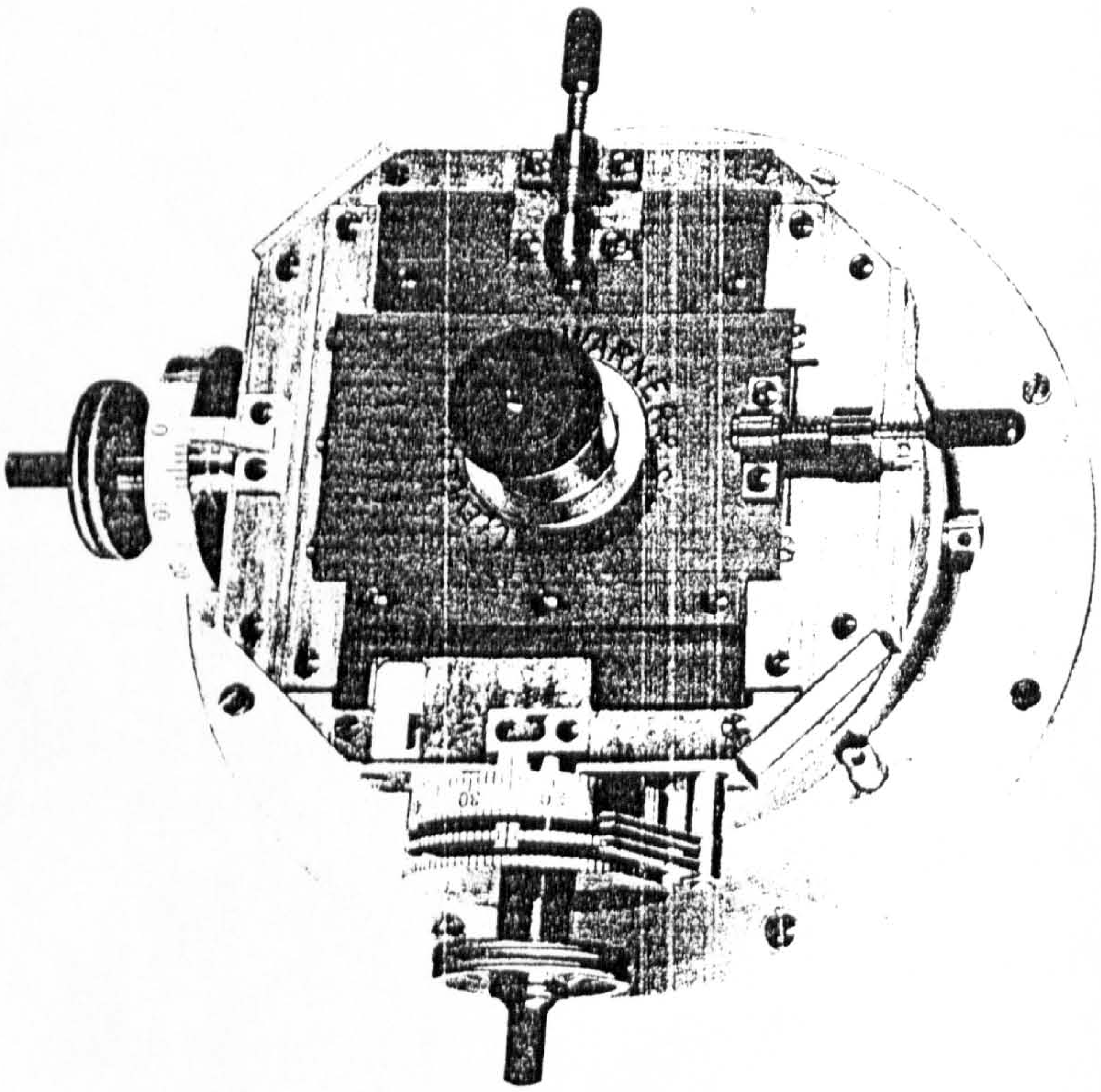
2 Jahrbuch der K.S.b., Munich, p.187.

3 *Proc., Vienna Academy of Sciences*, **20**, 253.



3.4.9b Warner & Swasey filar/position angle micrometer (ca.1880-5). Note the dial for recording the revolutions of the screw. The shaft below the body of the micrometer was to adjust the position of the wires with respect to the micrometer screw.

3.4.9c US Naval Observatory's position micrometer by Warner & Swasey. This instrument was made of steel.



3.4.1.6 Warner & Swasey's Micrometers:

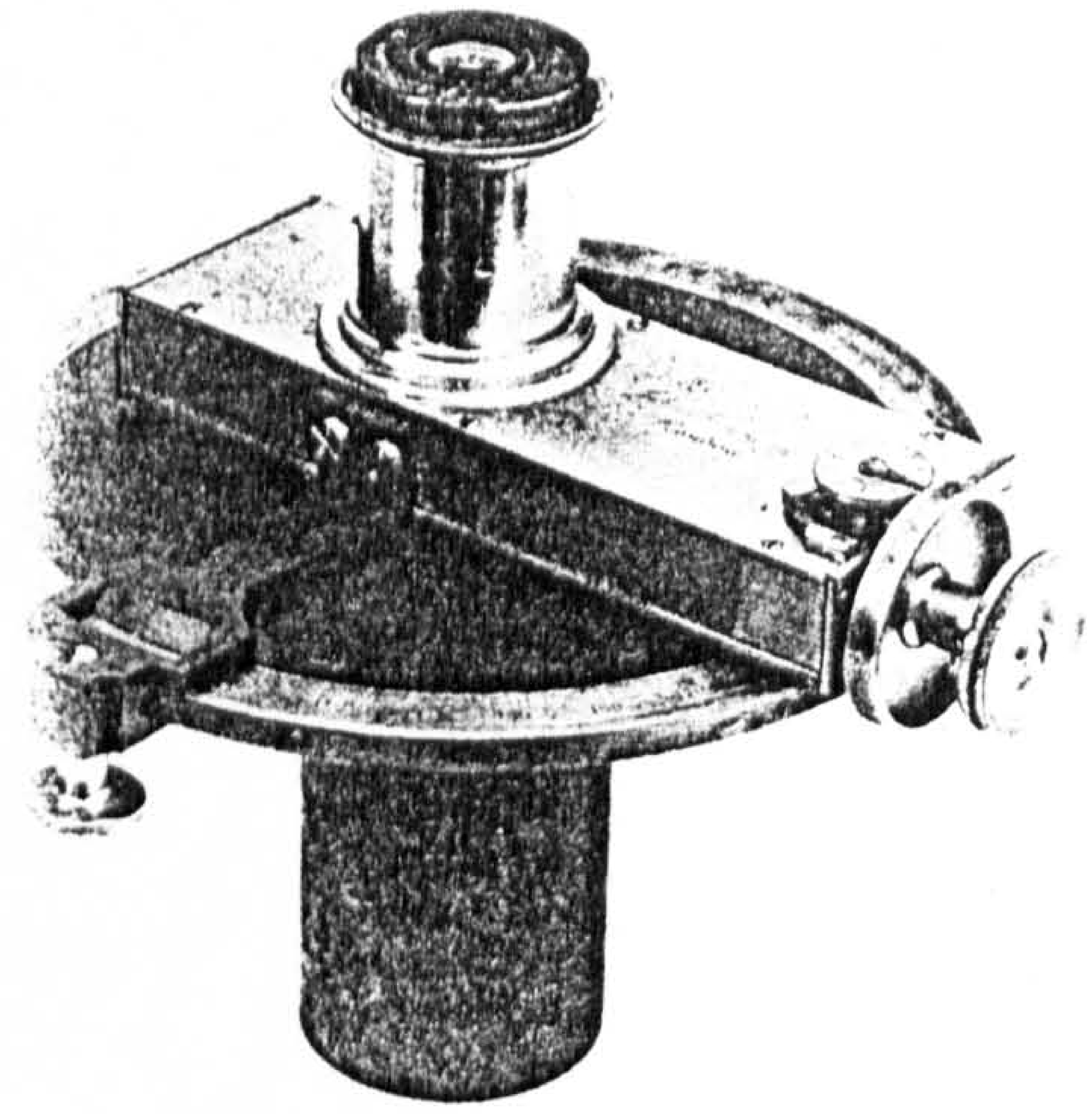
Warner & Swasey constructed a micrometer which was based on one of Alvin Clark's designs (Fig. 3.4.9a) for the 40in Yerkes refractor[1]. This instrument permitted position angles to be measured by two verniers with magnifiers in much the same manner as with Repsold's micrometer. Both makers basically employed the circular stages of surveyor's transit instruments on which the case of the micrometer was mounted. Like Repsold, Warner & Swasey moved the fixed web with an adjusting screw, thus allowing different parts of the micrometer screw to be used to eliminate effects of periodic error. Subdivisions of a turn were taken with a standard drum while whole divisions (0-50) were noted with a dial mechanism similar to that developed by Browning[2]. As in Troughton's much earlier biflar micrometers, rotation was accomplished with a pinion gear meshing with teeth machined on the exterior limb of the micrometer head. A vernier, with magnifiers, gave fractions of a degree for the position angle and illumination was provided by a small lamp housed on the side of the micrometer. Another micrometer which was virtually identical to that for the 40in Yerkes refractor is illustrated in Warner & Swasey (1900: pl.V) and here as Fig. 3.4.9b. While the Yerkes micrometer had a rack and pinion arrangement to adjust the zero of the screw, this simpler version had a screw for this adjustment similar to Repsold's arrangement. However, the lamp housing on the Yerkes instrument required that a rack and pinion arrangement be adopted for easy adjustment of the zero; the lamp housing required counter-balancing. The Yerkes micrometer had a ring to protect the position angle gearing and as an aid in mounting it on the telescope.

The steel micrometer of the 6in meridian circle of the United States Naval Observatory made by Warner & Swasey was a straightforward two axis micrometer (Fig. 3.4.9c). Two micrometer screws, each with drums graduated 0-60, were opposed by adjusting screws for varying the zero. The vertical motion (i.e. declination) screw apparently had no linear scale. The horizontal (i.e. RA) micrometer screw had an unusual structure adjacent but its purpose has not been determined, though it may be for determining the linear motion of the micrometer screw.

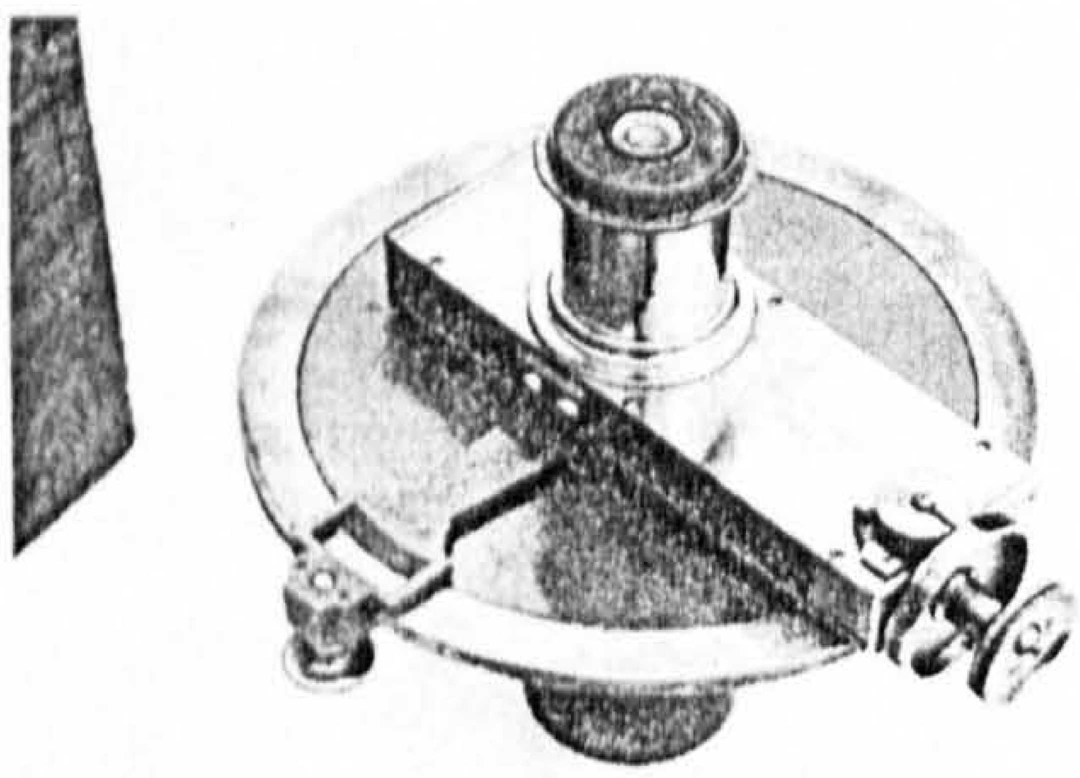
---

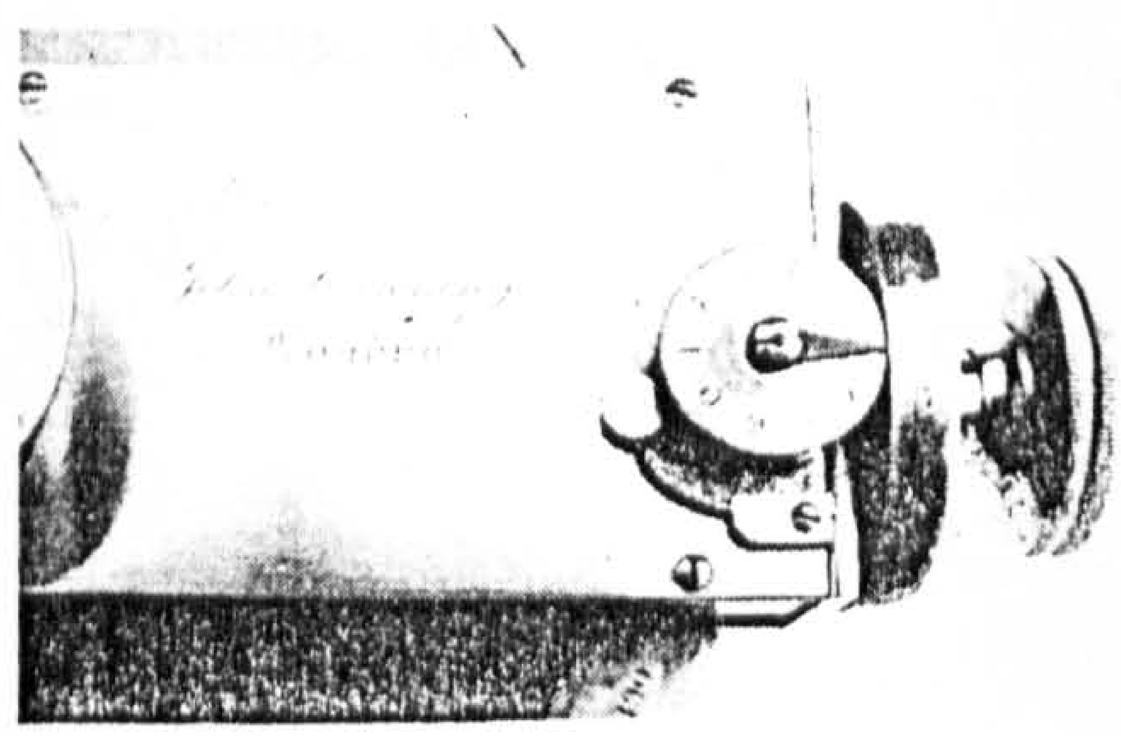
1 Warner and Swasey received the contract for the telescope in 1892 and it was completed in 1897 (King: 1979, p.316). Both men had previously been foremen at Pratt & Whitney.

2 Browning (1869/70) was one of the first to develop a micrometer for measuring spectral lines. These were based on his single screw model.



3.4.10a Filar micrometer by Browning (ca. 1875). Note the dial and spring detent for recording the turns of the micrometer screw adjacent to the drum.





3.4.10b Repsold's Cape Observatory micrometer (ca.1878). Note the double drums--one for whole turns, one for part revolutions of the screw--with magnifier.

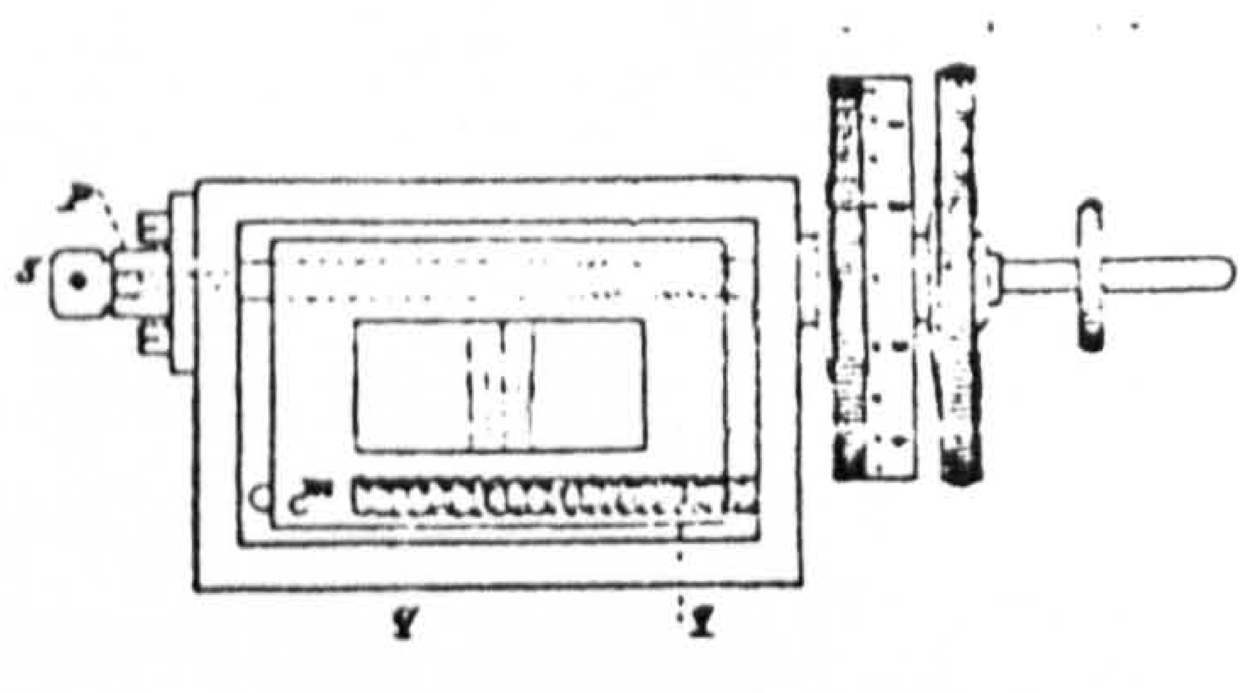
3.4.1.7 Repsold's contributions:

Troughton's micrometer screws were nominally 100 TPI[1] with the drum divided to 100 divisions. Thus a precision of 0.0001in was possible. However, reading the linear silver scale for the whole number of turns was difficult with the low illumination desired in an observatory. The comb arrangement of Ramsden which could be viewed in the field was almost always incorporated in filar micrometers. In the second half of the century Browning and Repsold designed mechanisms to make the task easier. Browning's solution was simpler and applicable to small and large sized micrometers (Fig. 3.4.10a). He employed a principle similar to the mode of operation of an odometer, i.e. as the screw turned a small pin meshed with a cogged wheel on each turn and advanced a small dial. It could be operated in both forward and reverse directions and was held in place by a round stop on the end of a curved spring which held the stop in a detent until the pin advanced the dial with the next turn of the micrometer screw. Repsold's solution was straightforward but the mechanism was more applicable to the large instruments employed at major observatories. The first micrometer to have this system was the complex example made by Repsold (ca.1870) for the Cape Observatory (Fig. 3.4.10b). The micrometer screw carried a pinion gear fixed to the shaft of the screw. This gear meshed with a pair of intermediate gears which in turn meshed with a second gear mounted on the screw shaft but left free to rotate. This last gear was fixed to a drum which read off the whole number of turns of the screw. The index for this drum was shared with the drum for reading off the sub-divisions of a turn of the micrometer screw and was a very convenient arrangement since both could be read simultaneously. The screw turned 24 times for each turn of the other drum.

A number of methods were employed to try to eliminate friction and resulting stress and wear on the micrometer screw. Troughton's micrometers and those of similar design had frames for the webs which had flat tops and bottoms which bore against the sides of the case. Grubb modified the slides to incorporate 'feet' designed to slide in grooves milled into the inside of the case. Repsold's reading micrometer had the entire frame with the webs carried on the micrometer screw. To maintain the frame's orientation in the focal plane, a defining pin inserted through the frame and extending slightly beyond each side bore against the inside of the case, but being only two small points, the contact friction was considerably reduced and in turn reduced wear on the screw. Repsold's Cape Observatory micrometer (Fig. 3.4.11a) was of this design but had the screw mating with a nut on one side of the web frame. However, a small error resulted from the clearance of the other end of the screw shaft through the frame which permitted shifts in the orientation of the webs. The error amounted to just 0.14" and this was determined to

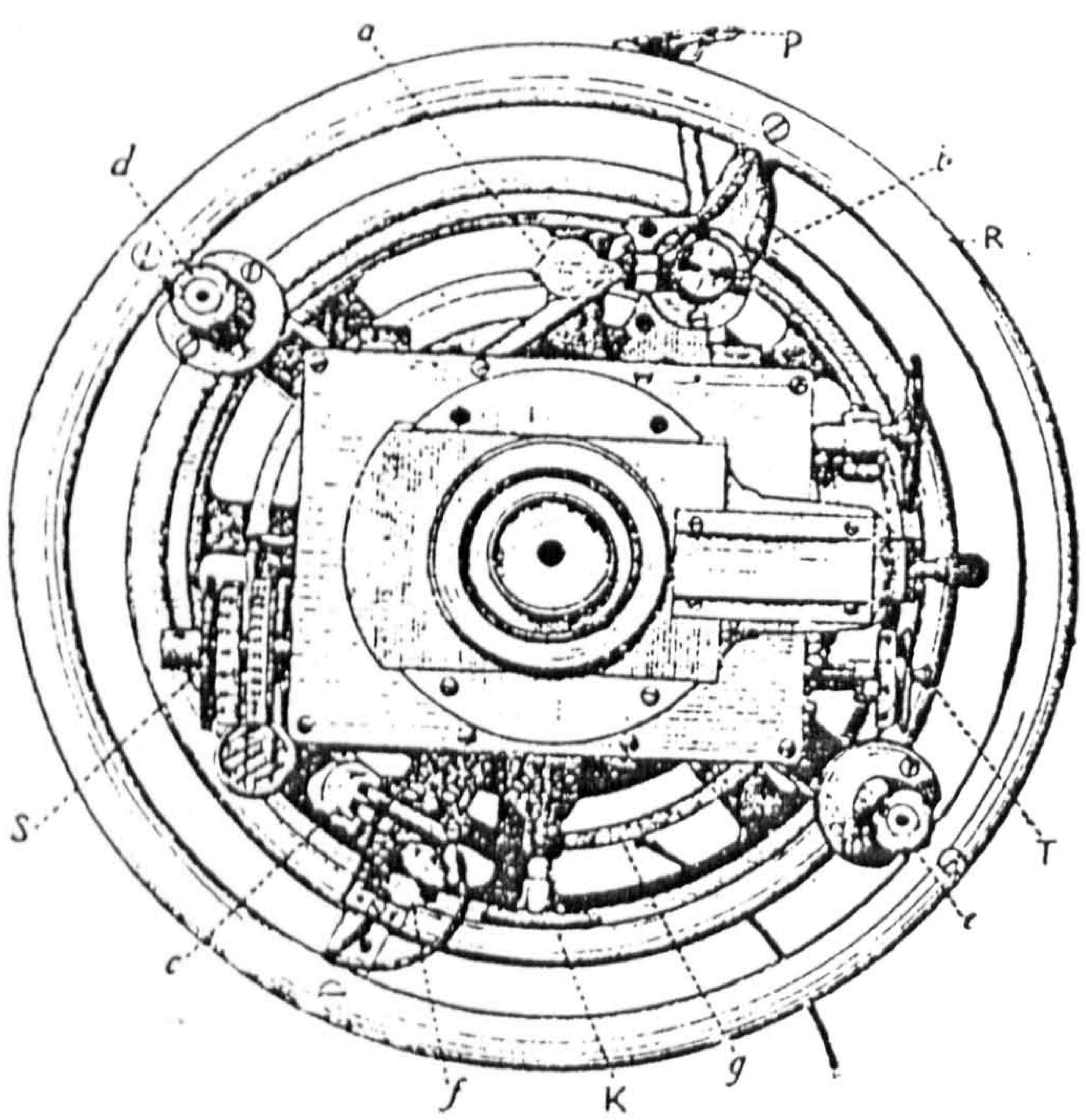
---

1 The pitch was normally ≈103.6 TPI. Those by Thomas Jones and Robinson of Devonshire Pl. were apparently similar but those of Dollond were closer to 100 TPI (Pearson: 1829, p.100).



3.4.11a Repsold's scale micrometer (mid-19th c). A pin 'M' through the movable frame decreased the friction thereby extending the life of the micrometer screw. The off-set screw and backlash spring was also a better arrangement than in the Troughton style.

3.4.11b Repsold's impersonal micrometer (1893) made for the Cape Observatory. The motion was by hand but was later replaced by a motor.



represent a clearance of 1/15000in--good workmanship for the day but a source of error none-the-less.

3.4.1.8 Repsold's 'Impersonal Micrometer':

Repsold's impersonal micrometer (Fig. 3.4.11b) was intended for meridian observations and was described by Repsold in **Astronomishe Nachrichten** (no. 2940). He had previously suggested (no. 2828) applying clockwork to a transit instrument to cause a star image to remain fixed in the field and to make measurements by means of a chronograph. This concept was never put into effect[1] but suggested features for his impersonal micrometer. These travelling wire or impersonal micrometers were developed by Repsold between 1889-95. Instead of moving the entire instrument, Repsold moved the wires of the micrometer to follow the star so that the images might be perfectly bisected. Registration of the time was accomplished by a chronograph which recorded the times corresponding to known intervals from the line of collimation. One problem was the method of varying the speed of the wires to correspond to the declination of the star being observed. The example made for the Cape Observatory is illustrated in Gill (1913, pl. XIX) and is not, except for the driving mechanism, very different from his other large telescope micrometers. At first, Repsold used hand operated driving mechanisms but small personal errors remained which were later eliminated with mechanical and electrical driving mechanisms (Watts: 1944, p.179).

From 1893 Repsold used a design similar to that for the Cape micrometer in a model intended for large telescopes. It had a clamp screw and ring to move the micrometer head in position angle and had a second screw opposite and working parallel to the micrometer screw by which the coincidence of both the fixed and moveable wires could be changed. This permitted using different parts of the micrometer screw in order to eliminate periodic errors of the screw, and originated with Fraunhofer's auxiliary screw to move the 'fixed' wire in the field; this arrangement had been used on many of Repsold's earlier large micrometers. Later versions provided a third screw moving at right angles to the others which was intended to allow the observer to determine the zero of position angle for his moveable webs with the same accuracy as could formerly be done only with position angle webs[2].

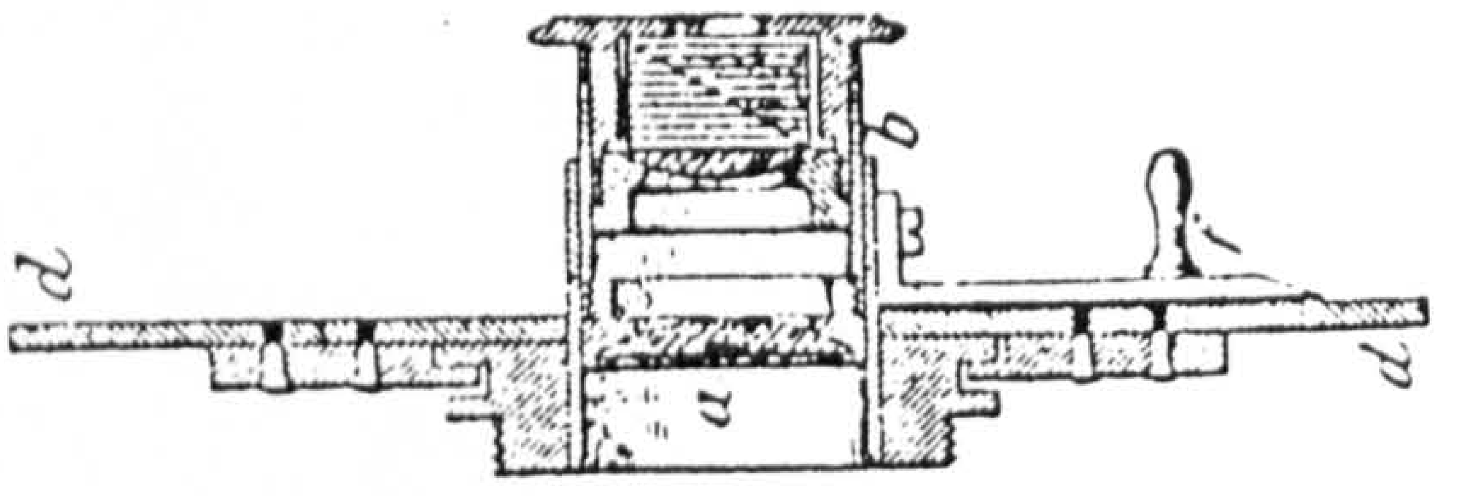
3.4.2 Heliometers:

A number of heliometers of note were developed in Germany and of interest for surveying instruments of the 19^{th} c. Those of Abot (1777) and Boscovich (1777) had applications for optical comparators and were further developed by Clausen (1841) and

---

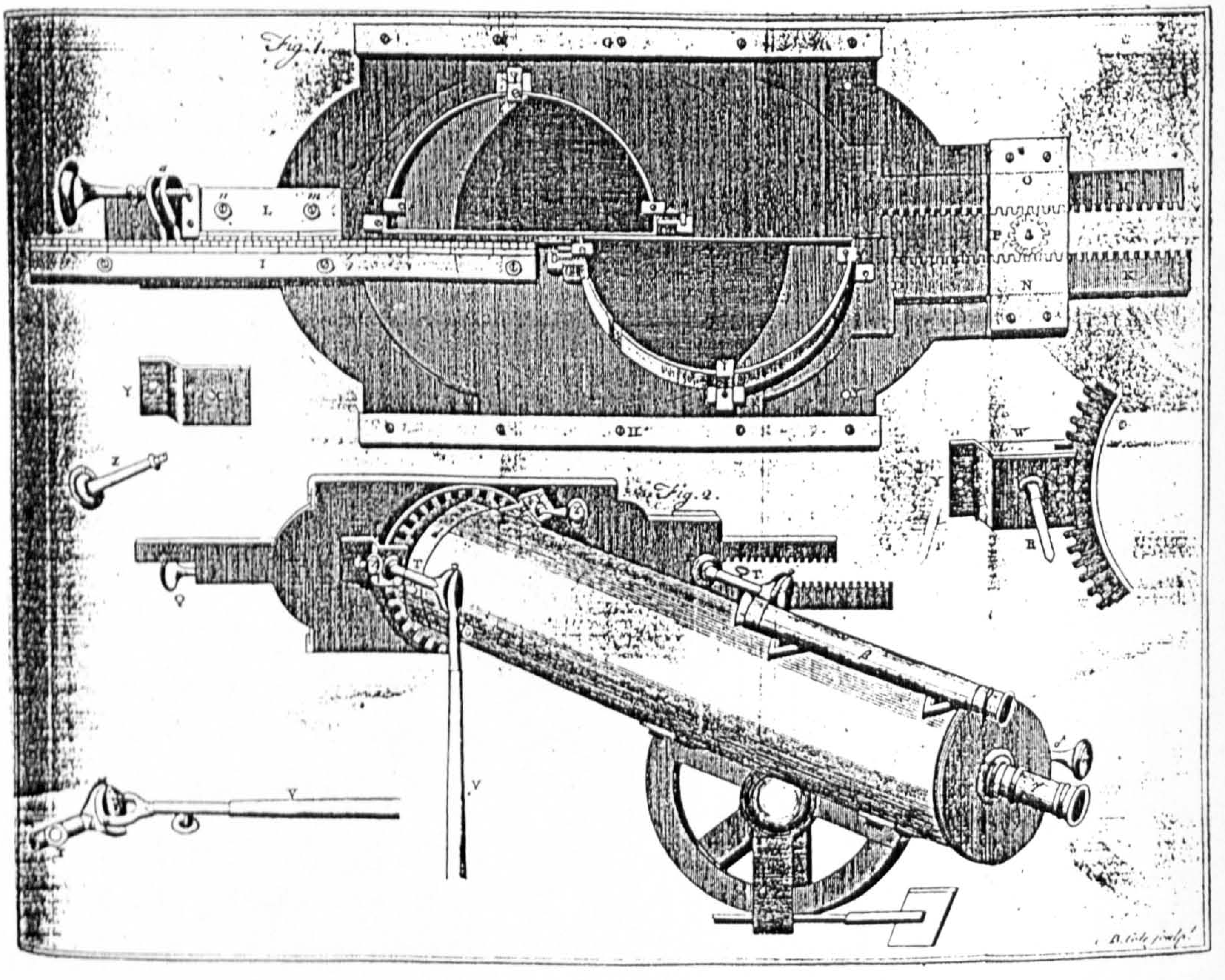
1 It was used on sextants for airplane navigators from ca.1920.

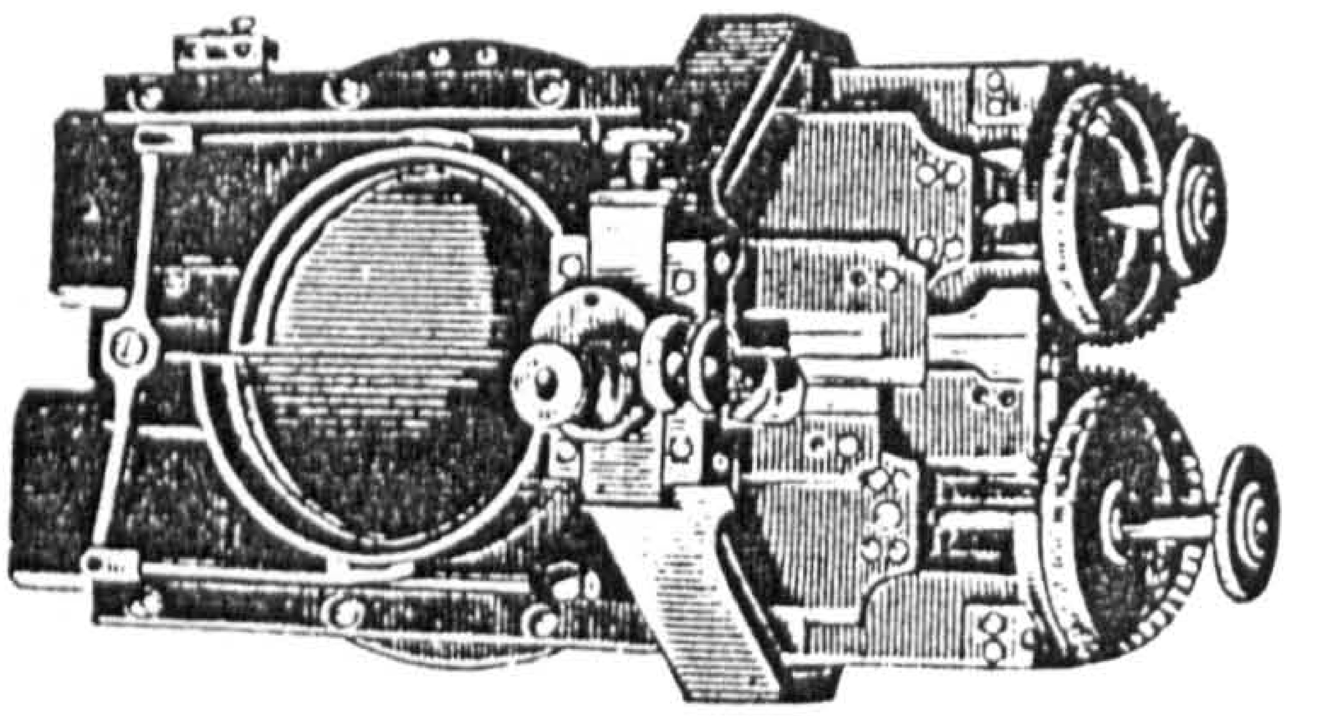
2 By 1911 Repsold was working on a micrometer which was to record the observation on paper in a manner similar in concept to the chronograph.



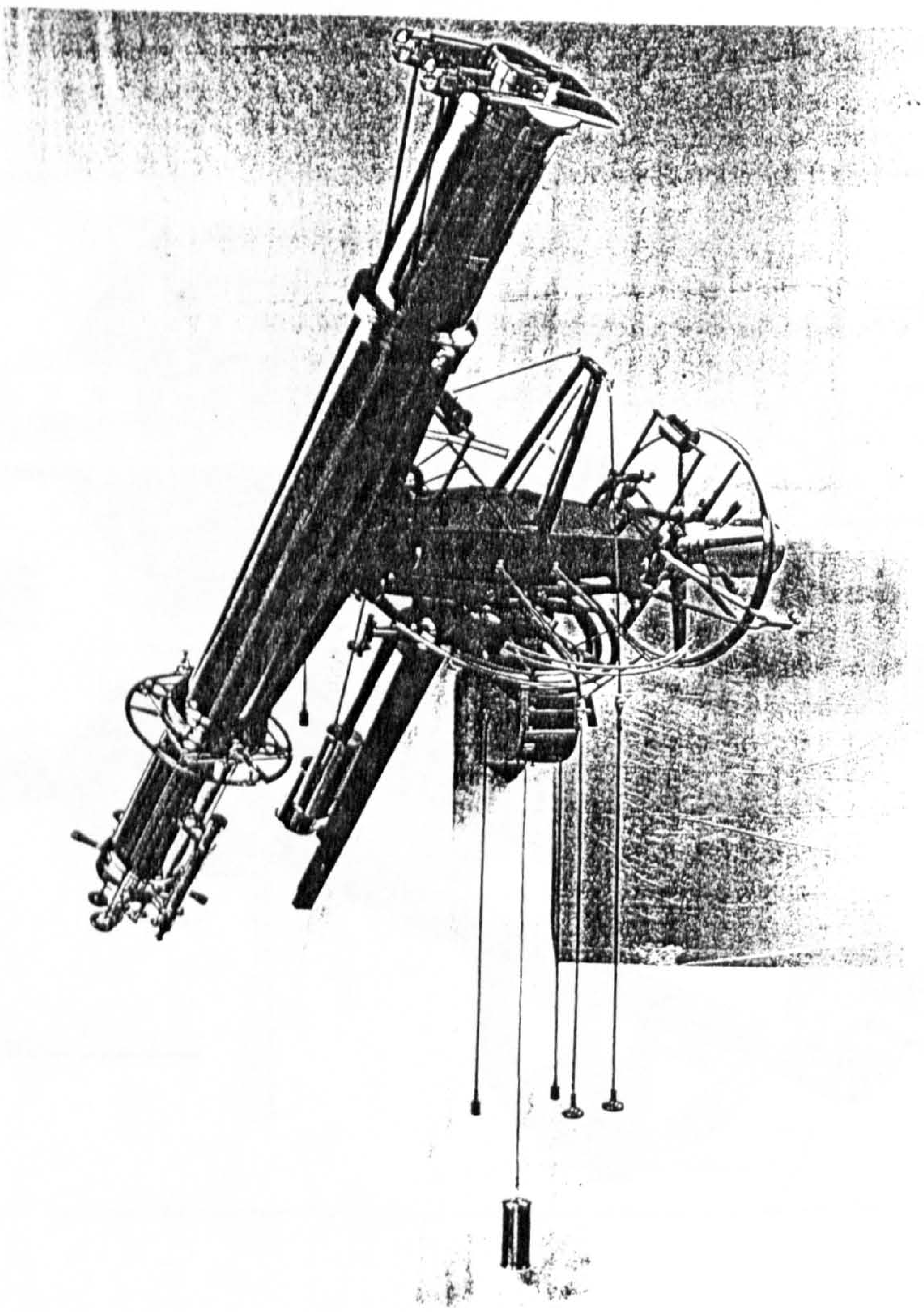
3.4.12a Wellman's prism micrometer (1789) which was similar in principle to Rochon's and Maskelyne's.

3.4.12b Dollond's divided object glass micrometer with vernier replacing the original screw micrometer system of measurement (q.v. Fig. 3.3.16).





3.4.13a Fraunhofer's heliometer (ca.1825) made for the Göttingen Obs. This instrument was similar to that made by Utzschneider for the Königsberg Obs. and with which stellar parallax was finally discovered (1838).



3.4.13b Repsold's 7.5in heliometer made for the Oxford University Obs. in 1848. Here as in the above instrument, micrometer screws were employed to make the fine measurements as had been tried in the mid-18th c.

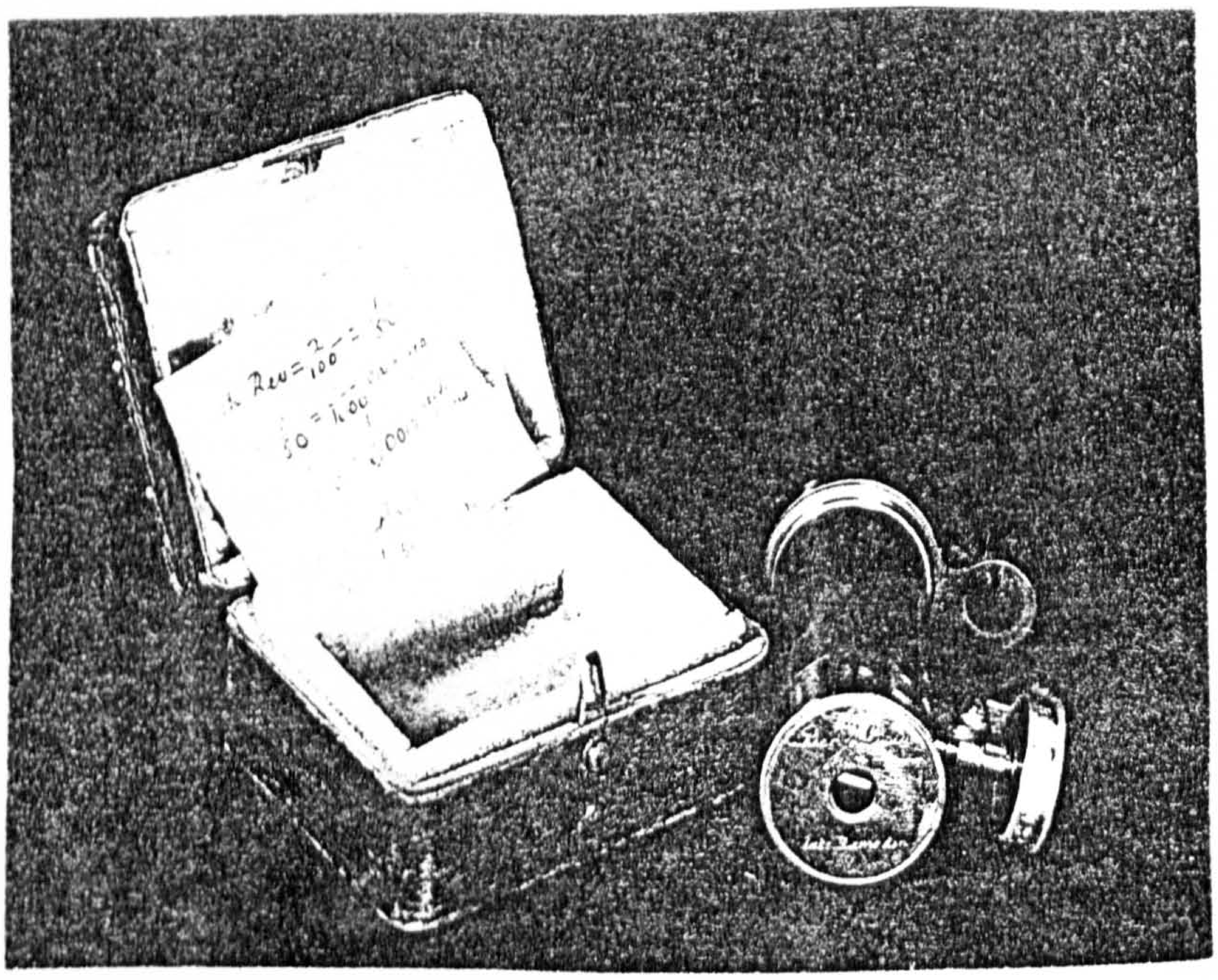
Porro (1854); they also predated the parallel plate micrometer. Using a principle similar to that employed in Rochon's prism micrometer, Wellmann designed a variation in 1789 (Fig. 3.4.12a). However, a heliometer which deserves special note is that of Fraunhofer which closely followed the design of Dollond's heliometer of 1755 (Fig. 3.4.12b). For the Göttingen heliometer (Fig. 3.4.13a), Fraunhofer returned to the original design employing screws for the measurement of the motion of the lens halves. But instead of a single knob, each half was adjustable by its own micrometer screw. Herrmann (1984, p.163) states that the first parallaxes measured by Bessel with Utzschneider's Königsberg heliometer corresponded to a shift of the lens halves of just 0.005mm. The heads of the micrometer screws were large enough as to allow 1/1000th part of a revolution (1/20") to be detected (Main: 1843, p.53). The Oxford 7.5in heliometer (Fig. 3.4.13b) built in 1848 by Repsold (see King: 1979, p.242-3) also used two micrometer screws and, as King notes, the drums were illuminated by electric current passing through platinum wires and read with low power micrometer microscopes mounted at the eyepiece end. The lens halves moved in a curved plane to compensate for the aberrations resulting from their separation. This instrument is in the Science Museum. On the use of heliometers Maskelyne noted that the angles measured varied with the focus of the eye. Hamilton (1810, p.25) stated "[the heliometer's] imperfections are; that to different eyes, and under different circumstances of the same eye, the length of the focal distance, that suits distinct vision, will vary, and of course the quality of the measures given by the scale is liable to a small variation". The problem is not unrelated to that affecting the calibration of filar micrometers.

3.4.3 Dynameters:

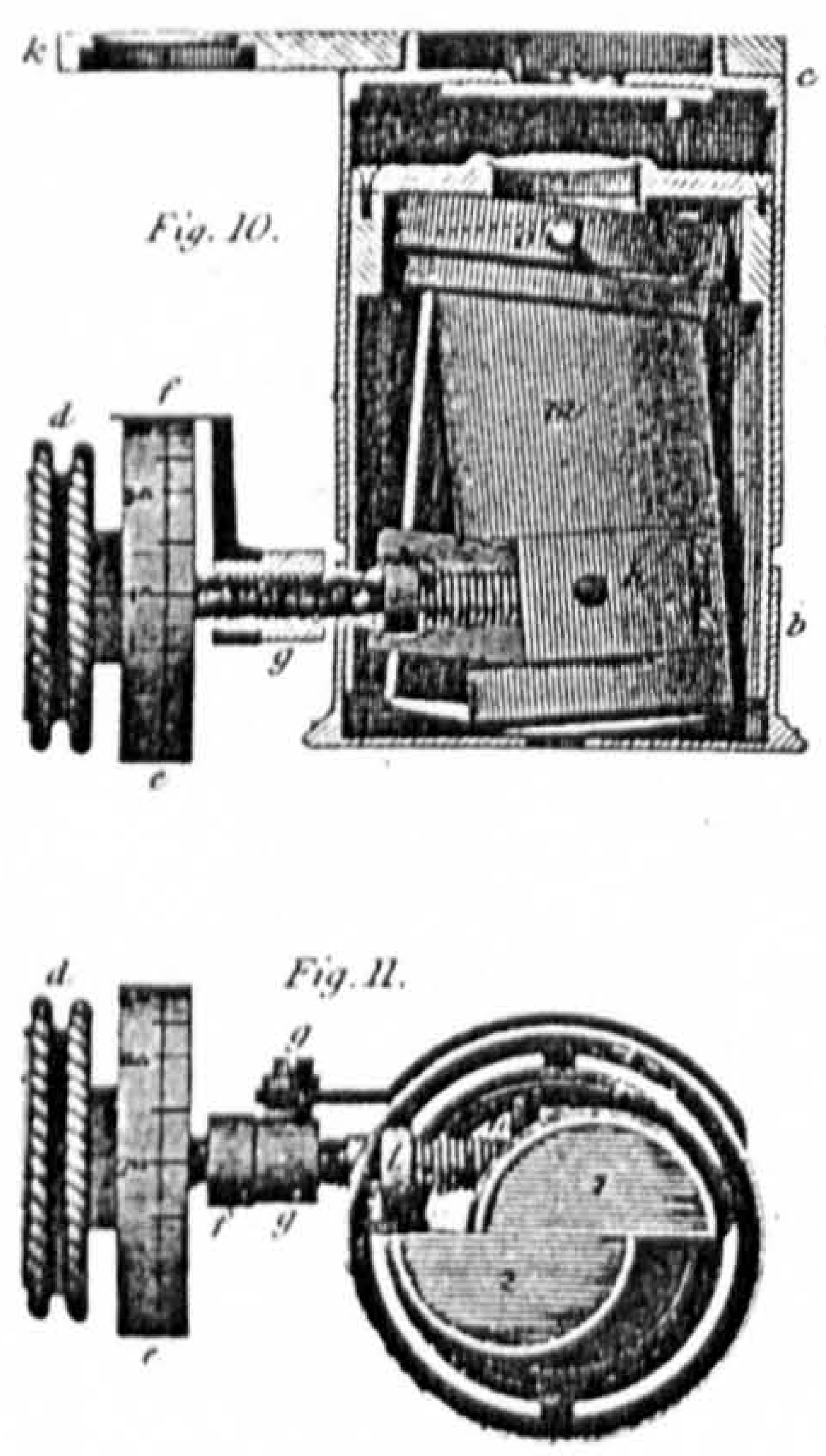
3.4.3.1 Origins--Nairne and Jones:

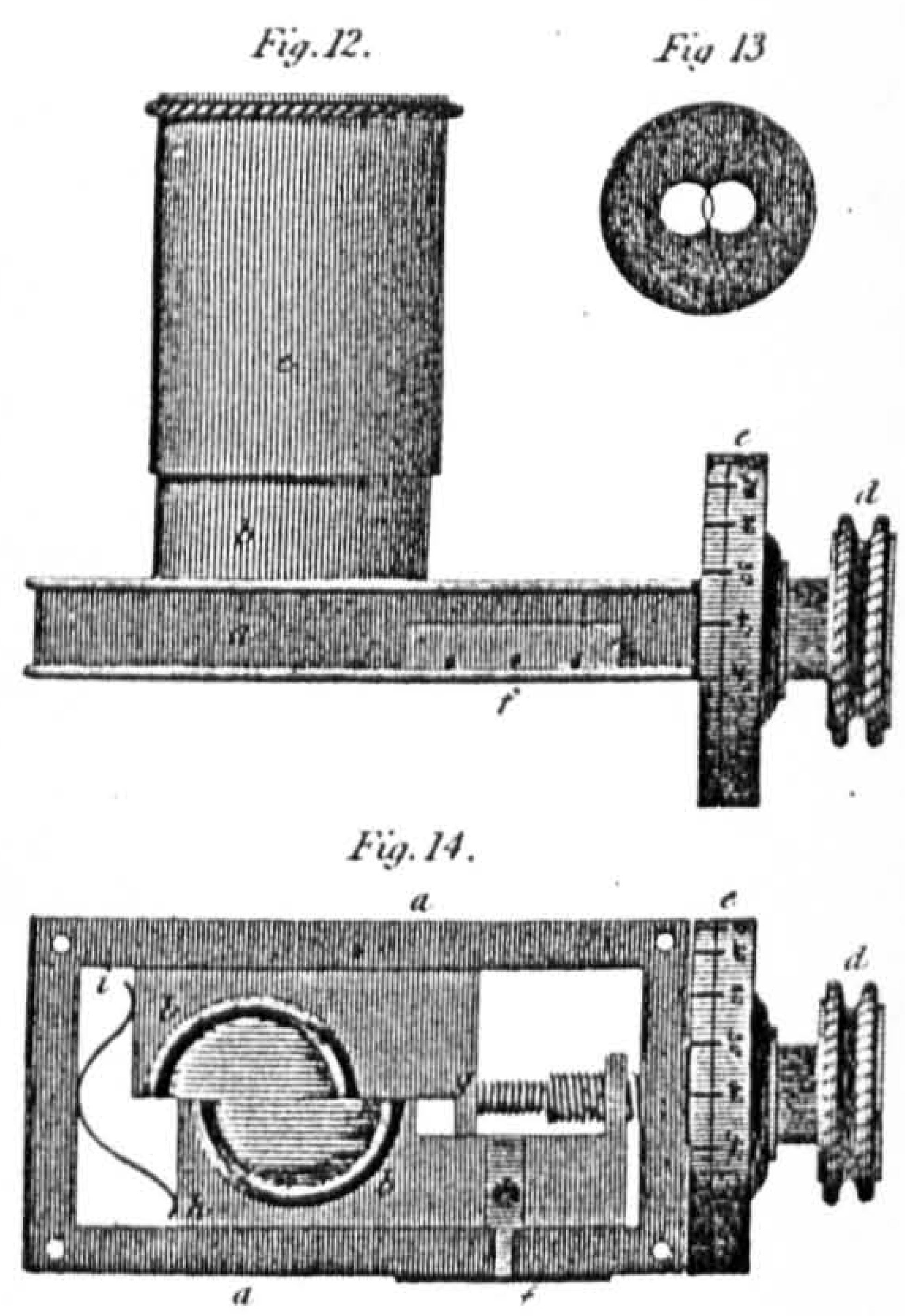
According to Edward Troughton (Pearson: 1829, p.185) the 18th c origins of the dynameter may have been the result of the breaking of a lens in a terrestrial telescope owned by a Capt. Countess (R.N.). The third lens (of four) was broken and when used in this condition, the telescope showed multiple images each proportionally bright according to the segment's size. Edward Nairne used the idea to make a 'coming-up glass' which used a double screw to separate the halves. This screw was similar to the one used by Gascoigne in his original micrometer--i.e. it had two parts with one part of twice the pitch. It is thought that this 'coming-up glass' provided the concept for Ramsden's dynameter and also for his double image micrometer already discussed. It seems Nairne's original purpose was to make a device for measuring the angular size of an object (e.g. a ship or land object) being approached as a means of estimating the speed of approach which was particularly useful when approaching or 'coming-up' to a moving ship; the military use is obvious.

By ca.1819 Jones was still making a device for terrestrial telescopes the purpose of which was similar to Nairne's (Pearson: p.185ff.). This contrivance was not unlike a



3.4.14 A Ramsden type dynameter made by Mathew Berge (ca.1800-20).





3.4.15 Thomas Jones' dynameter (ca.1820) using a screw/nut arrangement similar to that on Ramsden's dynameters.

3.4.16 (right) Dollond's dynameter design (ca.1820) using one screw axial to another drilled and tapped to accept the smaller. The screws were of opposite handedness unlike those of Ramsden and Jones.

dynameter though not as carefully designed or finished. The example examined by Pearson had a screw with 35 and 70 TPI threads. In Jones' version the segments of the screw were the same length but the nut on the coarser was much shorter than that on the fine pitched segment. The scale and drum were otherwise similar to those on dynameters but the mechanism was contained within a tube designed to mate with the terrestrial telescope. If the separations of the lenses of the telescope were adjusted, then the device could be used at a variety of magnifications and such a telescope with micrometer was called by Pearson a pancratic dioptic micrometer. However, one needed to have the tube marked and calibrated for the position of specific magnifications. Though intended for terrestrial observations, this device had the capability of being used for celestial observations, e.g. with suitable filters to measure the diameters of the Sun and Moon for comparison with the published values in the Nautical Almanac.

3.4.3.2 Ramsden's dynameter:

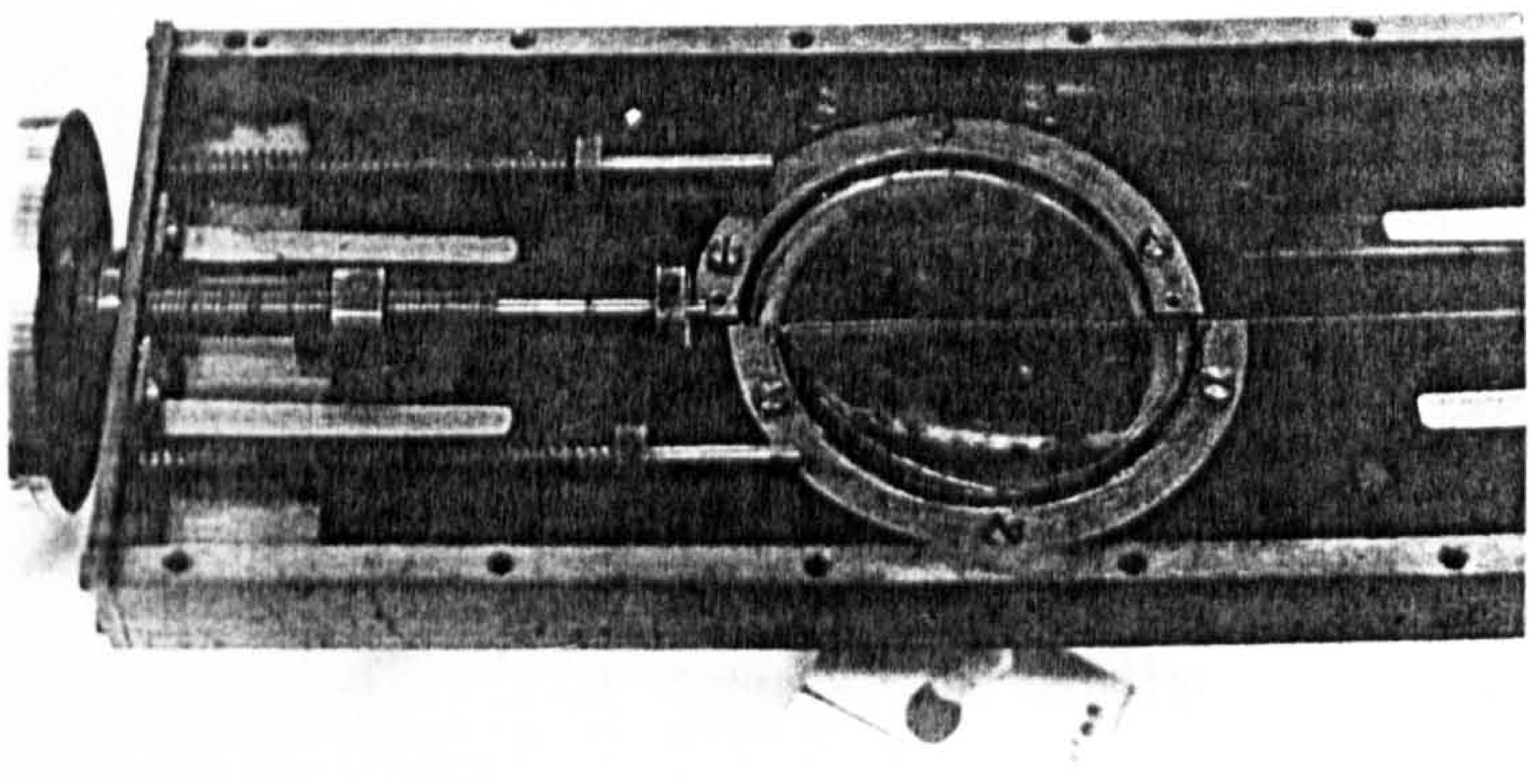
It is often important to know the exact magnifying power of a telescope/eyepiece combination when making micrometrical measures. Ramsden provided the solution with the invention of the dynameter. The instrument's principle was based on the fact that magnifying power is the aperture of the objective divided by the aperture of its image at the focus of the eyepiece; essentially the dynameter was a calibrated magnifying glass to measure the diameter of the exit pupil of the eyepiece. In practice a small triangular piece of paper was slid from the edge of the objective towards the centre while observing the image in order to determine the effective diameter of the objective since a diaphram could obstruct a portion of the objective lens. When the triangle began to impinge on the edge of the image, this indicated the objective's effective diameter and also that the dynameter was focused on the objective not the eyepiece itself. To determine the magnifying power, the problem reduced to one of measuring the diameter of the image of the objective at the exit pupil of the eyepiece with the dynameter. A simpler means was to use a slip of mother-of-pearl divided to hundredths of an inch inserted in the focal plane. Dexterity and visual acuity were required to adjust the slip and to count the number of divisions across the diameter of the image.

To effect a more accurate determination of the image diameter, Ramsden's dynameter (Fig. 3.4.14) provided an alternative. It consisted of a positive lens divided in half and mounted so that the centres could be separated along the cut. In order to move the lens segments symmetrically, Ramsden used a screw with two threads of the same handedness but with one of twice the pitch to effect opposite motions of the segments. This method was also adopted by Thomas Jones as illustrated in his dynameter and Fig. 3.4.15 shows his mechanism though the rotation of the lenses about a pivot was different from Ramsden's. The drum was divided 0-100 and backlash in Jones' version was controlled by a long flat spring working between the lens cells. The scale had divisions equal to the and dividing by 2. A couple of methods were available to check whether the dynameter could separate the images sufficiently. The better method, as noted by Pearson (p.48) was to mount a piece of ivory or mother-of-pearl with a scale divided to hundredths of an inch on the dynameter. With the lenses centred, one image of the scale was formed but when the screw was adjusted, two images appeared. By adjusting the screw so that the first stroke aligned with the second, the third, etc., one could assess the size of the largest image diameter measurable while also indicating errors of the screws and errors in the scale of the order of 0.001in when a screw of 100 TPI and a drum divided into 100 divisions was used. One advantage of this type of dynameter was that when the second lens was mounted the magnifying power was doubled, and because of their 'joint power' were self-correcting in that they compensated for any differences in the pitch of the screws or if the finer screw was not precisely double the pitch of the coarser in Jones' model.

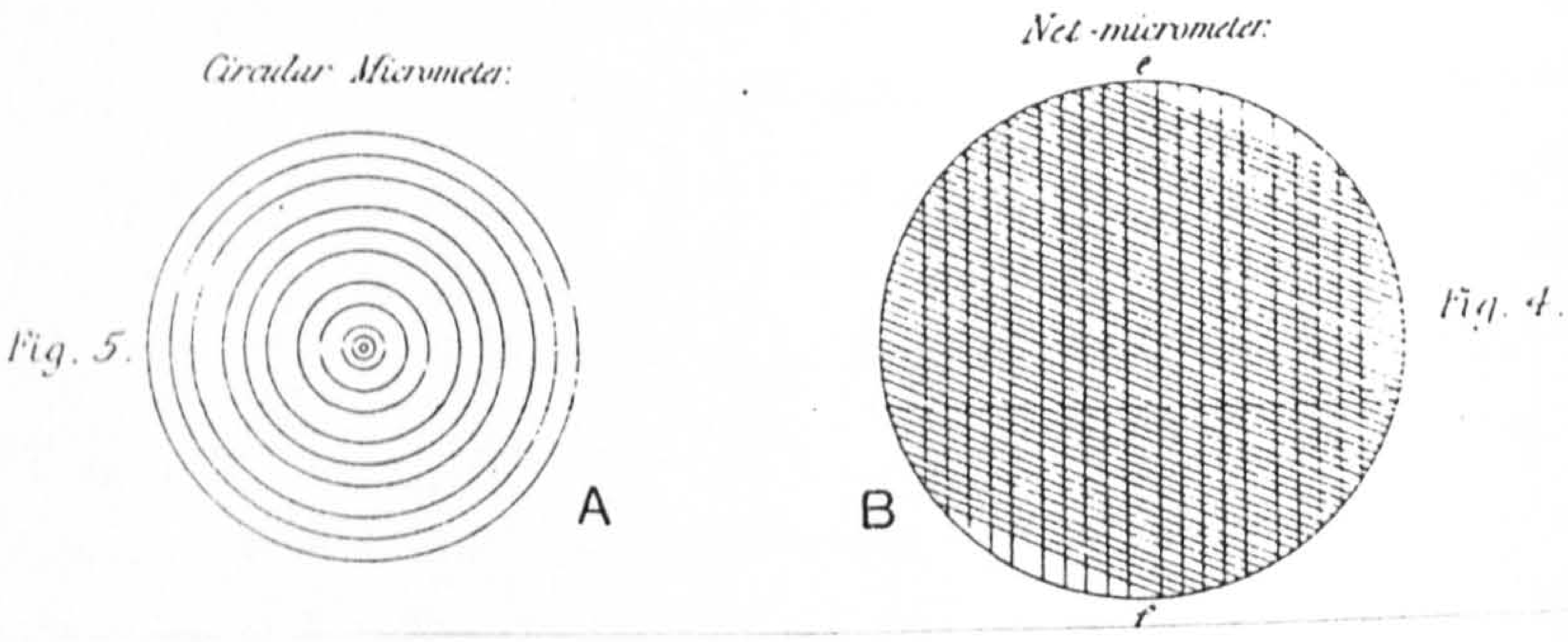
3.4.3.3 Dollond's dynameter:

A second construction of dynameter was designed by George Dollond. It also consisted of a divided lens, but the halves were mounted to slide back and forth in the same plane in the same manner as the frames of filar micrometers. The contrary motions of the lens halves were effected by two screws of opposite handedness and of similar pitch. One screw was of small diameter and mated with a female screw cut along the axis of the larger diameter screw. Backlash was controlled by a single leaf spring as had been employed in early 18^{th} c filar micrometers. This construction was simpler and cheaper to make yet had all the advantages of the Ramsden/Jones style. The screws were of 50 TPI and were checked by use of a divided slip of mother-of-pearl 0.1in long set in a tube which could be mounted over the tube for applying the dynameter to a telescope.

Dollond modified his dynameter so that it could be used with a telescope as a divided eye glass micrometer (though not with Cassegrain or Gregorian reflectors). The modification consisted of an adapting tube for the telescope with an additional negative field lens to provide a wider field of view (Fig. 3.4.16). When the lens segments were separated, the dynameter acted as a divided eye glass micrometer forming two images which could then be measured for diameter or separation. The negative lens followed the dynameter--not like a Barlow lens which is mounted before the final lens. Pearson (p.192) noted that this arrangement, i.e. of a dynameter used as a micrometer, was impractical for measuring close double stars since they must be measured very near the line of separation between the lens halves. If one object was faint, it was also difficult to see. The limit was ≈10" "when the stars are both of a considerable size". Troughton & Simms' dynameter was of Dollond's design; an example is in the WMHS.

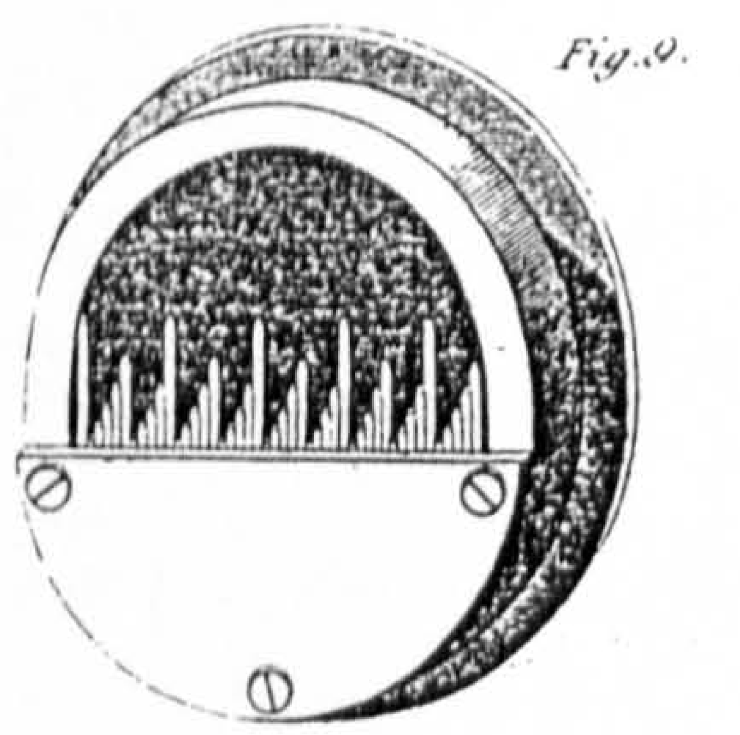


3.4.17 Airy's divided eye glass micrometer (ca.1840). This example is in the Royal Observatory (ROG-5). The moving components are similar to the corresponding components of other Simms filar micrometers of the period. Although unsigned, this instrument was probably made by Simms.



3.4.18 Fraunhofer's circular and 'net' micrometers (ca.1810).

3.4.19 Wollaston's 'wire' micrometer (1813).



3.4.3.4 Airy's Divided lens micrometer:

Closely associated with the principle of the dynameter is the divided lens micrometer. The first of this type was Ramsden's dioptric micrometer (which as we saw consisted of a divided lens at the conjugate focus of the second lens of an erecting eye tube of terrestrial telescopes) but neither this nor the version independently invented by Peter Dollond became popular. Amici's (1815, p.344-59) was more successful and used a similar concept. He introduced a divided negative lens between the objective and eyepiece of a telescope which formed a double image which could be measured with a micrometric screw. Better results were obtained by W.R. Dawes (1858, p.58) by using a filar micrometer to measure the separations.

Airy's divided lens micrometer (Fig. 3.4.17) is of particular interest since an unsigned example is found at the Royal Observatory (ROG-5). His design (Airy: 1846, p.199ff.)[1] employed a four lens eyepiece of which the second element was divided in two parts either or both of which may be moveable. This divided lens was at the focal distance of the first lens. The parts moved by screws in the same fashion as in filar micrometers of the day. The frame of the filar micrometer was simply modified to carry a lens rather than a frame with fine wires. The method of use was given by Airy in 1840 in the Introduction to **Greenwich Observations**. An unexpected source of error, but one Airy should have been aware of since Ramsden had also encountered it, was the introduction of what Airy termed prismatic dispersion. It was caused when the lenses were separated and by the fact that the surfaces of the segments are effectively inclined to the incoming converging beam of light. This also caused problems when calibrating the scale since Airy found only one practical method of calibration. This was to separate the lens halves to create two star images and then to observe their transit across a wire which had been temporarily placed across the lens and lying in the meridian. Airy recommended that "the micrometer-screw for moving the divided segments should be rapid, and its range considerable as, on account of the great focal length of the divided lens, a large motion is required to separate the images widely" (Airy: p.207-8). He also noted that Mr. Simms had made the eyepiece for him. According to Airy, the device worked well with some minor problems similar to those encountered with heliometers, i.e. loss of light, and with the exception that it was not well suited to measure position angles. This type of micrometer, because of the optical configuration, had a varying value of the screw calibration which went unnoticed until F. Kaiser (1872, pp.101,274) pointed it out.

---

[1] A description of the first form may be found in *Cambridge Phil. Transactions*, **2** (1840) and **Greenwich Observations** (1840). The micrometer described by Airy in 1840 was an improved form. Other descriptions appear in *Abstracts of the MNRAS*, **6** (1843/5), pp.229-31; *Memoires of the RAS*, **15** (1846), p.199-209; and, *MNRAS*, **10** (1848), p.160.

3.4.4 Other Micrometers:

3.4.4.1 Fraunhofer's glass micrometers:

A link between Brander's glass micrometers and the superb microscope test plates of Nobert was the net micrometer of Joseph Fraunhofer. This was meant to be an improvement of the rhomboidal micrometers (of Bradley, Bradley, LaCaille and Wollaston) and consisted of a glass disc (Fig. 3.4.18) divided by many parallel lines and with a second set engraved obliquely to them. These were illuminated with a small lamp. According to Pearson (1829, p.144), Fraunhofer developed a ruling engine with rotating table with which to rule lines with separations as fine as 0.0001in. For his net micrometer, the angle and separation of the second set were chosen such that the cosine of the angle gave the same separation between the lines for both sets of lines. This meant that a star crossing the field would undergo the same number of transits from either set of lines. In ruling the lines, Fraunhofer made the separation between every 5th and 6th line, 11/2 times the normal separation which was intended to help read the number of divisions. Though not widely adopted, Struve used a number of Fraunhofer instruments at Dorpat, to obtain respectable results. A feature of this device was that the cell could be rotated in conjunction with a revolving graduated circle to measure position angles.

3.4.4.2 Optical micrometers:

There were any number of micrometers which did not rely on screws in their use or their manufacture--what we might term micrometers with passive measuring elements. Of these optical micrometers, the most common were those made by George Dollond (his crystal micrometer of 1821[1]), Clausen (1841) and Heckmann (parallel plate micrometers) which were not very different in principle from those of Abat (1777) and Boscovich (1777) and lead directly to the stadiometers of the 20th c.[2] One of the more ingenious was the chronometer micrometer of Breguet which was intended to note transit times more precisely by giving a visual indication of the fractions of seconds rather than the audio stimulus used in Bradley's ear and eye technique.[3] Baden Powell (1847) used a thin wedge inclined to the optic axis as a micrometer device, the concept of which is still used in modern spectroscopy in the Racine wedge for creating off-set secondary images. However, we will again restrict discussion to those of more immediate interest.

Cavallo's:

Tiberius Cavallo described a simple form of micrometer (1791, p.283-94) which simply consisted of divisions drawn on a piece of mother of pearl thin enough to be partially transparent. Its size was of necessity small since it was intended to be fixed to the diaphragm at the focus of a convex eye lens and could not obstruct too much of the

---

1 See G. Dollond: 1821, p.101.

2 See König (1937, p.139ff.) for a brief description of some of these.

3 See Breguet:1818, 431 or for an English version Breguet: 1819, p.323.

field. A slight motion of the diaphragm was desirable so that it could be moved back and forth to permit objects to be lined up with a division of the scale. The scale was ≈0.6in long with divisions ≈0.01in apart and presumably divided with some sort of dividing apparatus. The value of the divisions was of course dependent on the instrument to which it was applied.

Coventry's:

Probably the most frequently referred to micrometer which was not a filar micrometer or heliometer was that devised by John Coventry (1735-4/12/1812)[1]. About 1774 Coventry displayed several of his grid micrometers to the Royal Society. These were primarily intended for use with microscopes. The lines of the original versions were drawn 50 to the inch but he proceeded to improve them to 100 then 1000 per inch. Nothing has been found describing Coventry's method of dividing (dividing engine or lever principle) but it is known that he used a fine diamond for the ruling.

Fraunhofer's and Baily's Circular:

Fraunhofer made a circular micrometer (Fig. 3.4.18a) by drilling a small hole in a piece of glass and drawing several concentric circles about it. This was placed in the focal plane of the telescope objective and eyepiece and the times of stars to cross the respective circles noted. This form became popular on the Continent being used successfully by Soldner. A number of observers had used circular diaphragms, but Fraunhofer extended the usefulness by including 11 circles on the same glass disc. On one instrument, Fraunhofer measured the diameters to be (Pearson: 1829, p.147):

1= 0.0038	7=0.4426	(Paris inches)
2=0.0248	8=0.5264	
3=0.0840	9=0.6338	
4=0.1678	10=0.7178	
5=0.2513	11=0.8012	
6=0.3590		

These discs were engraved on a lathe with the tool mounted in a cross slide. The main problem with their use was lack of an eyepiece which could focus well over a sufficiently large field to include all of the engraved circles simultaneously. A later version by Fraunhofer had a small hole (≈1/2in diameter) drilled in the centre of the disc. This was then filled with silver and another hole drilled in the silver leaving a thin border (≈1/16in wide) which appeared as an annulus suspended in the centre of the field of view when observed through the telescope. This version became known as the suspended annular micrometer. Francis Baily used the same circular discs but cut them in half recombining them in a variety of patterns. As long as the relative diameters were known,

1 See details as given in his obituary in W. Bicknell, *Gentleman's Magazine*, **83** (1813), p.180.

formulae could be developed to yield the difference of right ascension and declination.[1] The technique does not appear to have been widely used however.

Nobert's:

The cleverest glass grid micrometer was that of Alfred Nobert of the mid-19th c (Turner: 1967-1, p.344). It consisted of lines drawn in 5 groups of 11 lines with each group separated by 15" when viewed through a telescope. Each band was 1/300 Paris inch (7.52µm) wide which was the width of a common micrometer filament and the line separation was 0.736µm. A special property of this arrangement was that tilting the angle of illumination changed the colour of the bands, i.e. Nobert used the diffracting properties of the closely spaced lines. The colour changing property could be used to measure the relative colours of stars by measuring the angle of the illumination. By altering distance of the illumination, a simple photometer was created. Thus this instrument could perform three functions with some simple adjustments.

Walker's:

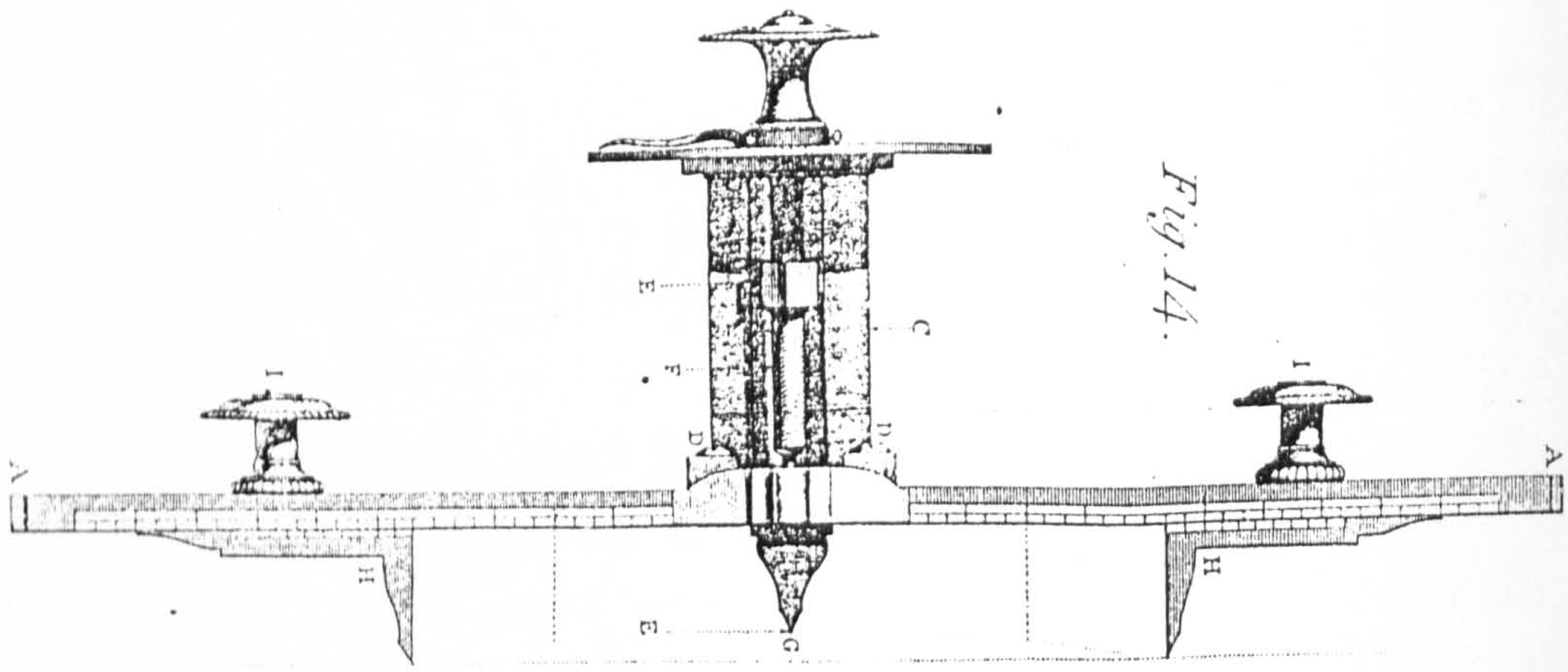
Ezekiel Walker first published a description of a grid micrometer in the *Philosophical Magazine* (1811, p.127) which he had conceived about 1805 at which time he had had examples made for him by William Cary of London and by Miller & Adie of Edinburgh. Brewster provided a description in his book (1813) which indicated that lines were on mother of pearl but this was incorrect and prompted Walker to publish a correction (1816, p.14-16). The lines were in fact drawn on glass. Walker claimed to have succeeded in making examples with sets of lines 1/1000th inch apart and drawn at right angles but settled on lines separated by 1/100th inch for use with microscopes or telescopes. Walker's method of drawing the lines was not described but we can assume that the lines must have been accomplished with some sort of dividing engine or lever device.

Wollaston's:

William Hyde Wollaston described his 'single-lens' micrometer in 1813 (Fig. 3.4.19). It consisted of a 1/12th inch focal length lens focused on a diaphragm which had fine wires of 1/50th inch diameter fixed side by side and in contact to act as the scale. The object to be examined was placed in a small frame and inserted in a tube carrying the lens and having the appearance of a telescope. The tube was drawn out to one of the marks on the tube indicating the scale size; the sample was then moved laterally and its size compared to the wire scale.[2]

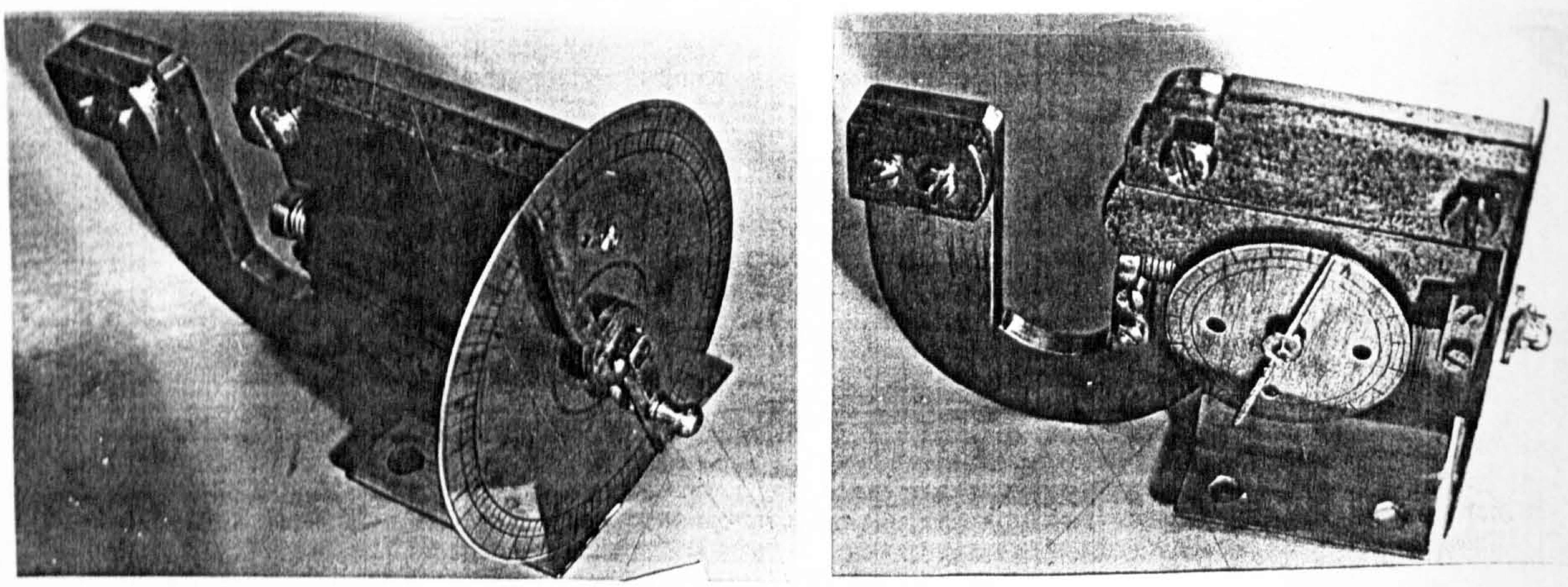
---

1 See Baily: 1824, p.177 or Brewster: 1824, p.104.
2 See Wollaston: 1813, p.197.

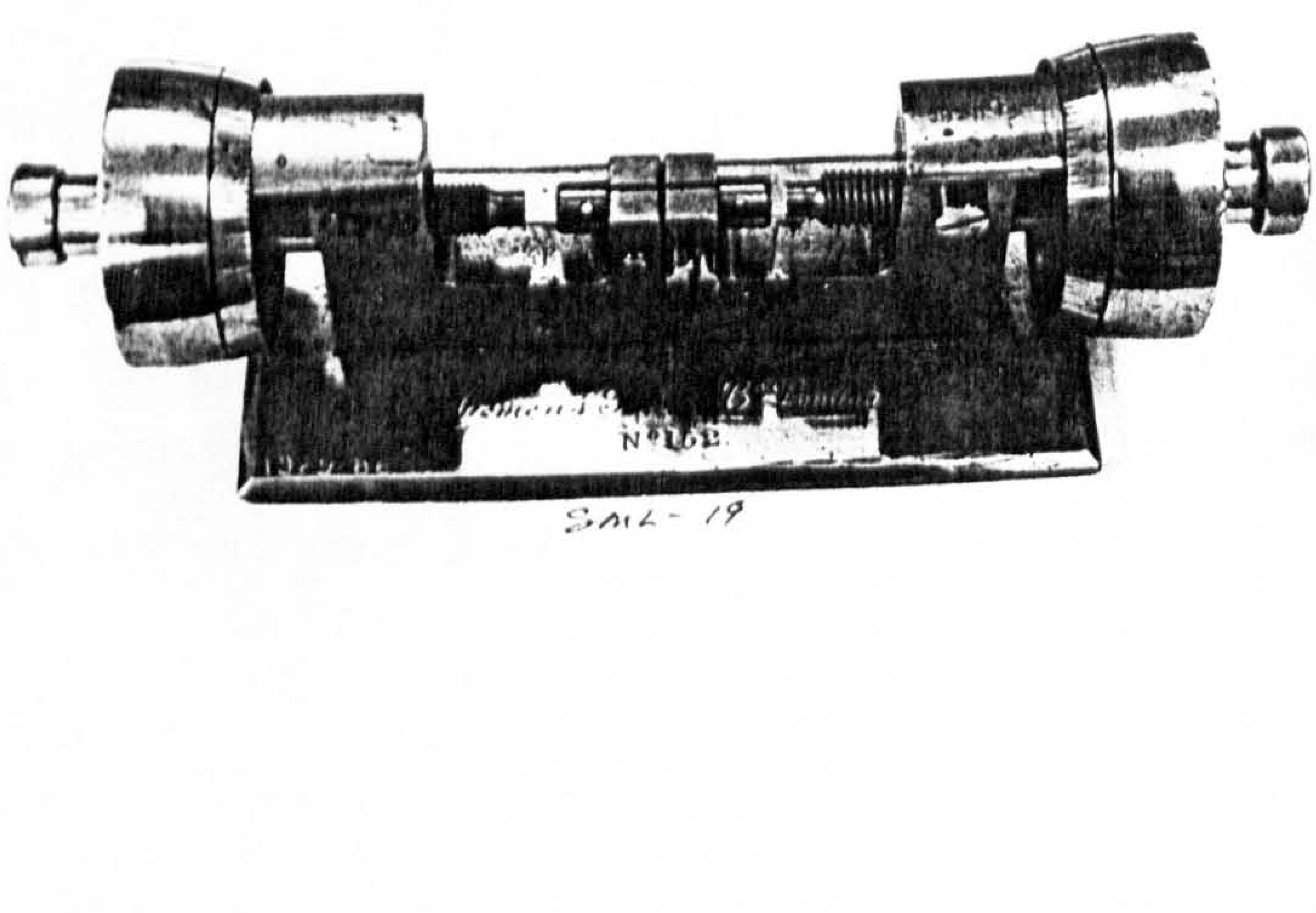


3.5.1 Chaulnes' two-legged 'spherometer' (ca.1767).

3.5.2 Watt's bench micrometer which is in the Science Museum (SML-20).



3.5.3 Siemen's English/Metric micrometer (ca. 1880).
This specimen is in the Science Museum (SML-19).



SML-19

3.5 Bench Micrometers and Comparators:

An important application of the micrometer was, of course, for measurements of mechanical components by machinists or scientists. The first would appear to have been that of Brunn and Treschler (1609/1619). The micrometer was not only applied to length measurement but also to angular determinations such as the circumferentor of Heintz and later protractors of the 19^{th} c. Troughton & Simms employed a micrometer in their bubble level tester (WMHS-1). A similar use was the 'spherometer' for measuring the curvature of lenses and mirrors which may have been the idea of the Duc de Chaulnes (1767). It (Fig. 3.5.1) consisted of a scale to which were attached two pointers adjustable in position along the scale. The micrometer screw was at the centre of the scale. The point was raised and lowered by a precision screw but the pointer was a simple index rather than a vernier as he used on his micrometer microscopes. This instrument was used in his investigation of the focal lengths and refractive indicies of lenses for achromatic telescopes and is the first representation of a spherometer encountered though with 2 rather than 3 feet.[1]

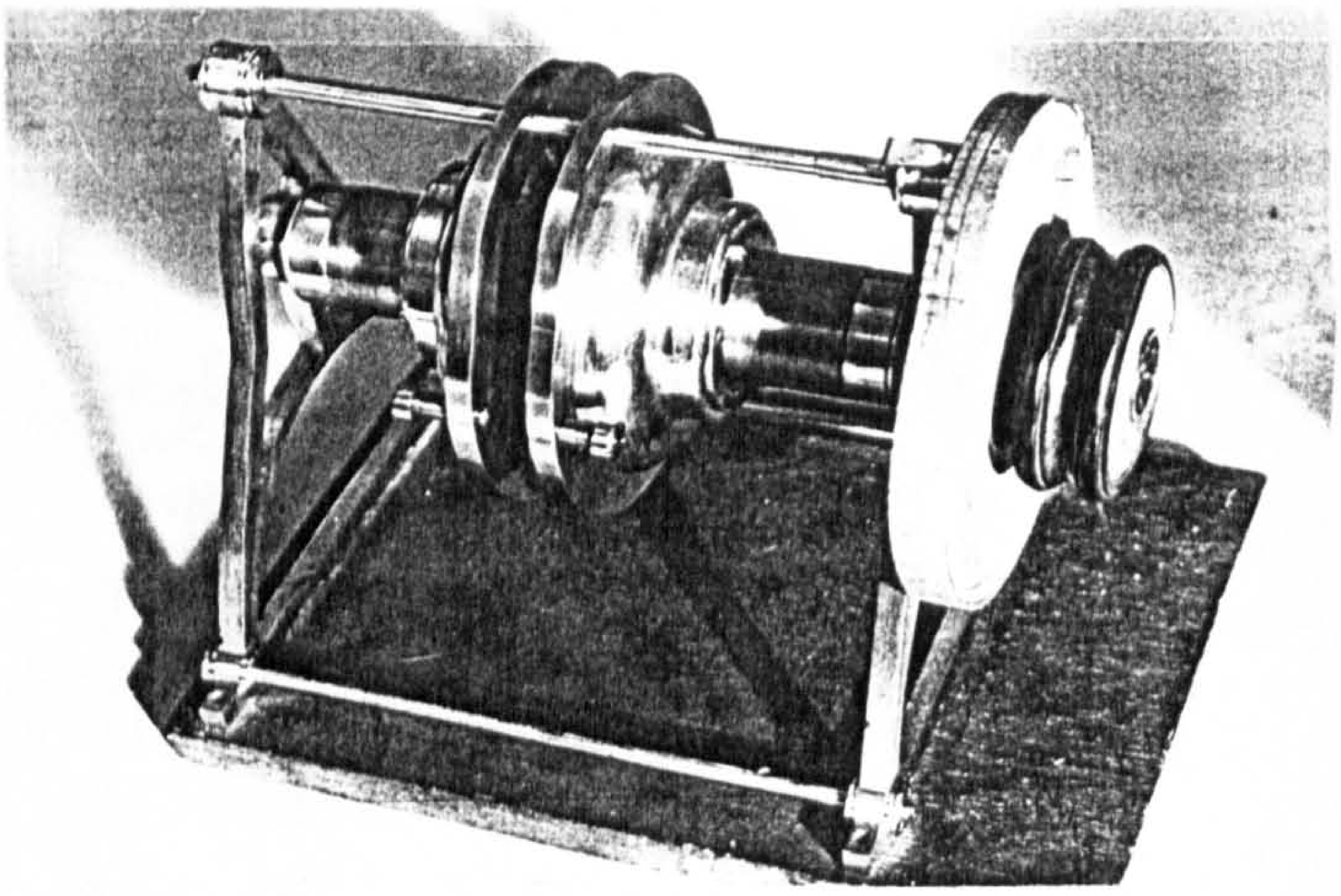
Bench micrometers are mechanically simple, with their precision dependent upon the accuracy with which the screw and nut are made. Watt's bench micrometer (Fig. 3.5.2) is considerably larger than standard 'C'-type micrometers of today. James Watt, best known for his steam engine and engineering work, made a number of micrometers including one preserved at the Science Museum[2]. This micrometer (SML-20) is thought to have been made ca.1770 although no contemporary documentary evidence has been found to support this belief. It is a bench micrometer--the earliest such micrometer found[3]--for the use of a machinist. Although intended to be mounted on the bench, it has the basic form of the common 'C' micrometer. The screw of this micrometer is very coarse by comparison with astronomical micrometers of the time (1.397mm or ≈18 TPI). Since the micrometer does not function at all smoothly, with the threads of the screw and nut being badly mismatched, one wonders if it has been restored. This poor match is contrary to what one would expect since Watt had begun his career as an

---

1 A large part of this 1767 paper is devoted to an analysis of achromatic objective lenses and various combinations which he had attempted. He also included the formulas calculated by Bezout.

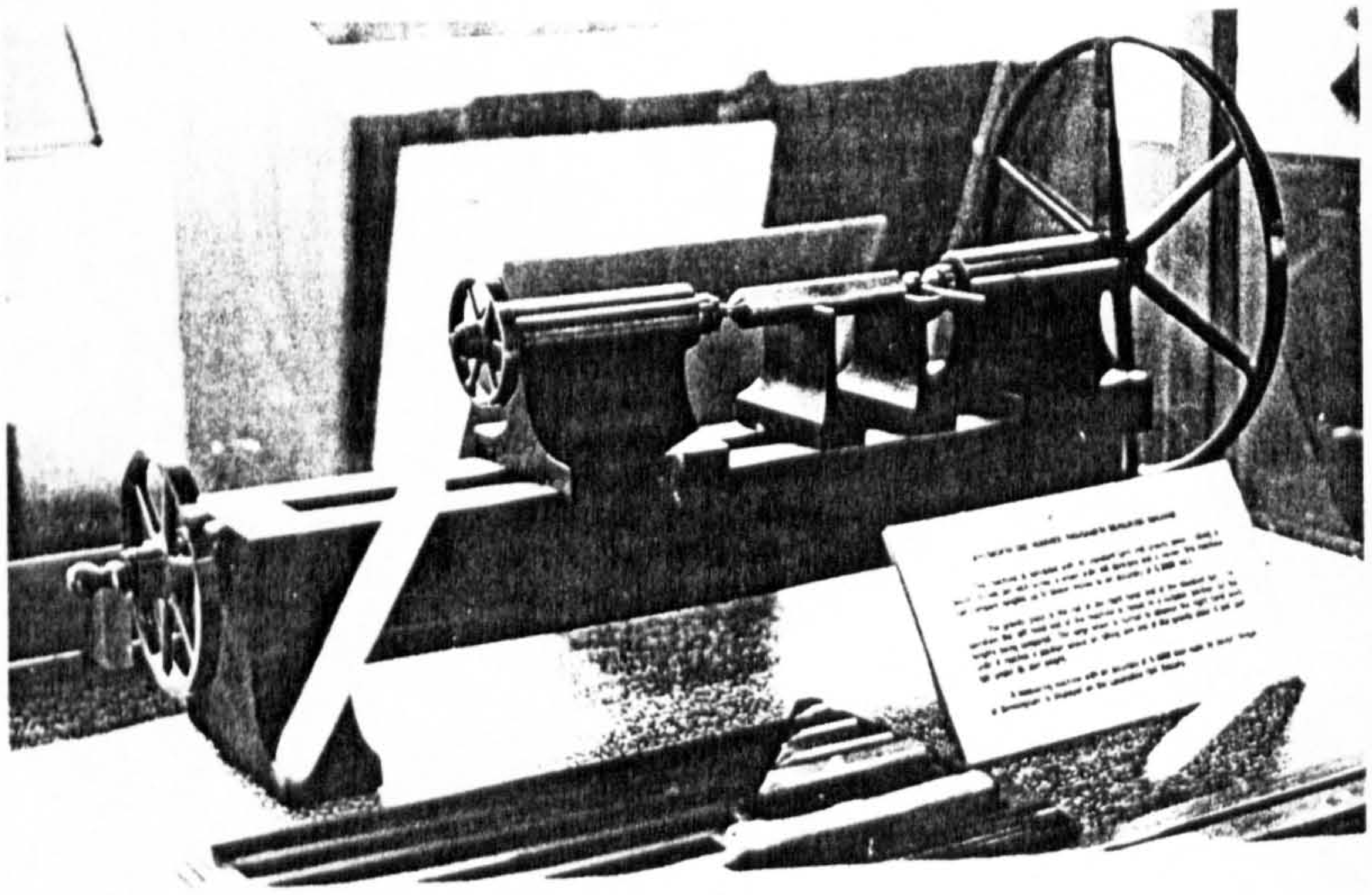
2 Watt was also the designer of a copying machine for use in offices and for copying plans. In a letter to his frequent correspondent, the chemist Joseph Black, and dated Dec. 15 1772 Watt states "I send you this days coach, My plans of Tarbert and Crinan with sections of them both, the parallel lines in the sections were drawn by the help of the dividing screw" (Robinson, McKie: 1970, p.34). In another letter (22 May, 1773), this time from Black to Watt, we find "...I must beg the favour of you to bring when you come, the divided plate for graduating thermometers--Your machine with the Screw is admirable for its exactness but the plate will be exact enough...(p.39).

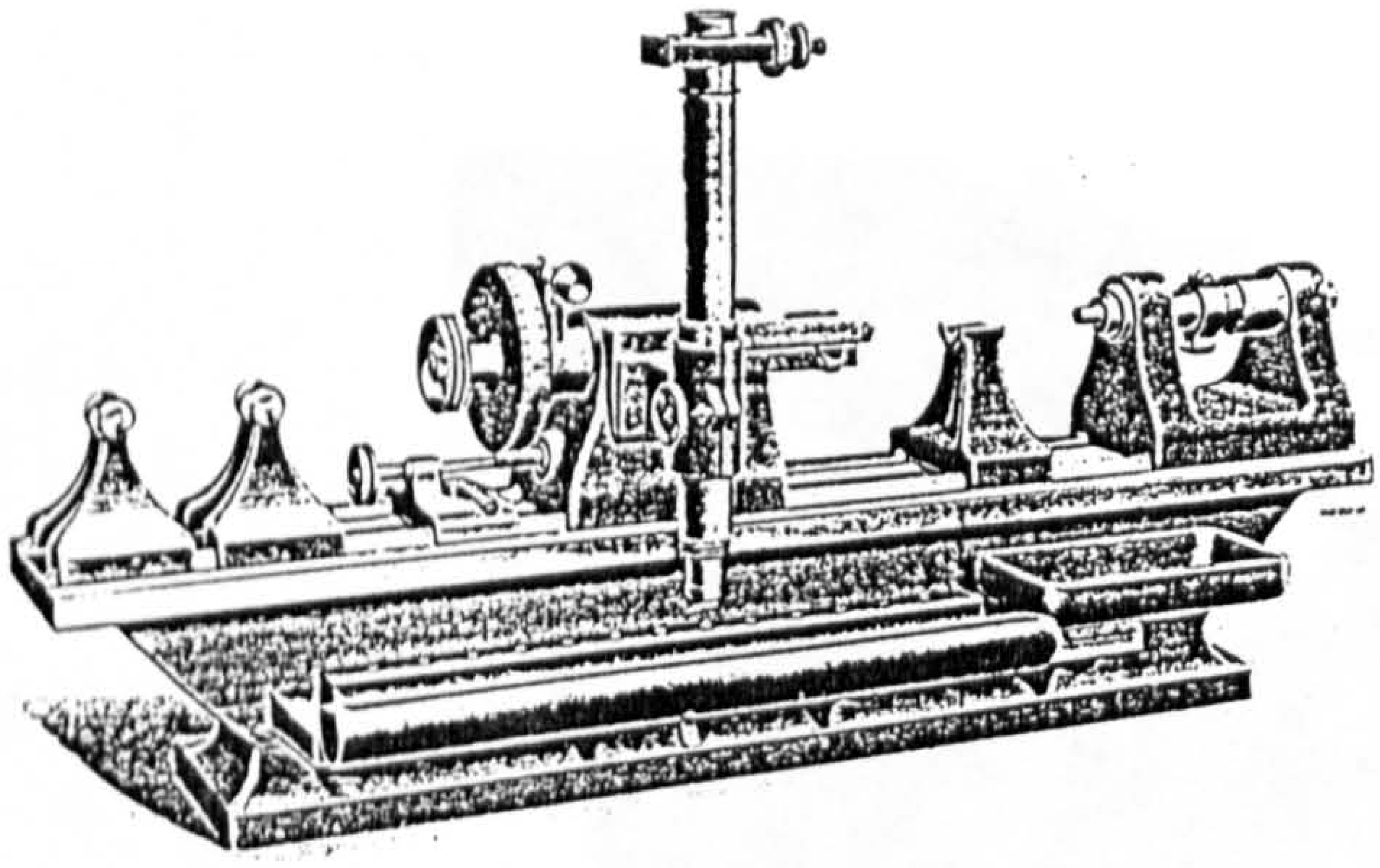
3 The Brunn/Treschler device may have been for a machinist but its exact purpose has not been determined. It is also lost, making the Watt micrometer the oldest surviving bench micrometer.



3.5.4 Burton's 'atometer' (1805) which is in the Science Museum (SML-22).

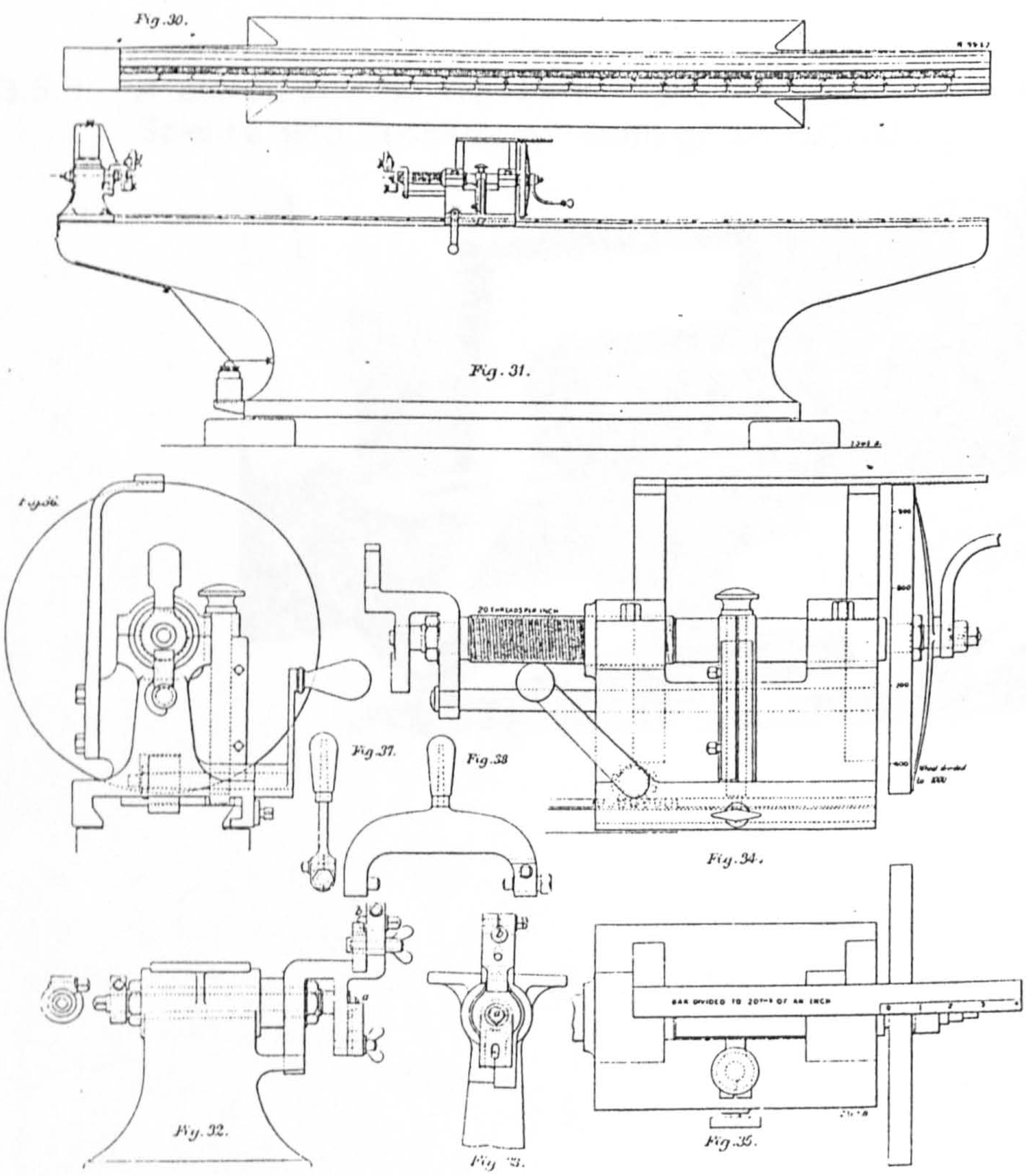
3.5.5 A comparator by Whitworth (1869) in the Museum of Science and Technology, Birmingham (MSTB-5).





3.5.6 A comparator by the Hartford, CT. firm of Pratt & Whitney (1899). Note the main wheel but also the micrometer for reading the scale and for positioning of the micrometer head.

3.5.7 A comparator by Cooke of York (1894). The screw was 20 TPI and the wheel divided into 1000 parts. The micrometer head shown in the lower figures had a range of 4in.



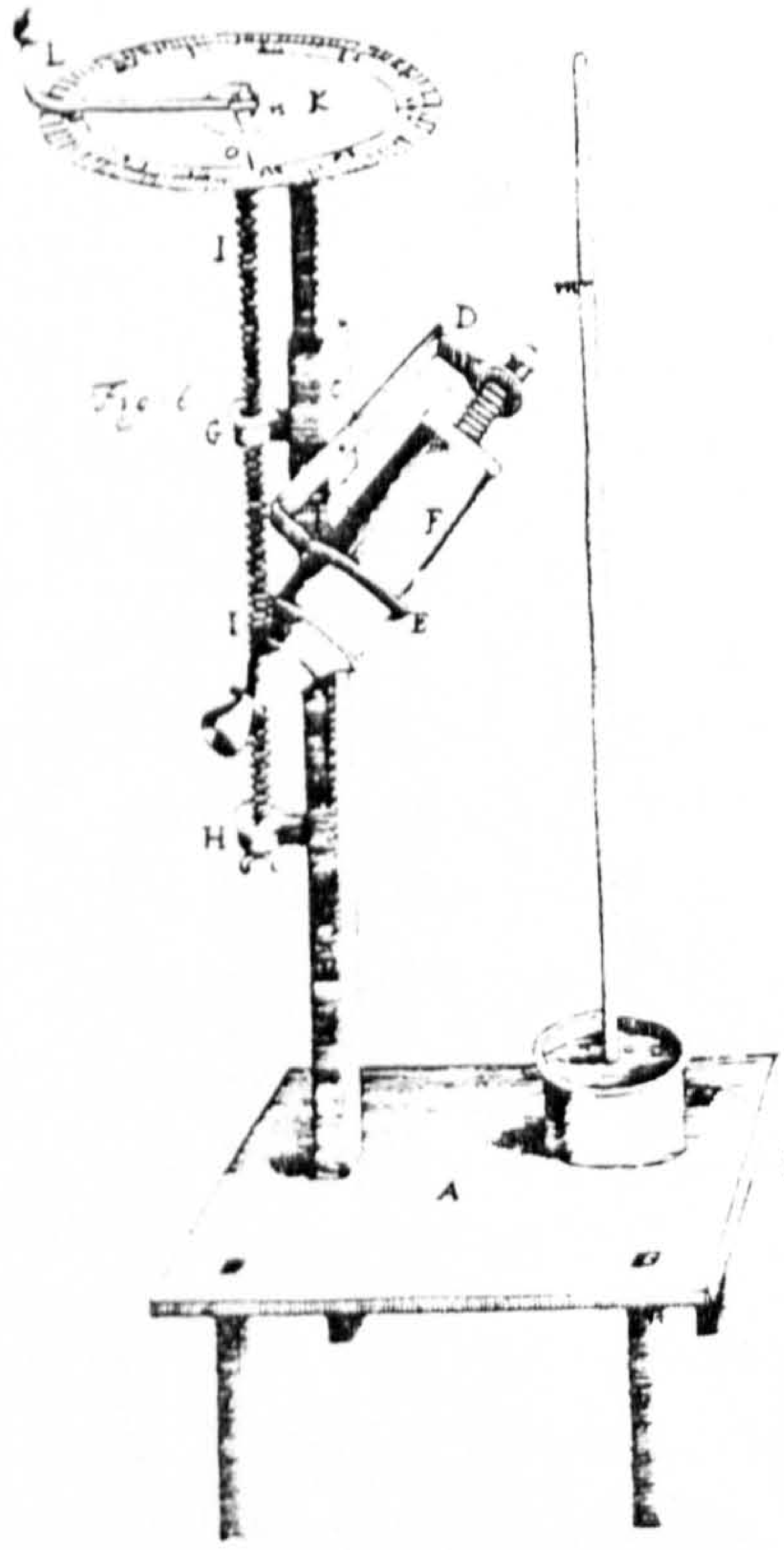
instrument maker to the University of Glasgow. The nut on this instrument is 0.75 inches long and there is no provision to control backlash.

Early models by Maudslay (e.g. SML-21) were not of the simple form to develop later in the 19th c, but yet were the first to be of moderate precision and of course his Lord Chancellor was the most accurate micrometer/comparitor made until the 'millionth inch' comparitors of Whitworth. The common 'C'-type micrometer was patented in France in 1848 by Palmer (French Patent #3762)[1]; a small example is in the Science Museum. Other makers often sold Palmer type micrometers as the 'German-Silver wire gauge'. A modification of Palmer's design was the digital micrometer which was made in Britain late in the 19th c. It used an 'odometer'-type mechanism and some even had a ratchet mechanism to ensure consistant force on the sample when taking a measurement. Seimens Bros. made a combined English and metric bench micrometer (SML-19 and Fig. 3.5.3) which used screws of the same pitch (English) but made the adjustment for the difference between 1in and 2.5cm by simply inclining the fiducial line with respect to the axis of the screw on the drum of the metric side.

Barton's 'atometer' of 1805 (Grodzinski: 1947-9) (SML-22 and Fig. 3.5.4) used two large diameter, fine pitched screws of slightly different pitch to make a comparator but, assuming its current condition is good, tests indicate that it was not reliable. This was largely due to slackness in components and to screw threads which do not mate nicely with those of the nuts. Superior comparators were designed by Whitworth (Fig. 3.5.5) which employed a gravity feeler piece to indicate when contact with a specific force was applied. These machines were capable of differential measures to a millionth of an inch, but were not intended for absolute measures as is demonstrated by the results recorded in Chapter 6. The Connecticut firm Pratt & Whitney used Whitworth's gravity feeler on a sturdy bench micrometer (Fig. 3.5.6) employing a 12in long, 50 TPI screw with a drum with 400 divisions to reach a precision of 0.00005in over the 12in range (*Engineering*, **64** (1898), p.595). The York firm of Cook had also reached this precision (*Engineering*, **59** (1894), p.696) in a machine with an 8ft 3in capacity (Fig. 3.5.7). This machine used a 7in screw with a head stock moveable by the screw and a dial of 9in diameter and 1000 divisions. The screw was 1 1/4in diameter and 20 TPI driving a nut ≈2 1/4in long. The other headstock was positioned by pins fitting in holes accurately positioned 4in apart. One is referred to Sweet (1901) for an illustrated discussion of workshop micrometers and comparitors of the late 19th c.

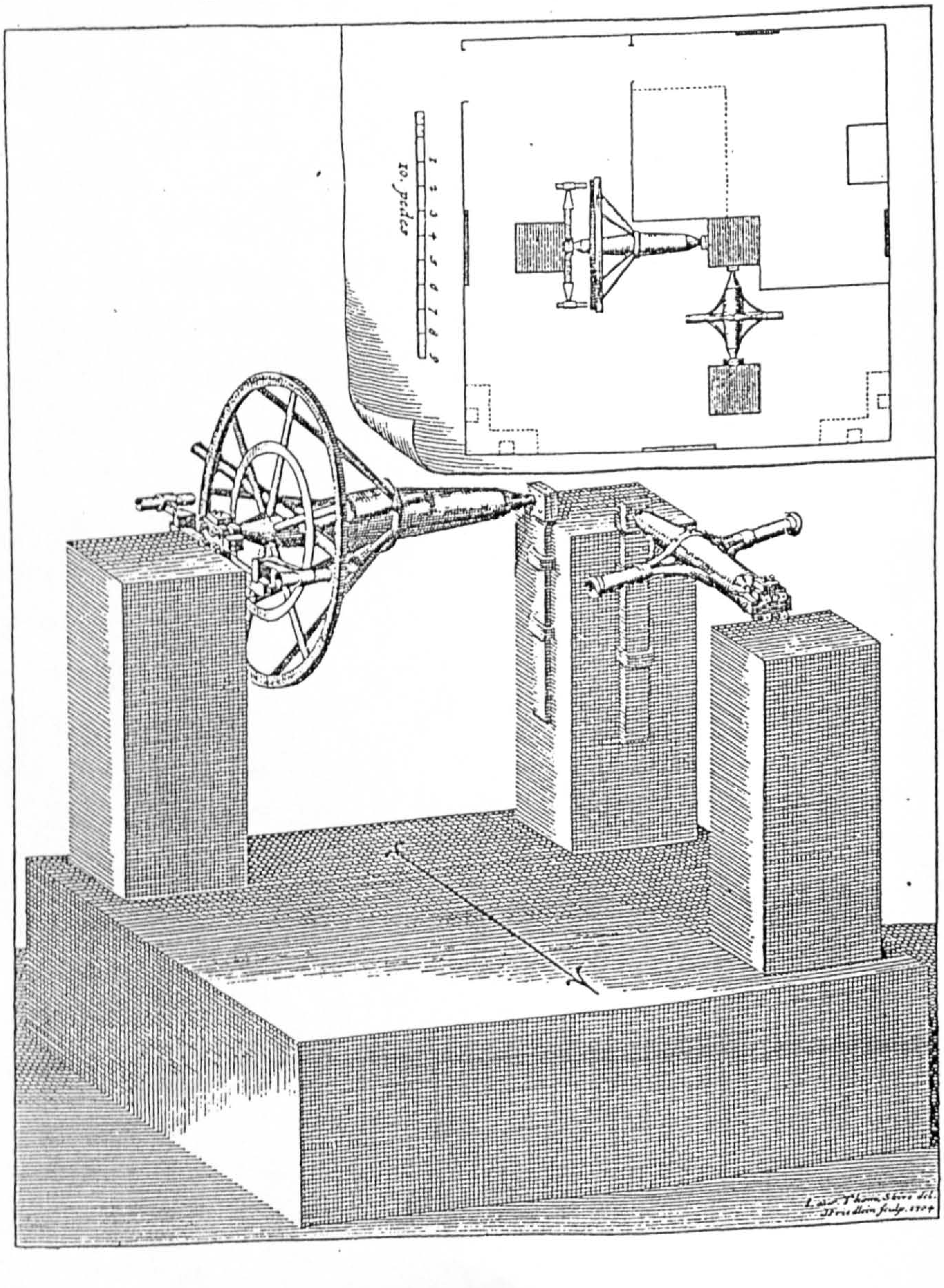
---

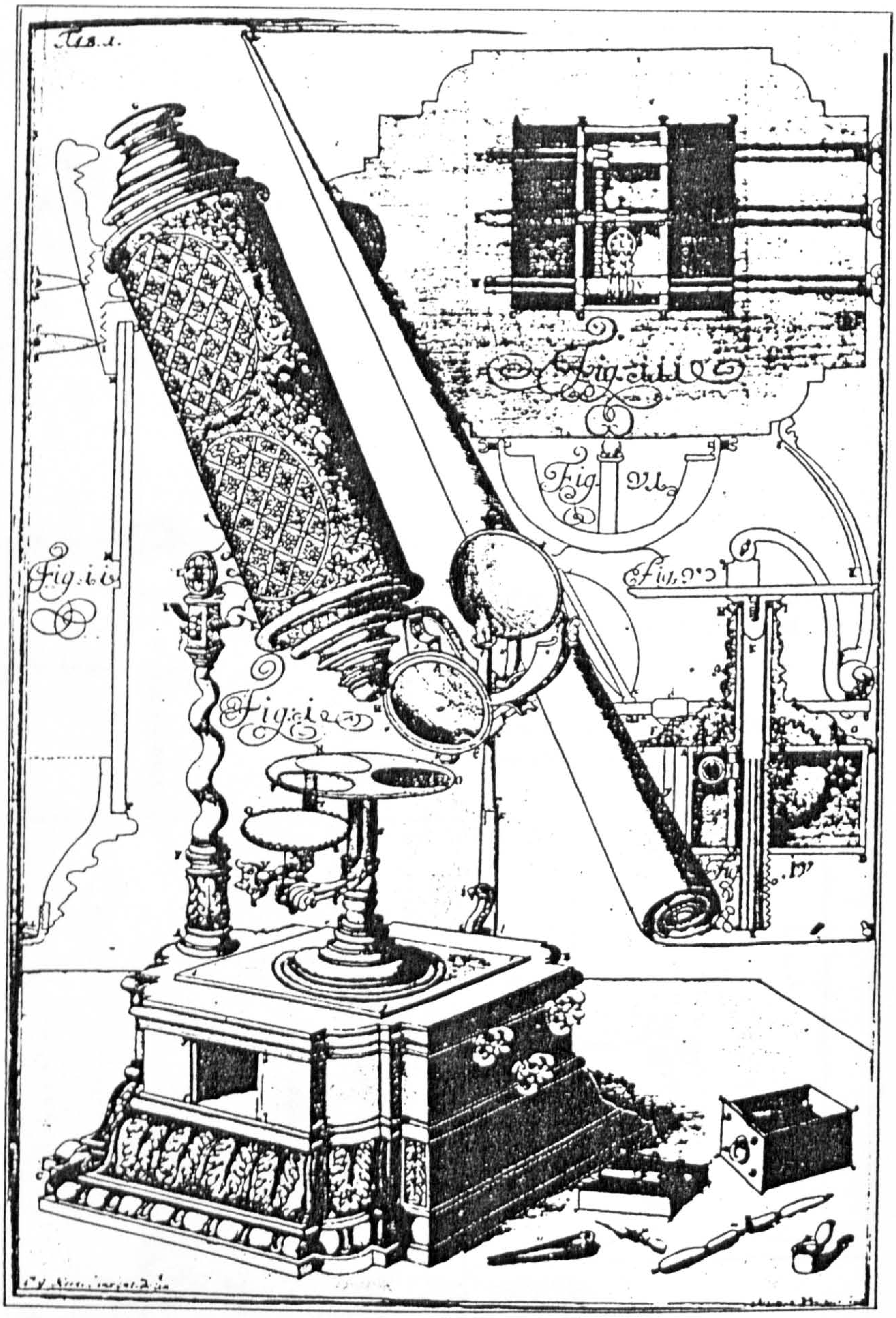
1 An example is illustrated in Roe: 1914, facing p.212 and may be compared to some of later date by Brown & Sharpe. MSTB-7 is similar though of finer pitch to the one designated 'D'.



3.6.1 Gray's barometer with microscope micrometer for reading the level of the mercury (1698).

3.6.2 Römer's transit (1704) with the scale reading micrometers.





3.6.3 Hertel's microscope with two-axis mechanical stage (ca.1720). The stage is illustrated in the upper part of the diagram.

3.6 Micrometers used with Microscopes:

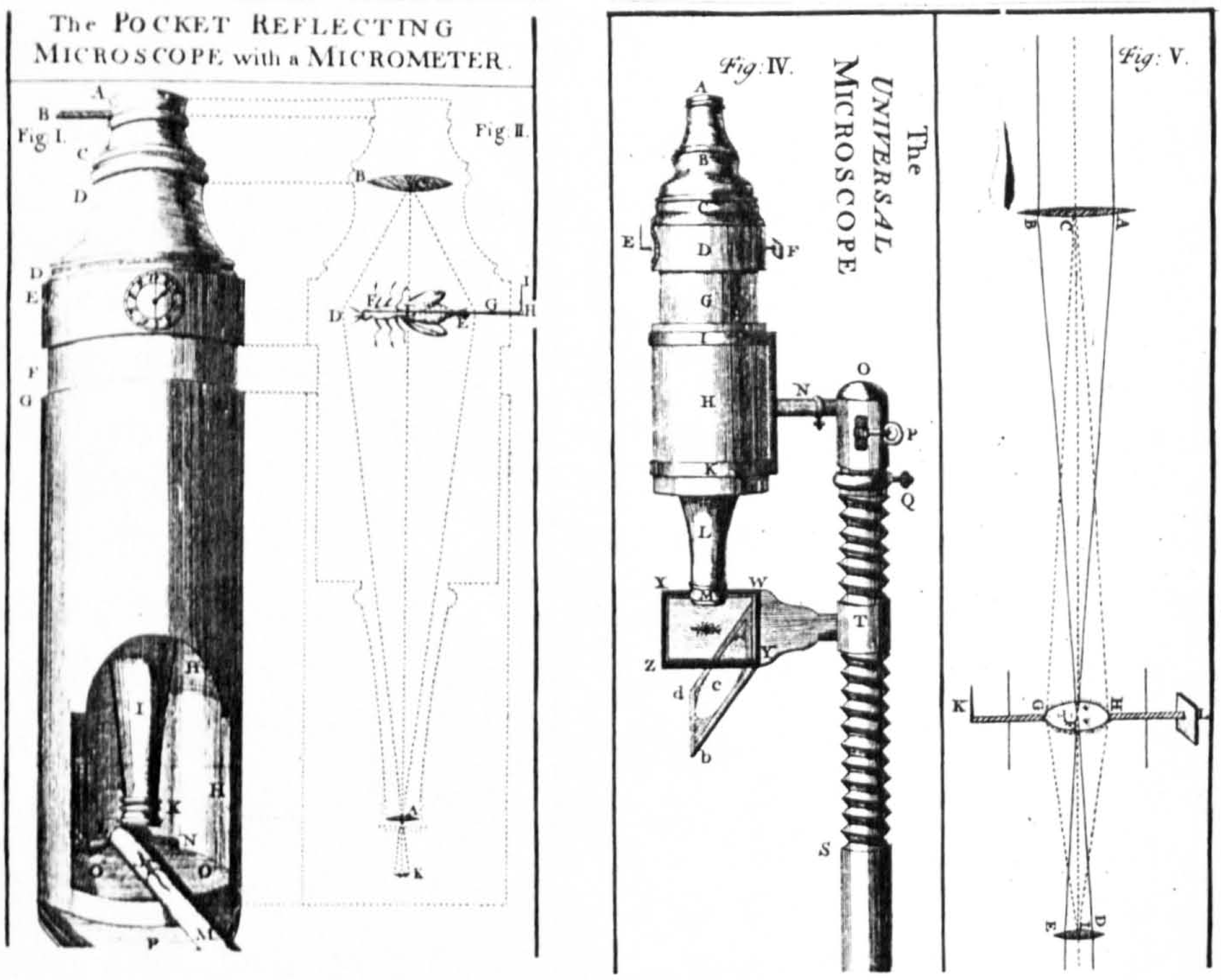
It would appear that the first use of a screw in combination with a microscope was that employed by Stephen Gray to help measure the height of columns of mercury in barometers (Gray: 1698, p.176-8; see also Wolf: 1950, v.1, p97-8) (Fig. 3.6.1). King (1955, p.104) says that Römer was the first to use a microscope (sans micrometer) in reading the scale of his transit instrument. However, this opinion was based on Horrebow's 1735 description of Römer's work and instruments and the date of this application is not given. Römer made his first transit ca.1690 but at what time he incorporated microscopes for scale reading is not known. An illustration of his 'rota meridiana' was engraved in 1704 (Fig. 3.6.2) which shows two microscopes placed 180° apart. Thus we can deduce Römer was aware of the necessity to eliminate errors of eccentricity.

Clay and Court in their work on **The History of the Microscope** (1932) noted the use of micrometers with microscopes. The first use they recorded (pp.104-5) was the microscope of Christian Gottlieb Hertel which carried a 2-axis mechanical stage and both screw and net (i.e. ruled) micrometers (Fig. 3.6.3). They also recorded (p.155) that Benjamin Martin claimed he was the first to fit a micrometer to a microscope in his pamphlet **Pocket Reflecting Microscope** (ca.1738); this was his well known drum type microscope. Martin's micrometers (Fig. 3.6.4) consisted of a pointed wire attached to a screw with a dial and projecting into the field of view at the focal plane. The screw was 1/2in in length and of 50 TPI (Martin: ca.1738, p.8); in combination with the dial divided into 10 divisions and subdived in half it allowed measurement to 0.001in.[1] G.F. Brander made microscopes with similar micrometers (Fig. 3.6.5) in Germany. Martin apparently also fitted a micrometer to his larger 'Universal' microscope but on these the dial was divided into 100 divisions (Martin: p.25). Martin also introduced a glass micrometer with lines 1/40in apart of which he says "These lines I draw with exactness by a machine I contrived for the purpose" (Martin: p.32-3). John Cuff also used a '50 to the inch' micrometer with his microscope of 1747. It actually consisted of a lattice work of silver wires inserted 1 1/4in in front of the eyepiece. An example is in the Court Collection of microscopes (Clay & Court: p.139). Cuff also made a glass plate micrometer for use in place of a diaphragm; it was inserted by unscrewing the eyepiece. It too had 50 divisions to the inch being ruled with a diamond.

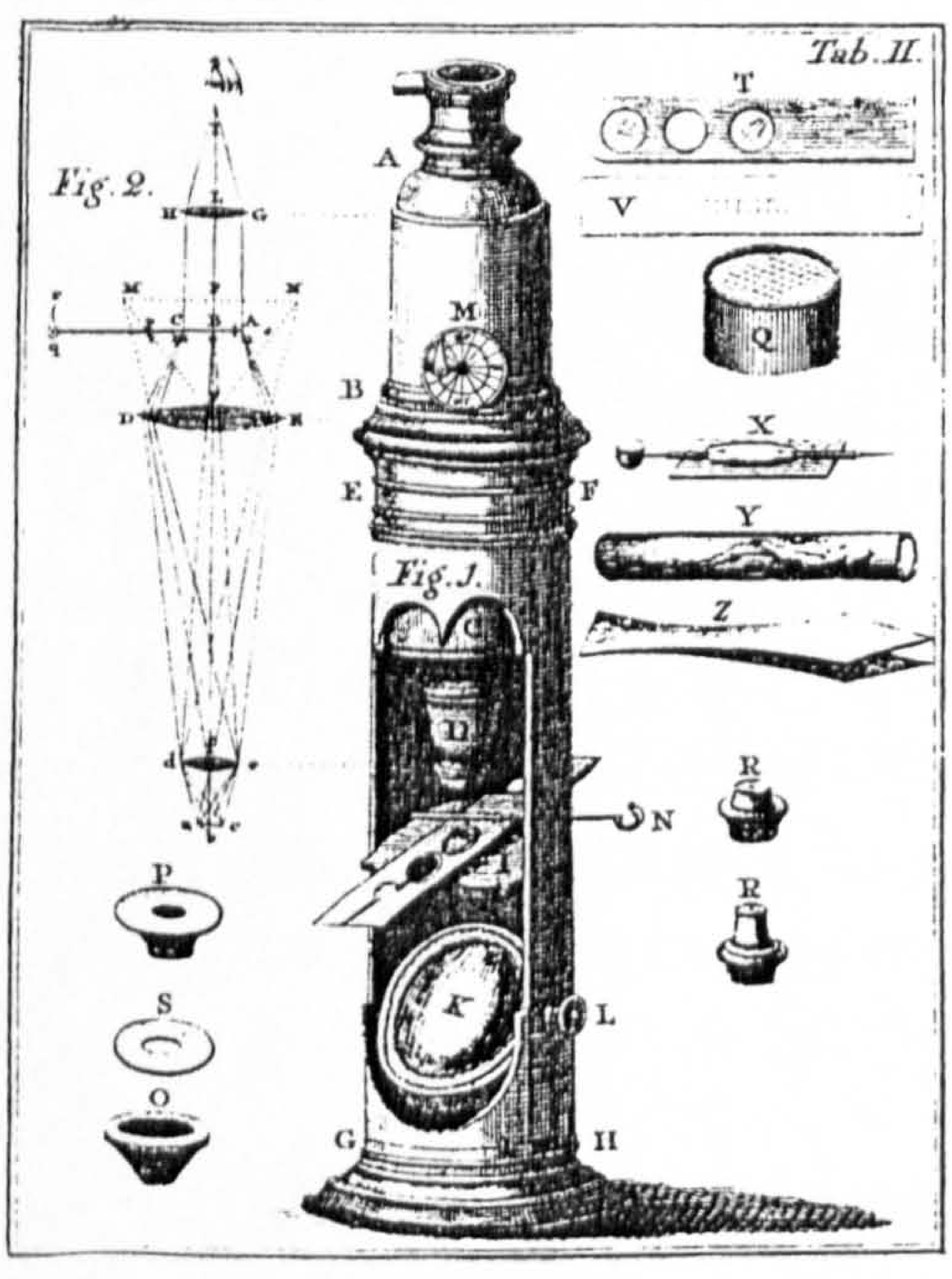
George Adams Sr. made a silver microscope (1751-60) which he called the Prince of Wales microscope (Clay & Court: pp.174-6 and Fig. 3.6.6a). This instrument carried **XY** screw micrometers on one of its three stages. The screws were 100 TPI and employed split nuts but without tightening screws. With a dial divided into 100 divisions, this

---

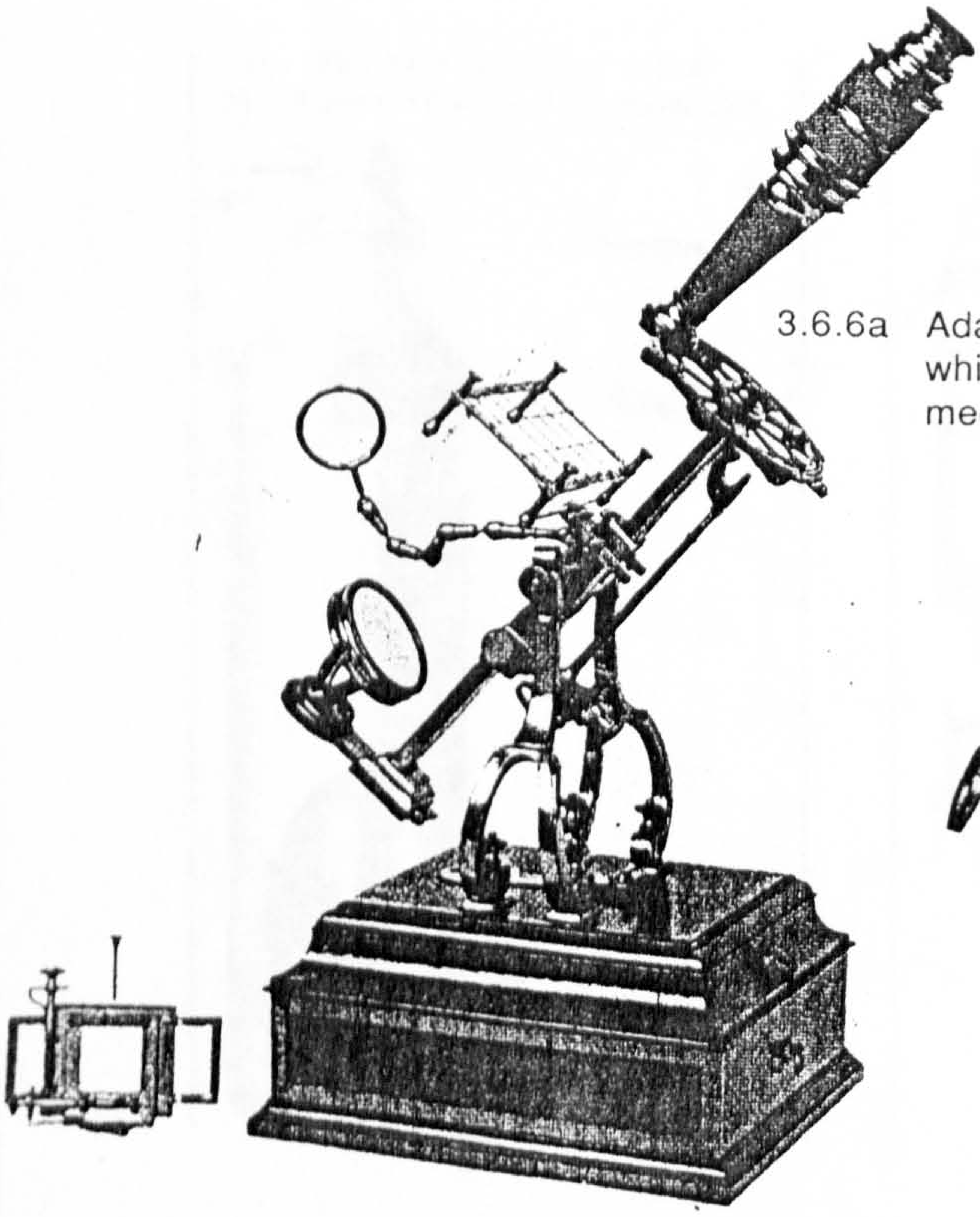
[1] Martin, by error or design, claimed the resolution was 1/10,000th in. These micrometers cost 10^{s} 2^{d} (Martin: ca.1738, p.1).



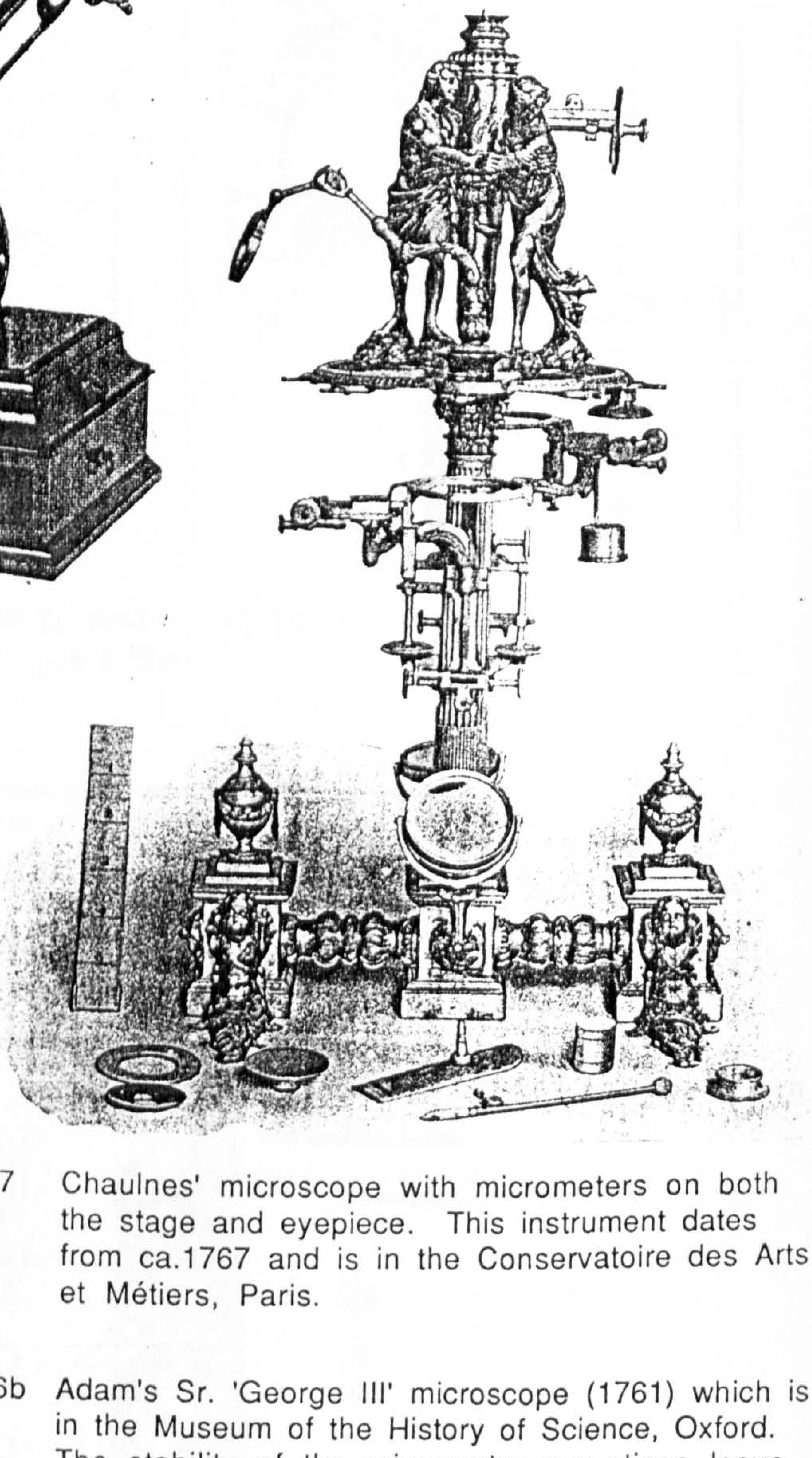
3.6.4 Martin's pocket (left) and universal microscopes with micrometers (ca.1738).



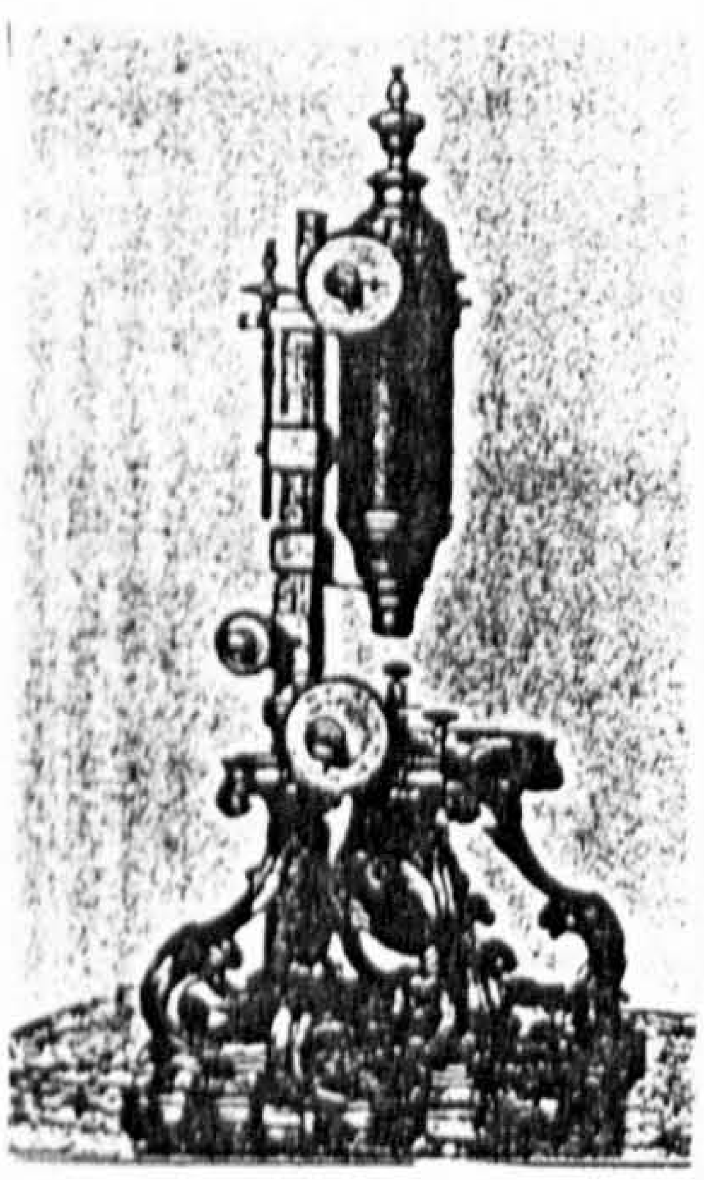
3.6.5 Brander's pocket microscope (ca.1760). Note the similarities to Martin's. The optics of the microscope are better allowing the specimen to be placed below rather than in the microscope tube.



3.6.6a Adam's Sr. 'Prince of Wales' microscope (1753-60) which is in the Science Museum, London. Note the mechanical stage in the bottom left corner.



3.6.7 Chaulnes' microscope with micrometers on both the stage and eyepiece. This instrument dates from ca.1767 and is in the Conservatoire des Arts et Métiers, Paris.



3.6.6b Adam's Sr. 'George III' microscope (1761) which is in the Museum of the History of Science, Oxford. The stability of the micrometer mountings leave something to be desired.

instrument was the first microscope to be able to reach (in theory) 0.0001in. Clay & Court also describe (pp.176-9) the companion instrument, the George III microscope (made 1761; Fig. 3.6.6b). This example carries micrometers with 50 TPI screws and a rack to provide fast motion. Revolutions are read off from a 1in long scale divided into 50 divisions--this arrangement is similar to modern spherometers. Also about this time the Duc de Chaulnes made micrometers for microscopes (Fig. 3.6.7) which he used in connection with his circular and linear dividing engines. These are discussed in Chapter 4 in the section on his dividing techniques.

In the 19th c, micrometers used with microscopes were simply a subset of those used for astronomical purposes. Glass grid micrometers were popular due to their low cost, e.g. Jackson's (Carpenter: 1891 p.232 or Heather: 1924, p.81) but the better examples were single screw filar versions usually employing screws of 50, or sometimes 100 TPI. The New York instrument making firm of Benjamin Pike illustrated (1856) both astronomical and microscope filar micrometers. The astronomical version cost $30 while the microscope version was just $3.50; for comparison, telescope eyepieces were $5.00 while those for microscopes were $3.50.[1] Illustrations of microscope micrometers may also be found in Carpenter where examples by Nelson, Zeiss, Browning and Powell & Leyland are illustrated. Carpenter also provides discussion of testing the divisions of the micrometers. Screw micrometers were mounted either on the eyepiece or on the stage. When in the eyepiece the errors were multiplied by the eye lens magnification, but when on the stage were multiplied by the magnification of the entire optical train. No special attempt has been made to search out microscope micrometers which deserve more attention in the future.[2]

3.7 Fabrication and Mounting of Fiducial Wires:

Malvasia (1662) employed silver wires for his grid micrometer, which was an advance over the solid pointers used by Gascoigne ca.1640. Auzout's original micrometer had solid edges but these were replaced with silk or silver wires in the second version described by him (1667). At even moderate powers, the silk fibers were not completely satisfactory due to their nature and due to their tendency to slacken with increasing humidity. The same problem affected the hairs advocated by Hooke for a Gascoigne-type micrometer. Felice Fontana (1755[3]) of Florence was the first to suggest the use of spider's webs but it was not until Edward Troughton considered the problem that their

---

1 Prices for the late 18th c micrometers may be found in LaLande: 1791, p.LX-LXIII.

2 Related to microscopic work is the microtome for slicing thin sections of samples. The first appears to have been invented by Cummings ca.1760. Adjustment was by a micrometer screw of 40 TPI (Cattermole and Wolfe: 1987, pp.166-8).

3 In the entry "Micrometer" in the *London Encyclopedia* (1835, 9th ed) the date of this idea is given as 1775. They also agree with Gill that Troughton was the person who next adopted spider's webs. In 1718 Louville had paid 70 livres for a micrometer by É.-J. LeFèvre (≈£3 at that time).

> would measure exceedingly small distances exactly, that I have continually been endeavouring to improve these instruments.
>
> The natural imperfections of the parallel wire micrometer in taking the distance of very close double stars are the following. When two stars are taken between the parallels, the diameters must be included. I have attempted in vain to find hairs sufficiently thin to extend them across the centres of the stars so that their thickness might be neglected. The single threads of the silk-worm, with such lenses as I use, are so much magnified that their diameter is more than that of many of the stars. Besides, if they were much less than they are, the power of deflection of light would make any attempt to measure the distance of the centres this way fruitless: for I have always found the light of the stars to play upon those lines and separate their apparent diameters into 2 points.

In France silver was drawn into very fine wire between plates and a diameter of 0.001in was achieved. The **London Encyclopedia** (1835, v.14, p.496) claimed that the skill was lost during the Revolution and that the finest wires made in England were only 1/650th inch. William Hyde Wollaston (1813, p.114-118) advocated platinum. He proposed that it be prepared by surrounding the platinum wire with a cylinder of silver; this was then drawn out thereby reducing the diameter of both the silver and platinum core.[1] The silver was dissolved with nitric acid leaving the very fine platinum wire for use in the micrometer. Brewster was able to make a fibre only 1/1200th inch in diameter by drawing out glass. However, the refraction of star images in the fibre caused some problems with the zeroing but the properties of the glass also created an even finer line about a third smaller in diameter than the glass fibre itself. Brewster tried sealing wax drawn out when melted but these were not very regular in diameter.

Along similar lines to eliminate the difficulty of drawing out extremely fine wires, Ulrich (1846, p.294-5) conceived the idea (an adaptation of Wollaston's technique of which he may not have been aware) of placing a fine wire of gold within a hole in a cylinder of silver. This was then drawn out by the standard rolling technique but being of larger diameter did not have the susceptibility of breaking. The gold in the core was drawn out to very fine proportions having its radius decreased in proportion to the decrease of the cross section of the outer silver cylinder. Once drawn, the silver/gold wire was cut into short lengths to which platinum rings were attached at each end. The wire was then suspended by one of the rings in a bath of heated nitric acid which dissolved the silver[2]. The gold wire was then carefully laid over a ring and stretched by the weight of the two small platinum rings. Another ring was placed over the wire(s) to secure them and to enable them to be mounted in the micrometer being constructed. Ideally the rings were of gold so that expansion/contraction due to temperature changes did not break the fine gold fiducials.

---

1 This idea may have originated from the UK patents of George Whatley (#905, 8/11/1768; and #908, 6/12/1768) which were for plating silver on metal wire and silver on gold and drawing to a fine wire.

2 Later practice was to mount the silver/gold wire and then dissolve the silver.

practical application was achieved (Gill: 1878, entry "Micrometer"). David Gill did not accept J.T. Quekett's suggestion made in his **Treatise on the Microscope** that Ramsden introduced the spider web. Gill's evidence suggested that David Rittenhouse of Philadelphia had drawn Troughton's attention to the idea. Ezekiel Walker (1802, p.22-23) was apparently the first to publish the idea of using spider's webs and in this paper he stated: "...an astronomical friend of mine hinted to Mr. Troughton that he might probably receive assistance in this delicate branch of his business from some of his spiders. This hint was not lost". Following some trials Troughton discovered that the stringer of the web (i.e. one of the radial filaments) was better because it was more elastic and permitted some stretching on the frame.[1]

Gill (p.248) described the processes used in England and on the Continent to web filar micrometers. A spider ("the variety is marked by a cross on the back and is found in English gardens about decaying wood") was placed on a wire fork which is somewhat larger than the frame of the micrometer to be webbed. The spider was then allowed to descend towards the ground on its web and as it did so the wire fork was rotated a number of times being cautious not to cross the web. After 10 or 12 turns varnish was applied to the fork to fix the web. The frame to be webbed was placed on a dull black surface against which the web could be easily seen (sometimes with the aid of a magnifying lens) and the wire fork placed over the web frame. The frame was generally thicker than the wire fork so that the web was stretched. The web was arranged in the furrow engraved in the frame by use of a piece of soft wood and once positioned was fixed in place with a drop of shellac.

On the continent the procedure was a bit different: a piece of silk was unwound from a silkworm cocoon.[2] To the ends of the fibre small pieces of lead were fixed with beeswax. One of the lead pieces was placed on a piece of cork floating in a container of water. The other end was allowed to sink into the water becoming saturated while also untwisting. The silk was then placed over the frame with the dangling lead pieces providing the tension. The web was positioned as before noted and varnished in place. Repsold beveled the edges of his frames slightly (ca.1870) which improved the accuracy of the procedure.

Herschel (1782, p.341) commented on wires thus:

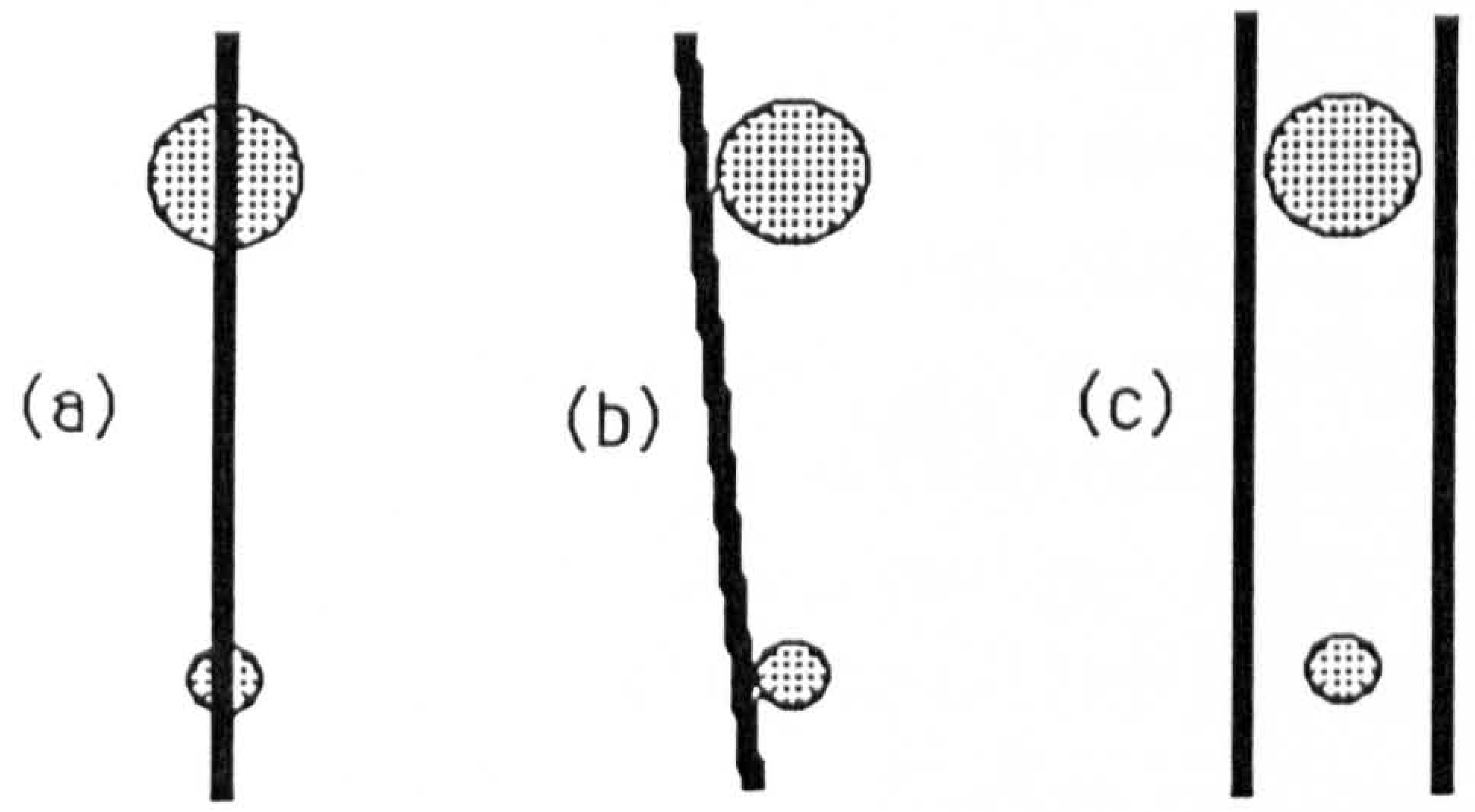
> The great difficulty of measuring very small angles, such as hardly amount to a few seconds, is well known to astronomers. Since I have been engaged in observation of double stars, I have had so much occasion for micrometers that

---

1 In Troughton's bifilar micrometers, the groves were made in each fork at the same time with a linear ruling engine to ensure that the wires would be precisely parallel. It was of course essential that the wires pass each other without touching or interfering with each other and without touching the brass frames. If the wires were interfered with in any way the results were very suspect; the process of touching was referred to as 'fiddling'.

2 Silkworms were probably not available in Britain at this time.

In the mid-19th c, micrometers were frequently used to measure position angle in addition to separations. The usual process was to place the wire to cover the star symmetrically but for faint stars, the web obscured the object. Therefore it became common practice to place the stars on one side of the wire in measuring position angles. However, the difference in apparent diameter caused an error in the position angle which was dependent on the difference in brightness of the two objects. W.R. Dawes (of Dawes limit fame) (Gill: 1878) modified his position angle micrometer to employ two wires separated by a small distance. The stars being observed were placed symmetrically between the wires. Wires were chosen because Dawes thought the eye could estimate the symmetry more accurately than with very thin webs. The purpose of this arrangement was to avoid the systematic error which arose when stars of different magnitudes--particularly when one was very faint--were placed at the edge of a single wire. The size of the stars were dependent on the magnitude and thus affected the position angle but by sighting the stars between the wires this error was eliminated.

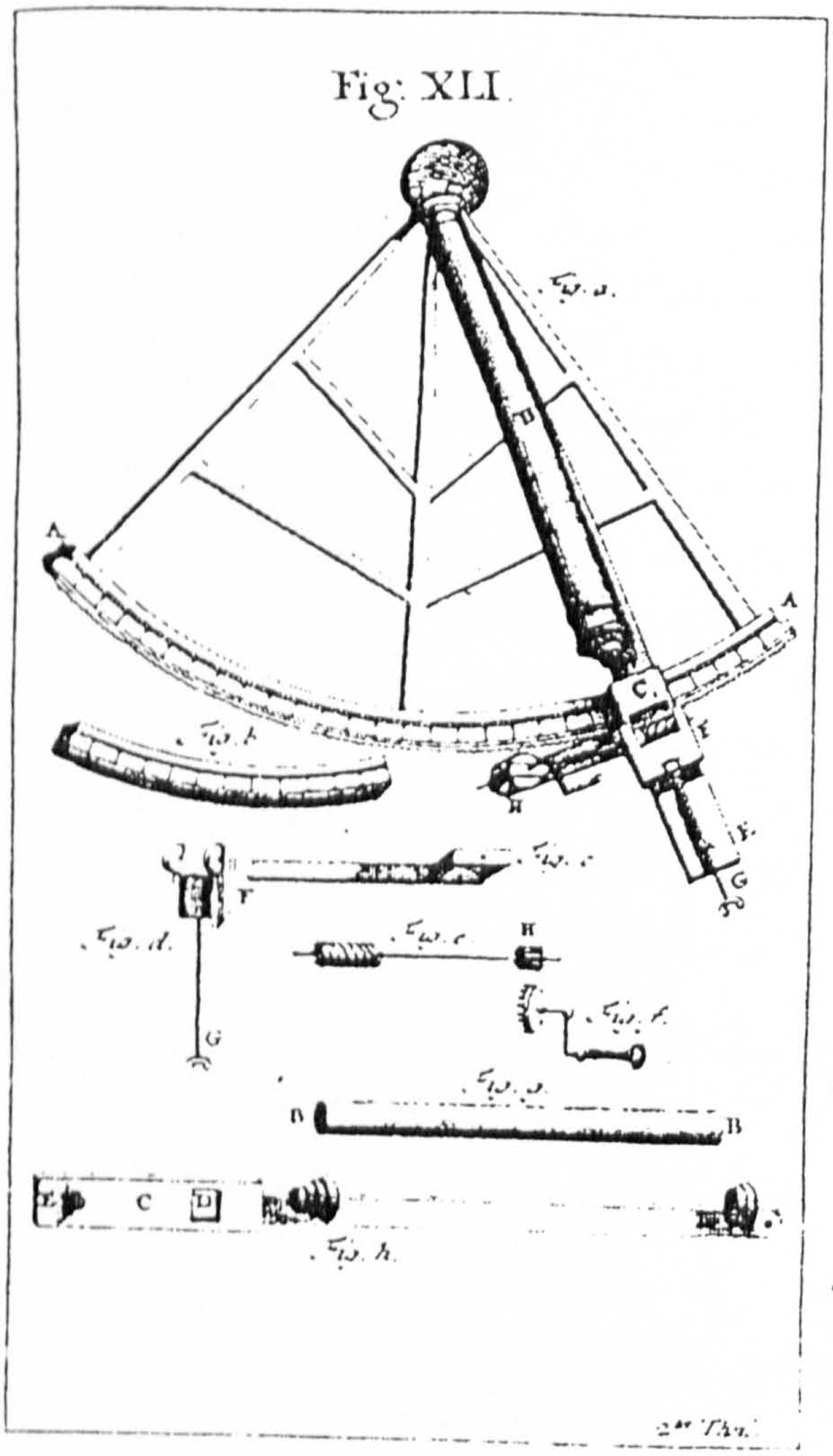


Techniques for Measuring Position Angles

a) standard method with single wire or web
b) method where one star is very faint
c) Dawes' method with two wires

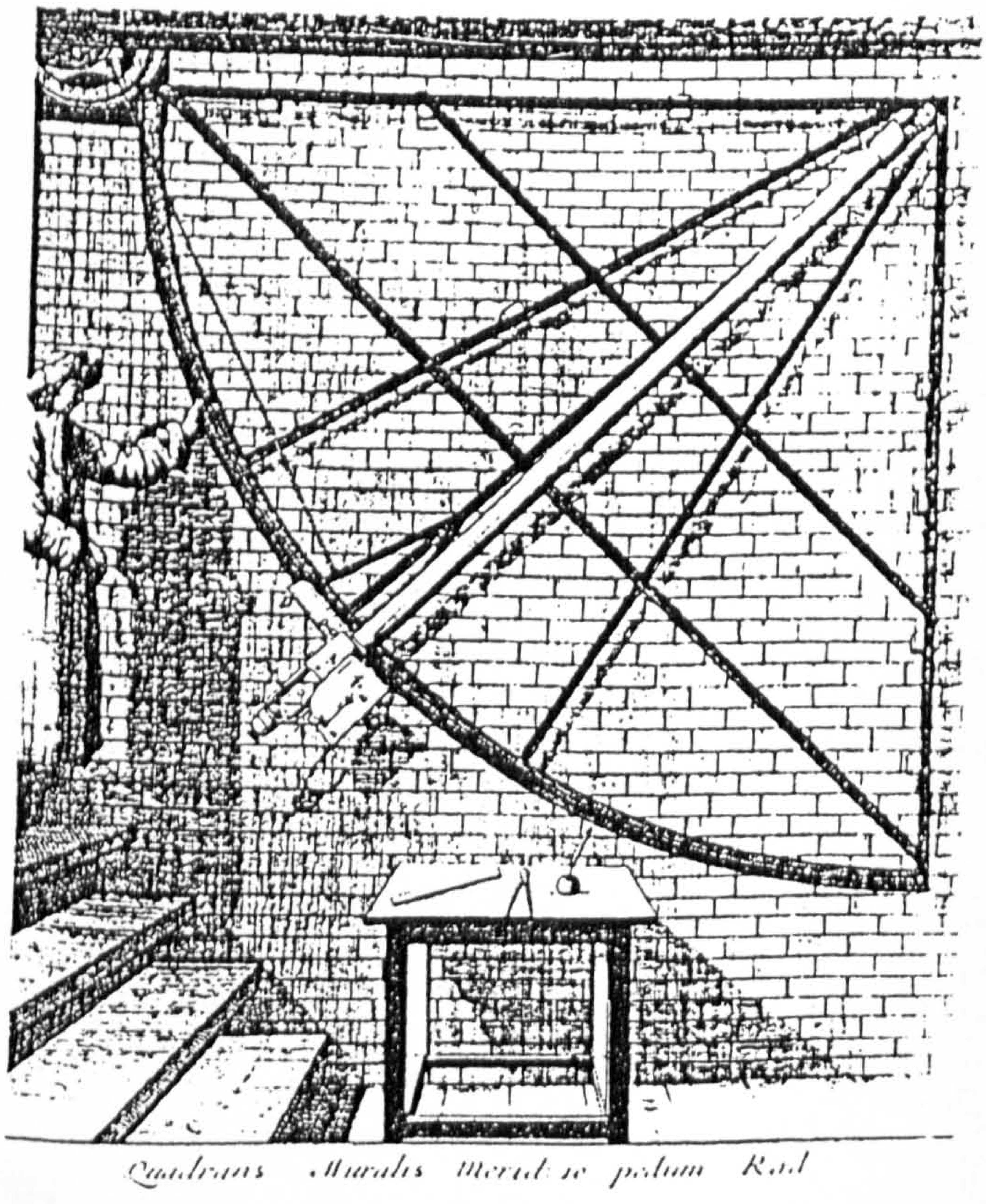
3.7.1 Position angle errors and Dawes' method of correction

Other astronomers also used the two wire or web method, but the zero for the position angle could not be determined with the same accuracy as with a single wire model. A standard micrometer (Gill's type A micrometers) with rotating and divided plate, could also be employed for this purpose simply by adjusting the wires to a suitable separation.



4.1.1a Hooke's 4 foot quadrant with screw limb as described in his **Animadversions** (1674).

4.1.1b Hooke's 10 foot quadrant made for Flamsteed at the Royal Observatory. It was a total failure.



Chapter 4

DIVIDING AND RULING ENGINES

4.1 Mechanical Basis of Instrument Division and Ruling:

Application of the precision screw to dividing and ruling engines requires the greatest degree of precision. Screws were the only mechanical device which could provide the required positional settings until the last decade or two which have seen the development of piezoelectric sensors take over the task of fine positioning (Schuchardt: 1986, p.92). By the early 20th c, the division of scales ceased to be the limiting factor in astronomical and surveying instruments (Abraham: 1926, p.61). The other mechanical and optical component errors and errors caused by temperature changes were larger than the errors of the scale division which had reached a millionth of an inch accuracy. To reach this lofty state in the mechanical arts, the machinist had to create a mechanism which not only contained a nearly perfect screw but could also hold that screw and the plate to be divided in a stiff relation while also controlling the 6 degrees of freedom of the plate, i.e. for rotary position(1), height(1), eccentricity(2) and face runout(2). Finally, attention should be drawn to the distinction between original division and division by means of a dividing engine. Through most of the 19th c the very best observatory instruments were divided originally but the vast majority of astronomical and virtually all surveying and nautical instruments were divided by means of an engine which itself had been divided by original means.

4.1.1 Hooke's Scale Division Technique:

The earliest use of a screw as an aid in the division of a scale was that by Hooke ca.1670 although it should be noted that this was not in a dividing engine.[1] About the same time, Hooke began limited mass production of gears when he made a machine (1672) which held a gear blank above a divided plate. The gear blanks were mounted on the same axis and once rotated to the desired position, were locked in position and the tooth cut by a rotating file (Taylor: 1967, p.346). Such gear cutting machines were the forerunners to dividing engines of a century later. However, Hooke's 4ft quadrant and 10ft quadrant (Fig. 4.1.1) of similar design (made for Flamsteed[2]) were failures due to the lack of skill in fabricating the screw (which was described in §3.2.8), general lack of precision in making moving parts which led in turn to wear of the screw and mating

---

[1] Hooke noted in his Diary ('Espenasse: 1956, pp.34,100) 18 March 1672/3 "began wheel cutting engine" and 2 May 1674 "To Thomkin (i.e. Thomas Tompion) in Water Lane...Told him the way of making an engine for finishing wheels, and a way how to make a dividing plate...about another way of Teeth work..."

[2] Flamsteed anticipated the failure of this instrument but Hooke insisted that it be erected on the wall Flamsteed had prepared for a mural quadrant. After Flamsteed had confirmed its uselessness, the annoyed Hooke demanded the instrument's return to the Royal Society.

thread. Although the concept was correct, the required accuracy of the mechanical elements was unobtainable. The technique to divide the quadrant was described by Hooke (1674); it was the first such attempt and anticipated the technique perfected to high precision in the 19^{th} c. To the iron frame, Hooke attached a brass rim, screwed and rivoted to the limb and projecting over the edge and ends. What we now call the index arm was fitted to a carefully prepared pivot or cylinder through the radial centre of the curved limb. The frame carrying the micrometer screw was attached and given provision for rolling along the limb. The brass plate was made round and centered on the pivot by use of a 'File or Plane'. Although not explicitly stated as to how the thread was cut in this plate, the attention Hooke paid to ensuring the screw frame was tangent and parallel with the brass limb indicates that he must have used the screw (or a duplicate) to cut the thread (p.88-90). The screw, being steel, was sufficiently hard to make a depression in the softer brass and was held against the brass limb "by a strong springing of one side of it" (p.90). Hooke simply racked the screw along the limb several times to deepen the profile. Once this was complete, he used the index on the screw frame and the reading on the dial to mark off the divisions. Where the traditional method was to step off equal divisions with a compass, Hooke substituted the revolutions of the screw to give the divisions. The required quadrant radius was computed from the pitch of the screw for the length of the quadrant limb. However, Hooke does not mention testing the accuracy of the 90° thus laid off. It takes little imagination or engineering expertise to recognize that racking the screw along the limb to create the rack is subject to gross errors due to slip, uneven 'cutting' action, etc. Typical of Hooke, his optimism exceeded his skill or that of his workman, Thomas Tompion, and the discussion of measuring to 1 arc second or better was purely theoretical and wishful thinking. The radius of this instrument was 48.6in[1]. For such a radius, reading to 1" corresponds to measuring to an accuracy of 0.0094mm which, as will be shown, was not feasible until the mid-18^{th} c. With this particular instrument Hooke found the divisions to equal (p.91):

Table 4.1

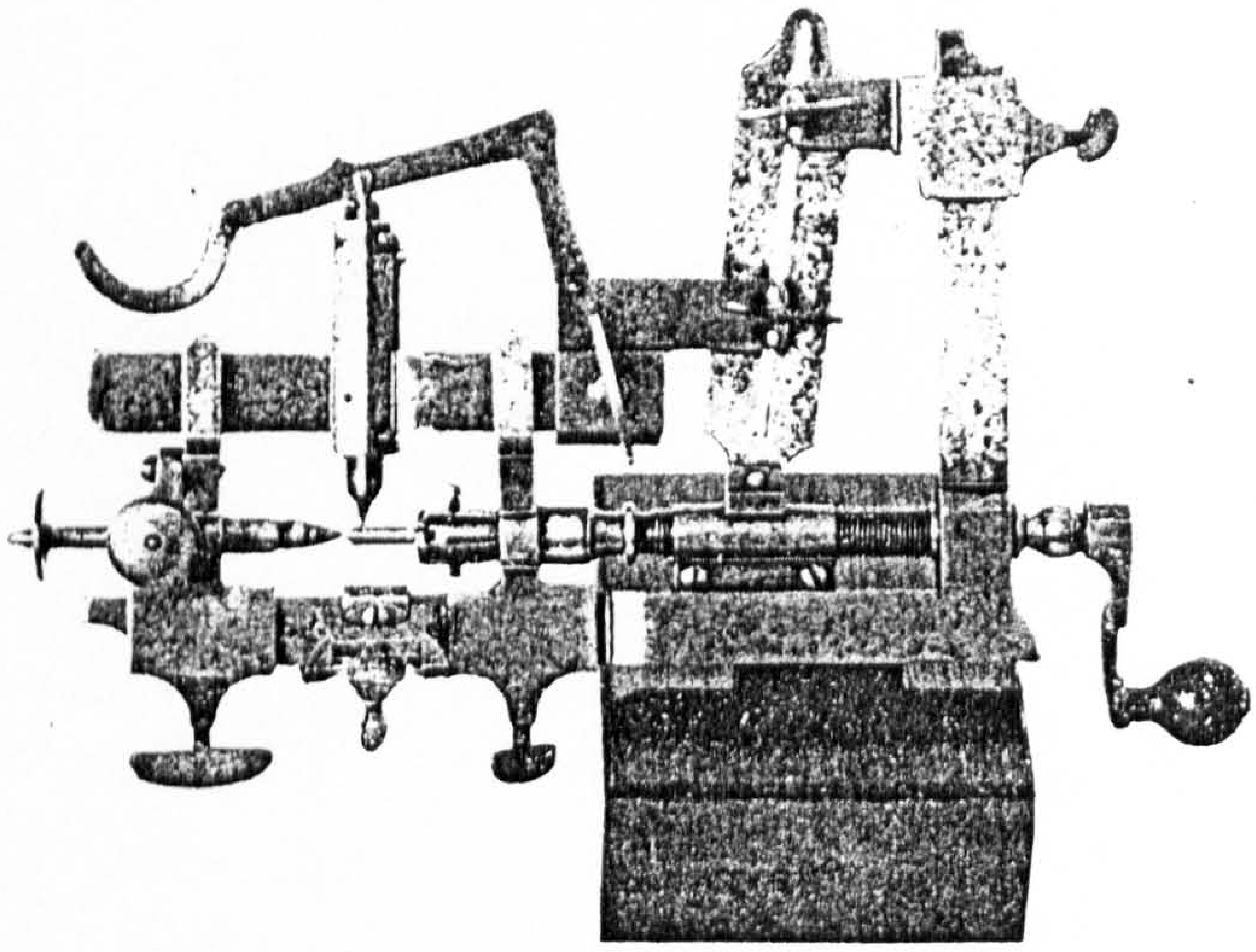
Hooke's 4 Foot Quadrant

	revolutions	+	divisions of the dial
90°	1600	+	912
1°	17	+	788
1'	0	+	296
1"	0	+	5

Knowing the radius and the number of divisions, we can confirm the pitch of the thread, vis. 0.0477" or 20.97 TPI which agrees with the 21 TPI he computed as that desired to match the length of the arc (p.88).

---

1 Hooke (1674, p.88) refers to the "76 inches, and 36 centesms of an inch, making this Product the Radius" which is the length of the quadrant limb, not the actual radius.



4.2.1 An 18th century fusee engine used by clockmakers and the basis for dividing engines and screw lathes.

4.1.2 Methods Employing Beam Compasses:

The method of using compasses to step off divisions evolved from Römer via Graham to Bird who took the technique to its pinnacle.[1] Although Römer was the first to ignore the normal 90° scale by successively dividing off individual divisions and using a table to convert his scale divisions to degrees, his attempt was unsuccessful. He used a fixed compass (opened to 1/10th or 1/12th inch) to avoid springing and even became the first scale divider to use a micrometer microscope to examine the divisions. George Graham was more successful with the 8ft mural quadrant for the Royal Observatory which was the first instrument to carry two scales--one with the traditional 90° scale divided into 90 divisions and a second with the 90° divided into 96 divisions which permitted subdivisions to 5' by continual bisection. This instrument was successful, and showed the utility of being able to compare two scales prepared by different methods, but the accuracy was compromised by the use of a brass arc riveted to an iron frame. By 1742 the arc had warped and substantial errors were detected by Bradley. In making successive instruments Graham and Bird took this into consideration and Bird went so far as to take great care to maintain constant temperature during the dividing procedure. Ramsden and John Troughton used beam compasses for their original dividing but when Edward Troughton (1809, p.106) attempted the method he found that bisecting the points caused the shape of the dots to be deformed by inserting the compass points in them, causing errors he could not correct. He also stated that the common method in London was to follow Bird's method and then to 'correct' the position of the points by deforming them in the required direction by use of a fine conical point and then to burnish them. The results were, however, far from pleasing to the eye and the points ill-defined.

4.2 Dividing Engines of the 18th Century:

It should be noted that there is a close relation between the technology of dividing engines and fusee engines (Fig. 4.2.1) and gear cutting machines for fabrication of clock components. Thus, it is not surprising to find that the first person to make a dividing engine was a clock maker, Henry Hindley of York.[2] Was there also a connection between the invention of the chronometer and work on dividing engines in the 18th c? Henry Hindley's work closely followed John Harrison's first chronometers H1 (1736) and H2 (1739) while Chaulnes's dividing engines were being made almost simultaneously with the chronometers of Berthoud and LeRoy. Ramsden turned to the problem of dividing engines about the time Harrison's H4 had successfully completed its sea trials. We can only speculate if this link was real since no documentary evidence as to the motives of Hindley, Chaulnes and Ramsden has been found. It was well known that Harrison was

1 See Bird (1767) and Smeaton (1786) for details of these methods.

2 It is amusing to note that Ambrose Swasey claimed Hindley was from New York in his 1904 address to the American Society of Mechanical Engineers.

working on a chronometer[1] and the competition between Berthoud and LeRoy to first perfect a chronometer was general knowledge among the scientific community in France. Scientists and mechanics were aware that success in achieving the severe limits imposed by the Board of Longitude Prize (similar limits were sought for the prizes offered by other governments) would require a new standard of the other instruments of navigation; some simple calculations were sufficient to show the need to improve the accuracy of scale division on the small instruments used by navigators if the chronometers were to be used to their potential. Smeaton (1786, p.22, Scott:1919, p.11) stated that Hindley had "a kind of foresight that from the superior merit of the Hadley quadrant a demand for that and other instruments for the purpose of navigation was likely to increase, and that he might live to see a public reward offered for a method of dividing them with greater accuracy and dispatch than had at that time appeared." Troughton noted on this point (1809, p.112):

> Ramsden's well-known method of dividing by the engine unites so much accuracy and facility, that a better can hardly be wished for; and I may venture to say that it will never be superseded, in the division of instruments of moderate radii. It was well suited to the time in which it appeared; a time when the improvements made in nautical astronomy, and the growing commerce of our country, called for a number of reflecting instruments, which could never be supplied, had it been necessary to have divided them by hand: however, as it only applies to small instruments, it hardly comes within the subject of this paper.

There are some limitations to the fineness one can divide a circle. In theory the lines of a scale divided by a dividing engine can be almost infinitely close together but the width of the lines and the ability of the eye to detect displacements of lines between the scale and vernier places a lower limit on the spacing. Scott (1919, pp.9-10) remarks on the requirements of scale division as far as the size of divisions and sight are concerned.

> It is found in practice that a line as fine as it can be clearly seen will appear broken in its continuity with another equally fine line, if at the meeting the rectilinear displacement is as much as 2/10^{ths} the part of the diameter of the line. It therefore follows that we may read closer by displacement of parts of a single line than by any possible series of lines that can be drawn in spaces apart from a surface. Now on a circle of 5 inches diameter the rectilinear distance between the centres of two lines is about 22/1000^{ths} of an inch, as there are 30 lines of the vernier to 29 on the circle, the difference between the distance of two lines on the circle and two lines on the vernier is about 7/10,000^{ths} of an inch....Therefore what is required in dividing circles is that the divisions be EXACTLY equal, not very near it, for it must be borne in mind that we are dealing not with thousandths of an inch, but with ten-thousandths of an inch; and with the micrometer microscope of the present day 1/10,000th of an inch on an eight inch diameter circle can be easily measured.

Although the numbers are different for scales of differing diameters, the same sources of limitations apply to any scale divided with a dividing engine.

---

[1] In 1735 Edmund Halley, James Bradley, Robert Smith, John Machin and George Graham recommended that Harrison be given some "encouragement" for his chronometer.

4.2.1 Hindley's Dividing Engine:

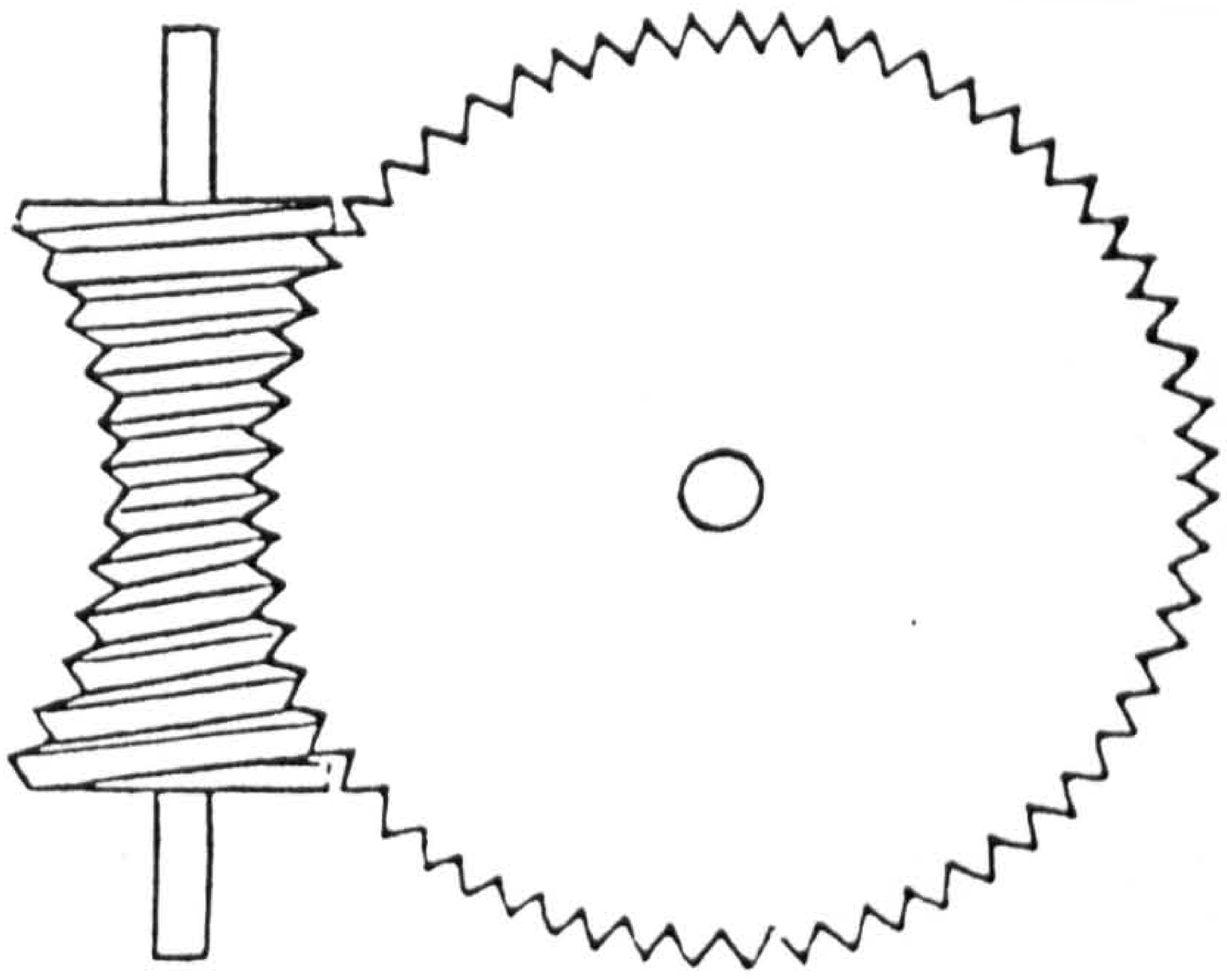
Henry Hindley was primarily a clock maker and saw the parallel between gear cutting and division of scales. It appears that he tackled the problem out of interest rather than for economic reasons. Gear cutting was in Hindley's time (ca.1740) still a manual operation requiring the gear blank to be divided into the required number of spaces and then cut with a file. Anyone who has attempted fine filing is well aware of the skill and care required to achieve good results--let alone achieving multiple gear teeth perfectly spaced with the face of each tooth perfectly parallel to the shaft of the gear. In addition, one requires 2 or more such perfect gears and any imperfection is transmitted through the gear train to the final work; the motion of the gear train will also be irregular and wear will result.

Our knowledge of the dividing engine made by Hindley comes from the account of John Smeaton (1786) made some 45 years after he had seen the instrument. In the autumn of 1741 Smeaton was given the opportunity to visit Hindley's workshop which included a demonstration of the dividing engine--a privilege which Hindley did not even extend to his brother. The engine, which had been in operation for some time,[1] was equipped with a dividing plate with numerous holes on circles of different diameters with which gears for clock work could be cut. This was not unusual but Hindley had a second wheel for the engine which was "about 13 inches in diameter, very stout and strong and cut into 360 teeth" (Smeaton: 1786, p.19). The wheel for dividing purposes was made on the gear dividing plate but Hindley did not know at that time how it had been made. To this new wheel Hindley applied an endless screw not of cylindrical form but cut so that the 15 teeth along its length were in constant contact with the wheel.[2] This was made by first cutting the gear blank with a form to fit the outer diameter of the wheel and then, with a cutting tool on an arm attached to the wheel, the wheel itself was advanced to cut the thread on the screw blank. To advance the wheel, Hindley had made an endless screw of the same pitch as the wheel on his clock lathe. The curved endless screw and wheel were then--using Smeaton's terminology--'ground' together until they were perfectly free to turn without backlash or sticking. Smeaton (p.22) states "Furthermore, that the screw and wheel being ground together as an optic glass to its tool produced that degree of smoothness in its motion that I observed."

---

[1] Stancliffe (1812, p.121), who had worked for Hindley and who had used the dividing engine, believed the engine had been made by Hindley ca.1739.

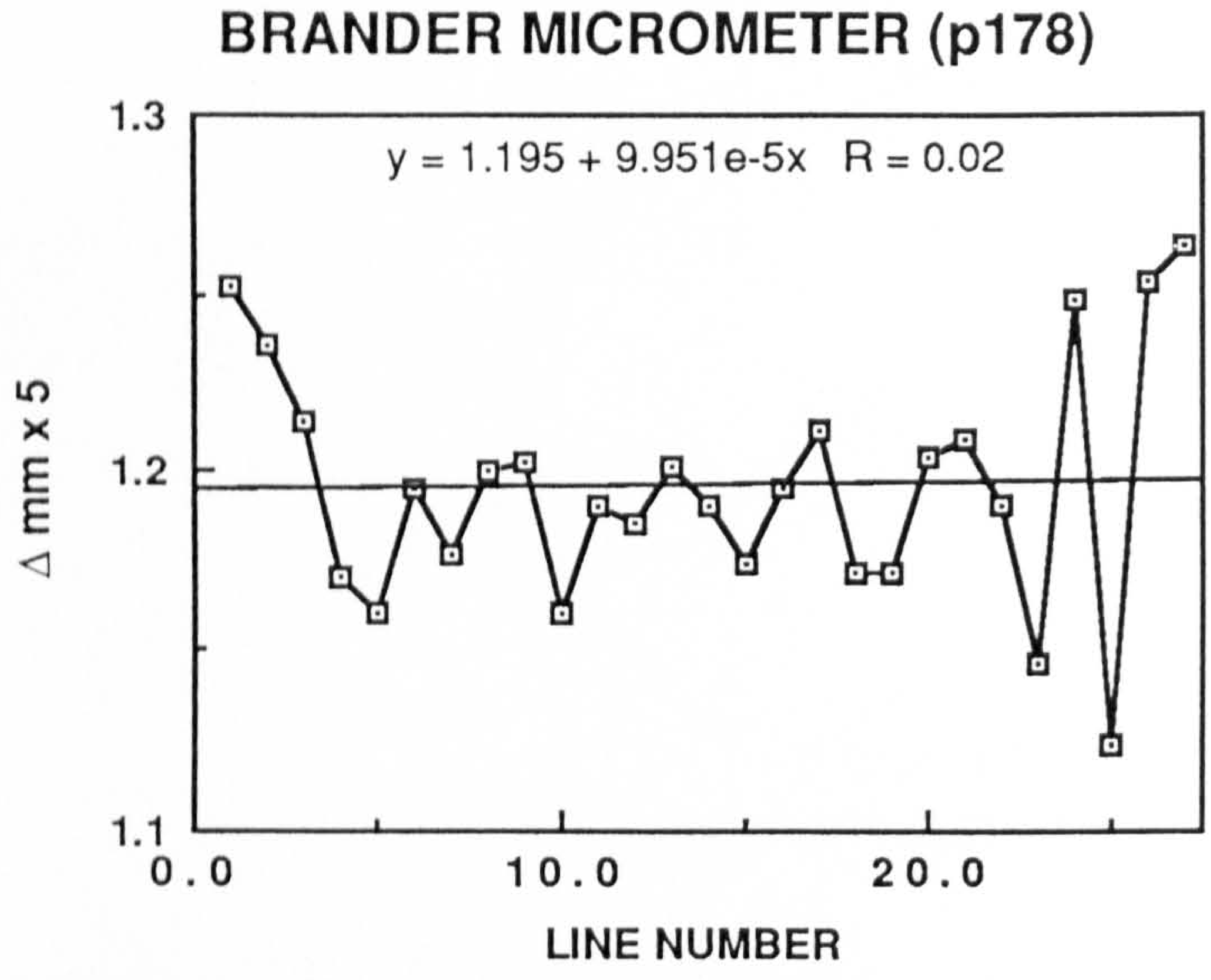
[2] It was thought that such a worm design gave greater accuracy but this was shown by Willis (1841) to be incorrect. See also Fig. 4.6.8.

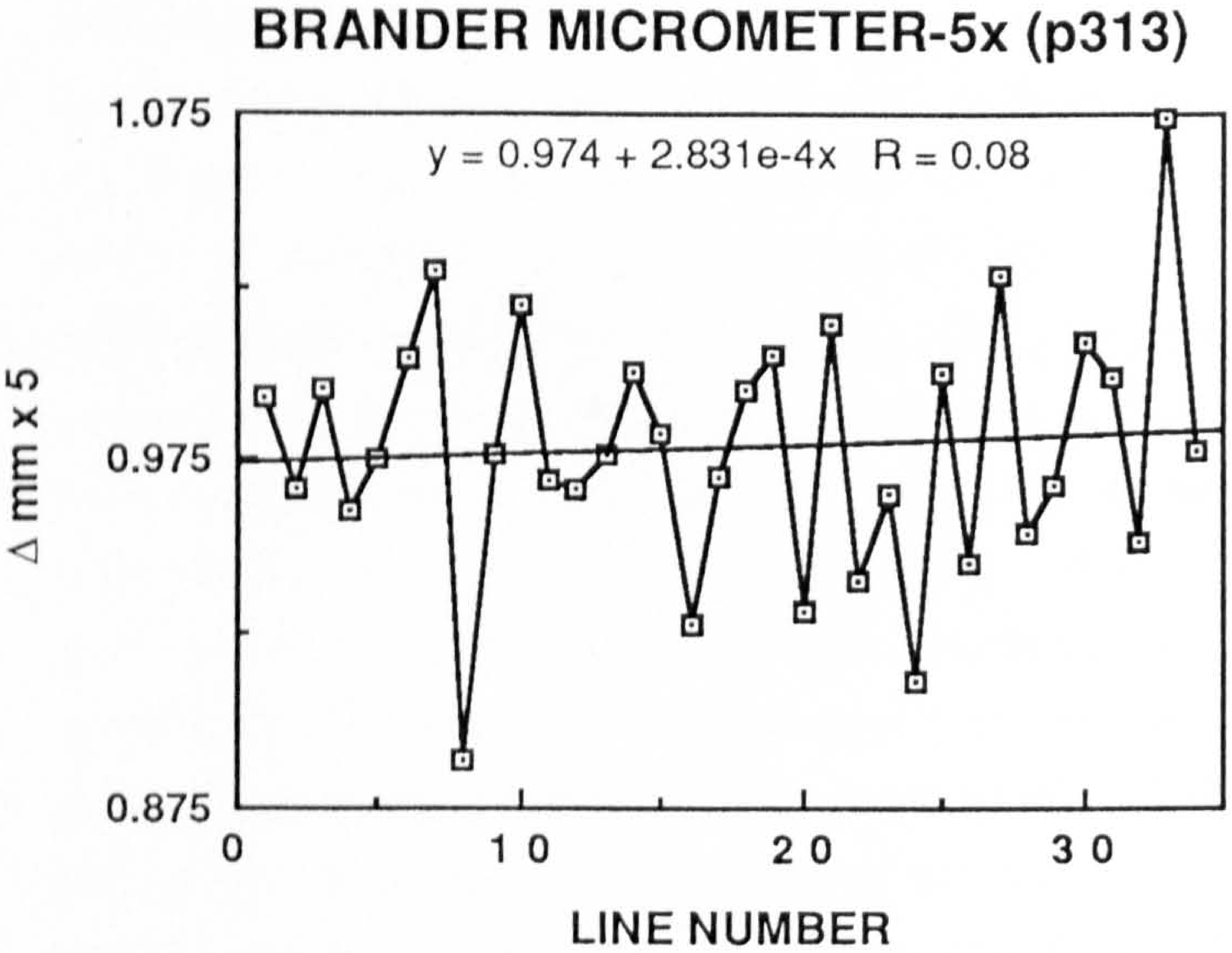

4.2.2 Shape of Hindley's worm screw

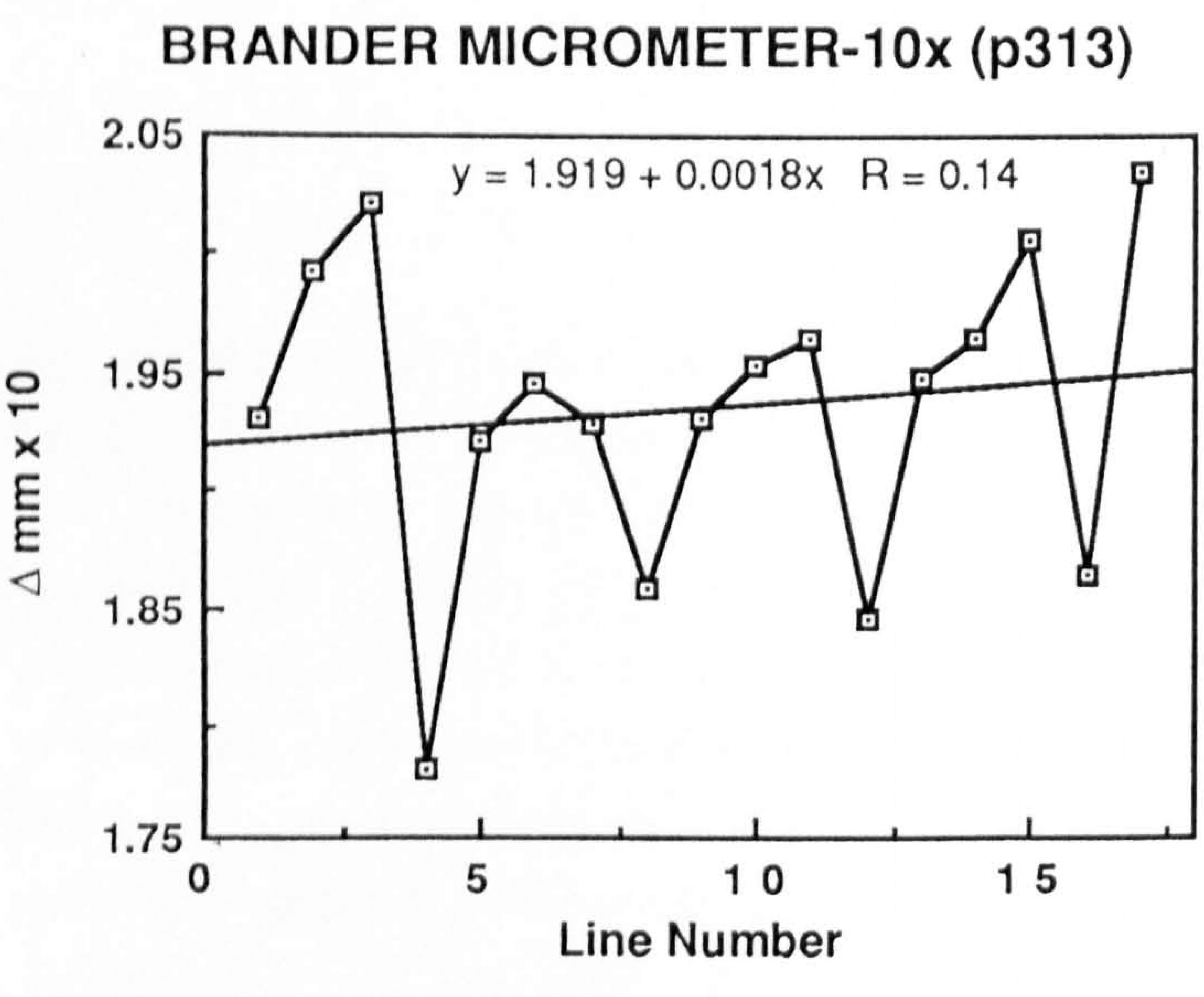
The success of Hindley's dividing engine was the precision of the original dividing plate and Smeaton was not originally given the secret of its fabrication. However, Smeaton was given the details in a letter in 1748. The method was to attach a brass hoop to a large wooden wheel and then to cut the maximum number of guide holes in the hoop. The dividing plate was attached to the wooden wheel and the plate divided off using the holes in the hoop as the guide. A small steel plate was then attached to one end of the brass hoop and another hole in the steel plate was used to screw the plate to the hoop at the next lower number of desired holes; the wheel then had to be turned down to the appropriate size and the hoop remounted. The dividing plate was remounted and marked with this number of divisions and the procedure repeated until the various circles on the dividing plate had the required number of holes. The care taken by Hindley in the various steps is described in his letter (Smeaton: p.25ff). Smeaton suspected that Hindley's method was not so precise as Hindley had thought and Edward Troughton (1809, p.112) did not accept it as an appropriate method to divide astronomical instruments because of the "violent operations with blunt tools".

4.2.1.1 Smeaton's proposed improvements:

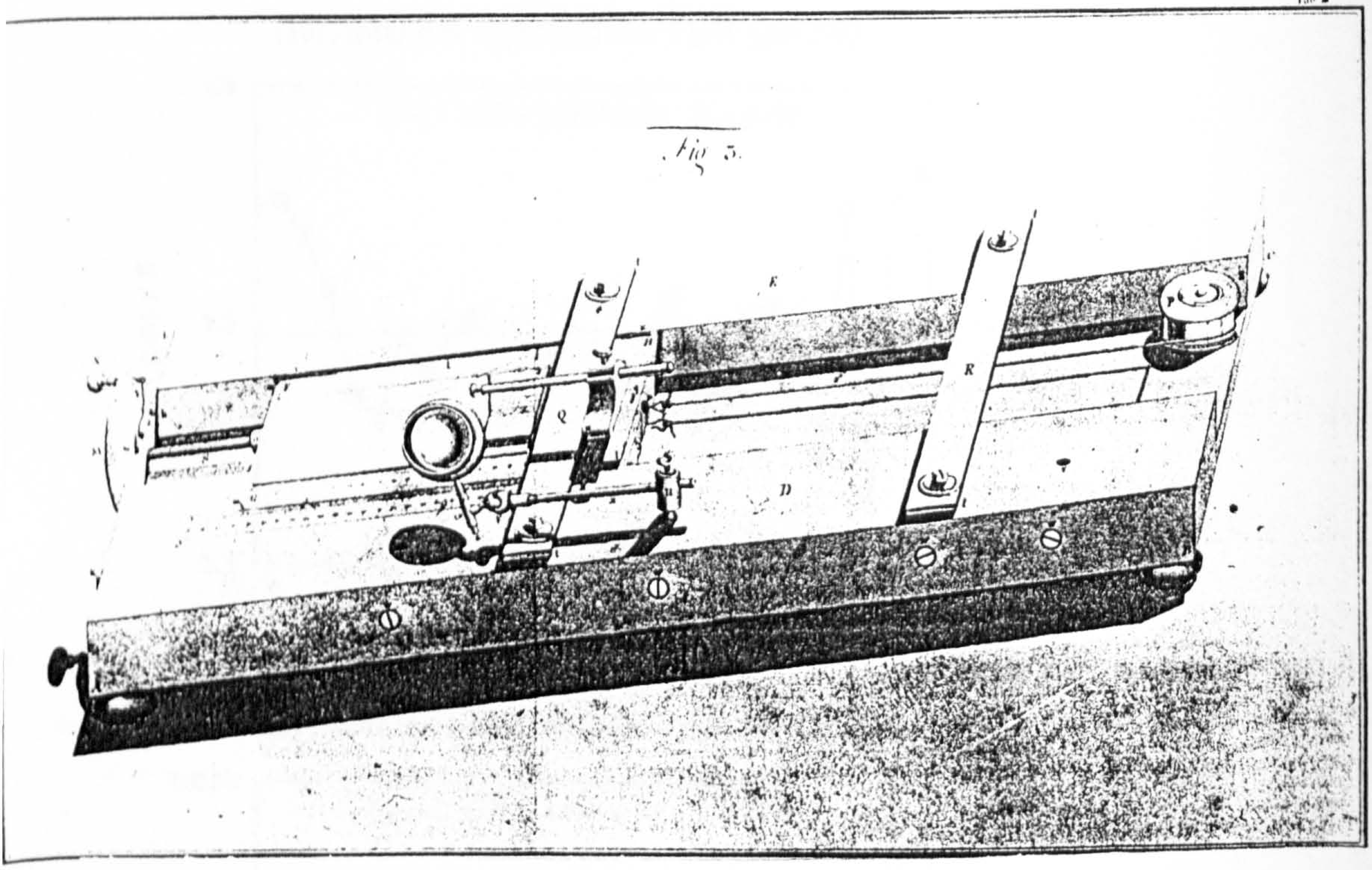
Smeaton therefore went to great lengths to propose improvements to the technique of using a hoop though it was the same in most respects and suffered the same types of error but perhaps to a smaller degree. As far as can be determined, no one actually attempted the method since it had long been surpassed by the method of Ramsden. The refinements were to the method of laying off and drilling the holes, matching the ends and included using 1440 holes rather than 360. The hoop was used as the guide to make the teeth in the rim of the dividing plate using the cutter frame of a clock maker's engine. To grind the teeth to equality, Smeaton proposed using two screws prepared by Ramsden's method which, for the diameter he was proposing for the dividing engine and for the number of teeth, would have made contact with "ten or twelve teeth". These screws were cylindrical and not of Hindley's form and were placed at a 90° separation and Smeaton advised making them slightly tapered to compensate for wear. The grooves in which the teeth were to be cut were parallel and thus would grind those parts at the extremities of the grooves. Once



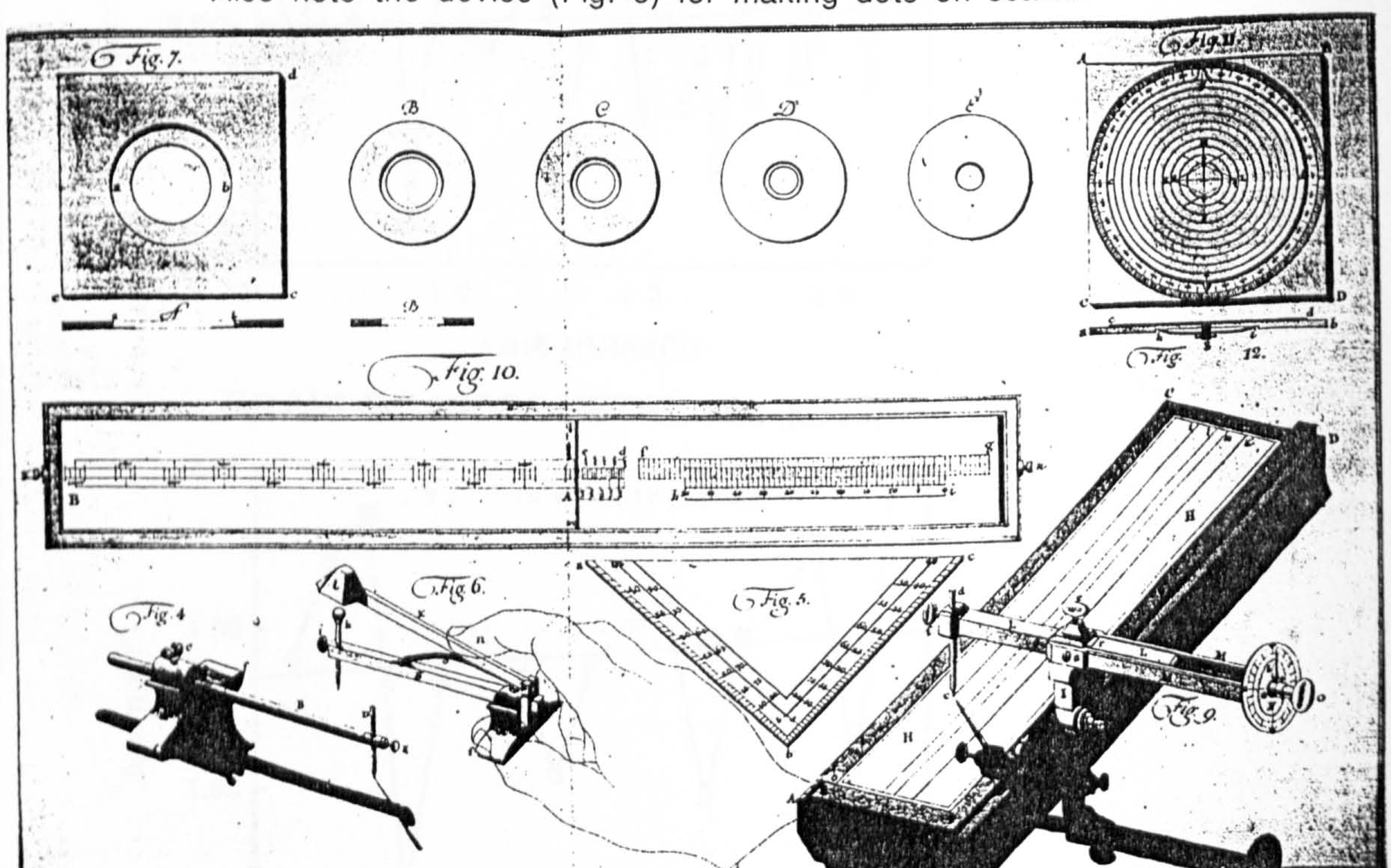




4.2.3 Errors in spacing of lines on 3 glass micrometers ruled by Brander. Measurements were made from illustrations in Brachner (1983) on the pages indicated. Ordinate units are mm.



4.2.4 Brander's linear dividing apparatus and scribing apparatus. Note the hand controlled scribers, Figs. 4,9 (with micrometer). Also note the device (Fig. 6) for making dots on scales.



finished, the teeth became the divisions on the dividing plate and the two screws and their frame were removed.

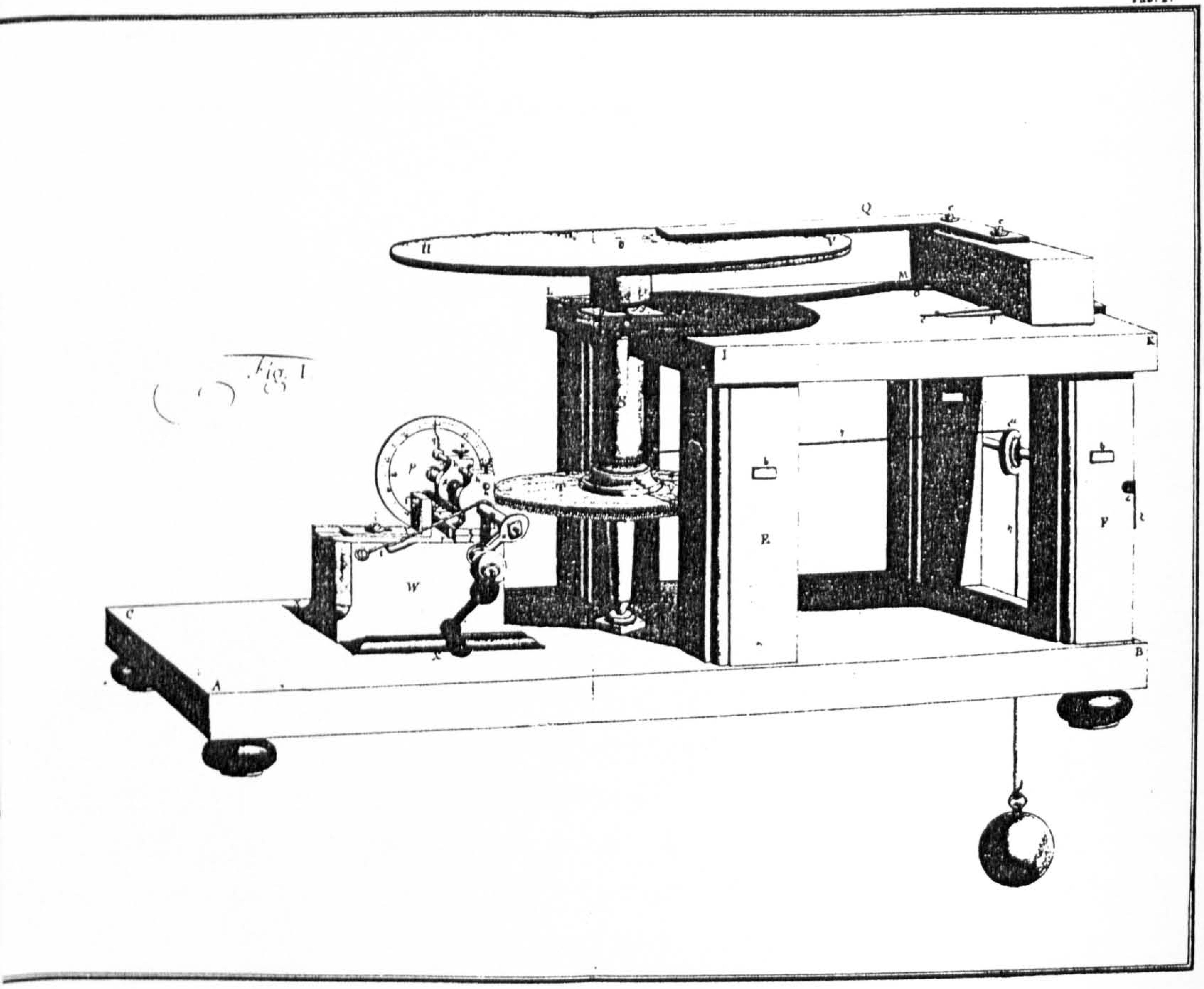
To prepare the dividing plate for the division of instruments, Smeaton proposed using a plate which would encompass 5 or 6 inches of the rim of the plate. To this he attached two steel pins to mesh with the threads on the rim--the length of separation was sufficient to minimize errors potentially caused by the pins not seating exactly the same as they were moved around. To the index plate he attached a beam compass with fixed separation equal to that of the pin separation and this was used to mark the divisions on the limb of the instrument being divided. The beam was made from white fir but enclosed in a tube of tin or brass to isolate it from moisture and heat. Once the instrument was mounted on the dividing plate with the centre pin mating with the centre hole of the dividing plate, the division process could begin. The index plate with pins was moved from thread to thread in the dividing plate, this being held in each successive place by a springing mechanism. Smeaton speculated that this method of 'feeling' the divisions was good to 1/60000th part of an inch and where the scale could be read to 1/4000th inch, then on a circle of radius the error amounts to 1 1/3". His preference for a method which depended on feel was prompted by his experience with his pyrometer built in 1753 (see §3.3.8.2). However, it should be re-iterated that the instrument and method as just described were not put into practical operation.

4.2.2 Brander's Dividing Engines:

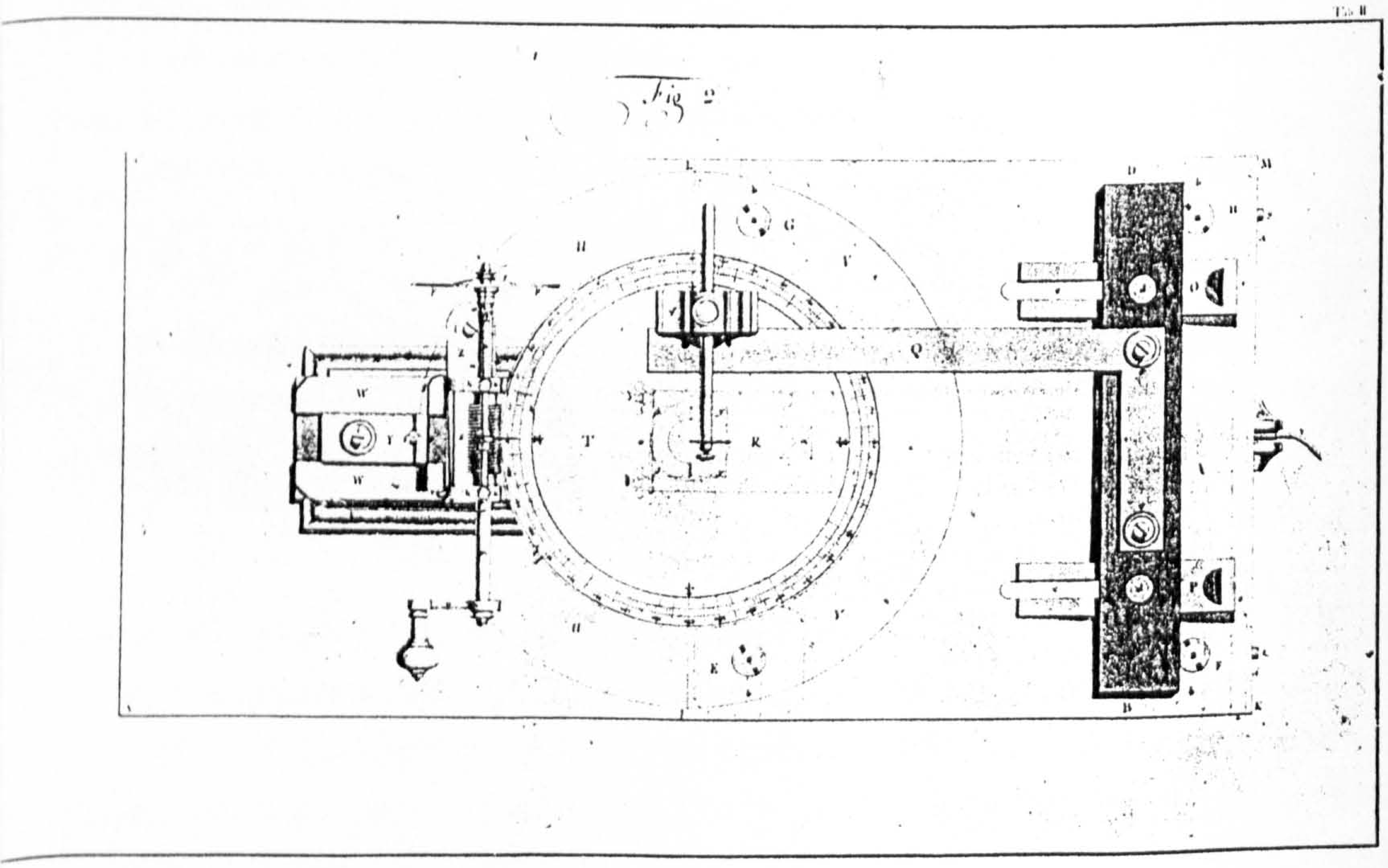
Georg F. Brander (1713-1783) made the next dividing engine of which we have some details in 1759. This was a circular dividing engine and was followed 2 years later by a linear dividing engine. A description of his equipment and techniques is given in Brachner (1983, p.349ff) based on various published and unpublished (Brachner: p.385, a-h) descriptions by Brander. The results of some of Brander's dividing on glass is shown in Fig. 4.2.3 and it was these glass grid micrometers for which Brander was so well known. The machine illustrated for linear division is not very complex particularly with respect to the mode of carrying out the scribing of lines--a technique which was repeated in his circular dividing engine and was without doubt the limiting factor in these machines' accuracy.

The linear dividing apparatus (Fig. 4.2.4) incorporated a carriage carrying the piece to be divided and moved within a track without dovetailed ways. Motion was imparted with a long micrometer screw which had a divided dial to indicate the amount of motion. On the opposite end of the carriage a string or wire was attached and ran around a cylinder at the opposite end of the base and over the edge to a weight. This was to ensure that the carriage and micrometer screw were under (more or less) constant tension. As a check of the progress of division, both the carriage and side of the track within which it

Tab. I.



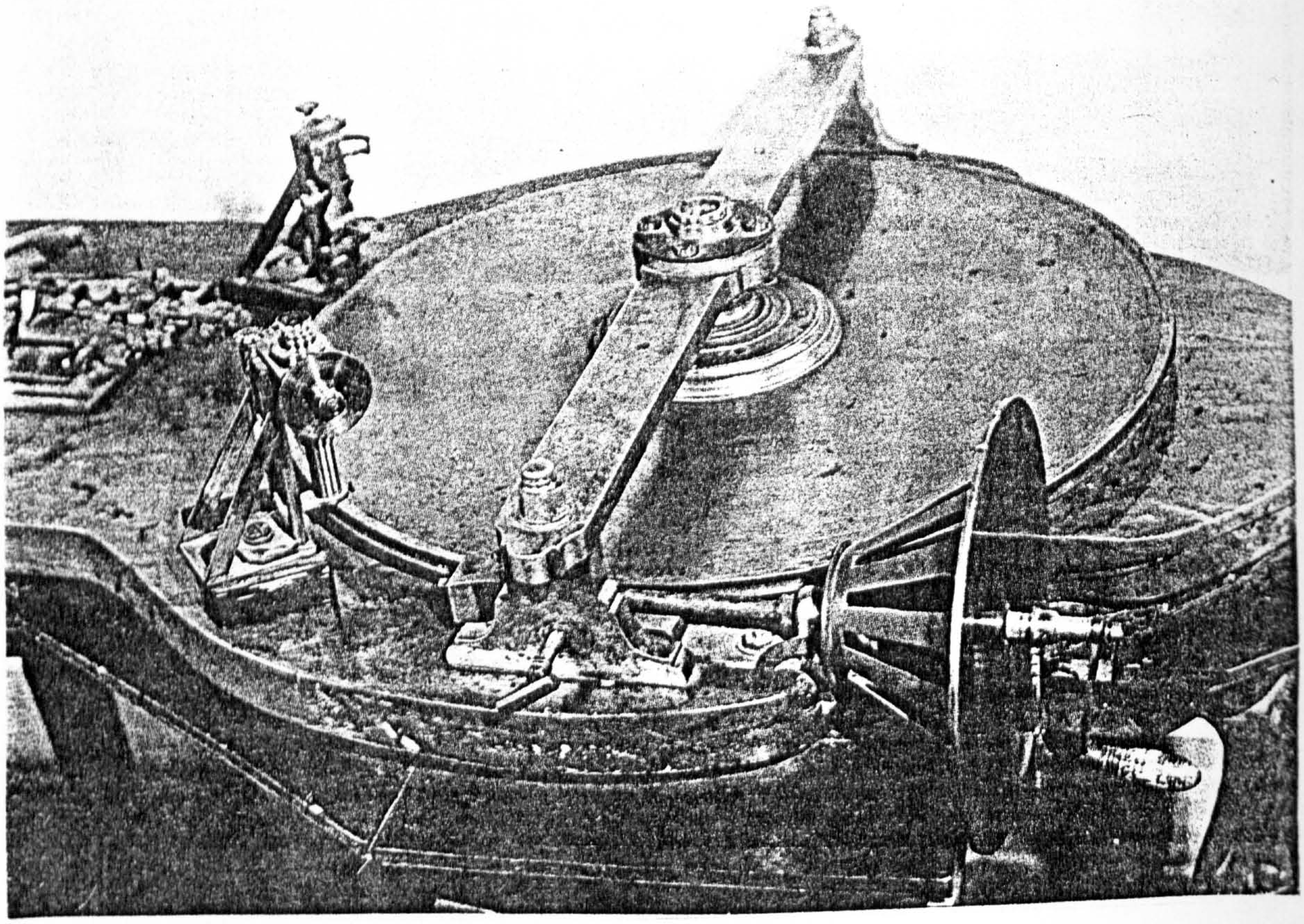
4.2.5 Two views of Brander's circular dividing engine. Again note the hand held scriber in the lower figure. The wire marked 't' was to control backlash between the worm and wheel by acting on the worm shaft.



moved had a scale engraved on them. One of two cross members mounted with its edges perpendicular to the motion of the carriage was used as the guide for the scribing tool which was used in the manner of a carpenter's scribe--i.e. the scribing point is mounted on a block which is drawn along a straight surface as a guide. Brander used three styles of these scribers: the simplest had a rod mounted through a hole in the guide and could be adjusted in length by a clamp screw; the next had a bar through the guide and was intended to place dots on circular scales; and the most complex which was intended for marking longitudinal lines on scales incorporated a micrometer screw to adjust the length of the bar (just why he thought it necessary to have these so precisely positioned isn't obvious). The scribing process could be watched with the aid of a magnifying lens. A number of weak points are obvious. Probably the most serious was the means of doing the scribing. This was subject to the person's skill and caution in drawing the scribe along its guide--a slight twist of the scriber would cause the lines to be non-parallel. In addition, heat from the mechanic's hand would have been directly transferred to the metal rod holding the scribing point thereby causing variable length of the guide surface to scriber point--although it must be admitted that this would have been small compared to the potential error due to twisting of the guide. The thin plate that attached the micrometer screw to the base was also a weak point, being susceptible to flexure during advancement of the micrometer screw and to wear on the screw shaft and on the diameter of the hole through which the screw passed. Despite these flaws, Brander's skill allowed him to carry out remarkably fine division on glass as has been demonstrated.

The circular dividing engine (Fig. 4.2.5) is much more complex but unfortunately also limited by the nonautomated scribing method. Here again Brander used a straight edge to guide his hand held scribe or his gagit to place dots on the scale; the straight edge was simply a square mounted to the frame and this would have been susceptible to flexure in the vertical and horizontal planes. The dividing plate was mounted on the top of a shaft and was held in a bearing (of appreciable diameter) near the top and in a pivot at the bottom. Both these points would cause concern when trying to achieve high class work. A string or wire wrapped around this shaft was attached to a weight with the intent of keeping constant tension between the toothed wheel and the driving screw. The toothed wheel was mounted approximately midway between the bearings. It carried divisions to 1° and had 360 teeth to match the worm gear. Unfortunately I have not been able to determine the diameter of the wheel.

The tangent screw was of cylindrical form and was on a shaft turned by a handle with a dial on the opposite end; it was held in a pillow block arrangement though the bearing points appear simply to have been holes drilled in the blocks and longitudinal motion of the screw prevented by shoulders on the shaft. The tangent screw was forced against the wheel by a 'U' shaped spring whose tension was adjustable by moving a sliding plate; this would have been necessary to 'balance' the rotational force of the weight pulling on the



4.2.6 Duc de Chaulnes' circular dividing engine (1762). The large dial on the right is divided into 1000 divisions. The 'T' shaped on the front of the cross bar controls the force with which the worm mates with the wheel. The wheel and micrometer microscopes are all mounted on a slab of marble.

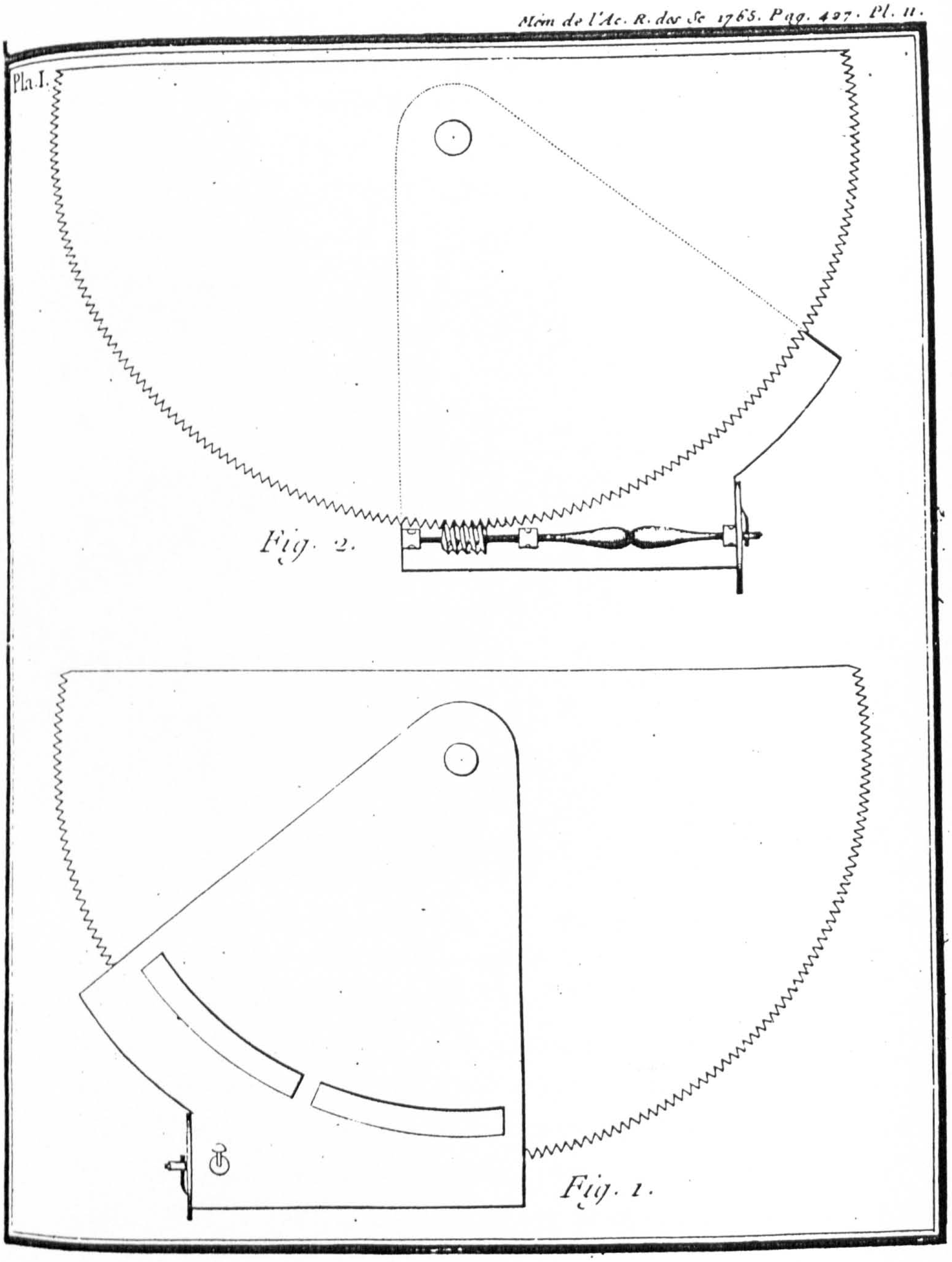
shaft of the wheel. To prevent the weight from rotating the wheel and tangent screw, Brander used a straight spring mounted to press down on the shaft of the screw. The fact that this was necessary suggests that the wheel and worm rotated with some ease. Finally, the dial for setting the position carried 100 divisions which, in conjunction with the 360 divisions on the wheel, required tables to be set up to convert to fractions of degrees (copied in Brachner: pp.365-8). These included a table which gave the number of degrees for any number of divisions from 2 to 360; one which gave the positions for 25 divisions in 360° and one for 57 divisions in 360°. Realistically we can estimate the precision of the divisions made with this machine to have been accurate to ≈10" at best.

4.2.3 Chaulnes' Dividing Engines:

The next person to tackle the problem was Michel Ferdinand d'Albert d'Ailly, Duc de Chaulnes (1714-69) in France. His was the "next dividing machine of which we know in some detail" according to Daumas (1972, p.197); Daumas seems to have been unaware of the descriptions given by Brander. Two dividing engines by Chaulnes are preserved in the IMSS, Florence with the circular dividing engine (Fig. 4.2.6) dated 1762 and the linear dividing engine thought, by the museum, to be of the same date.[1] These have not been described in the literature and the circular dividing engine is very different in design from that described by Chaulnes (1768 II). His 1765 paper illustrates a circular dividing engine on the same principle as that in Florence but of different design. In the 1765 engine it appears that the screw and octagonal plate rotate around the wheel, while in the Florence engine the wheel rotates on a frame to which the tangent screw is fixed. When inspected, the instruments in Florence were not complete, the mounted microscopes and scribing apparatus being missing. Some components were in storage during renovations to the museum. Nothing is known of the technique used to divide the wheel of the dividing circle although we might speculate that the scales of these instruments embodied the unrefined germs of the technique published in 1768. The wheel is ≈85cm in diameter and the worm has a diameter of 18.3mm and carries a dial of 39mm diameter and divided into 1000 divisions. The worm is forced against the wheel by an adjusting screw but no other provision for backlash elimination was apparent. A steel strip attached to the upper edge of the rim of the wheel is divided into 4000 divisions marked every 20 divisions, with each division equal to ≈5.4'. Inside this scale, in pencil, 360° are marked off and labeled in both forward and reverse directions. In addition, and also in pencil, sectors are marked off from 0, 1...15 representing 24° divisions. A frame is mounted across a diameter above the wheel and this carries the upper bearing of the axis of the wheel. The important parts are mounted on a piece of

---

1 Daumas notes that there is a circular dividing engine, sans the microscopes, dated 1768 in the Conservatoire National de Arts et Metiers in Paris (#832). Attempts to get information and to gain access to it were fruitless and a visit to the museum failed to find it among the exhibits.



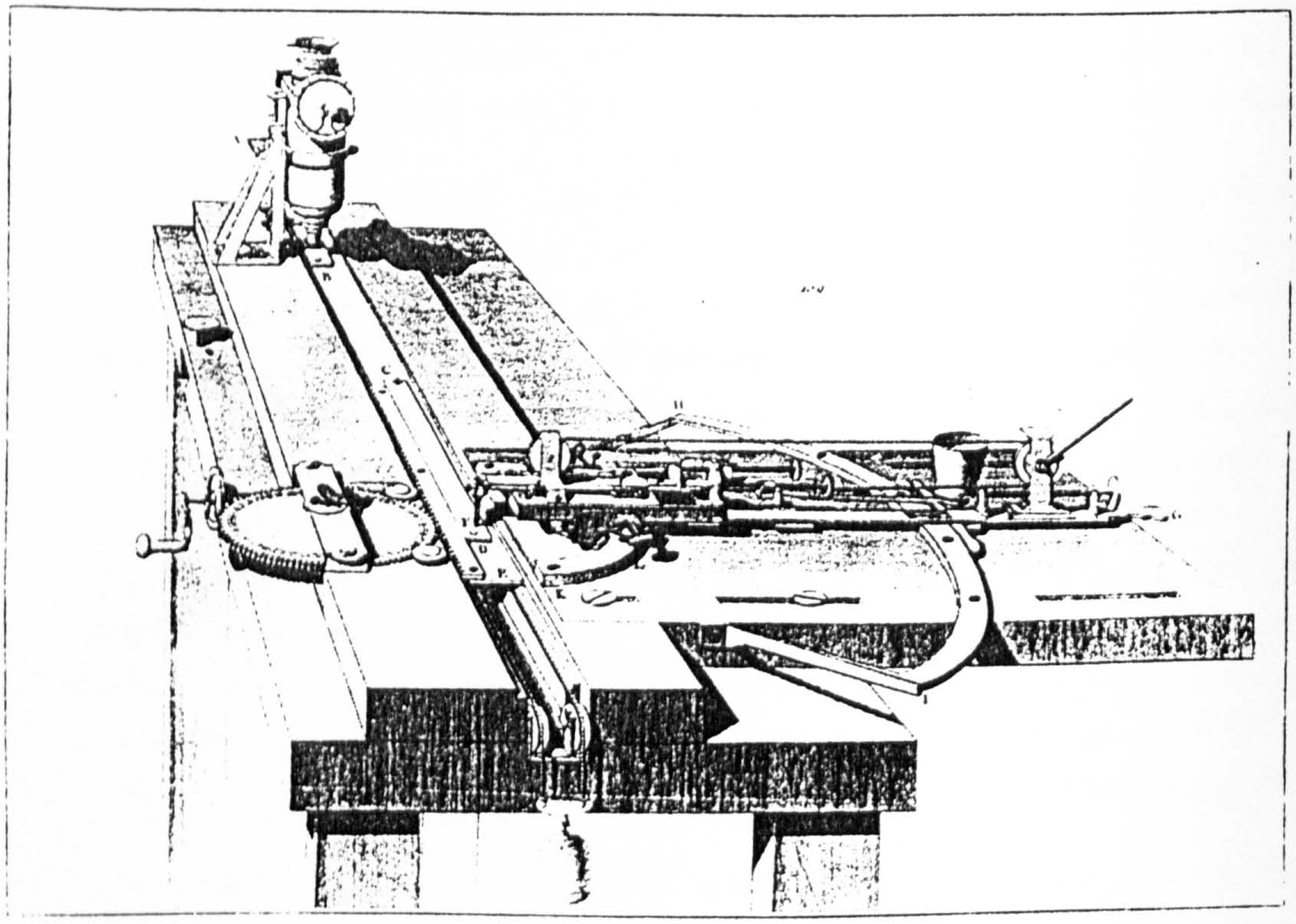
4.2.7 Chaulnes' circular dividing engine designed in 1765.

granite ≈4cm in thickness and this is mounted on a purpose made mahogany table of elegant design; the extension on one side held the scribing apparatus.

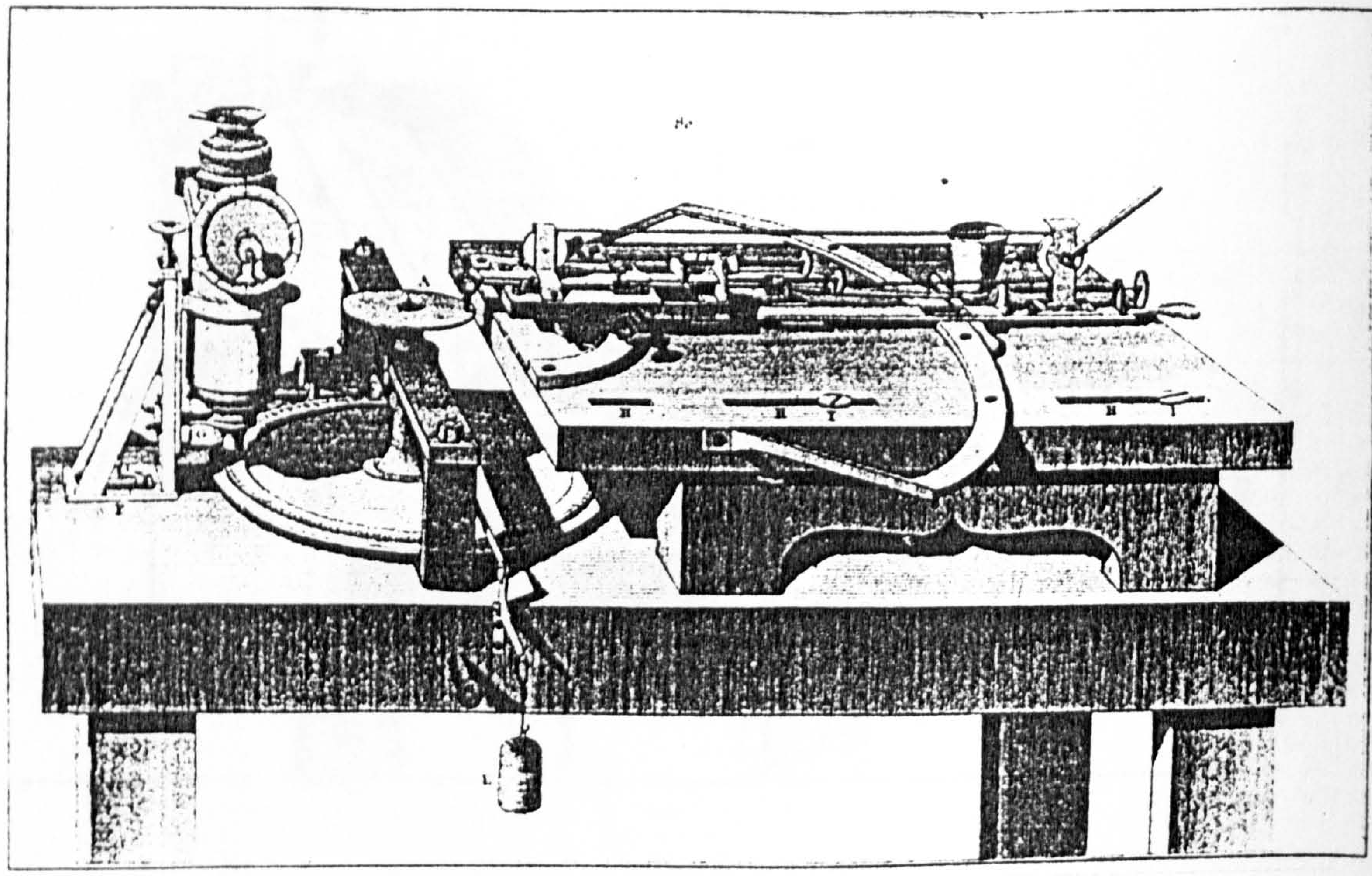
Chaulnes (1765, p.415) noted that he had been using microscope micrometers for 20 years, that he could then measure 4/1000^{ths} inch (≈0.08mm) and that it occurred to him that this ability could be employed in the division of instruments. The instrument (Fig. 4.2.7) to be described was primarily intended for graduation of octants. The wheel or 'index quadrant' of the instrument was about one pied (≈32cm) in diameter and 2-3 lignes (5-7mm) thick. It had a truncated conical shaft of speculum metal attached at the centre to act as a pivot. A segment of plate 50° wide was mounted on the 1 pouce (27mm) diameter shaft centered on the wheel. It was to this plate that he attached his 'micrometer'--really only a dial attached to the worm; the worm moved a plate 7 pouce in length and 1.25 pouce wide. It was to this piece that the instrument to be divided was attached. The dial was divided into 100 parts and subdivided by a 'Nonius' (i.e. a vernier) with 10 divisions; thus Chaulnes was able to measure to 1/1000th part of a revolution.

A worm screw of 5 or 6 teeth worked against the edge of the wheel. The grooves on the rim were made by carefully machining the teeth to match the depth and pitch of the worm in the same manner that Ramsden later used. Once the teeth were completed the worm was racked back and forth many times to even out the teeth. To check the accuracy Chaulnes divided the index wheel into 10 sections (i.e. 36°) and these into 10 subsections (3°36'). 10 revolutions of the worm equalled 1 section and the divisions could be crudely checked by watching the index position as the worm was racked along the limb. He then identified the 0° and 90° points and using lenses attached to the index quadrant and to the wheel he measured the turns and parts of revolutions of the index to advance from 0°-90° finding 499.13 turns. With this he then set out a table showing the number of revolutions for 1°, 2°...90°. The scribing mechanism (which he did not describe in detail) was mechanized to the point where it lifted as the wheel rotated between scribing operations. A test was then run on a sample but it became immediately obvious even to his unaided eye that the divisions were far from equal; these were erased and repeated several times but without success. Chaulnes ascribed the failure to using materials of different hardness for the worm and wheel and uneven wear in the wheel. This method was abandoned.

The next attempt employed two microscope micrometers to determine the divisions rather than relying on the accuracy of the worm and wheel. One microscope was attached to the plate and one to the table that the wheel was mounted on. Silk threads were placed in the fields of the two microscopes to act as the moveable fiducials. 'Fixed' fiducials for the wheel consisted of small copper squares (3 lignes square) engraved with fine crossed lines. He again laid off 90° checking the number of turns (320.87) with the micrometer. The 45° point was found by using the two microscope micrometers to compare the 0°-45° and 45°-90° arcs. If they did not match he calculated the required motion forward



4.2.8 Chaulnes' linear dividing engine (1768) with semi-automatic scribing apparatus which was interchangeable with his circular dividing engine (Fig. 4.2.9)

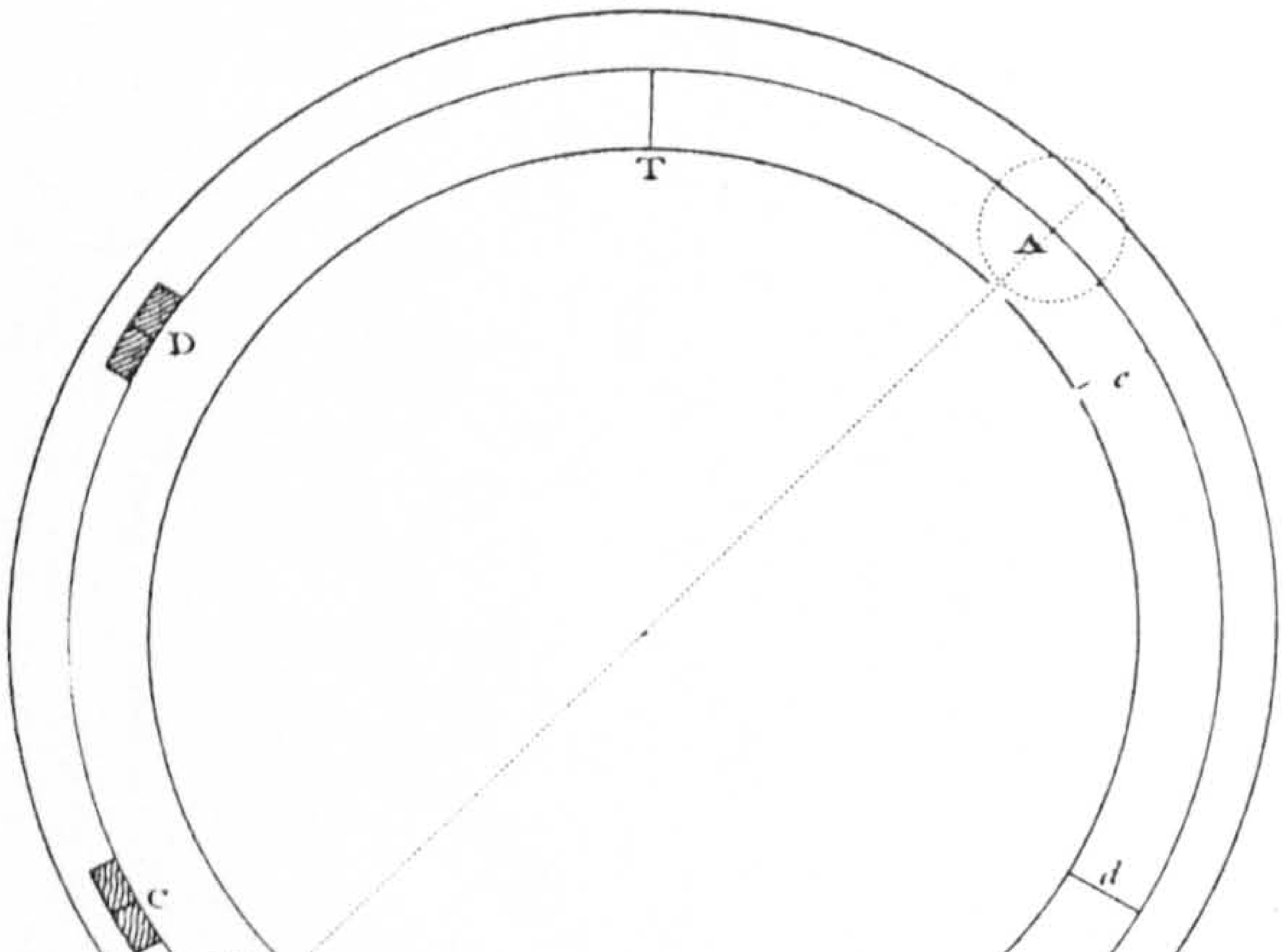


4.2.9a Chaulnes' circular dividing engine (1768). The scale being divided is the upper disc noted as "A".

4.2.9b Illustration of the dividing technique employed, i.e. reversal of the circle to detect eccentricity.

duc de Chaulnes's Dividing.

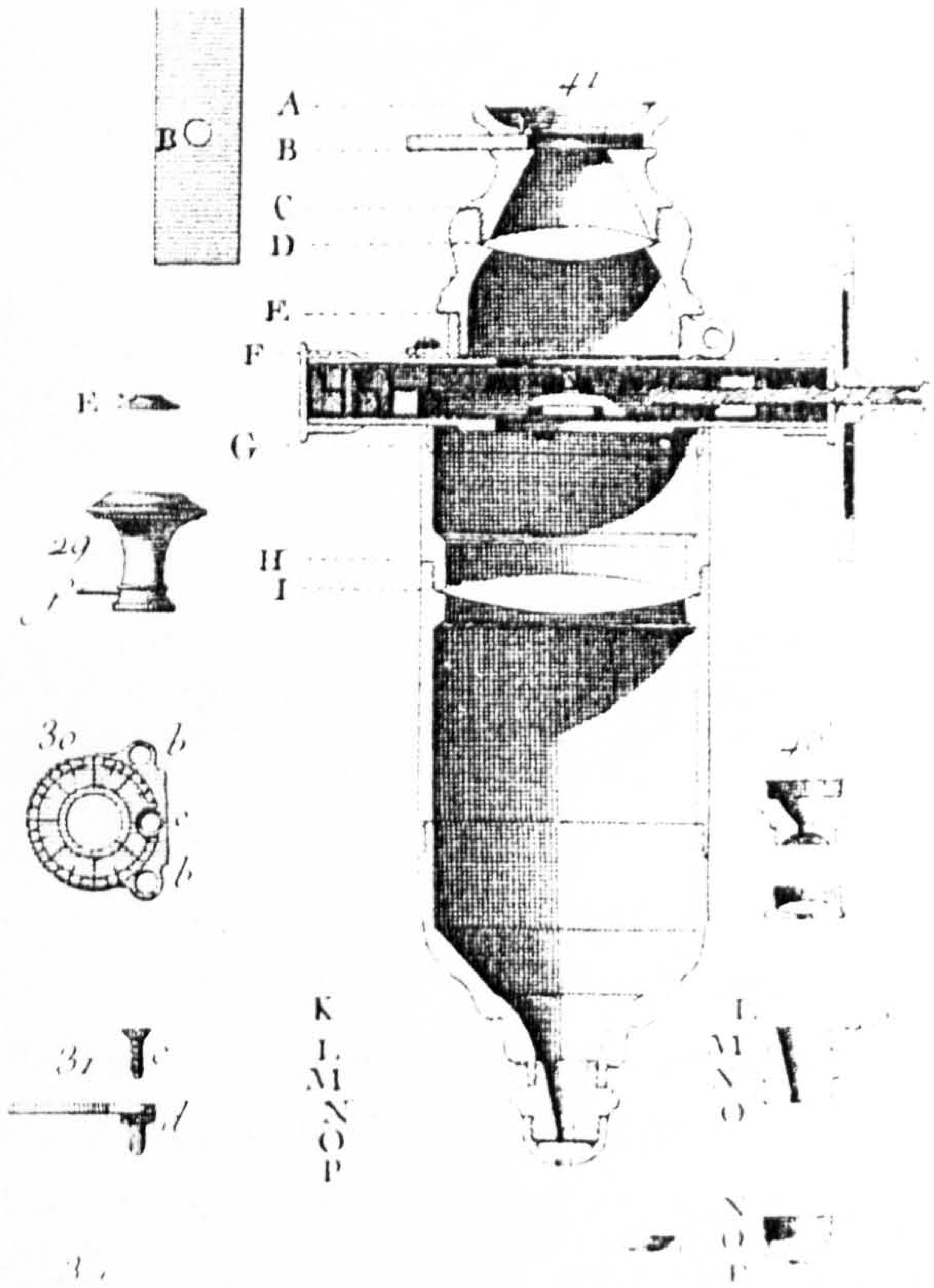
Fig. 3.



or backward; he was thus using the micrometers as points of a compass. This process of bisection was continued down to the smallest separation permitted by the physical size of the micrometers (4°-5°). The worm driving the wheel could then be used to step off the primary divisions around the wheel but subdivisions still had to rely on the accuracy of the micrometer screws and worm each being compared with the others. Chaulnes claimed that he could make a division then come back to it later and repeat the division with the line only being slightly widened by this operation. Thus by March of 1765 Chaulnes had established the basis of division which was to be so successful in the hands of Edward Troughton some thirty years later. Once the primary division of Chaulnes' wheel had been accomplished he was in a position to carry out a straightforward copying of these divisions onto a nautical quadrant or other instrument.

In 1768 Chaulnes published **Nouvelle Méthode pour Diviser les Instruments de Mathématique et d'Astronomie**, which minutely illustrated every component of the circular and linear engines in 15 plates. A very important element which Chaulnes incorporated was a mechanical means of scribing the lines. Such a mechanism was used on his 1765 machine but was not described. The new mechanism was complex and one wonders whether this was more of a limiting factor in the engines' use than the method of moving the piece to be divided. The scribing tool could be balanced by a small reservoir and was activated by a handle and pulley system. There were screws for the adjustment of the radial position and stroke length of the scriber, and the whole apparatus was mounted on a base in such a way that it could be swung through an angle of ±45° from the centre position with the centre of rotation corresponding with the axis of the wheel; thus either an 'X' could be scribed for fiducial marks or simple straight strokes. The scribing mechanism was mounted on a sturdy board which was interchangeable between circular and linear dividing engines and when on the linear engine, the ability to rotate the scriber permitted Chaulnes to make scales divided by transversals.

Unlike the linear dividing engine in Florence, the 1768 engine (Fig. 4.2.8) did not have a screw to provide the motion, this being provided by a moderately large diameter toothed gear working against a rack. This mode of providing the translational motion may have been chosen after experience with his previous linear engine where a large eccentricity of the screw caused binding and inevitable errors--assuming the one in Florence was Chaulnes'. In the new engine the actual setting of the workpiece, which was fixed to a moving counterbalanced bar along with a master scale, was controlled by a micrometer microscope; this microscope was of the same design as described by Chaulnes the previous year and was also interchanged between the linear and circular engines. The master scale and copy were mounted on a common arbor and rotation was by means of an endless screw which could be advanced using an attached index. On the circular dividing engine, (Fig. 4.2.9) the microscope was again used to set the position of the work piece by reference to a steel scale mounted on a master wheel of ≈8 pouce (Chapman has 11in



4.2.10 Detail of Chaulnes' microscope micrometer with micrometers on both cross and vertical motions. He had begun using microscope micrometers as early as the 1740's.

diameter) diameter. Thus Chaulnes had dropped his dependence on a screw in this engine as well as settling on a method of copying a master scale made simply by drawing equally spaced lines on wood. When subdivisions finer than those on the master scale were required, or for making verniers to match the divided scale, the micrometer on the microscope came into use. Normally the fiducial wires of the micrometer were left fixed but for the subdivisions, the space was measured with the micrometer, divided into the required number of parts, and the micrometer then set successively to the required positions of the subdivisions. The work piece was then rotated by means of the worm--the fixed wire being set on the primary division and the moveable wire indicating the position of the subdivision to be scribed. Hence for the finest divisions, the responsibility for the instrument's accuracy relied upon the micrometer screw.

The position of the micrometer microscope and master scale limited the diameter of the scale being divided to be of smaller diameter than the master. Placement of the master above the work piece would have solved this problem. One may envisage that division of a circular scale was fraught with some problems especially with respect to the centering of the workpiece on the arbor. Thus, for the very best work, Chaulnes resorted to the method he employed in making the master, i.e. using two moveable fiducials and two microscopes 180° apart and rotating the work. Chaulnes' 1767 paper on optics includes figures of the microscope micrometer but unfortunately does not provide details of the components. The case is much the same as those used on contemporary filar micrometers of French manufacture but whether there were springs for backlash may only be speculated upon. The microscope was mounted on a frame which was intended to hold samples for inspection under the microscope and this frame incorporated a second micrometer for moving the stage for direct measurement of the sample. This micrometer was illustrated in detail but does not include springs. It was used in conjunction with a small scale scribed by a diamond on glass to test one micrometer screw against the other and to set up a table of errors for the screws (1767, p.428). The dial was divided into 100 divisions and these subdivided with a vernier to 1/1000th of a turn. The pitch is not given but is quite fine if the figures are accurate. It is worth noting also that Chaulnes illustrated a spherometer in this paper (pl. VII) which had two feet adjustable in a radial direction and with a scale and vernier for reading the radius (see §3.5).

Presumably in response to requests prompted by his 1767 paper, Chaulnes described his microscope in a short monograph (1768 I). The figures were taken from the former paper but supplemented with numerous detailed figures. In Pl. III of this monograph we find a cross sectional figure of the micrometer (Fig. 4.2.10) including some lines which might be interpreted as an anti-backlash spring. But given that virtually every component is figured separately and that no spring is illustrated, it is assumed that no spring was used. The stage micrometer is again figured and described (p. 9) in detail (the micrometer in the microscope is not described in detail) as is the spherometer (p.15). The stage micrometer could be rotated through a small angle by means of an endless screw arrangement.

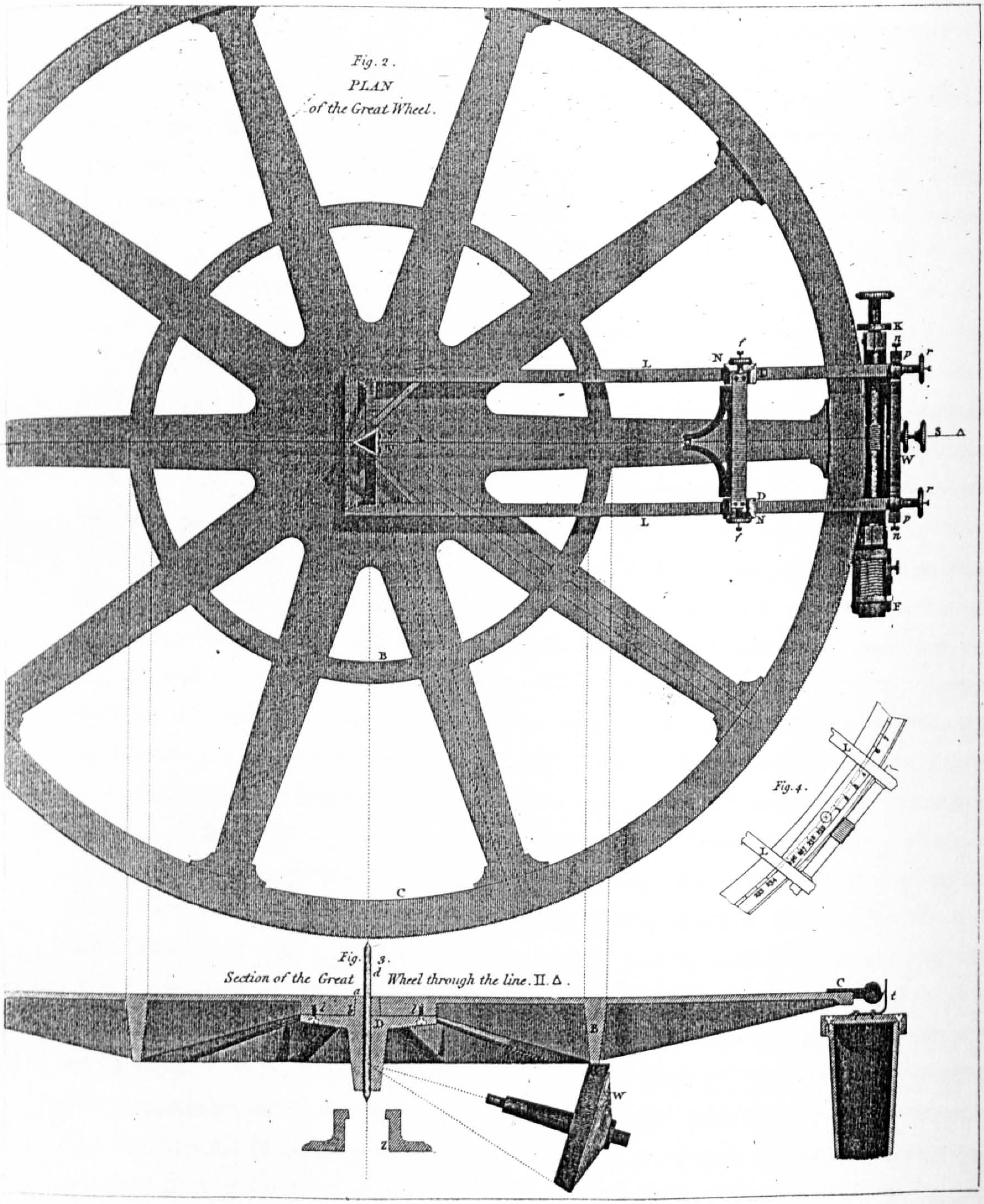
The process employed by Chaulnes (1768, p.33-8) to make the master scale and to set off the primary divisions for the circular dividing engine depended upon the reversibility of circles[1] Part of Chaulnes' success was adopting micrometer microscopes to the process but unfortunately he did not use Graham's expedient of progressing by continual bisection. The first step was to find diametrically opposing points on the circle. Lines were drawn on small slips of brass and mounted on the limb with wax at ≈180°. Two micrometer microscopes were mounted on the frame and the slips viewed; the circle was rotated 180°, the slips once again viewed and one of the micrometers adjusted to measure the error. One slip was then moved half the error and the procedure repeated until the lines were perfectly placed. Similarly, 60° and 120° positions were found by trisection and so on until the circle was divided into 10° segments. This technique did not heavily depend on the accuracy of the micrometer microscopes, errors being eliminated by successive reversals. However, this was not the case for other steps for divisions less than 10°. By trial and error, Chaulnes found the position of 9° and then stepped off 10° segments to give 19°, 29°, etc. with the use of the micrometer microscopes. Likewise using the 9° space he could find 18° and step off 28°, 38°, etc. and this procedure used to fill in all the 1° divisions. For the half degree divisions, Chaulnes subdivided 15° to get 7 1/2° and this was used to fill in the required half divisions. In essence, the micrometer microscopes at this stage were being used as the points of a beam compass. Further subdivision was carried out by dividing a 7ft rod into 12 parts and observing it with a telescope fixed to the circle to be divided from a distance where the ends of the board corresponded to one degree division marks. The intermediate marks were then scribed onto a 'pattern plate' which was then transferred to the circle with the aid of a microscope--rather crude compared to the other steps and, as Chapman points out, a third hand copy of untested divisions on the 7ft rod. Although this engine had the potential for reasonable accuracy, it would have been slow to use since each division had to be set and inspected visually--a flaw which Ramsden overcame with his self-acting engine. In France, a clockmaker, Pattier, is reported to have made two engines along the lines of Chaulnes' 'mark II' engines but little is known of their features or precision.[2] Indeed the accuracy of Chaulnes' later engines is unknown and no instruments survive which are known to have been divided on them.

---

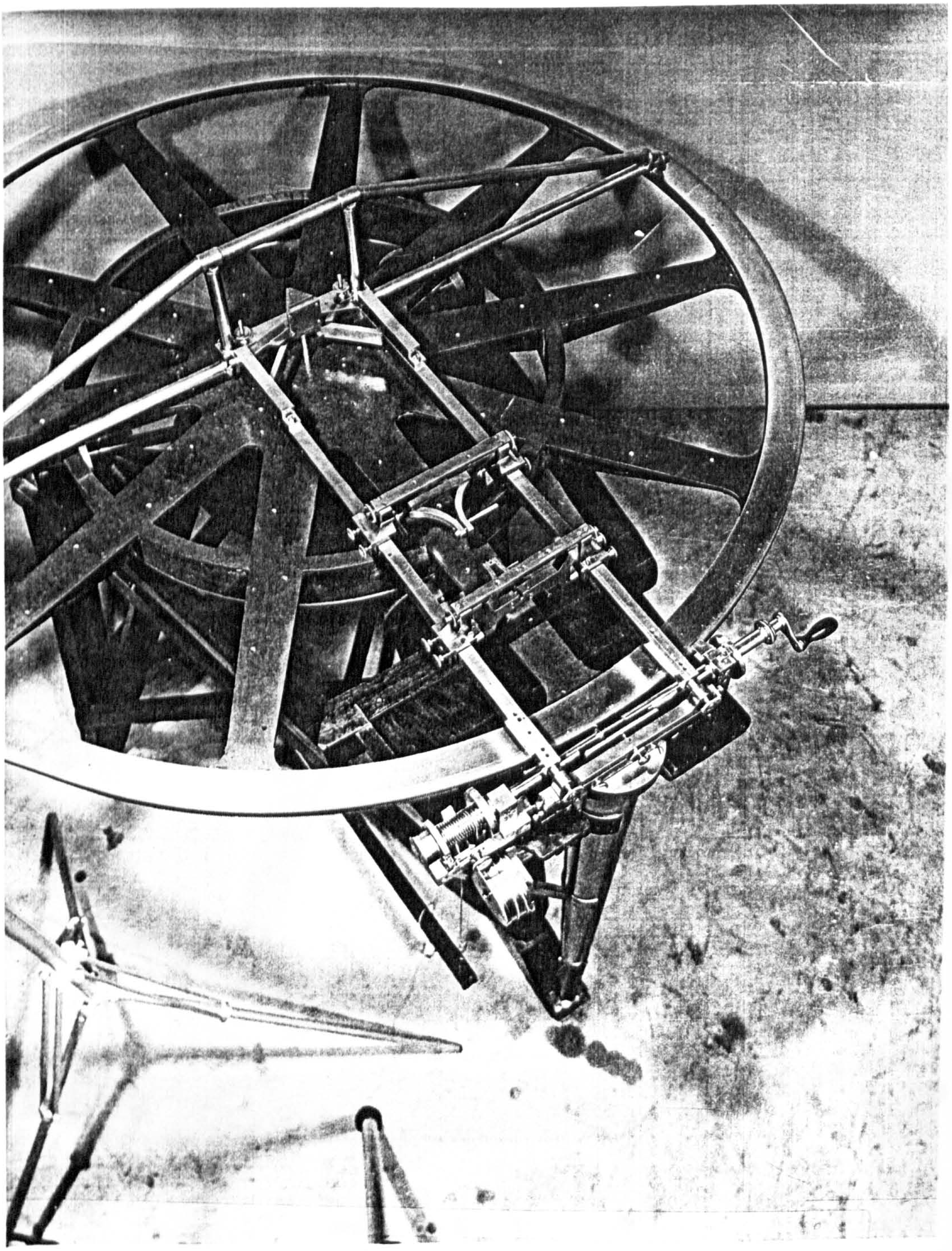
1 Chapman (1976 I, p.236ff) has described the technique in some detail.

2 See Daumas: 1972, p.199 and Histoire de l'Academie des Sciences: 1771, p.95.

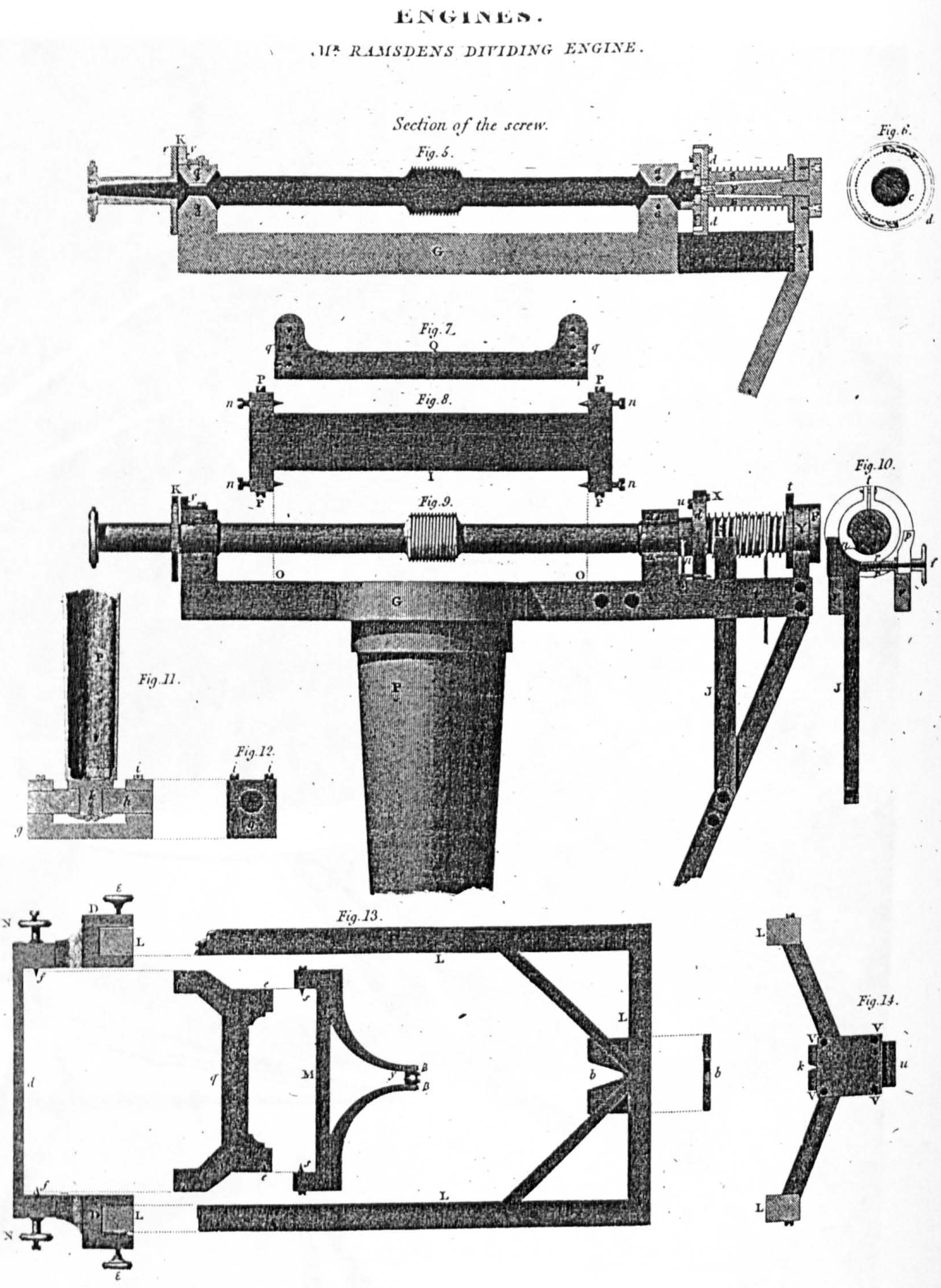
Mr RAMSDEN'S DIVIDING ENGINE.



4.2.11a Ramsden's 1774-5 dividing engine which won the Board of Longitude Prize (1777). This illustration is from Rees (1819) following the illustration provided by Ramsden himself and by Troughton (1809).



4.2.11b Ramsden's machine as it now exists in Washington. The cross members across the diameter were apparently added later (>ca.1840's) to steady the engraver frame. The screw has also almost certainly been replaced based on Troughton's use of a spirally grooved worm from 1793.



4.2.11c Details of the mounting of the worm and engraver frame on Ramsden's circular dividing engine.

4.2.4 Ramsden's Dividing Engines:

Jesse Ramsden's (6/10/1730-1800) reputation was unsurpassed in the dividing of instruments in the 18^{th} c (though surpassed in skill by John Troughton). His method of original dividing was kept a tight secret and was not described in print until Pearson's contribution on scale dividing in the **Edinburgh Cyclopedia** although it was apparently known to London workmen at the time of Ramsden's death in 1800. Ramsden had learned his trade and engraving under the London thermometer and barometer maker and divider of instruments, Mark Burton, who did work for both Short and Bird. Certainly Ramsden's foreman, Mathew Berge, knew his technique, which used a beam compass to lay off the primary divisions and was related to Chaulnes' technique of using 'moveable' dots or 'coaxing' of the dots and microscopes to compare divisions 180° apart. But it was the success of Ramsden's circular dividing engines which is of interest to us. He apparently began considering the problem as early as 1760 completing his first engine in 1766; this machine had a wheel 30in in diameter. It is generally considered that Ramsden was the first to make a truly successful dividing engine in his second machine completed in 1774/5. For this accomplishment he received an award (£615 ca.1777[1]) from the Board of Longitude and achieved commercial success as a result of being able to quickly, and accurately divide scales of instruments like octants. It has been speculated that Ramsden learned of Hindley's dividing engine and some of its features from John Stancliffe who worked for Hindley and then entered Ramsden's workforce after moving from York (Chapman: 1976 I, p.282).

The principle of Ramsden's engine (Fig. 4.2.11a,b,c) was not very different from Chaulnes' first circular dividing engine (1762) but was more refined. Chaulnes had initially attempted a mechanical means of dividing, but finding the results wanting, had adopted a 'scientist's' approach by using microscopes as the important element. Ramsden, being the finest mechanician of the 18^{th} c, took the mechanical route; as a result of his skill he reached a successful solution to the problem. It is from the description he was required to produce of the 1774 instrument, that we learn of his method of producing and using screws in the process.[2] Ramsden's success was a result of the care taken to make the tangent screw and to make the teeth on the bronze wheel and the fact that it was, to a degree, self-acting. To make the screw, he made a lathe consisting of a lead screw mounted on a triangular bar; the tool was moved along by the lead screw by turning a hand crank which transmitted the force through gears. The tool was also triangular shaped and tipped with a diamond to cut the steel screw blank. Two worms were cut--one with the teeth cut to act as a cutting tool and the other to be the screw used for the dividing process

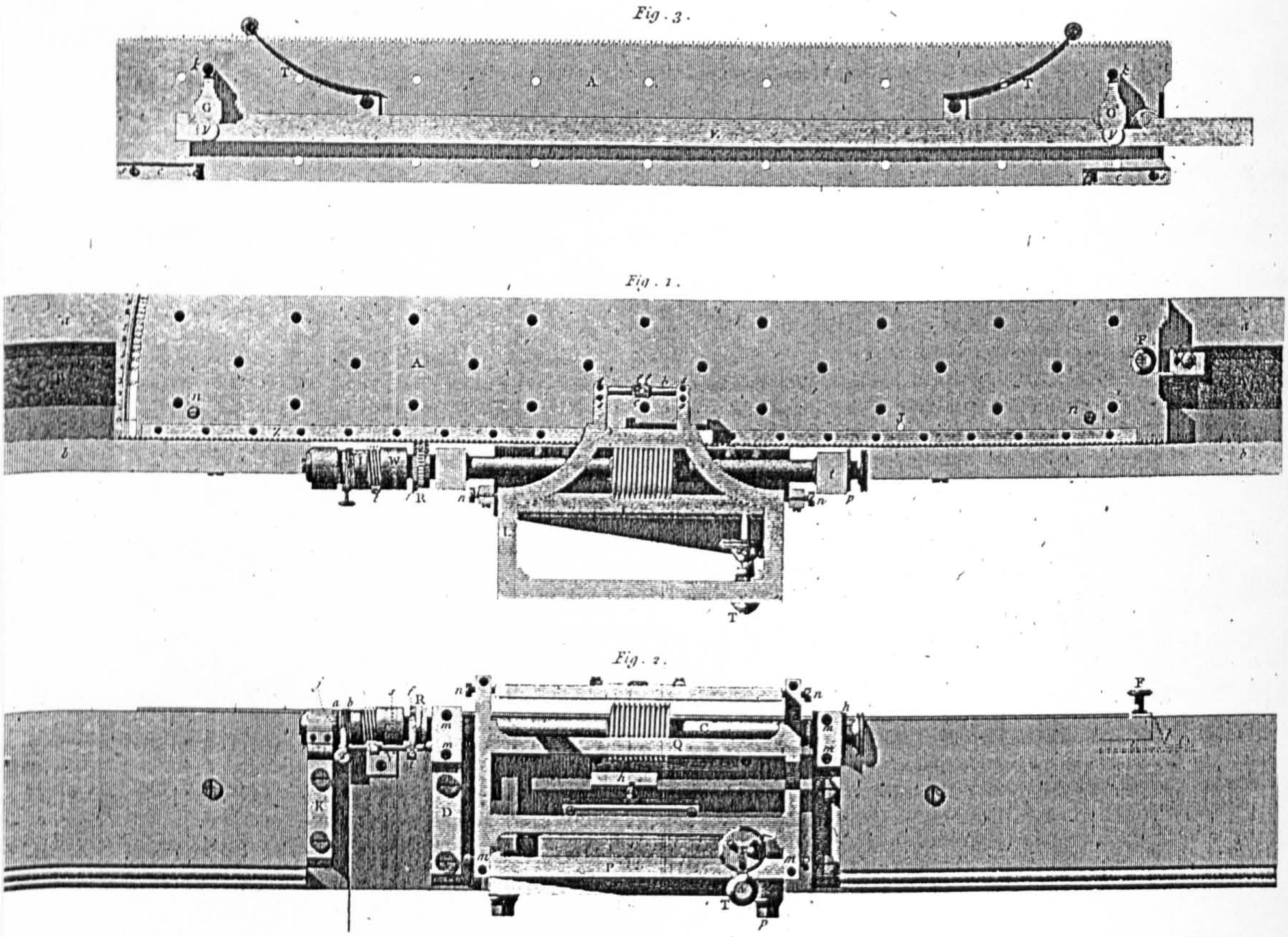
---

1 See Chapman: 1976 I, p.284, n.3 for a discussion of when this instrument was completed and prize awarded.

2 The method used for the first engine of 1766 is not known.

ENGINES.

RAMSDEN'S ENGINE for dividing Straight Lines.



4.2.12 Ramsden's linear dividing engine. This machine never reached the accuracy of his circular dividing engine because of the reliance on a long rack. Note in Fig. 1 (middle), the scale (left) for inclining the plate holding the scale to be divided to allow scales of different spacings to be engraved.

on the wheel. Both the screw lathe and dividing engine are preserved in the Smithsonian Institution. The method of making the screws has been dealt with in detail in §2.4.3.

To cut the 45in diameter wheel, Ramsden marked off a 60° segment which was of slightly larger radius than the final wheel would be. The edge was cut with the screw-tool and the number of teeth in the 60° segment counted; by calculation Ramsden determined the precise radius required for 360 teeth in 60°. The wheel was then marked with this radius and another sightly larger by an amount equal to the depth of the teeth. The wheel was cut down to this larger radius. Ramsden marked off the circumference in spaces which corresponded to 9 teeth and the process of cutting each of the segments begun. To avoid cumulative errors, the cutting proceeded within each segment by lining up the division line with a thread fixed to the frame and viewed with a microscope. Each successive segment was started at the end away from the previously cut segment and cut backwards, i.e. from 2 to 1, from 3 to 2, etc. around the circle. Ramsden predicted an error of 2.5" per tooth and a total error of 10' in the 360°. Each tooth was to equal 10' of arc which thus required 2160 teeth in the edge of the wheel. Thus with a dial with 60 divisions, one could measure to 10". Once the preliminary teeth were cut, the wheel and cutting screw were run around a number of times to deepen the teeth on the wheel and to make them smooth and even.

Some of the design features deserve mention. The wheel was mounted on a vertical axis and was supported by runners on a mahogany frame. The wheel was spoked and reinforced with a ring; the top surface of the rim was of course made perfectly plane to accept the divisions. A frame carried on the centre of the wheel and reaching out over the edge held the tangent screw. Its pressure could be adjusted by means of a screw and spring. Rotation of the wheel was imparted by a cord wrapped around a spirally cut cylinder driven by a treadle. Motion was in one direction being limited by a ratchet wheel and the advance was limited by an ingenious mechanism with stops which was adopted in numerous dividing engines through the 19^{th} c.

Ramsden's linear dividing engine (Fig. 4.2.12) incorporated a screw of 20 TPI which was finer than that on the circular dividing engine and was made on another specially made screw lathe which used the idea of a tangent screw working against a toothed plate. Motion was transferred to the tool via a pulley and rotation to the work piece via a large pinion gear meshing with a beveled gear (see Daumas: 1972, fig.114). The newly made screw was then mounted on the linear engine to work against a thread cut in the side of a bar to which the scale blank was attached. The rack thread was made with a slotted screw as in the circular dividing engine, subsequently replaced with a plain screw. The endless screw was forced into the bar by two curved springs on the underside of the frame. Motion was imparted by a cord wrapped around the shaft of the screw. Daumas (p.202) states that Ramsden achieved an accuracy of 0.001in with a vernier on this dividing engine though Troughton (1830, p.357) claimed the accuracy was 1/4000in. The screw had a dial attached with 50 divisions and the dial had a vernier providing subdivision to 0.0002in. The author of the article "Graduation" in the **Penny Cyclopedia** (1838, p.338) stated: "In the form proposed by Ramsden the machine has not been deemed of any value, since a long screw can never be made so accurate as a scale divided by continual bisection. Mr. Bryan Donkin has contrived a machine where a screw is indeed the scale, but where the errors are corrected with additional mechanism. We do not think that this machine has ever been figured or described [this deficiency has not yet been corrected!], but scales have been divided, and screws cut by it of extraordinary accuracy."[1] Ramsden's linear dividing engine was used not only for making measuring scales but for all sorts of navigation scales, sectors, etc. It is worth noting that Ramsden was aware that he could make scales to foreign measure simply by inclining the scale to the screw by the appropriate amount. This idea was used by Siemens Bros. for their bench micrometer as noted previously.

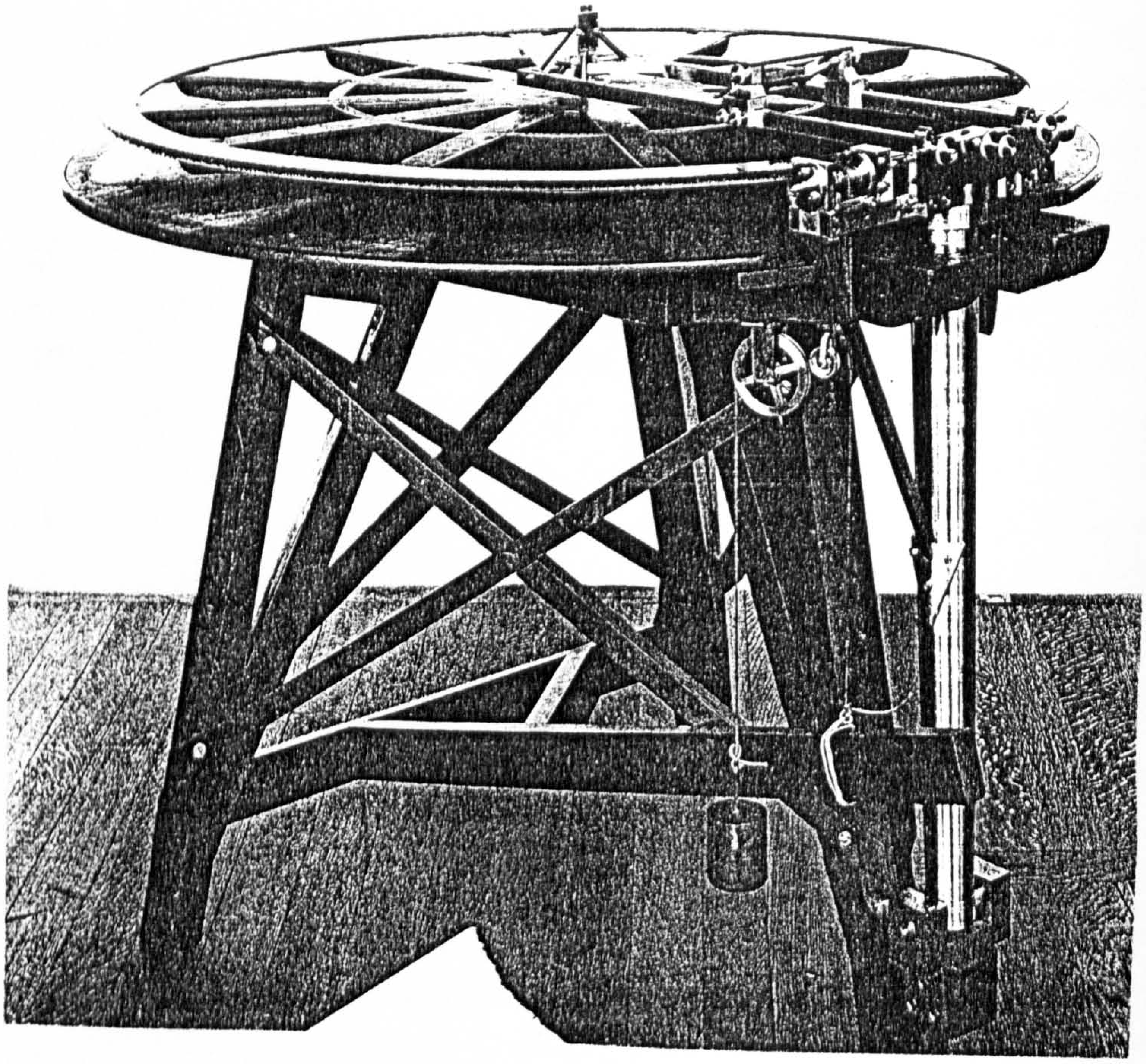
Before Ramsden had applied himself to improving the division of scales, he noted that errors of 5' were common but with his second circular dividing engine he was able to divide a sextant to 5" of arc in 20 minutes. As a requirement of his award for the dividing engine from the Board of Longitude, he was to be available to be contracted to divide the scales of instruments of other makers for 3 shillings. He is reported (Piazzi: 1803, p.255) to have made 983 sextants himself, these ranging in size from 1 1/2in to 15in radius but with a preference for those of 10in radius. Another requirement of the award was that he instruct several other instrument makers in the design and use of the dividing engine; the ownership of the machine became the property of the Board of Longitude but they permitted him to keep possession of it--which he did until his death. Those instructed included Edward Troughton and John Stancliffe, both of whom made their own engines as a result. Interestingly Peter Dollond had made a dividing engine before Ramsden had described his in 1777 though nothing is known of its design.[2] It was apparently only used to divide their own instruments but considering the family and business relationships between Ramsden and Dollond, we may be correct in assuming that Dollond was given a peek at Ramsden's engines. By 1830 there were 10 or 12 dividing engines in London based on Ramsden's 1774 engine (Baxandall: 1923/4, p.138). Abraham (1926, p.64[3]) states that nearly all dividing engines made in Europe and America followed Ramsden's basic plan. By 1926 the worms were made of hardened steel and optically finished and when lapped together consistently gave results better than 1" even without the use of error compensating apparatus. Thus, in a sense, in this 150 year period dividing engine technology had come full circle and still relied on principles conceived by the great Ramsden.

---

1 Pl. cclxxx in the Edinburgh Cyclopedia is of Ramsden's linear dividing engine.

2 See ***Edinburgh Cyclopedia,*** 1830, article "Graduation", p.353.

3 This paper gives a description of the improvements in technique used by Casella in making their dividing engine ca.1925. The improvements were mainly in the cutting of the teeth on the limb.



4.2.13 John Troughton's (1778) circular dividing engine made according to Ramsden's instructions. This instrument is in the Science Museum.

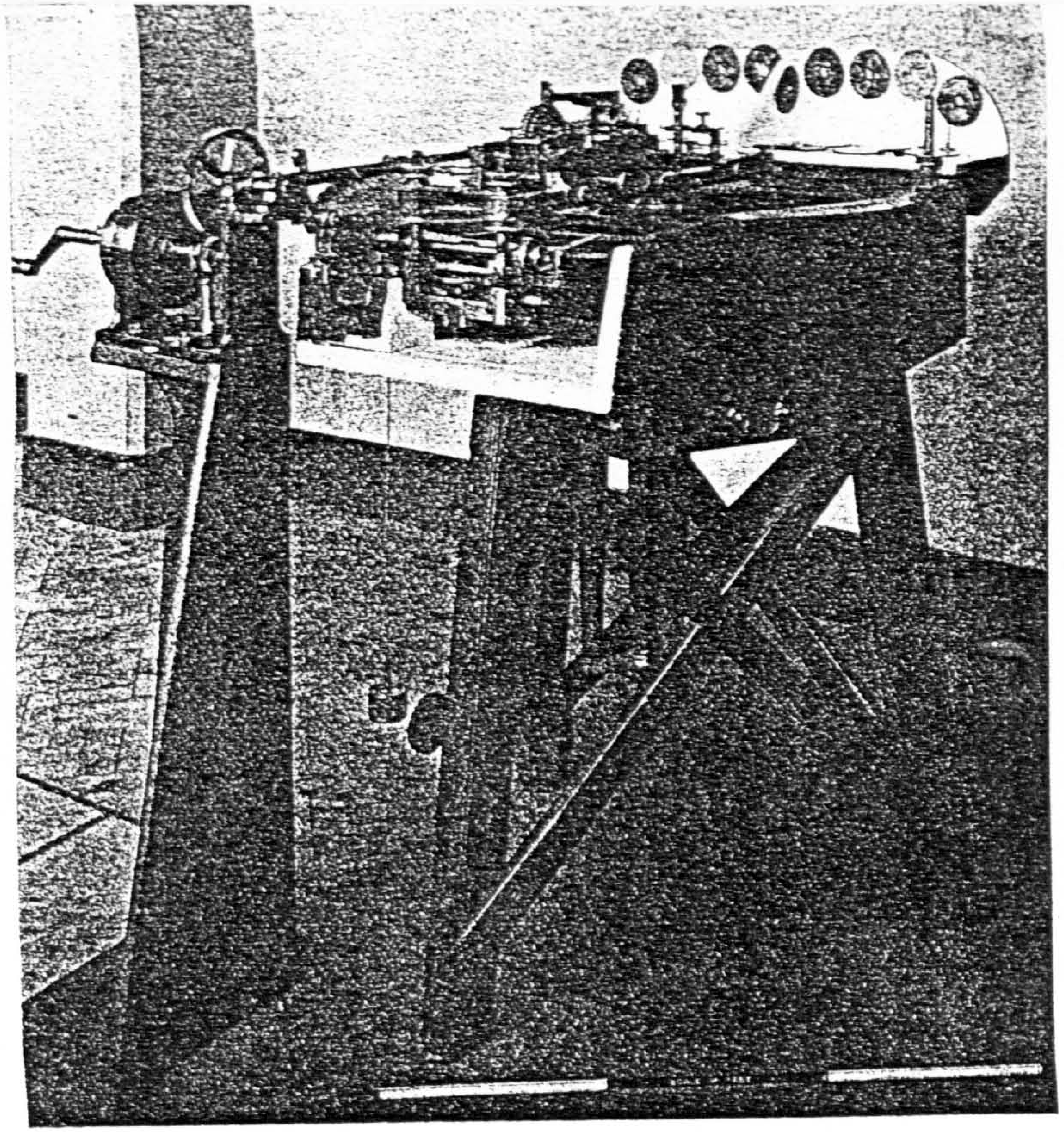
4.2.5 Troughton's Circular Dividing Technique:

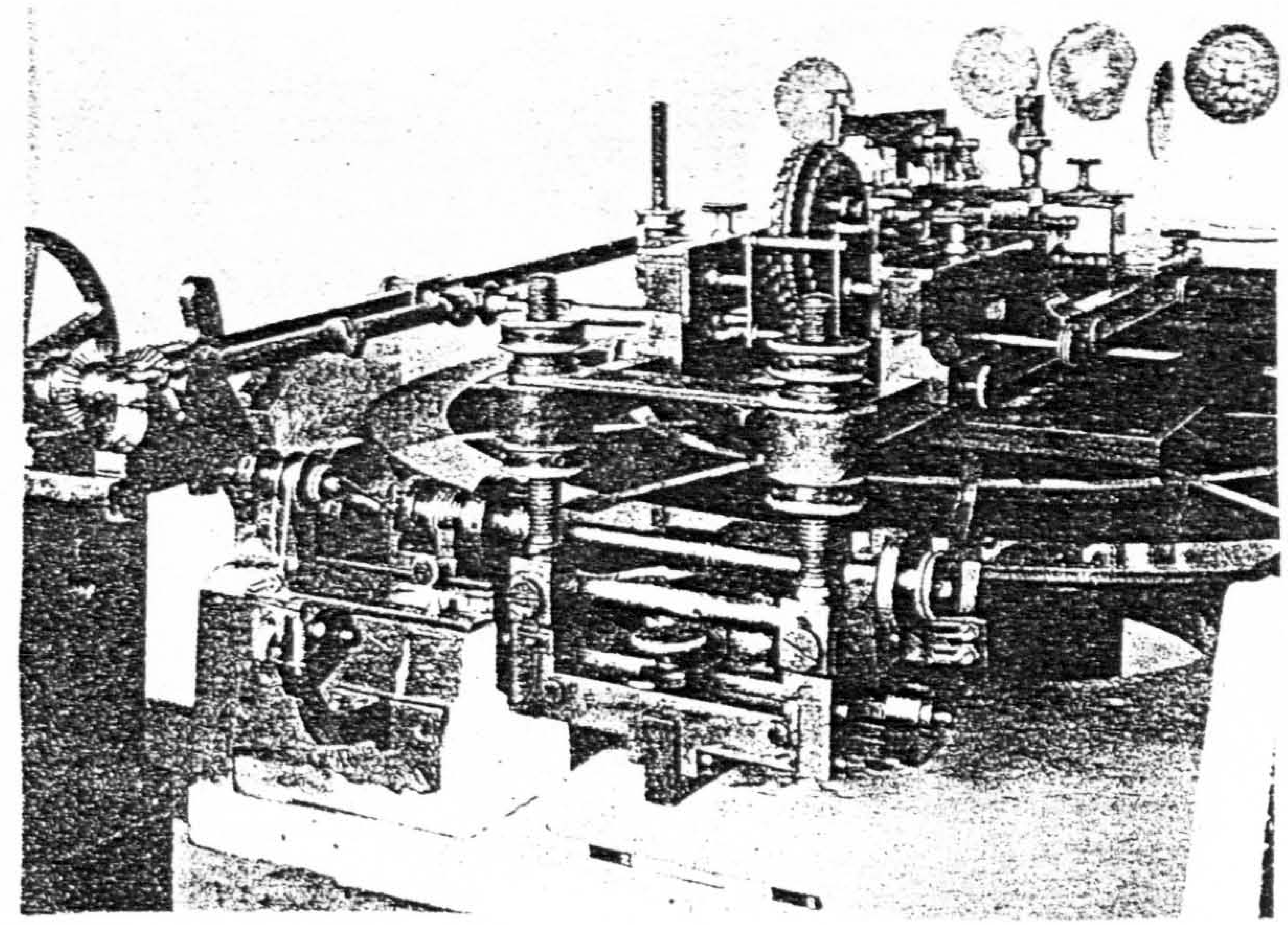
John Troughton was one of those instructed by Ramsden as a result of one of the conditions of the Board of Longitude Award. He began making his circular dividing engine (Fig. 4.2.13) in 1775, completing it some three years later. According to Edward Troughton (see entry "Graduation" in **Edinburgh Encyclopedia**, 1830) it was superior in precision to Ramsden's though of similar design. Both machines were capable of inscribing 24 divisions/minute with 30 possible for a short time. It has a plate of 4ft diameter thus being slightly larger than Ramsden's. However, it was difficult to use to the point where John's brother, Edward, said it was injurious to the health of the operator, and it was this which led Edward to develop improvements based on his method of original dividing. John's engine is in the Science Museum (SML-36) but it is very probable that the screw was replaced[1] or modified in the 1790's because the idea of employing spiral grooves on the 'generating' worm originated with Edward for his 1793 engine (Troughton: 1830, p.355). Ramsden and John Troughton had originally used a hob with grooves parallel to the shaft and these would have 'clunked' as the hob was rotated causing an uneven cutting action. Edward noted that the straight groove design required frequent sharpening of the screw that cut the teeth in the wheel, and that it was replaced when cutting was completed by a duplicate for the actual dividing. However, the wear on his spiral grooved screw was minimal and he was able to use the original in the finished machine.

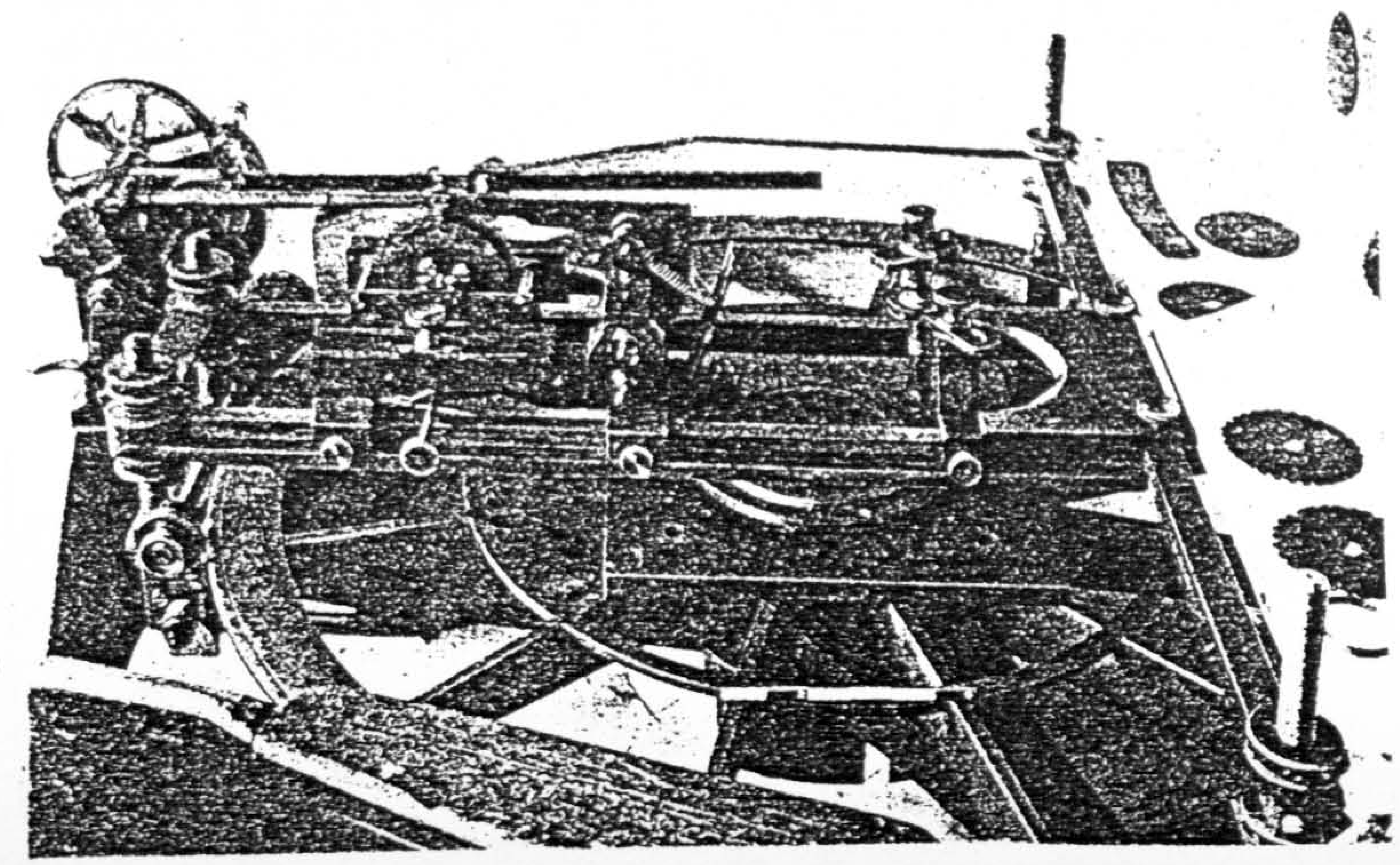
The next major advance in dividing technique was made by Edward Troughton while he was working with his brother, John. Edward Troughton's instrument is now in storage at the Science Museum, London, but was exhibited before the Optical Society (U.K.) in 1924 during a lecture by David Baxandall. Baxandall described it briefly in the *Transactions* of that society (1923/4, p.135-40) partially basing it on Edward Troughton's 1830 description. Completed in 1793, this engine had a wheel of only 34in diameter and was turned by a 20 TPI endless screw working against 2160 teeth cut in the edge of the wheel. These were cut using a screw or hob with grooves inclined to the shaft which made for smoother cutting and dispensed with the need for a second duplicate endless screw. The original division was accomplished by his method described in 1809. With the automatic or self-acting mechanism added by William Simms (ca.1843 and based on that employed with his dividing engine of 1843) the machine was used continuously until ca.1920 though in its later years was used only for scales of 1' divisions.

---

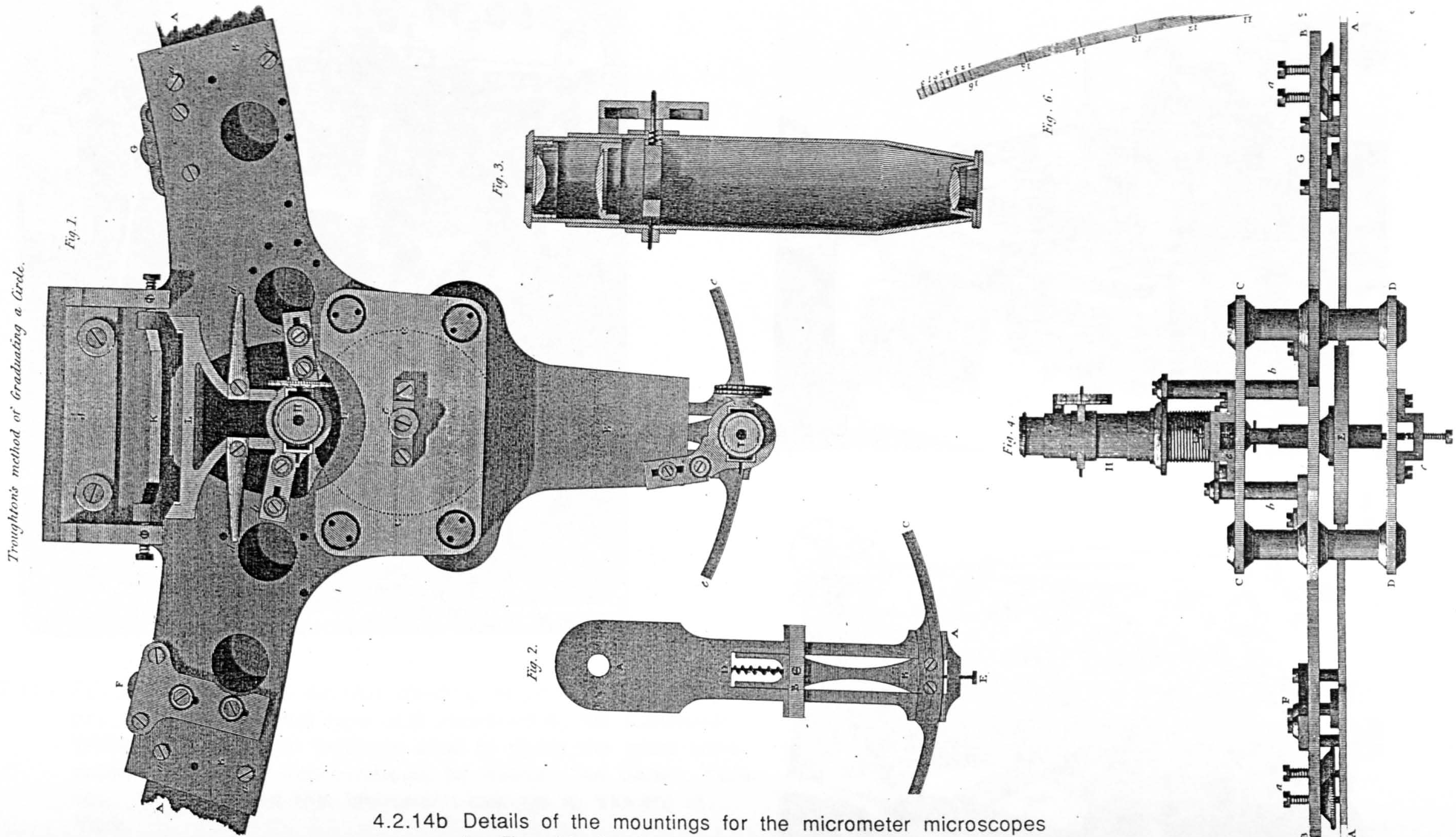
[1] It is quite possible, if not probable, that Samuel Rhee made the original screw. He was known to make the best screws and is also known to have done work for John Troughton (Holtzapffel: 1854, p.640).







4.2.14a Edward Troughton's circular dividing engine (1793) which proved to be the best type until improved by his successor, William Simms. The methods used to divide the scale were copies with minor improvements by makers like Jones, Kater, etc. It is believed this instrument belongs to Vickers in York.



4.2.14b Details of the mountings for the micrometer microscopes for Troughton's circular dividing engine.

4.2.5.1 Troughton's original dividing technique:

For original division, Edward Troughton developed his own technique which falls within the scope of this research by its dependance on micrometer microscopes. The method was first used on a 4ft meridian circle for Stephen Groombridge and was the method he used to place the divisions on his dividing engine (Fig. 4.2.14) in 1793. To begin, he used a roller[1] of slightly conical form moving around the rim of the dividing plate (16 turns) in order to mark off the divisions (256) but he found that the roller slipped and did not yield consistent divisions being in error by as much as 30". He thus adopted a procedure to determine the errors of the positions of the dots similar to that used by Chaulnes. Two microscopes were placed 180° apart across the diameter of the plate to be divided.[2] The dots for the 0° and 180° points were examined and centered in the microscopes and the plate then rotated 180° for comparison under the microscopes. With the 180° mark exactly bisected by one microscope, the 0° dot was examined by the other microscope and the error measured with a micrometer. The error was measured and half the error was assumed to be in the 180° dot. The micrometer microscope was then repositioned 90° from the other and the errors of the 90° and 270° dots determined in a similar manner as before. The micrometer microscope was then moved to the 45° position and the errors found for the 45°, 135°, 225° and 315° dots. Once the 256 dots (corresponding to divisions of 1°24'22.5"[3]) were all examined with this bisection technique (à la Graham), a table of errors was set up.[4] The micrometer microscopes (see Fig. **4.2.**14b) incorporated a small rectangular box soldered into the microscope tube. The cross wires were mounted at a 30° angle and when viewed were about 2/3[rds] the diameter of the dots. A coil spring around the micrometer screw and a guide pin were incorporated and the micrometer head divided into 100 parts, 50-0-50 with each division equal to 0.2" or 5.6 equal to 1". One division was thus equivalent to 1/50,000in (0.00051mm) and although Troughton did not believe them very accurate, he read off and used the tenths of a division in preparing his table of errors.

---

[1] Troughton got this idea from the perambulator or waywiser used by surveyors. It should also be noted that the numbers for the scale were engraved prior to doing the scale dividing for as Troughton stated (1809, 122) "Dividing is a most delicate operation, and every coarser one should precede it".

[2] Troughton incorporated 3 verniers on many of his later instruments to detect errors of eccentricity but as Edward Riddle pointed out (1819) this only worked if one of the three lay directly on the line of the eccentricity. Thus instruments with 2 or 4 scale microscopes were more desirable.

[3] Because of the size of the micrometers, neighbouring divisions could not be compared. Therefore Troughton compared divisions 4°13'7.5" apart--i.e. one division of 2°48'45" + one of 1°24'22.5"

[4] The errors were handled as follows ("Graduation" in **Penny Cyclopedia**: 1838, 339n): Let e and e' be the errors of any two dots, a and b, and + when too far forward and when behind their true place, and the distance to the bisecting dot c be from a=m and from b=m+k: then the apparent error of c is -k/2; for it should be at a distance m+k/2 from a. But the dot a is wrong by e and the dot b wrong by e'; therefore there is a further correctio of (e+e')/2, and the whole error of c is ((e+e')/2)(k/2) care being taken to assign the proper signs.

Troughton then returned to his roller to which he attached a small sector with 16 divisions to give a larger scale. This allowed him, at the same time, to convert the divisions to 360° divisions and to divide 5' intervals on the scale. The final procedure to carry out the actual division of the scale was to start the roller from zero and to check and scribe the divisions from 0-1 rotation of the roller, i.e. from 0° to 22°30'. The sector and micrometer head had to be constantly reset and divisions checked and rechecked but by progressing around the circle the division was accomplished. The errors of the micrometer screw were thus imposed on the scale at the 5' level; above this limit the errors were determinable by cross checking. By Troughton's admission the micrometer screws were accurate to no better than about one division of the head or 0.2" or 1/50,000in. However, a run in the periodic error might have increased this error to some extent. As a final note, it is interesting to note that Troughton commented on the ease with which the French metric or centesimal divisions (i.e. quadrants of 100°) might be accomplished with his method. He also described in brief the application of the roller to dividing a bar for linear division and predicted that the scales divided with such a machine would be 3 times as accurate though he had not completed such an engine by 1809. He had used a 'make-shift contrivance' to divide standards for Sir George Shuckburgh Evelyn (1796), Dr. Pictet of Geneva and the Magistrates of Aberdeen.

This method of circular division won the Copley Medal of the Royal Society for Troughton. The procedures were described in 1809 and were followed by Troughton's successor, William Simms and by his rival Thomas Jones. There were, of course, some limitations. The method was inappropriate for circles under 2ft diameter since original division was not necessary. Problems could also result if insufficient attention was used in making the pivots perfectly circular, for if they are not, then the line on the circle's rim to be divided and the rim on which the roller moves would not be perfectly circular, these being defined by the pivots. Secondly the rim on which the roller moved was of steel and it was common to have 'knots' of hard material in the steel. The instrument maker was advised to use a diamond point to finish the surface. Troughton used three microscopes on many of his instruments to find the eccentricty, but as Riddle (1819, p.161 and see footnote on previous page) pointed out this did not completely correct the error. Other practitioners of this method of original dividing used four (or more) microscopes thus allowing detection of any eccentricity of the circle. The results were improved because two measures of each point's error were determined by comparisons of different arcs.

4.2.6 Other English Dividing Engines of the 18th Century:

The majority of dividing engines of the 18th c in Britain were similar in concept to Ramsden's. This was largely due to the fact that he had been successful with the design and because the best instrument makers of the time were instructed in the details of its design by Ramsden as a condition of the Board of Longitude prize. However, James Watt's dividing machines were independently made with a different purpose in mind.

4.2.6.1 Watt's dividing apparatus:

James Watt was the maker of a bench micrometer previously discussed. Along similar lines he records having made a dividing engine (of sorts) in a letter (dated Glasgow, 7 March 1773) to his friend and correspondent, Dr. Small. He states (Muirhead: 1854, pp.39-40): "My dividing-screw can divide an inch into 1000 tolerably equal and distinct parts on glass..." and almost a year later he informed Smith (3 March 1774) (Muirhead: 1854, pp.75-76):

> I had occasion to use my last dividing-screw for the first time the other day. It divided 9 inches into 20ths, and did not err the 1/200th of an inch in the whole 9 inches. I did not find that there was the least inequality among the divisions, though I subjected them to the most severe trial, and I found a way by which I can divide a foot into 1/1000ths of an inch without erring above 1/200th of an inch in the whole length, and the divisions shall be equal among themselves; so I reckon that machine exceeding near perfect, and find it very useful, as it saves much needless compass work, and, moreover, can divide lines into the ordinates of any curve whatsoever.

However, Smith was not convinced that Watt's optical devices were as accurate as he would like. He notes (Muirhead: 1854, pp.76-77):

> I rejoice in all your improvements, but have many optical difficulties that lessen my confidence in observations made with the most accurately divided instruments. For example, no optical instrument hitherto constructed, catoptric or dioptric, or catadioptric, produceth an exact copy of any object; so that all the visible points of every object of sensible apparent diameter are represented in the field of the instrument in situations in relation to each other very different from what they ought to occupy....

Joseph Black wrote to Watt (22 May 1773) requesting that he bring his "divided plate for graduating Thermometers" (Robinson & McKie: 1970, p.39) when he came to Edinburgh from Glasgow. Black comments: "Your machine with the Screw is admirable for its exactness but the plate will be exact enough for some operations I wish to have done--and it saves calculation". Thus there was at least a small community of scientists aware of Watt's dividing apparatus and it was in demand. It appears from the extant evidence that Watt primarily concerned himself with the application of the screw to measurements in the period ca.1770-73.

4.2.6.2 Harrison/Atherton patent:

U.K. Patent N^{o}. 1179 was awarded to William Harrison and Peter Atherton in 1778 for "Making Screws, &$^{c.}$ for the Dividing of Mathematical Instruments". Harrison was the son of the more famous John Harrison, winner of the Board of Longitude Prize for his 'H4' chronometer. The technique was to employ inclined planes to create the thread of a screw. To quote from the patent:

> To make screws perfectly true, and likewise to employ a screw so made for the dividing straight and curved lines, and thereby render it easy to make a great number of those mathematical instruments, which are the most essential to science and navigation, perfect, and for want thereof have been imperfect, the said screws are to be made is by truly transferring the motion generated by two planes, inclined towards each other, sliding so as to approach or recede from each other or by an equal motion to a point, cutting a screw upon a cylinder, moving round its own axis or to the cylinder, letting the point remain at rest; or when such screw is so truly made, by making another screw from it. The strait or curved lines are to be truly divided by employing a screw so made to move a rack, or to be moved thereby, to which the instrument to be divided being fixed, it will be made to approach or recede from a given point, upon which a cutter is placed, to a distance equal to one thread of the screw, by one revolution thereof, and consequently to any fraction of that distance by the same fraction of one revolution, which fraction is ascertained by means of an index.

Little else is known of the Harrison/Atherton technique although there may be some connection to the dividing engine in the Science Museum (SML-34) which was used by John Barton to make his diffracting 'Barton's Buttons'. Barton was apparently the son-in-law of Harrison. The article in the *Edinburgh Philosophical Journal* by 'O' (1822, p.128-32) stated that Barton used an engine by Harrison to make his diffracting patterns but the Science Museum attributes the machine as possibly by or made with the assistance of Maudslay; the quality of workmanship and design would tend to support that view. The screw on the engine is stamped with the pitch in the same fashion as the screws with the small Maudslay screw lathe in the Science Museum (SML-18).

4.2.7 French Dividing Engines of the 18th Century:

By the time of the French Revolution several instrument makers had dabbled with dividing engines--mainly linear engines. Little is known of the linear dividing engine made by Mégnié (ca.1780) in Paris. Two engines by Richer are preserved in the CNAM, Paris. The first could divide a ligne (≈2.2559mm) into 1600 parts and the other (no.6589) was for dividing sectors. Fortin's linear dividing engine of 1778 had a plate driven by a lead screw and although he would not divulge details of his method, he did indicate that it was made by cutting a second improved screw and with that a third which Fortin considered as perfect as his skill and the properties of the metal would allow (Daumas: 1972, p.203). The lead screw carried an index which moved over a dial divided into 100 parts and was also provided with discrete stops. Fortin's circular dividing engine, probably made after 1799, also incorporated a hand operated screw with a dial with 0-180 divisions and of only 25mm diameter. There were two pointers which indicated the angle of displacement between each scribing operation. Jecker's circular dividing engine was also a simplification of Ramsden's design but was treadle driven. The screw was made for this engine on a machine designed by Jecker. His dividing engine was presented to the CNAM in 1793.

4.3 Dividing Engines of the 19^{th} Century:

Astronomy was still the science pushing the talents of the instrument maker to the limit and this remained the case through much of the 19^{th} c. Although it was not yet recognized, the essential elements of engine dividing had been described by Ramsden. There were obviously improvements to be made, and many of these were identified by Edward Troughton and later by William Simms. But, as in any endeavor of this magnitude, other avenues had to be followed to prove the correctness of the procedures earlier described. During the 19^{th} c the dividing engine for instrument scales evolved into the ruling engine for spectral gratings which required a still higher degree of precision. Fortuitously the gratings themselves provided the means to test the accuracy of these engines. This evolution provided the instrumental means for the shift from positional to physical astronomy which was begun by William Herschel.

4.3.1 Some Early but Insignificant Contributions:

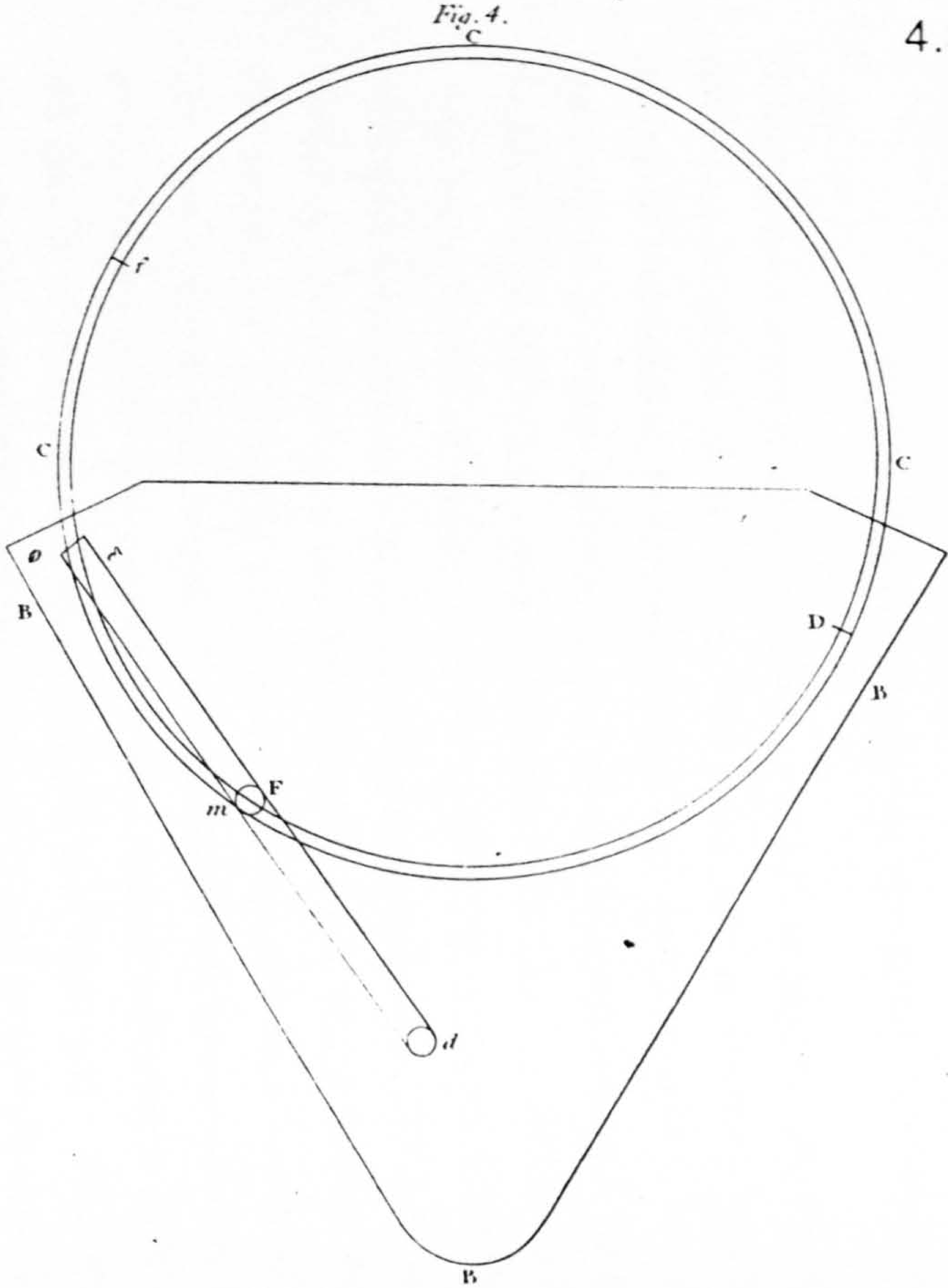
Numerous proposals were made by mechanically minded men to improve the state of instrument division whether it was to be original or engine dividing. Most were put forth by men without first hand knowledge of the procedures of instrument division and therefore were of limited (if any) merit.

4.3.1.1 Hornblower's device for "measuring any aliquot parts of an inch":

A number of short communications on the use of the screw for precision work can be found in the mechanical journals of the early 19^{th} c. That by Hornblower (1803) illustrates the lack of understanding by non-professional instrument makers. Hornblower had need for a square ruled with lines for use with an optical instrument, but living where scientific apparatus was not available locally, he made one himself. Starting with a good tap he made a pair of dies and with these made a screw of brass which he found had a pitch of 26.6 TPI. He wanted the grid to be divided into tenths of an inch; to achieve this he had left a collar on the screw which was to hold a divided plate. A second collar allowed this to be drawn tight while an index was firmly attached to the screw. To divide the grid, Hornblower loosened the collars and set the divided plate to 0 and then fixed the plate. He then turned the screw 2.66 revolutions and fastened the screw thereby having set off 0.1in. The plate was then set free and returned to 0 and the procedure repeated. It appears that he was under the impression that errors of the screw were thus eliminated though this is clearly not the case. Indeed the tightening and loosening of the divided plate would have disturbed the alignment sufficiently to destroy any accuracy which might have been achieved.

Mr. Cavendish's Dividing.

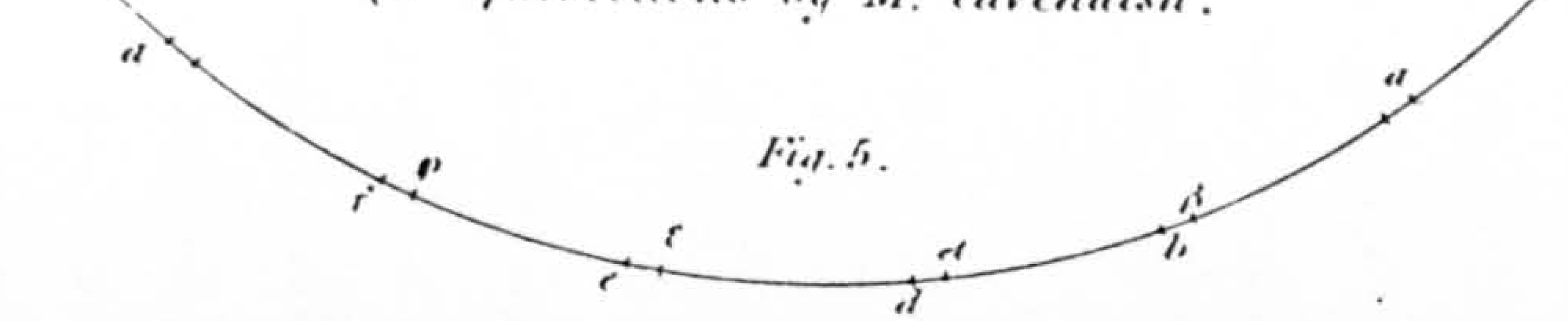
Fig. 4.



4.3.1 The method proposed by Henry Cavendish to replace John Bird's beam compass points with a 'point' defined by crossed micrometer wires in order to avoid distorting the shape of the dots on scales.

Quinquesections by Mr. Cavendish.

Fig. 5.



4.3.1.2 Cavendish's proposal for original dividing:

Having read Troughton's account of his dividing technique and his reluctance to use a compass point in a dot already laid off, Henry Cavendish (1809) conceived the idea of replacing one point of the compass with a microscope (Fig. 4.3.1). Although Cavendish described three techniques of proceeding to divide a circle, he had not tested his method and the ideas were never adopted in any widespread manner. Troughton (1830, p.383-3) critically discusses the techniques proposed by Cavendish and concludes: "To follow him through his whole paper would be useless; for, notwithstanding that much ingenuity is displayed in pointing out such errors as he foresaw it would be liable to, and in contriving means to obviate them, we consider it as altogether inconsistent with practice, and inelegant in design."

4.3.2 Allan's Technique of Making the Teeth on a Dividing Engine:

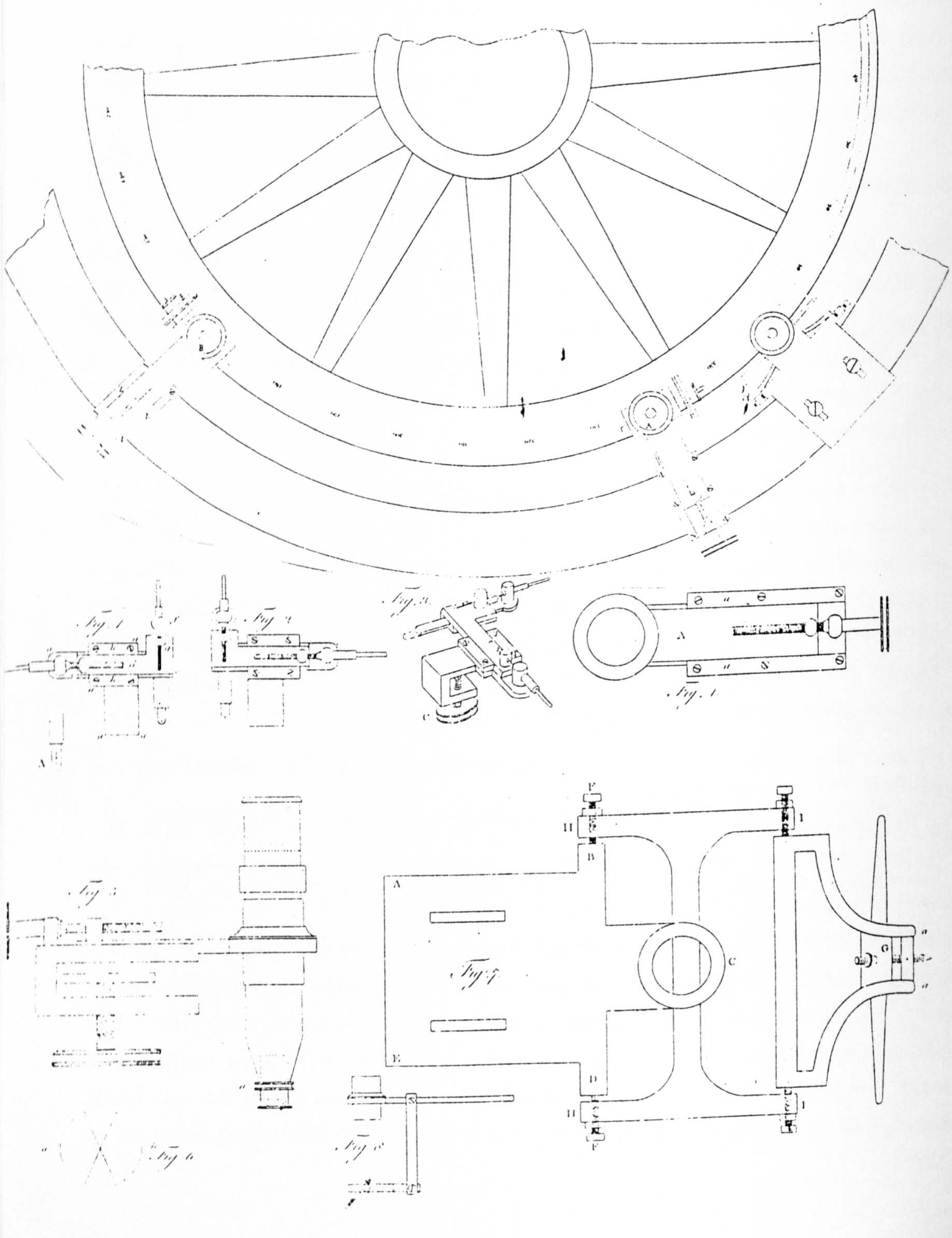
James Allan (fl.ca.1785-1825) is known for his contributions to precision screw making having won the Silver Iris Medal of the Society of Arts (1816). He won a similar award and £100 from the Board of Longitude for his dividing engine. The original version was made and demonstrated to the Society on 15 Dec.1810. The original version was not universally praised for John Stancliffe (1812, p.121) came to the defense of the method used to make the teeth on the wheel.

The wheel was of wood with a ring with teeth cut into it. The wheel was much larger than in other dividing engines (up to 6ft diameter) and was a cause of concern to Stancliffe though he thought the problems could be overcome. The purpose of the ring was to act as a guide in cutting the teeth though after completion of the initial teeth, the ring was moved around 180° and the screw racked along to even out the teeth; the ring was then moved around by 90° steps and the racking renewed. Stancliffe described the procedure he would use to make the teeth on this plan, vis.:

1) start with Ramsden's method of laying off dots for each tooth and cut the teeth to half the required depth,
2) using the ring the screw would be engaged and racked around to deepen the teeth on the wheel,
3) after the wheel had been racked around a full turn, the ring was rotated alternately a half and quarter turn and the racking continued one turn for each shift of the ring.

Stancliffe was of the opinion that this method would achieve the high degree of accuracy claimed by Smeaton in 1785 for methods working on contact rather than on pins or lines. However, Stancliffe was not exactly unbiased since Allan contracted dividing work out to Stancliffe; on the positive side he had considerable experience with dividing engines over the years, having used Hindley's, been trained in 1778 by Ramsden in the use of his technique, and subsequently having made his own dividing engine along the lines of Ramsden's.

4.3.2 Henry Kater's method for detecting errors in carrying out the original division of the wheel of a circular dividing engine. His 'moveable dots' are illustrated in Figs. 1 and 2; these once mounted could be moved in both X and Y directions to correct errors detected with the micrometers.



4.3.3 Kater's Dividing Technique:

Capt. Henry Kater was interested in a variety of scientific topics including pendulums,[1] magnetic phenomena,[2] and dividing of astronomical instruments. The procedure he outlined was for the original division of major astronomical instruments and as will be seen was too cumbersome for smaller instruments with less demanding constraints. The technique was equally applicable to circles, zenith sectors or even straight lines. The method he proposed was similar to but more refined than that by Chaulnes; it should be pointed out that Kater had not actually used the method at the time he wrote the description for the Royal Society members. Kater's technique used 3 instead of 2 microscopes and 'adjustable' dots (Fig. 4.3.2) which were designed to be moved with adjusting screws in both X and Y directions. These adjustable dots (he also advocated substitution of crosses for the dots) could be clamped at any point to the rim of the circle to be divided. Two of the microscopes were furnished with standard scale-reading micrometers and clamp bases which permitted them to be attached to the outer rim of the dividing apparatus which was ≈120° long. The other microscope, with fixed cross wires, was mounted on the frame which carried the scriber. As advocated by Edward Troughton, this was an elliptical point held at about 50° to the surface being scribed. Kater was not pleased with the scribing frame since a lateral motion of 1/16,000in resulted in a 1" error in a circle of 2ft diameter. Another area of concern should have been that the 120° rim had to be fastened to the instrument to be divided; with the weight of the rim, three microscopes and engraving frame distortion of the instruments was a distinct possibility.

The details of mounting the microscopes, adjusting the focus, (it should be noted that Kater was careful to eliminate any parallax in the microscopes by careful adjustment of the objective) and adjusting the scriber to go through the centre of the wires in the fixed microscope, etc. are of minimal interest here. The method of division is more interesting. Once the adjustment of the engraving frame and fixed microscope were completed, Kater attached one of the micrometer microscopes, A, to the rim near the fixed microscope. The second, B, was placed 72° (1/5th of 360°) along the rim from A. Under A he mounted one of the moveable dots and adjusted its position to correspond with the centre of the wires. The circle was then rotated and the dot observed under B and B's position adjusted by means of its base so that the dot exactly coincided with the centre of its wires. Both A and B were then focused on the dots. The circle was then turned back to the original reference line drawn by Kater under the fixed microscope. An adjustable dot was placed under B and properly positioned. By moving the circle from B to A and adding more adjustable dots, 5 were stationed around the circle; on the first positioning these were of course not precisely 72° apart but the placement of the last gave the amount they

1 One type which is now referred to as Kater's pendulum.

2 For one aspect of his work on magnetism see Brooks: 1987

were too close or too far apart. Using the micrometers the dots could be repositioned and the error in 360° again found and further corrected. Once these were satisfactorily positioned each dot was brought under the fixed microscope and removed for the scribing process.

The next stage was to subdivide each 72° segment into three parts of 24°--initially by estimation. The adjustable dots were again positioned and adjusted in the same manner as above. Once the 24° is found between A and B the dots could be removed and the divisions scribed successively around the circle. The 24° segments were then trisected in the same fashion and the 8° divisions scribed. As the micrometers could not be brought closer than 8°, other methods had to be used to find the divisions to 1/2°. The first step to this end was to bisect one of the 24° segments in the same manner, i.e. by comparing the lengths of the segments between A and B. This yielded a 12° segment but also gave two 4° segments. The 12° arc length was then to be used to give divisions 4° apart around the circle. By dividing a 20° segment one obtained a 10° segment and division of the circle to 2°, an 18° segment gave division to 1° and a 17° segment gave division to 30'. To trisect the 30' Kater used a 10° segment then measured off 1/3 of a division (i.e.10') with one of the microscope micrometers. An adjustable dot was placed under A and by moving the circle as before another was placed under B. These dots were adjusted until the spaces laid off were precisely equal. This space was then used to lay off all the remaining divisions.

Kater reiterated the precautions which were necessary (p.434):

1) The microscopes must be perfectly free from parallax,
2) The vertical angles formed by the intersection of the wires in the microscope must accurately bisect the divisions which pass through them,
3) The intersections of the wires in A and B must lie between the lines defining the inner and outer limit of the lengths of all division lines and must be equally distant from the pivot,
4) Likewise the dot on the cutting frame must always pass through the intersection of the wires of the cutting frame.
and 5)the motion of the cutting frame must be in a diameter of the circle to be divided.

4.3.4 Gamby's Dividing Engine:

By 1824 Henri Gamby (ca.1788-1838) had made 3 repeating theodolites, the last of which was made under the direction of Arago. It could be read to 2" although the circles were only 25cm in diameter. The dividing engine he developed did not require the circles to be centered but he kept his procedure secret (Zahrtmann: 1824, p.252).

4.3.5 Donkin's Dividing Engine:

Bryan Donkin (22/03/1768-27/08/1855)[1] is primarily known among historians of technology for his contribution to perfecting the machines for making paper ca.1801/2 and for the many paper-making machines he put into operation. He invented a number of devices and received the Gold medal of the Society of Arts for two of them and also invented a spring level which he applied to the transit instrument in his own observatory.[2] But our interest is in his linear dividing and screw cutting engines. The first was made in 1826 and improved in 1828 (Holtzapffel: 1854, p.652). Many screws were cut on this engine and given to his scientific friends including Whitworth. These 'standard screws' were made with a compensating bar to correct for the defects of the originating screw. Unfortunately there appears to have been no description or illustration of the dividing engine as noted by the *Penny Cyclopedia* of 1838 in its article on "Graduation". The author of that article also stated: "...scales have been divided, and screws cut by it of extraordinary accuracy". The machine consisted of a platform moving on a 'railroad' and supported by 4 or more wheels and four more to control the lateral motion; two of these were spring loaded to prevent deviation from the linear motion desired. The platform was made of two plates which could move slightly with respect to each other. The lower platform carried the fulcrum of the lever which had a 50:1 ratio; the lever moved in the vertical plane with the longer arm moving on the compensation bar. The bar was the same length as the screw, i.e. 24in and had 48 metal slips attached with screws. Each slip's position was meticulously adjusted by a procedure of bisection of the screw's length and compared with results of trisection.[3] The screw had been made by Maudslay and required a maximum correction on the bar of 1/8in which meant that the error of the screw was ≈1/400th inch. This screw and compensating bar were used as the lead screw to make a new screw but this reduced the error only by 1/3rd with the readjusted compensation bar having a deflection of 1/20th inch. According to Holtzapffel (1854, vol.2, p.654), Donkin made a second machine in 1842 with a screw of 42 inches and of 40 TPI. The compensation bar had a ratio of 60:1. In this machine the counting wheel indicated 1/60,000th inch--half that of the previous engine.

4.3.6 The Dividing Engine and Dividing Method of Andrew Ross:

The Society of Arts was sufficiently impressed with the dividing technique described by Andrew Ross (1798-8/08/1859) to award him their Gold Isis Medal and 50 guineas. Ross is best known for his large output of microscopes. The method he employed for division was essentially that of Troughton with some modifications particularly to do

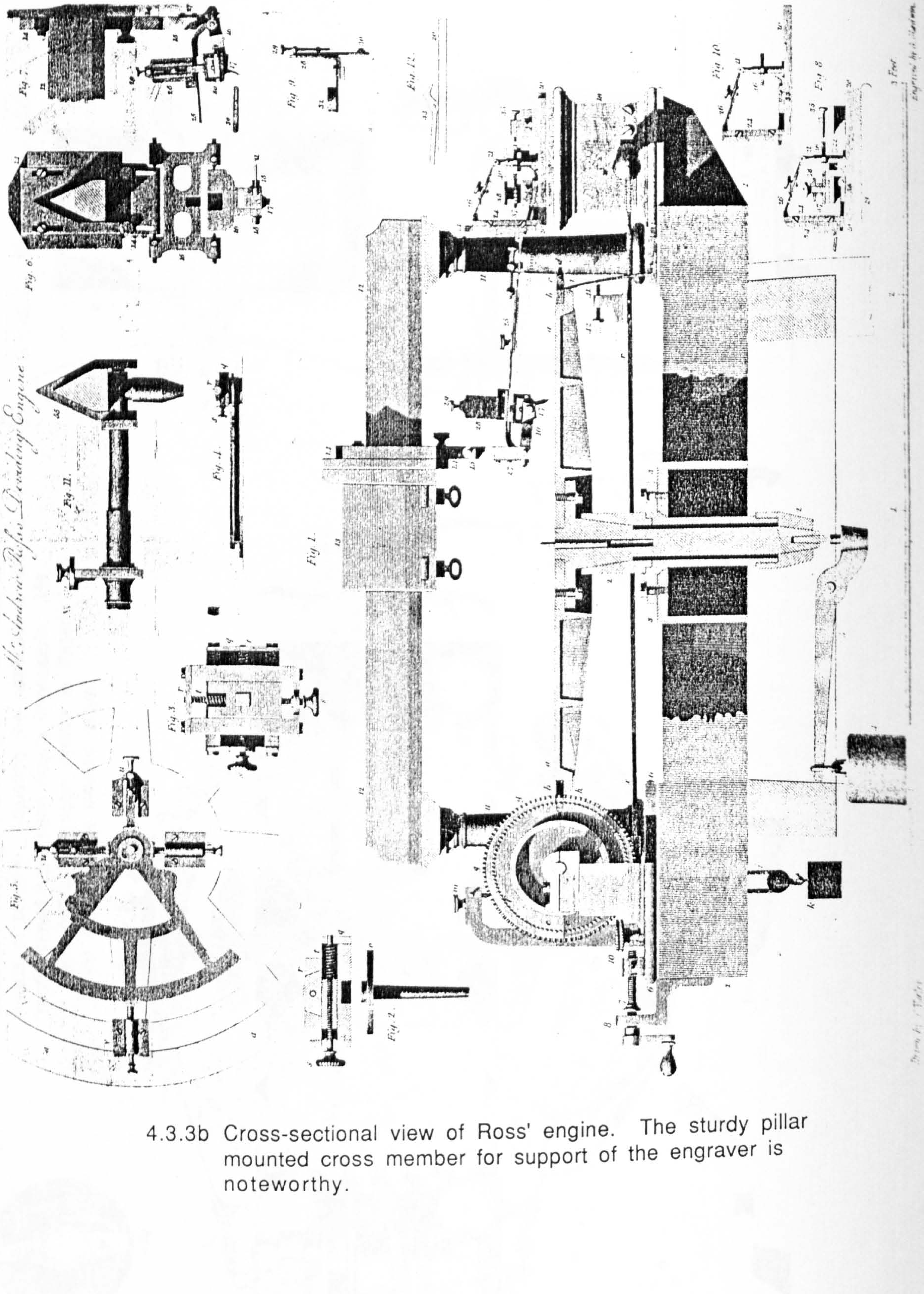
---

1 Donkin was one of the founding members of both the Institution of Civil Engineers (1818) and of the Astronomical Society (later RAS) (1831) of which he was the first President. He became a FRS in 1838.

2 See Donkin, *Abstracts of Memoires of the R.A.S.*, **4** (1838-9), p.75.

3 See Holtzapffel: 1854, v.2, p.653-4.

4.3.3a Andrew Ross circular dividing engine (1830) using adjustable bearing surfaces and a worm defined by the heads of screws. Adjusting the positions of the 48 'teeth' would have been nearly impossible. He adopted a technique similar to Kater's for checking the divided scale.



4.3.3b Cross-sectional view of Ross' engine. The sturdy pillar mounted cross member for support of the engraver is noteworthy.

away with the roller which made the Troughton method undesirable. The theory behind the design of his dividing engine was sound but the application would have been tedious in the extreme although temperature effects between metals of different composition may have been a cause of concern. The figures (Fig. 4.3.3a/b) will be sufficient to show why the procedure was tedious![1]

Ross was attempting to correct the worst flaw (as he saw it) of machines based on Ramsden's, i.e. the lack of homogeneity of the steel and the cast metals of the wheels of dividing engines. The primary feature of Ross' machine were the steel contact surfaces whose positions were all adjusted by screws and then locked into place by other screws. All screws were capstan headed to allow adjustment. 48 cocks, as he called them, were screwed to the limb of the wheel and held the screws which became the bearing surfaces which were 7°30' apart. Each of the screws was of steel and prepared by grinding its surface flat, smooth and perpendicular to its axis in a brass jig. The worm was a cylinder with helical plate fixed to it. The helical plate had a pitch equal to one revolution and was pierced with 90 tapped holes to accept steel capstan screws with rounded ends. The choice of 90 screws for the worm meant that the maximum resolution of the divisions on the wheel was 2'30" (i.e. 3°45'/90). Each screw was fixed into its proper position by a second screw. The pivots of the worm's axis were grooved with a screw chaser and the bearings with corresponding grooves which prevented end shake. There were three microscope micrometers, each with 100 TPI screws and dials divided into 100 parts. Two of these were mounted on a 120° long frame concentric with the circle and could be moved relative to each other. The other micrometer was mounted with another microscope on the scribing frame. Other points of note were: the counter balance below the pivot of the wheel, the driving cord wrapped around the wheel and worm cylinder and the positioning screws for mounting the instrument to be engraved. The latter was to eliminate the error of eccentricity, which in some instruments he had seen, had amounted to 3'.

Ross identified two sources of error with his machine. The first was the difference in metals between the worm (bell-metal) and stand (cast iron); cast iron expands only about 2/3^{rds} that of bell-metal. A temperature change of 1°F changed the length of the worm 1/100,000th of its length or about 1/4" per degree. This being known, corrections could be made and the machine was usable when the temperature was 35-75°F. Making the corrections must have been tedious. The second source of error was the fact that the steel screws on the cocks were not perfectly flat and that the spherical ends of the screws on the worm do not come into contact with the same points of the flat ends in every instance. This varied as the secant of the angle with a maximum difference

---

1 The figures were drawn by the scientist and mechanician, Cornelius Varley. The paper following Ross' described the microscope for which Varley was awarded the Society's Large Silver Medal.

of 1/30in. This error could be halved but amounted to 1" in some places and in the extreme amounted to 3".

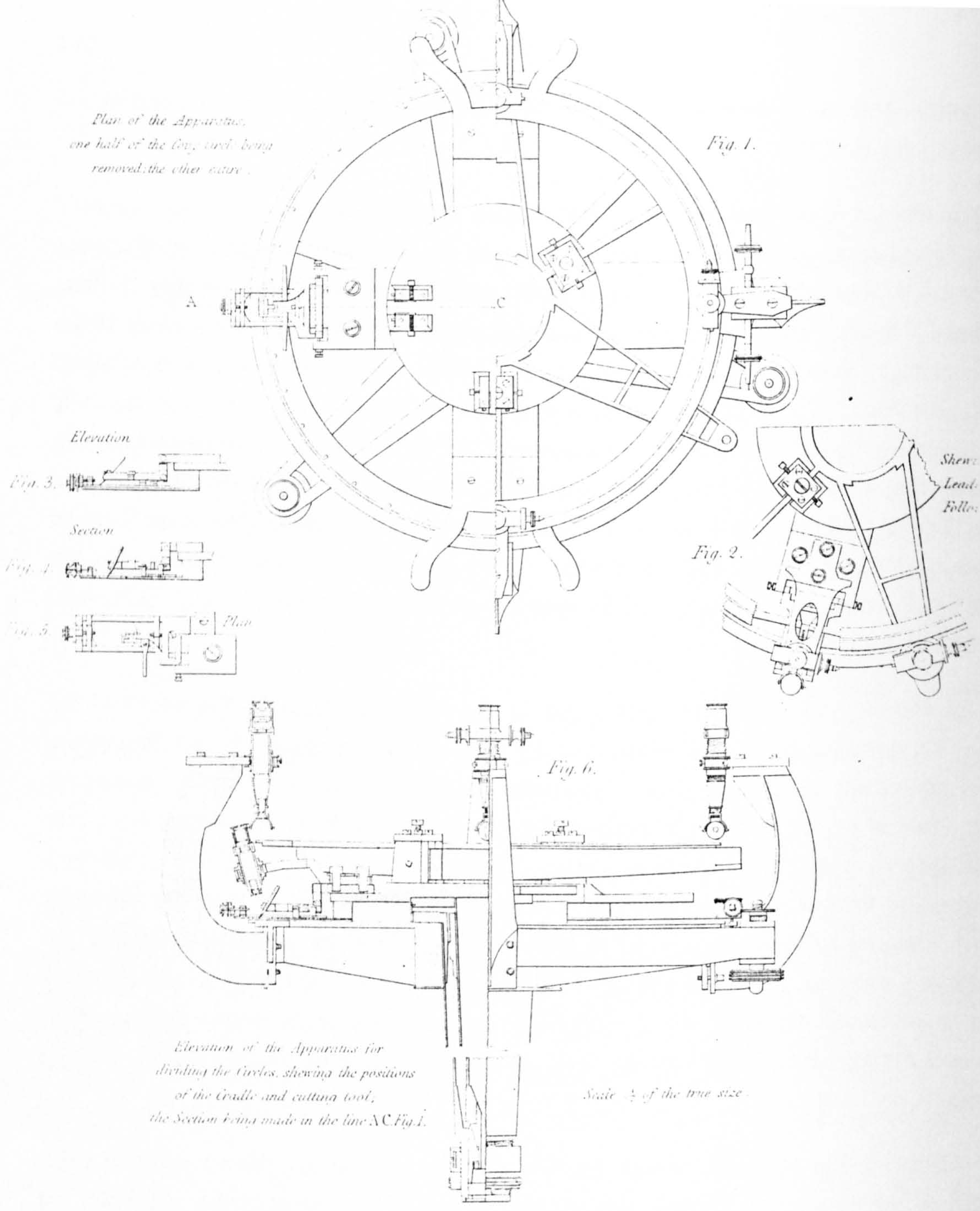
The method of carrying out the original division of the wheel was as follows. Instead of using rollers as Troughton had employed to lay off the initial divisions, Ross used a small circle engraved with 96 divisions 3°45' apart. This was done on any dividing engine. This small circle was placed on and concentric with the larger wheel along with a microscope for viewing the divisions of the small circle. The engraver was also mounted to cut divisions on inset silver dots at a point on the wheel which had been carefully prepared, i.e."turned with scrupulous exactness" for the purpose. The procedure was exactly that followed by Troughton. However, Ross carried out both trisection and bisections of the angles down to 11°15' as a check of the operations. The steps were as follows: using trisections and bisections: 120°, 60°, 30°, 15°, 7°30', 3°45' with the latter pair combined to give 11°15'; and by continual bisections: 180°, 90°, 45°, 22°30' and 11°15'.

Of course, using a flawed small scale as the reference required the errors of the initial 96 divisions to be determined and the divisions to be recut. Unlike Troughton, Ross carried out this process before completing the remainder of the divisions because he was afraid of making an error in applying the complex corrections. Otherwise there was little difference in the mechanical steps. While the final division of the circle was progressing there was nothing mounted on or touching the circle other than the engraving point. Indeed he took precautions to isolate himself from the circle by enclosing the circle in a glass case perforated to allow only passage of the long handle to the engraver. The microscopes on which the micrometers were mounted were longer than usual to prevent the transfer of heat from his body as well as to give as high a magnification as possible.

Ross writes in terms which imply that the machine had actually been made and used. If this is the case (and I believe this is), one glance at the figures of the apparatus will impress anyone of the incredible patience that Ross must have had. The perfect adjustment of the 48 screws on the rim of the wheel and the 90 on the worm would have tested the patience of even Job to the extreme.

4.3.7 Everest's Method:

Lieut.-Col. George Everest, Director of the Trigonometrical Survey of India, found himself, ca.1837, in need of two new azimuth circles in order to make a pair of astronomical instruments serviceable. These had been ordered from Troughton & Simms in 1829 and were received from London in 1832. Upon testing in 1837 they were found to be too unstable, i.e. "there existed so enormous a vibration so as to render it impossible to intersect a star...with any degree of accuracy" (Everest: 1840, p.142). To



4.3.4 Everest's method of copying a circular scale. The new scale is mounted below the original scale. Four men simultaneously viewed the scale through the micrometer microscopes.

correct this Everest undertook to substantially rebuild the bases which included replacement of the azimuth circles. Since there were no instrument makers in the region, he had to do the scale division himself.

Not having a machine for the purpose he determined to copy the divisions of one of the old circles onto the new, which was of cast iron with inset gold rim for the divisions, and with inset silver discs every 10° to receive the numbers. The old circle was firmly fixed onto the new circle and centered as precisely as possible (Fig. 4.3.4). The circles were mounted on a masonry pillar with the cutting tool free to rotate with the original circle while the new circle, mounted above the other, remained fixed with respect to the pillar. The four micrometer-microscopes were mounted on the old circle and readings made simultaneously by four observers. The cutting-tool was made by a local craftsman, Seid Mohsin, following the pattern of Hindley's cutter though Mohsin added a micrometer to control the length of the division lines. Everest was satisfied with the results he obtained with the method though he noted he had to work with the errors of his labours, small as they were.

Everest recorded that attempts to follow a similar line of attack should take precautions to monitor three particular lines, viz. (Everest: 1840, p.147):

1) the radius passing from the centre of rotation through that of the divided circle, which is called the nodal line,
2) the radius which is determined by the mean reading of the microscopes,
and 3) the radius passing through the point of the cutting tool.

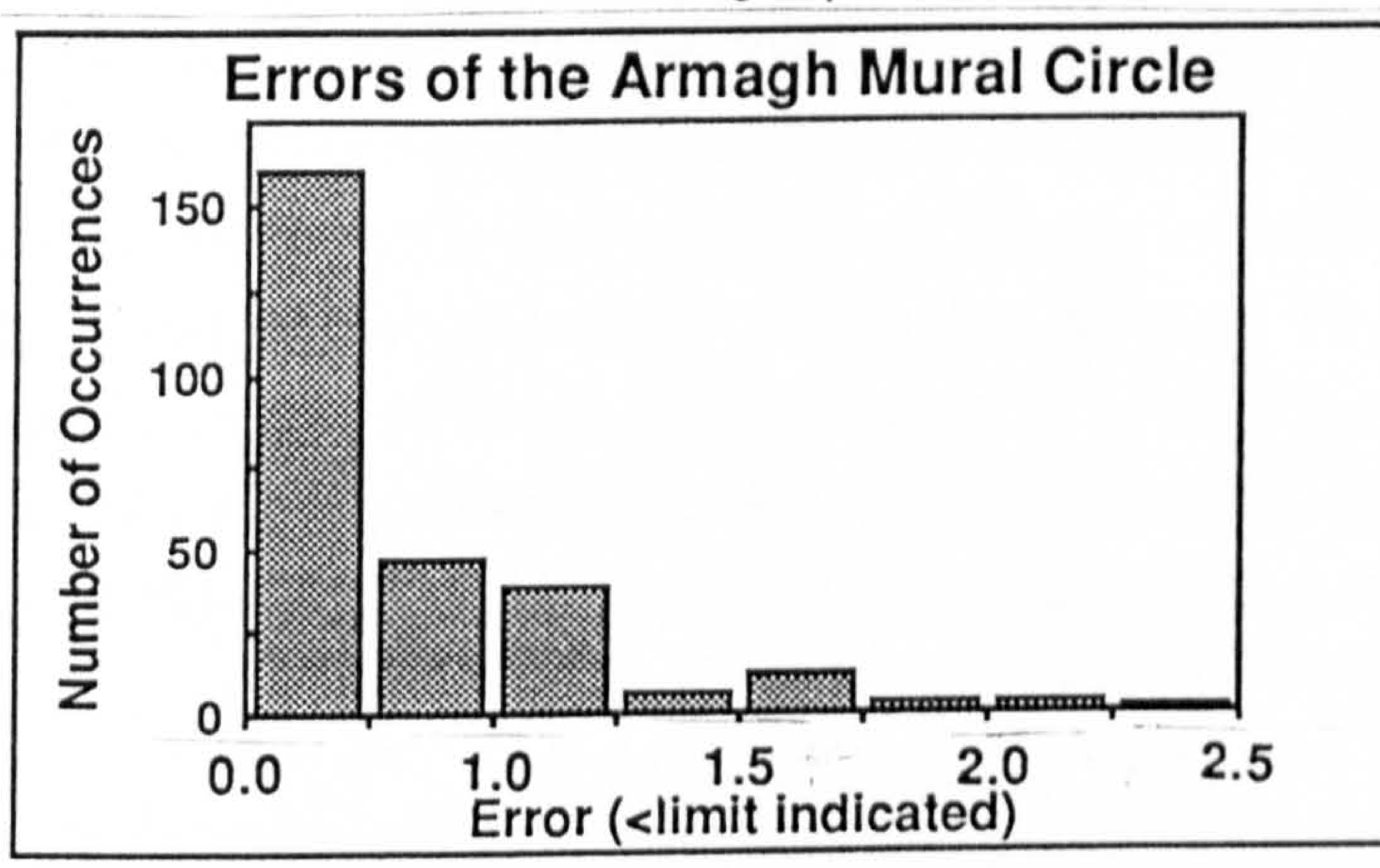
The first was least important and was corrected once the latter two were eliminated. The chief cause was unequal expansion in the entire setup. Using the 4 micrometer microscopes a mean position was determined and the division scribed; the four readings corrected for any eccentricity and errors in the division of the original scale to some extent, though small errors were introduced by the cutting-tool. The degree divisions were made first, followed by the half degrees, the quarter degrees and finally the 5' divisions. The whole division process took 18 days and towards the end he decided to drop use of two of the micrometer microscopes in order to speed up the operation though he had to sacrifice some precision. To control the temperature Everest also had a wooden cover made to encircle the circles with holes only where necessary for the apparatus; this replaced use of leather breathing cases which the assistants working at the microscopes found objectionable.

4.3.8 Some Errors Appear:

The Armagh mural circle was a 5ft instrument made by Thomas Jones (1832) and divided by Troughton's method. However, Robinson (1835, p.112) detected two errors, viz. an eccentricity of 20" and a 15° section of scale which was inaccurately divided and could, even for the mean of four microscopes, affect the reading by 2" in two readings.

Jones went to Ireland and reground the pivot and redivided the scale using Kater's method but the errors in diameters was as much as 6". In Nov. 1834 Jones again reground the pivot using a diamond tool and began to redivide the circle in situ. He used a method not unlike Troughton's but also used elements of Kater's method. Jones wanted two microscopes opposite one another to detect eccentricity and also employed a second pair which could be set at any angle (except as restricted by the micrometers' physical size) to the first pair. He then stepped off divisions down to 1°15'. Jones took 269 diameter measures noting the following distribution of errors from single pairs of observations:

Between:	
0.0 and 0.75"	161
0.75.......1.0"	46
1.0.......1.25"	38
1.25.....1.50"	6
1.50.....1.75"	11
1.75.......2.0"	3
2.0.......2.25"	3
above....2.25"	1



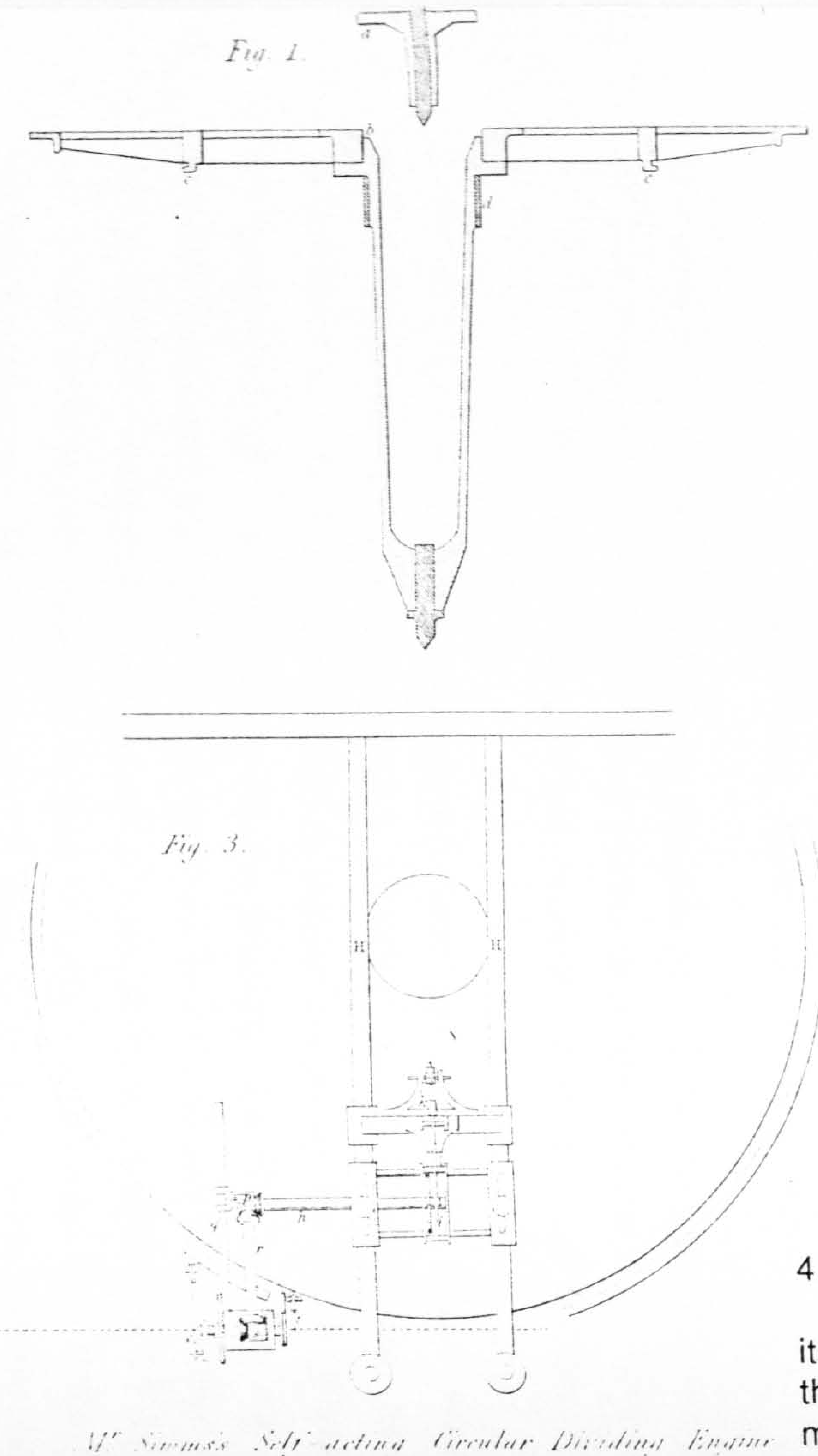
4.3.5 Armagh mural circle errors measured by Jones using 269 diameter measures

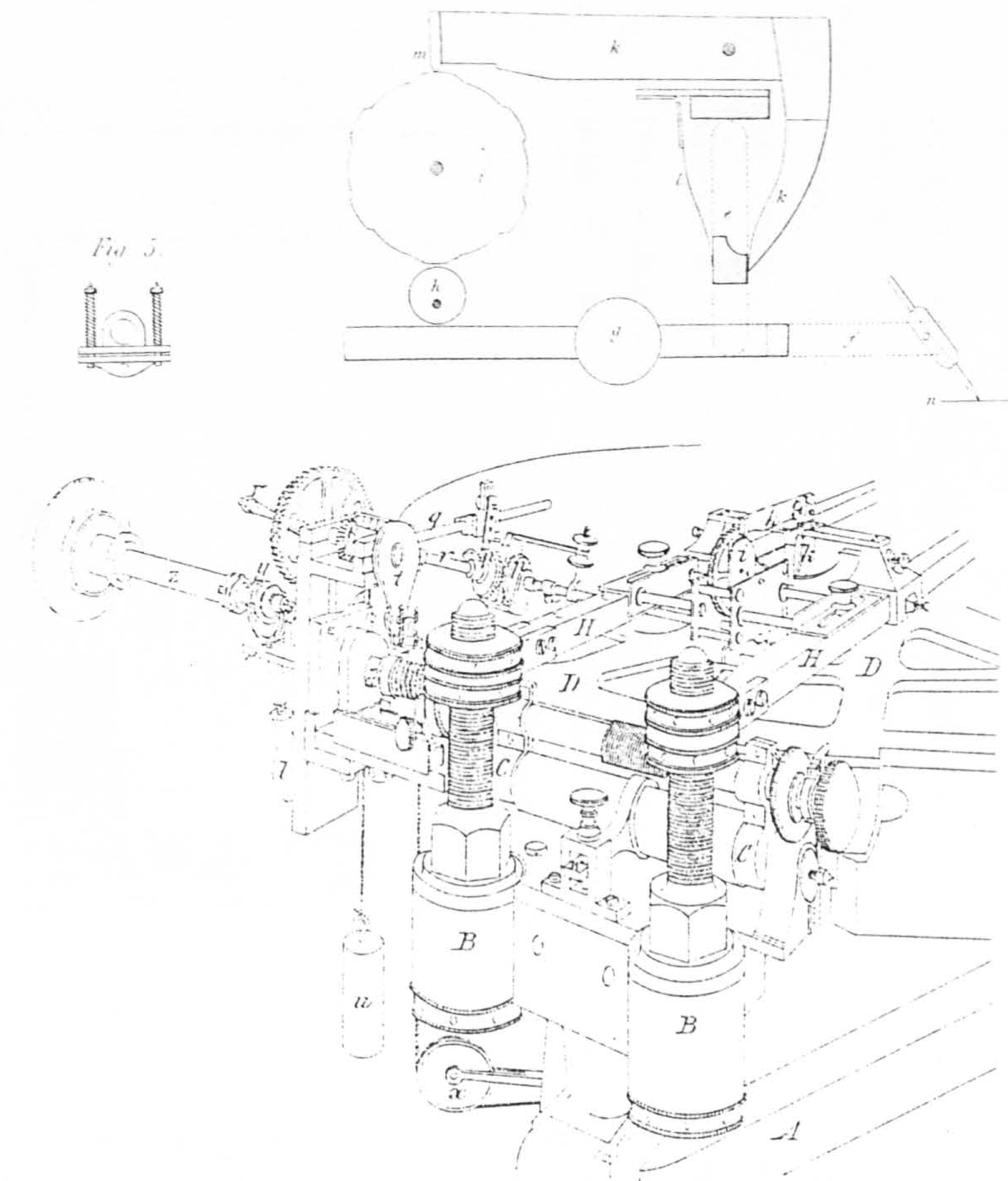
Jones considered that original division had attained the limit while engine graduation was open to unlimited improvement with their errors correctable and was hopeful that his countrymen would take up the path the Germans had successfully followed.

In the same volume of the *Philosophical Transactions* as Everest's contribution a letter appeared from Wilhelm Bessel (1839-43, p.265) which is worthy of note. In his studies of parallax he found the proper motion of Groombridge 1830 greater than that of 61 Cygni which was the star with greatest known proper motion. But in making the observations Bessel noted that reversal of his Repsold circle 180° gave readings differing up to 1" which he attributed to temperature changes in the observatory. Thus although instrument makers had taken precautions to ensure constant temperature during the division of instruments since the time of John Bird (from ca.1765), astronomers did not recognize such errors until instruments' precision surpassed the 1" level. Bessel advocated many repetitions of the determinations of scale errors as the means to detect temperature effects.

4.3.9 Simm's Self-acting Dividing Engine:

William Simms (ca.1793-21/06/1860) became the partner (1826) and successor of Edward Troughton. Being closely associated with Troughton, he had been influenced sufficiently to adopt methods not very different from those of his mentor. The self-acting





4.3.6 Details of William Simms' automatic dividing engine (1843).

Fig. 1 shows how Simms mounted the scale to be divided with its axis already attached which helped prevent errors of eccentricity in the finished scale. As in most engines following Ramsden's design, a micrometer head is found on the right-hand end of the worm shaft.

dividing engine Simms built was made on the same principles as Troughton had used (Simms: 1843, 1846). The dividing plate was of gun-metal 46in in diameter and was cast in one piece by Maudslay & Field (though note that Maudslay was dead by this time--ca.1843). The wheel had 4320 teeth ratched in its edge corresponding to divisions of 5'; thus one turn of the endless screw equalled 5' and the screw had a pitch of ≈0.0335in (≈29.9TPI). Two scales were divided on the wheel at the suggestion of Rev. Sheepshanks: one was divided directly on the gun-metal near the edge and the other on an inset silver scale. The first was divided as accurately as possible using the same manner as Troughton had used "with some slight variations". Simms divided the wheel completely then determined the errors in order to make corrections for the division of the second scale. The cutting frame was of Hindley's design but in addition a single circular cutter was mounted on the endless screw frame and used to finish cutting the teeth on the edge. Each division was brought under a microscope and the circular cutter brought up to each tooth in succession. Finishing the teeth was completed after three revolutions of the wheel. By this procedure Simms was of the opinion that the teeth were as accurately divided as the silver scale itself.

The basic machine, then, was not very different from Troughton's but two points improved the accuracy of the results obtained with it (Fig. 4.3.6). First, the axis of the wheel was hollowed out so that the axis of the instrument to be divided could be inserted thereby reducing the error of eccentricity caused by having to attach the shaft after completion of the dividing process. The second was one which also made the instrument very much easier to use while also making the results superior. Simms added a pulley and weight system (with a speed controlling brake system) to advance the wheel and to perform the cutting operation without the need for superintendence of the machine except for the winding up of the weights.[1] Once the cutting operations were completed, the machine stopped. This automatic apparatus was simple enough that any engine employing a worm and wheel arrangement--and this was the majority of those in operation in London--could be converted to run on its own at relatively little cost. Simms' machine could divide all but the largest class of astronomical instrument and as Ramsden's machine had reduced the cost of nautical instruments by mechanizing the most labour intensive operation, Simms' engine reduced it still further.

4.4 Discovery and Production of Spectral Gratings:

The most critical application of precision screws is in the fabrication of spectral gratings and fortuitously, the gratings themselves provide the most stringent test of the quality of the screw since defects of the screw manifest themselves in the appearance of the spectra. The observation that scratches on surfaces produced prismatic colours was

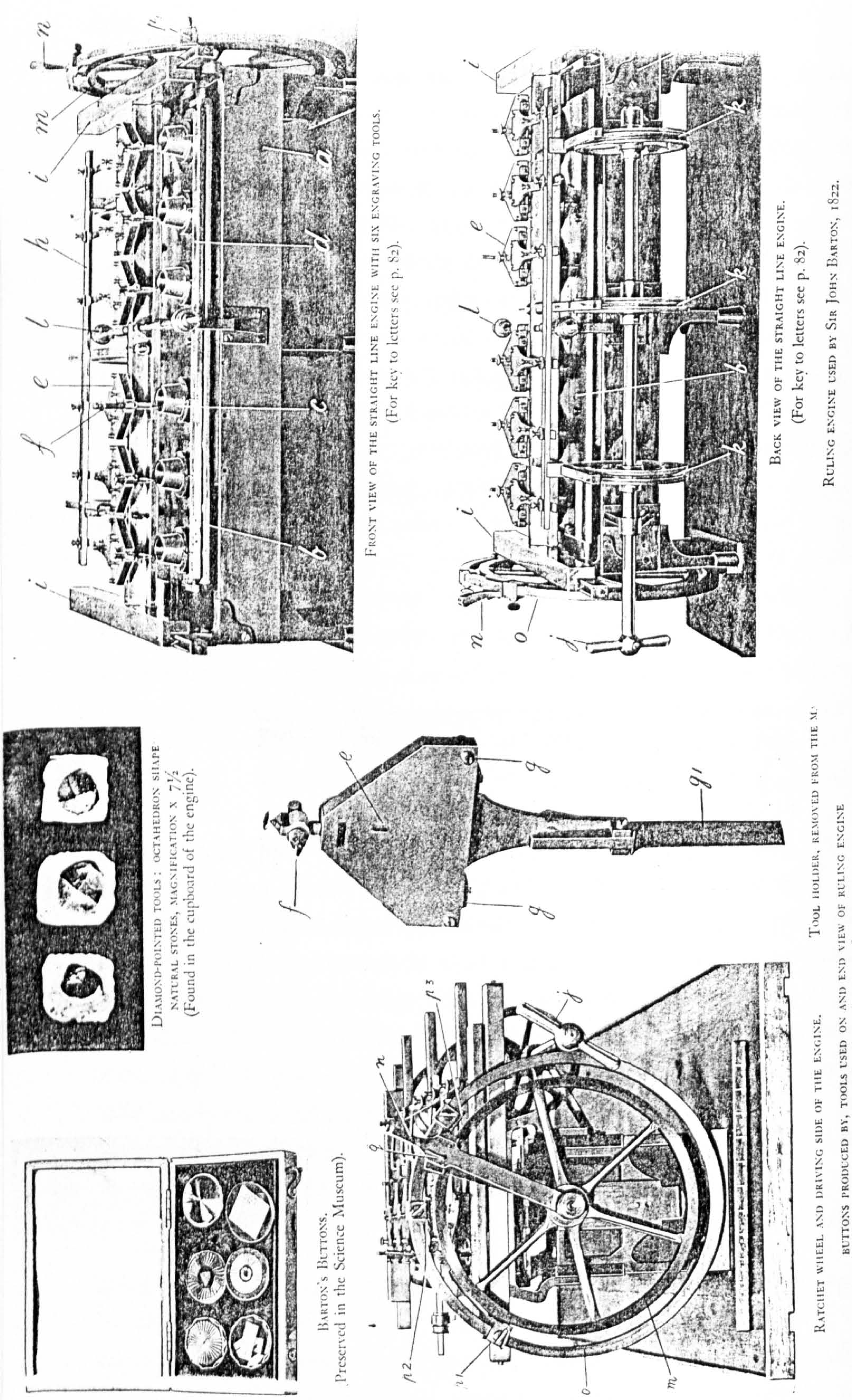
[1] The weights were in fact suspended in an open court to obtain maximum drop height. These could be substituted with a "boy turning a winch" or by steam power.

first noted by Robert Boyle and the phenomenon was later studied by Mazcas and Brougham. David Rittenhouse used parallel wires in 1785 to produce a grating as did Fraunhofer 30 years later when he made a grating with 260 wires. Dr. Young studied the colours displayed by Coventry's micrometers ruled on glass with 500 lines/in. Young ascribed the prismatic colours to interference of the light reflected from the two sides of the groove. In the sample he studied, the lines were in fact made of two or more lines separated by ≈1/20th of the line separation. Brewster also investigated the colours exhibited by mother-of-pearl and found with a microscope that the surface was covered with very minute grooves. He found he could transfer the grooves to such surfaces as wax, gum-arabic, tinfoil, fusible metals or lead. The lines could also be created in metal surfaces by a blow of a hammer. But the real invention of the glass grating may be attributed to Sir John Barton since he made gratings expressly to create prismatic colours. Brewster in his 1813 work on philosophical instruments (p.59) commented on the grid micrometers of Ezekiel Walker but incorrectly thought they were drawn on mother-of-pearl. In correcting this misapprehension, Walker (1816, p.15) provided some information on his dividing abilities if not on his instrument. He was able, "after an infinite number of attempts," to rule 1000 lines to the inch and to draw a second set at right angles with the same spacing. For his grid micrometers he used 100 lines/in.

4.4.1 Fraunhofer's Early Experiments:

The rulings of Fraunhofer are well known due to his discovery of what became known as the Fraunhofer lines in the solar spectra. About 1815, he discovered that a 'grate' made by wrapping very fine wire around two parallel screws and held in front of a telescope illuminated by a narrow slit created a number of continuous spectra when the Sun was viewed. In this grating the wire was 0.002021 Paris inch in diameter and the space between the wires was 0.003862 Paris inch (Herschel: 1849, p.488). The two screws had been made in the same dies and were thus of the same pitch making an easy frame for winding the 260 parallel wires. It was with this apparatus that Fraunhofer discovered the dark lines in the solar spectrum and made the observations to formulate his laws on the properties of spectra. He was also able to count 13 different spectra or orders on either side of the primary image.

To test his postulates Fraunhofer began making (ca. early 1820's) gratings on glass first covered with gold-leaf and then grease or varnish. Unfortunately no description of his dividing or ruling engine has been found. The maximum number of lines he could obtain with the gold-leaf covered glass was 1000/in above which the gold-leaf was scraped off. Double the number could be formed on glass coated with a thin film of grease but this was still short of the number he wanted. He found that grooves made in the surface of glass with a diamond point produced the phenomena; the maximum number of lines he was able to produce with equal spacing was ≈8200/inch. Fraunhofer noted that



4.4.1 Ruling engine (1820-22, SML-34) for ruling Barton's buttons. It may have been made by William Harrison but was probably modified by Barton or Maudslay to allow ruling of several buttons simultaneously. The wheel has 500 teeth or divisions with ratchet mechanism to set the interline spacing.

one grating gave brighter spectra on one side of the primary image than on the other. He interpreted this to indicate that one side of the grooves was sharper or more inclined than the other due to the form of the diamond point, and tests with grease gratings proved the latter to be the case--this then was the origin of blazing gratings for maximum efficiency for a particular order of spectra. Thus Fraunhofer was able to take the division of glass a step beyond those of his predecessors by controlling the depth, breadth and symmetry of the angles of the grooves. Samples with upwards of 30,000 lines per Paris Inch were made but Sir John Herschel found that examples with more than 8,200/Paris inch did not yield pure spectra due to uneven spacing of the grooves. Brewster found that Barton's examples of 10,000 lines per inch provided excellent spectra but was still envious of Fraunhofer's gratings and the research he was able to carry out with them.[1]

4.4.2 Barton's Contributions:

John Barton (5/08/1771-25/08/1834) was an engineer who served as Deputy Comptroller at the Royal Mint, London, in the early 19th c and also served as Treasurer of the Household of Queen Adelaide.[2] We have already discussed his differential measuring engine called the 'atometer' (SML-22) in §3.5 with results of tests in Chapter 6. The dividing engine we are about to discuss is in the Science Museum (SML-34, Fig. 4.4.1) and was intended to engrave what became known as Barton's buttons. These were ruled in various patterns with fine lines to cause reflection and diffraction and were intended for cosmetic rather than scientific use. However, the phenomena became of interest to Barton and he took up the study of light reading a paper before the Royal Society in 1831 though only an abstract was published. The buttons and the engine for making them are primarily of interest because of their relation to the early diffraction studies of Fraunhofer and subsequent work of Nobert.

The origin of the engine is not clear. Grodzinski (1947/9, p.80) reviewed the evidence and was not certain who actually made the machine. He concluded that, since Barton did not cover the machine under his 1822 patent (UK Pat. 4678, 2/08/1822) for the buttons, someone else must have made it. An article in the *Edinburgh Philosophical Journal* (1823) stated that "The engine which he uses was given to him by his father-in-law, the late celebrated Mr. Harrison. It was constructed by Mr. Harrison himself, and its merits depend chiefly on the beauty and correctness of the screw, the

1 See for example: Fraunhofer, Joseph. A Short account of the Results of Recent Experiments upon the Laws of Light and its Theory. *Edinburgh Journal of Science*, 7 (1827), 101-116.

2 Ramsden was apprenticed to the instrument maker Barton of Denmark St. and married his daughter. It may be possible that John Barton was the grandson of this earlier Barton. Eva Taylor noted that John Barton should not be confused with the watchmaker of the same name who married John Harrison's daughter and lived in Red Lion St. Barton also invented a floating compass which was tested by the Board of Longitude in 1792, 1798 and 1811 (Taylor: 1966, entry 926).

apparatus for cutting which, by an excellent inclined plane, also accompanied the engine." Taylor noted that Barton's will also referred to John Harrison as the maker. As Grodzinski noted Brewster's ***Edinburgh Encyclopedia*** [1] stated: "This, with the assistance of an ingenious workman, was made by the late Mr. [William] Harrison, a son of the celebrated artist who gained the great reward for finding the longitude at sea by means of timekeepers." Troughton goes on to say: "We know, however, that this engine is not idle; it is in the possession of John Barton..." However this is not the only possibility since Prof. D.S. Torrens of Trinity College, Dublin suggested a connection between the Harrisons and Bramah and Maudslay. He proposed that, had John Harrison (1693-1776) made the machine, then perhaps Bramah (1748-1814) modified it; or, had William Harrison (d.1816) made it, perhaps Maudslay (1771-1831) had modified it.

William Harrison, as has previously been noted, received a patent for a dividing engine (1778) whereas there is no other evidence to suggest John Harrison ever made a dividing engine. In 1822 'O'[2], stated that Barton used the Harrison engine to make his gratings but makes no mention of the fact that the engine could make several at the same time as can the extant engine. Considering the specialized nature of the extant machine, it is very likely that it was adapted from some earlier purpose with the ruling mechanism added to suit Barton's needs. The workmanship and finish of the table carrying the blanks is very similar to Maudslay's other small instruments in the Science Museum. During this study it was observed that the screw on the engine was stamped with numbers in the same fashion as the lead screws with Maudslay's small screw lathe (SML-21). Barton and Maudslay were well acquainted through their business relations with respect to the Mint and making of coins (Smiles: 1883, pp.151, 153). In 1810 each made a screw of exactly the same pitch and of 15in length. These were compared and "were found exactly to agree throughout their length and were considered perfect."[3] Holtzapffel (1854, p.646n) stated that Barton made the screw and that he used a diamond tipped tool for its execution. The workmanship of the machine is certainly consistent with Maudslay having been involved, and the analysis of the screw may provide the solution of his involvement though Barton was, as he demonstrated, capable of making precision screws. As further speculation, it is proposed that the Harrison/Barton machine was modified ca.1822 after Barton had successfully obtained a patent for his reflecting buttons, and that the modification to carry several blanks was an attempt to make larger numbers of buttons to fill the hoped for commercial demand. Some buttons were made in steel, and using technology he was so familiar with in the Mint, Barton made copies by stamping.

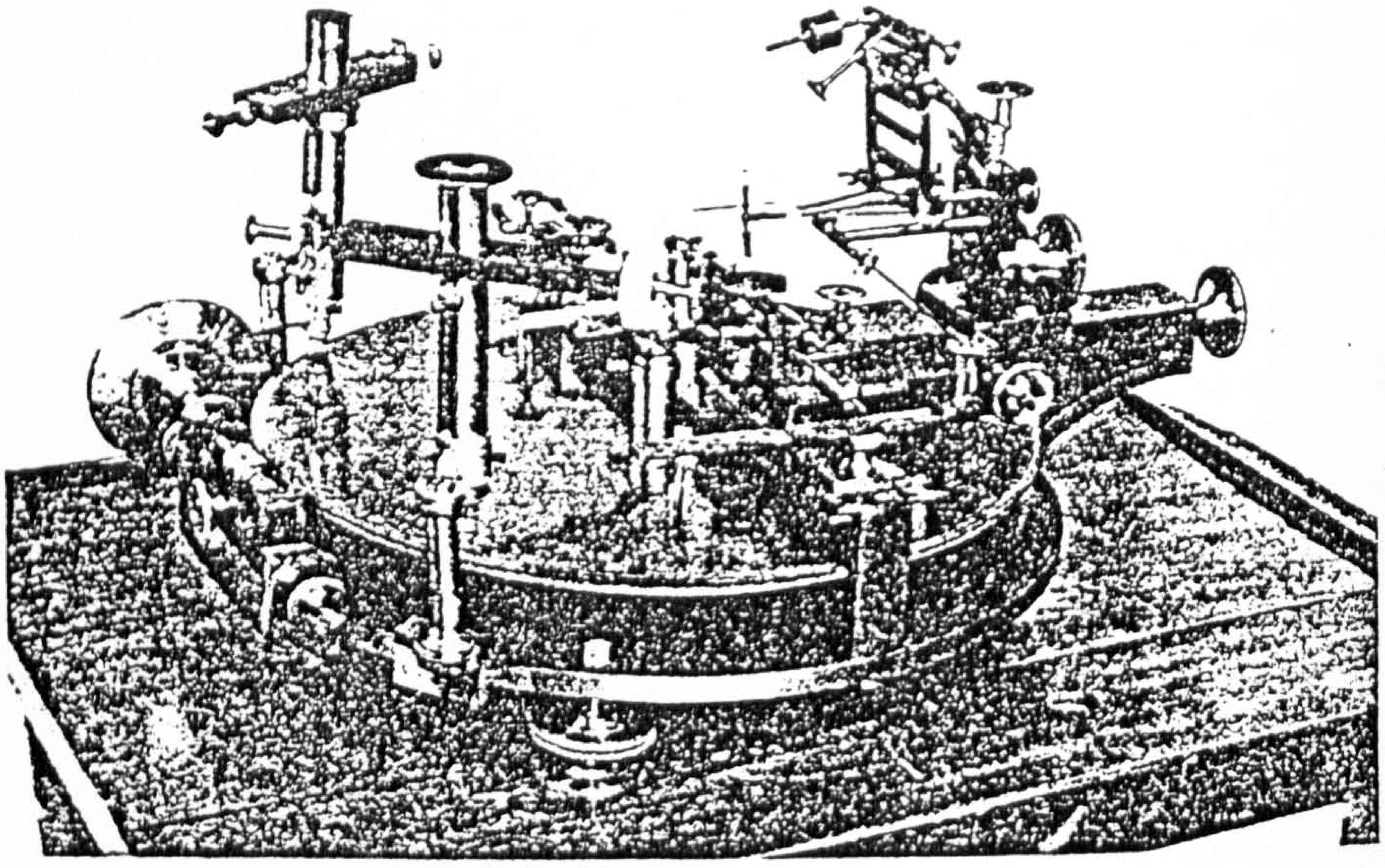
Grodzinski (p.81) provides a description of the machine and its operation. It could engrave 6 samples simultaneously and diamonds found in a drawer in the base suggest

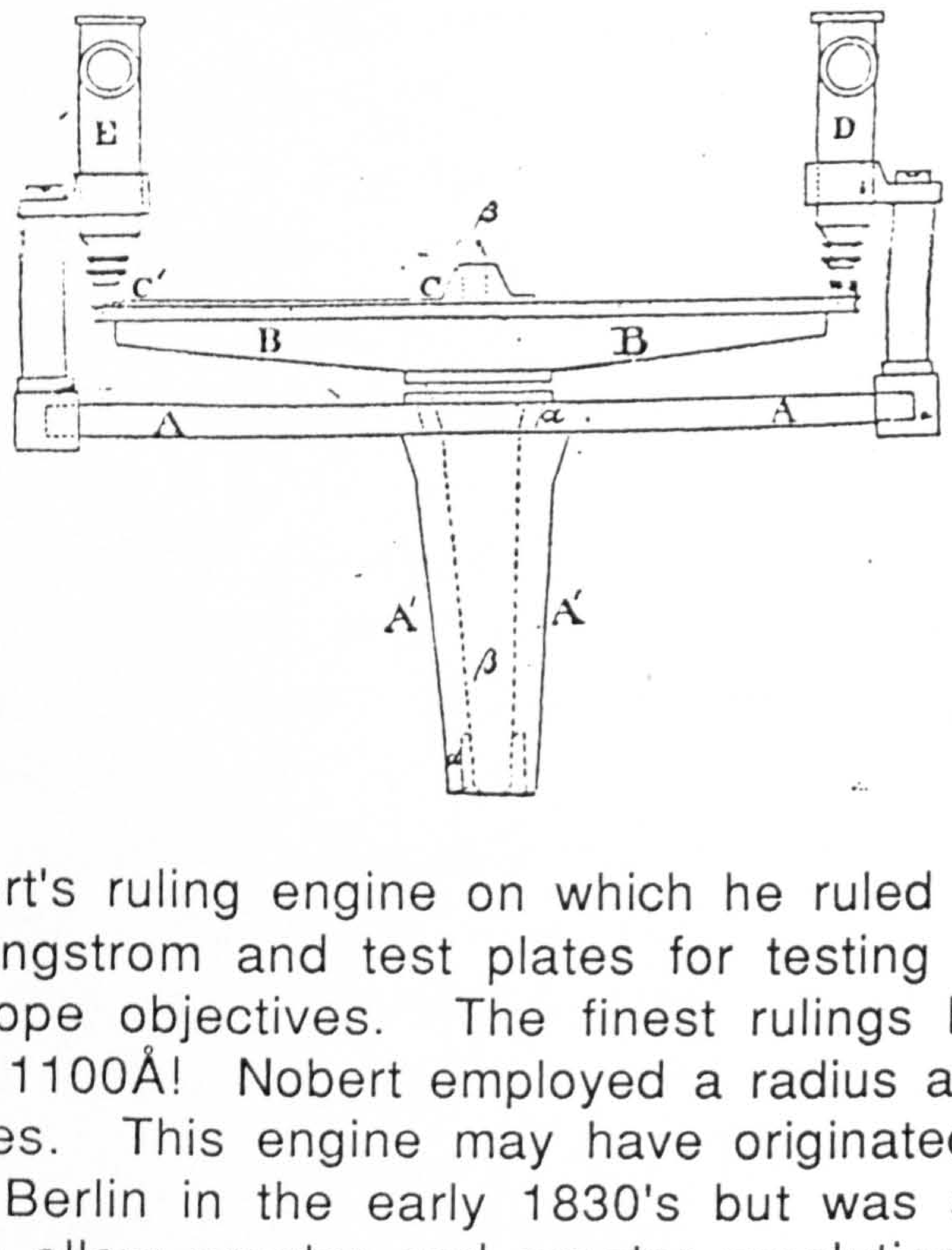
---

1 The article "Graduation" was written by Edward Troughton (1830). See p.361 for his comments on this dividing engine.

2 David Brewster.

3 Holtzapffel: (1854), 645-6 and see §2.5.





4.4.2 Nobert's ruling engine on which he ruled gratings used by Ångstrom and test plates for testing the resolution of microscope objectives. The finest rulings had interline spacing of 1100Å! Nobert employed a radius arm to rule straight lines. This engine may have originated during his studies at Berlin in the early 1830's but was successively modified to allow greater and greater resolution. Even so, the engine had to be manually adjusted for ruling <u>every</u> line.

Barton used diamond tipped tools for the engraving. Barton had earlier used diamond tipped tools to cut the threads for his differential measuring engine.[1] Besides using a 20 TPI screw for the longitudinal motion, Barton used two small micrometer screws with divided heads to control the length of the dividing stroke. Advancement of the main screw was controlled by a ratchet wheel of 500 teeth which means that the maximum resolution was 0.0001in without any error in the screw itself. In the discussion following the presentation of Grodzinski's paper (p.86) it was reported that the screw of the engine had been damaged in its travels and that it was not as good as Barton had left it. It should be reiterated that this machine was not intended for precisely dividing equally spaced divisions and that for creation of cosmetic diffraction phenomena it is not crucial that they be equally spaced although the quality of spectra is related to the precision with which the gratings were ruled. Indeed an inspection of the buttons extant in the Science Museum would provide additional information on the functioning of the machine.

David Brewster had requested that Barton make a grating with 2000 lines/in but the diamond stylus broke before it was completed and Barton did not attempt another.[2] It has been suggested that ruled specimens (5000 lines/in) by Robert Bate may actually have been made on Barton's engine ca.1826. After Barton died, the surviving engine was shipped to Australia becoming the property of his grandson in 1878. Robert Barton was Deputy Master of the Mint in Melbourne and took on the job of restoring the engine. It became part of the Science Museum collection in 1925.

4.4.3 Nobert's Dividing Expertise:

Surely one of the most talented instrument makers of the 19th c, though largely forgotten, was the German, Friedrich Adolph Nobert (17/01/1806-21/02/1881). The son of a clockmaker, Nobert took up this profession but aspired to greater heights, designing various watches and making chronometers surpassed in Germany only by those of Kessels. He managed to obtain a bursary to attend the Technical Institute in Berlin and in his first week learned dividing techniques. With this knowledge he made his own dividing engine, which is probably the one he used to rule diffraction gratings, test plates, ruled scales for astronomical instruments and cut chronometer gears (Fig. 4.4.2). After his training in Berlin, Nobert became technician and instrument maker at the University of Greifswald (1835). He returned to Barth after his father's death in 1846.

Nobert's talent is amply shown by the fact that he made a twenty-band microscope test plate (made ca.1873) with lines of the finest band separated by just 1100-2100Å. This resolution is beyond that of optical microscopes but was finally resolved in 1965 by

---

1 See: Early Uses of Diamond Tools for Cutting Metals, *Industrial Diamond Review*, **4** (1944), p.227-230 for a discussion of Barton's use of diamonds.

2 Warner: (1986), p.125-6.

Bradbury and Turner (Turner: 1967 1, p.338[1]) using an electron microscope. Nobert began turning his interest towards tests of microscope optics in the 1840's and it occurred to him (1845) that the technology of dividing engines could be used to make test objects engraved on glass. The idea was drawn from Fraunhofer's gratings (where spacings of 3.3-16μm were achieved) and was put into effect in 1846 when Nobert made a test plate of 10 bands with line spacings ranging from 1/1000 -1/4000 Paris line (1 Paris line = 2.25583mm) in a geometrical progression. Thus the first target with known spacing was made available for testing the quality of microscope optics; telescopes could be tested by observation of close double stars and had been for many years. Over the years Nobert made 7 different test plates culminating with the 'new' 20-band plate of 1873 noted above. Perhaps better known is that Nobert made the gratings used by Ångstrom in his important studies of spectra (Turner: p.p.343-4; Warner: 1986, p.126) and we have also noted (§3.4.4.2) his novel micrometer device for telescopes based on gratings.

The basis of Nobert's ability to make these test plates was his circular dividing engine and his use of a diamond point. The dividing engine Nobert used for most of his career is in the Smithsonian Institution. Mayall (1885) has given a detailed description of the machine but unfortunately was unaware of Nobert's description (1845) which appeared in an obscure journal and which might have helped him identify the purpose of some components.

The dividing plate is 12" in diameter and ruled to 5' on a silver scale embedded near the limb. The division was apparently accomplished using 20 concentric circles of holes and with the two microscopes with micrometers mounted on the base and adjustable around the dividing plate. Rotation of the dividing plate is effected by a tangent screw acting on the edge of the wheel. A graduated drum on the tangent screw shows the motion but the worm, mounted between conical bearings, can be disconnected from the wheel if desired. When engaged, the force exerted on the wheel is controlled by a counterpoise and lever arm. Although it is a circular dividing engine, Nobert could use it to produce his straight line test plates and gratings by using the radius of the dividing plate as a lever arm. Since this application was so crucial to Nobert's success, this method of application is described (following Mayall: 1885, p.711) in detail:

> For this purpose, he attached to the centre of the division-plate a bent arm, on which a bar faced with silver, having at one end a finely-polished steel point which can be adjusted by a scale and vernier so as to project more or less beyond the centre of the division-plate or axis of rotation. The radius of the division-plate thus becomes the long arm of the lever, whilst the radius of the projection of the polished steel point beyond the axis of rotation forms the short arm, the centre of the division-plate being the fulcrum. The motion of the short arm of the lever is communicated by contact with an agate plate to a polished steel cylinder, adjusted to slide at right angles to the movement of the

[1] This paper provides an excellent review of Nobert's life and contributions.

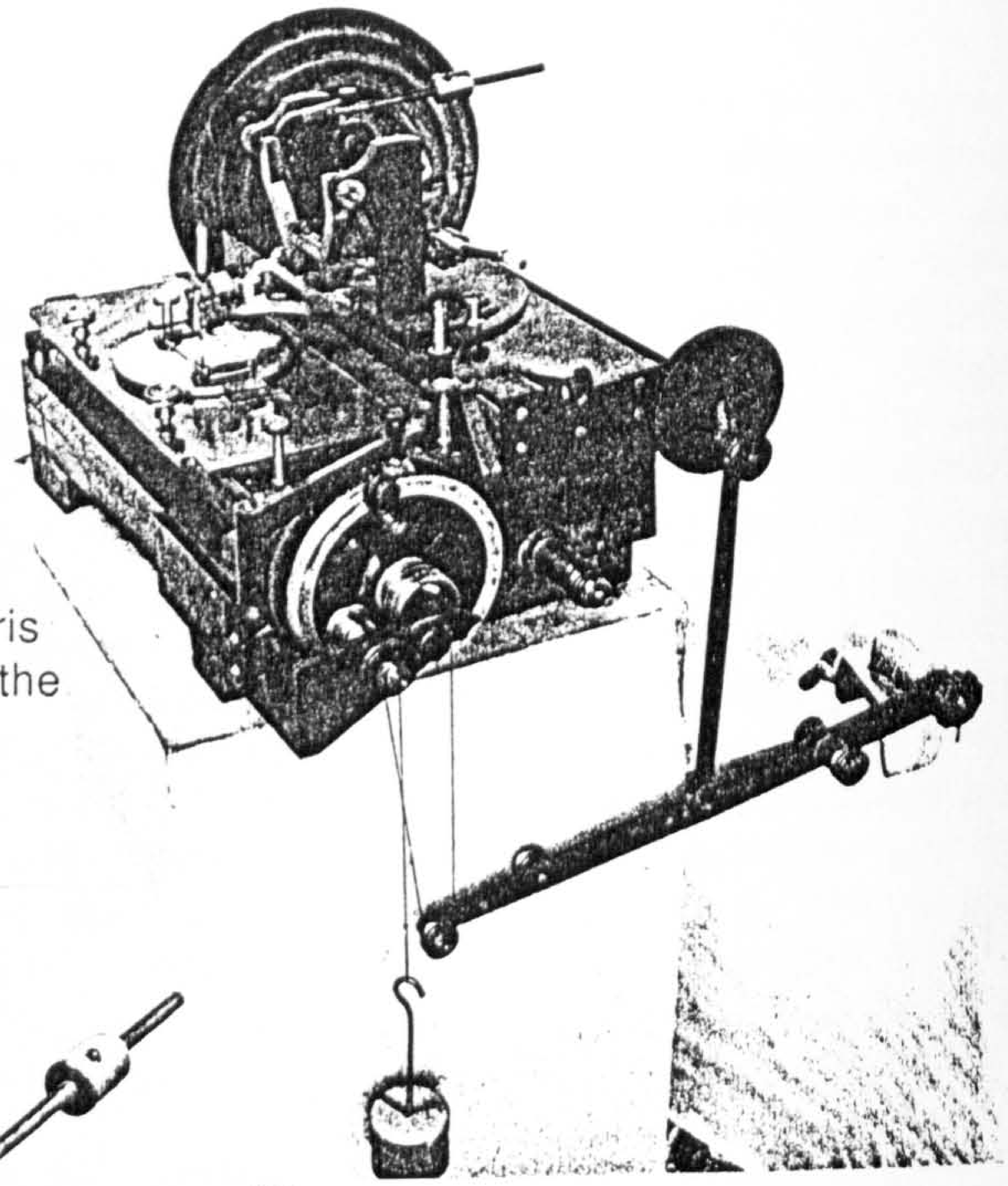
> ruling point in V-shaped bearings of agate. The steel cylinder carries a circular metal table, on which the glass plate to be ruled is fixed by wax and clamps. To diminish the friction of the steel cylinder on the agate bearings, a counterpoise is provided, to lift it on a roller, whilst a weight, attached by a silk cord to one end, keeps the gauge plate in perfect contact with the motor steel point. The motion of the lever arm is, of course, in arc, and hence the divisions would not be strictly equidistant unless compensation were made for the difference in length of the arc and its sine; but since the actual space included between the first and last lines of the test-plates hardly exceeds 1/50th inch, this difference would be inappreciable. It may be assumed that Herr Nobert used the arc motion during the process of division only, and that for moving the plate over the spaces of the blank bands between the rulings he utilized the fine screw connected with the agate plate in the steel cylinder, by which a motion of the plate of about 1/2000 of an inch can easily be effected; in this way he would reduce the total motion of the division-plate in arc to about one-half. It would be possible to increase or decrease the successive divisions of the bands by increasing or decreasing the length of the short arm of the lever; but in view of the risk which such adjustments would involve, it is highly improbable that such a plan was adopted.....
>
> The arrangement for carrying and adjusting the diamond point is specially ingenious. The questions to be solved were--(1) to provide means to adjust a diamond edge to any angle within required limits; (2) to balance it truly so that the weight-pressure for ruling could be perfectly controlled; (3) to raise and lower it strictly in one plane--that is to say, mechanically free from lateral play, so that the consecutive divisions of the ruling depended solely on the motion imparted to the glass plate by the dividing engine; (4) to cause the diamond to oscillate freely in one plane; (5) to control the length of the lines to be ruled; (6) to connect the whole mechanism to insure an even rate of speed in the ruling movement of the diamond.

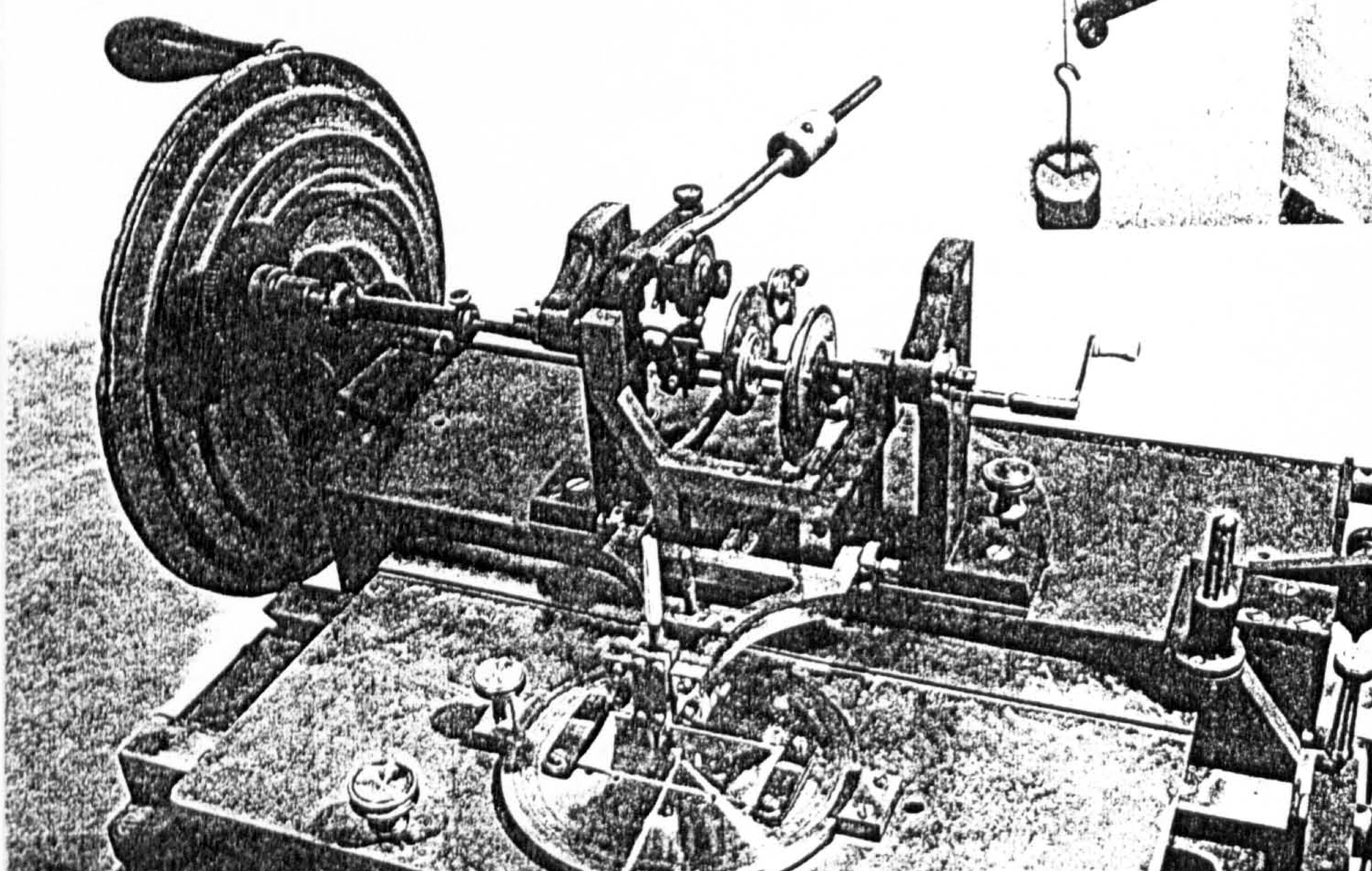
Nobert divided his test plates and diffraction gratings using the micrometer microscopes and graduations on the divided plate adjusting the position visually for <u>every</u> line cut. For some gratings this meant 12,000 adjustments. As Mayall describes (p.712):

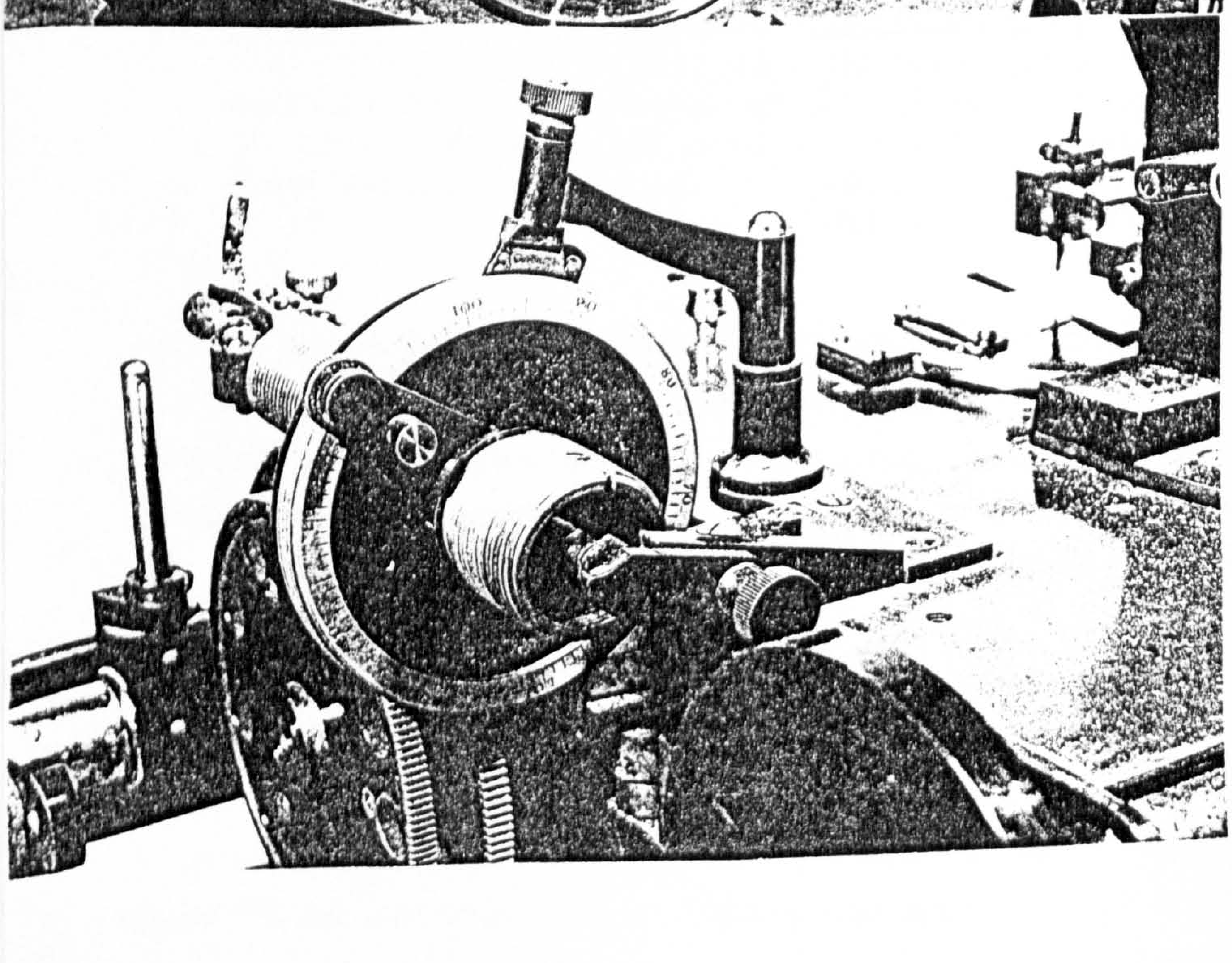
> Imagine the task of adjusting the divisions under the micrometer-microscope, winding up the train of wheels, lowering the diamond on the plate, starting the train, watching for a possible vibration in the mercury bath during the actual ruling, which might ruin the scientific value of the plate, then lifting the diamond by the eccentric roller preparatory to recommencing the whole operation--12,000 times in succession!

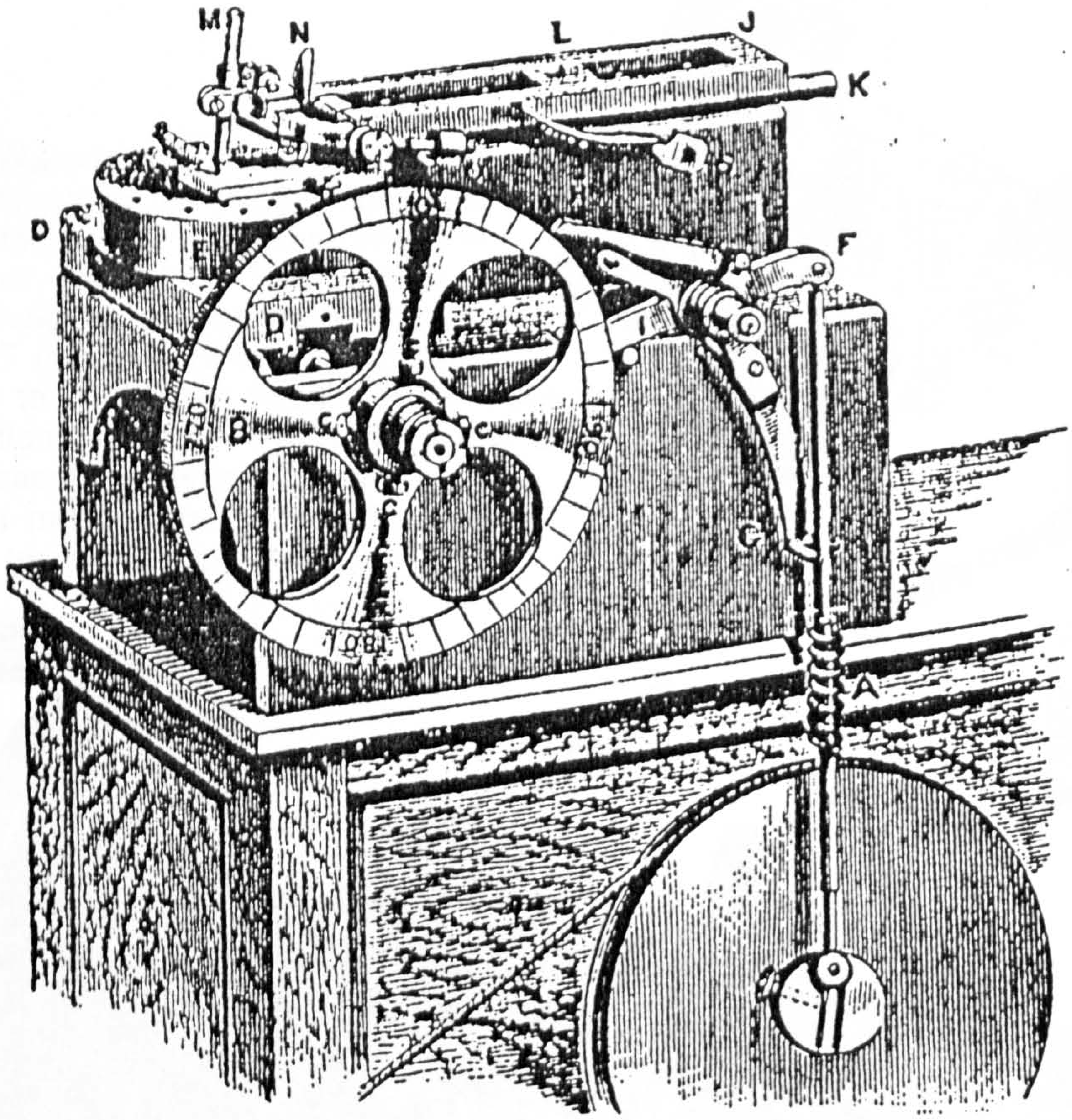
The properties of the diamonds selected by Nobert are discussed by Mayall (pp.712-3) and except for noting that Nobert used a force of 3-30grams for his rulings and that after 1869 he used 'mild' (i.e. soft) glass, we will not belabour Nobert's methods. Rayleigh (1874) carried out some experiments in making reproductions of gratings using a callodio-chloride process in which he used two gratings by Nobert of 3000 and 6000 lines on a square of 1 Paris inch and one by Rutherfurd of 6000 lines to the inch. He found Nobert's much superior though the 3000 line version demonstrated three distinct zones which he attributed to use of three different diamond points. He also found that these three zones were reproduced in the copies and were visible to the unaided eye. Rayleigh was able to observe almost all of the lines Ångström had plotted in his solar spectrum with both the 3000 line original and its copy; he also noted that the 3rd order spectrum was the brightest.

4.4.3 Waterhouse ruling engine found in the RMS collections. The mechanism for controlling the interline spacing is very similar to that found on the Perreaux engines in the ITT in Florence and which are known to have been bought at the Paris Exhibition of 1855. The accuracy of the line spacing is defined by the ratchet mechanism and not by the worm and wheel precision.









4.4.4 Rutherfurd's ruling engine.

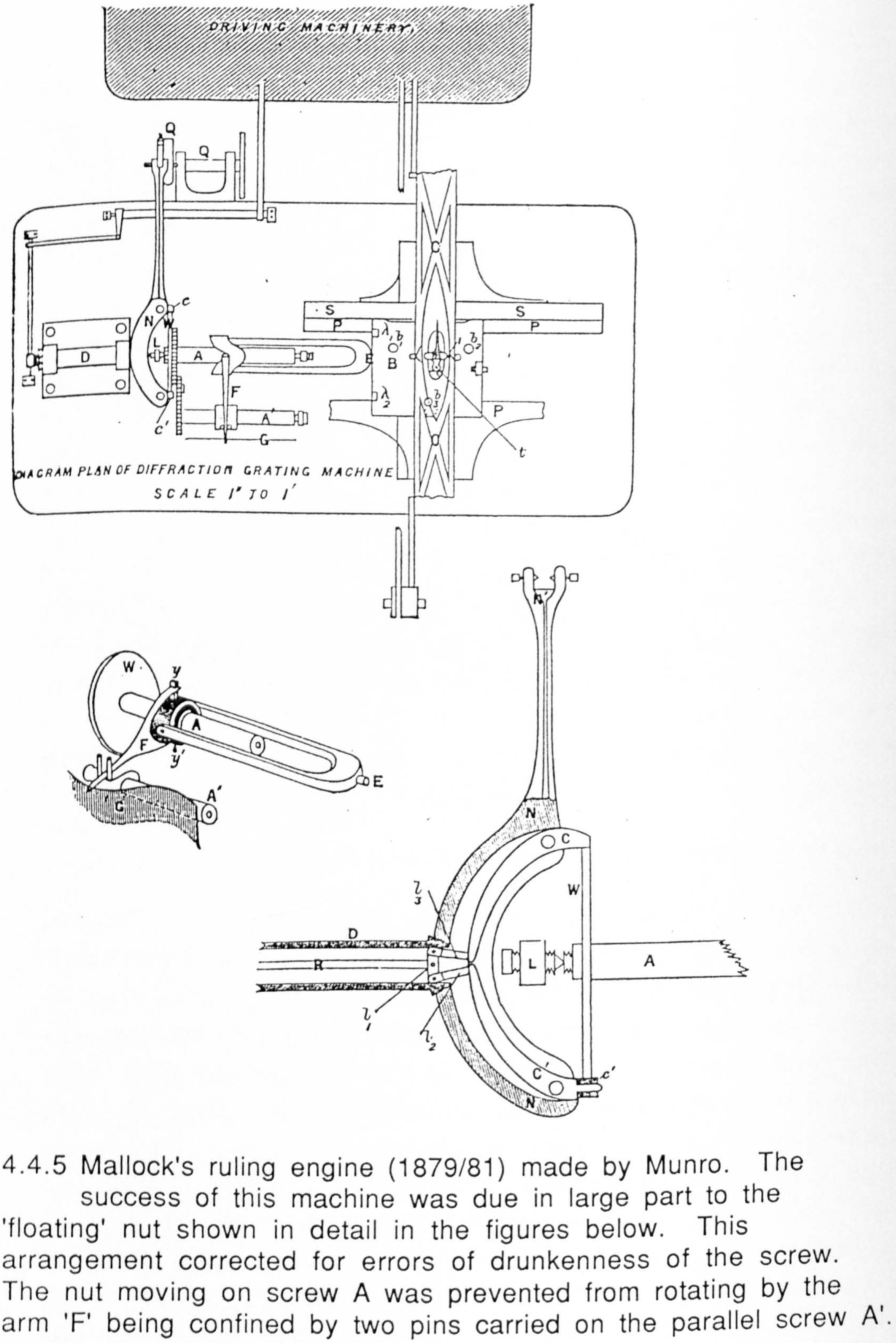
4.4.4 Waterhouse Ruling Engine:

According to Turner (1988), the Waterhouse ruling engine was made by John Waterhouse (FRS, ?-1879) and was presented to the Royal Microscopical Society on 8 Oct. 1879 by his brother, Major James Waterhouse. The date of the instrument has not been established but from design considerations (Fig. 4.4.3) probably dates from the 1860's or 70's. It has its roots in the dividing engine of Ramsden but shows modifications similar to those found in the Troughton, Barton and Perreaux engines.

The subframe is of mahogany and carries both the travelling carriage and the ruling assembly. The carriage is carried forward by a split nut working on the lead screw which is of 50 TPI (the diameter is not known). The screw can be driven in either a direct mode for coarse ruling (≥ 0.1mm) or may be driven through a reduction worm gear (1:200) for fine ruling. Maximum ruling length was ≈15cm. The tool drive mechanism is much more complex than that on the closest instruments in size and age that have been inspected, i.e. the Perreaux engines at ITT, Florence. The actual spacing was set in much the same manner as on the Perreaux ruling engines, i.e. with 2 ratchet wheels and pawl. One pawl was fixed and the other adjustable with a resolution for coarse ruling of 1/200^{ths} of a turn. Theoretically this would have given a resolution of 0.0025mm. For fine ruling a ratchet wheel with 100 teeth was employed and the resolution was--theoretically!--0.000025mm. However, Turner's assessment suggests that the ruling assembly in its current state is far from able to reach this limit.

4.4.5 Rutherfurd's, Rowland's and Other Contributions in the U.S.:

In the U.S., the first ruled grating was made in the early 1840's by Joseph Saxton, a balance maker at the Mint in Philadelphia. He had been in London, had made a machine to copy medals and had considered making jewelry similar to that of Barton whom he probably knew. John William Draper used a Saxton grating to produce the first photo of a diffraction spectrum (1845). The grating was only 1/3in wide and 5/8in high. Lewis M. Rutherfurd, a lawyer, began making gratings ca.1863 and was able to make 1in square gratings of 6000 lines of good quality and by ca.1880 had made acceptable examples with 30,000 lines on a 1.75in square which was just short of the 2in capacity on his machine (Fig. 4.4.4). These were on speculum metal and showed more spectral detail than had previously been observed. Yet only one in four of his gratings were usable and only an occasional one could be considered first class (Rowland: 1882, p.172). Rutherfurd was wealthy and gave his gratings away; they were used by Rutherford, Young and Lockyer among others and were the best available until Henry A. Rowland turned the resources of the physical labs of Johns Hopkins University to the task. William A. Rogers, a Harvard Astronomer, made an engine to produce gratings to compete with those of Rutherfurd. Rogers, using the facilities of Buff & Berger, instrument makers in Boston, and the



4.4.5 Mallock's ruling engine (1879/81) made by Munro. The success of this machine was due in large part to the 'floating' nut shown in detail in the figures below. This arrangement corrected for errors of drunkenness of the screw. The nut moving on screw A was prevented from rotating by the arm 'F' being confined by two pins carried on the parallel screw A'.

Waltham Watch Company (Warner: 1986, p.127). As we have discussed in Chapter 2, Rogers was able to make a very precise screw probably exceeding in accuracy any other to the 1880's; his investigations on screw making resulted from his interest in constructing a grating engine. Unfortunately for Rogers, Rowland began producing gratings about this time and although Rogers' gratings were much cheaper, Rowland's reputation and commercial success surpassed his.[1]

As always, the limiting factor in achieving optimal performance was the quality of the screw. The screw for Rowland's machine was made by the university's instrument maker, Theodore C. Schneider,[2] and was according to Rowland accurate to 0.00001in with no detectable periodic error. Rowland quickly produced a grating with 43,000 lines per inch and made one with 29,000 lines per inch and with a total of 160,000 lines. The maximum capacity was 6.25 X 6.25in.[3] Upon thinking of the cost to make telescopes sufficiently large for use with such large gratings, Rowland (p.470) noted that there was no reason that the grating could not be made on a curved surface in order to make the spectrum come to a focus. Modified to make curved gratings, the dividing machine could make gratings 6.25 X 4.25in with every one able to split Ångström's line 1474 of the solar spectrum. One division of the drum on the screw was equivalent to 14,438 lines/in and Rowland also made versions with double or even triple this number of lines per inch with good results. He was also able to blaze the rulings for a particular order of spectrum as for example the one he made for Langley's study of the infrared spectrum. This had a more concave surface than usual and Rowland found that the diamond cut differently on different parts of the plate. It should be noted that it is a coincidence of nature that the lines required on a curved surface are straight, otherwise Rowland would not have succeeded in this enterprise.[4]

4.4.6 Mallock's Ruling Engine:

In 1882 Mallock described the ruling engine he had designed and which was made by W.R. Munro of King's Cross Rd. in London. It was made with the assistance of a grant from the Royal Society and took two years to complete (1879-81). This engine (Fig. 4.4.5)

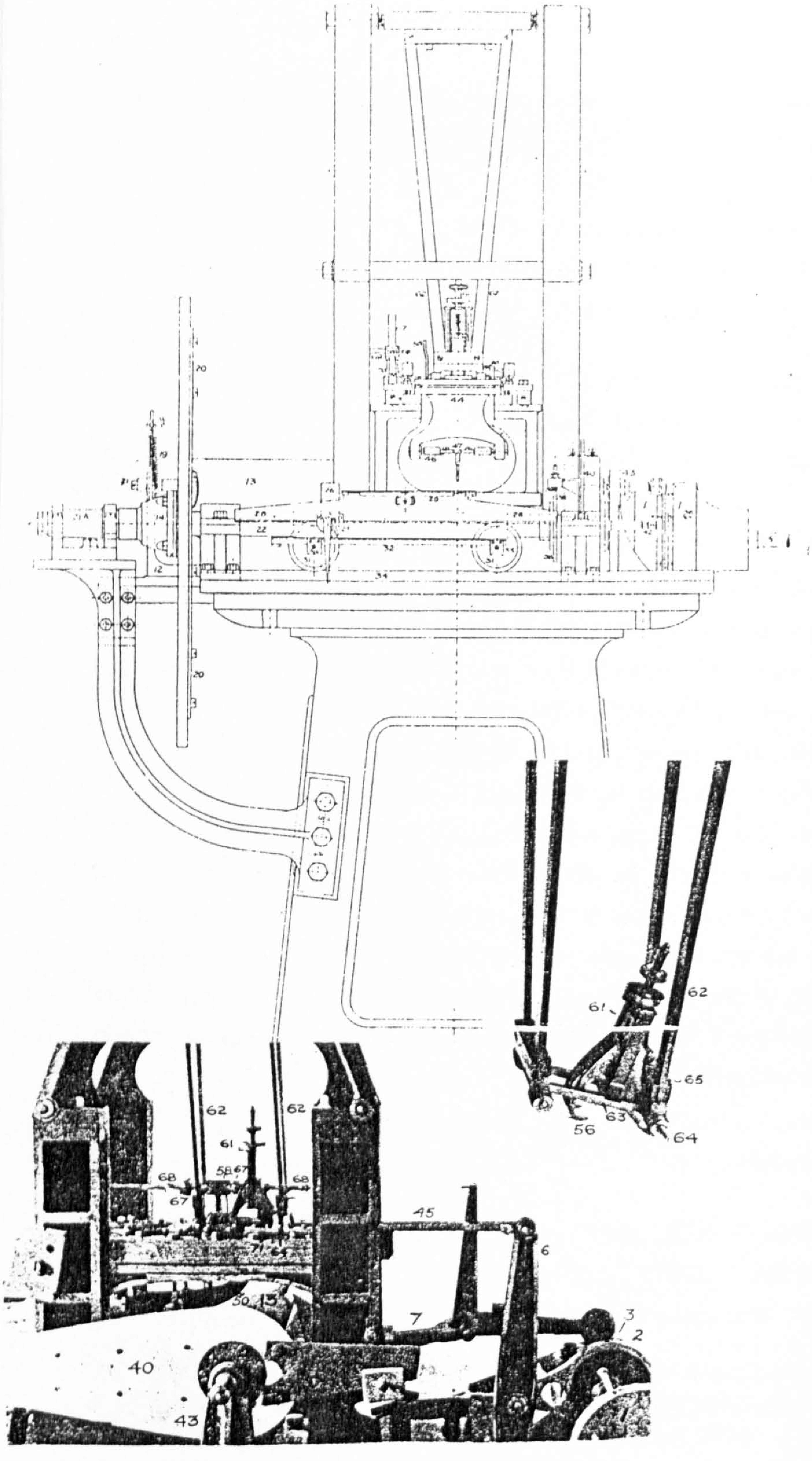
---

[1] Another maker working in the U.S. was Charles Fasoldt. He had emigrated from Germany in 1848 and in the 1880's was making test plates similar to Nobert's. Fasoldt's engine is in the Smithsonian.

[2] Schneider had previously worked for W. & E. Gurley in Troy, New York. He also oversaw the actual ruling of gratings while Rowland did the testing.

[3] The optical flats used by Rowland were made by Brashear in Pittsburgh (Strong: 1986, p.138). Brashear also handled the distribution which by January 1901 had amounted to 250-300 gratings with a value of $13,000 not including those given away (Warner: 1986, p.129).

[4] Rowland built two other machines (1889, 1894). The later was damaged by fire after Rowland's retirement but was rebuilt with improvements by John Anderson who used it to produce rulings from 1910 (Babcock: 1986, p.153--This paper details some of the advancements in the U.S. in the first decades of the 20th c).



4.4.6a Blythswood ruling engine (SML-33) originally made by Adam Hilger in 1888 but later modified until these figures were drawn to accompany Scoble's 1912 description. This is a front view showing the micrometer (identified as 61) which controls the height on the engraving point. A cam mechanism on the right-hand end of the worm controlled errors in the run of the worm but the large wheel (20) on the left was used to correct errors of the screw of less than one turn.

could rule 6.5 X 6.5in gratings compared to Rowland's 6 X 4in and at a time when the normal size was just 2 X 2in. Mallock identified four errors:

1) eccentricity or lack of straightness of the axis;
2) gradual error of pitch over long sections;
3) pitch error equal to the lead screw error, and;
4) periodic error for each revolution of the screw.

To overcome the periodic error Mallock used a free nut mounted in a gimbal which allowed motion about a cone; the apex of the cone then moved free of periodic error. He measured the error of the screw to be 0.001in over its full length but found the error in the pitch of only 0.00001in. Mallock did not describe the method used to determine these errors. By 1882 he had ruled 5.5 X 5.5in rulings with 2800 lines/in on curved plate glass chosen for its curvature. These were blazed for the 5^{th} order spectrum. The operating speed was 4 lines/minute.

Some comments of Mallock's are of interest. He noted that Rayleigh had worked out the conditions for good spectra and that the accuracy was proportional to 1/4n λ where n is the order of spectra. "The definition of a grating depends, caeteris paribus, on its width, in the same way a telescope depends on the diameter of the object glass. It is very doubtful if any optical work hitherto produced approaches the extreme exactness which 1/8wave-length error indicates..." (Mallock, p.466).

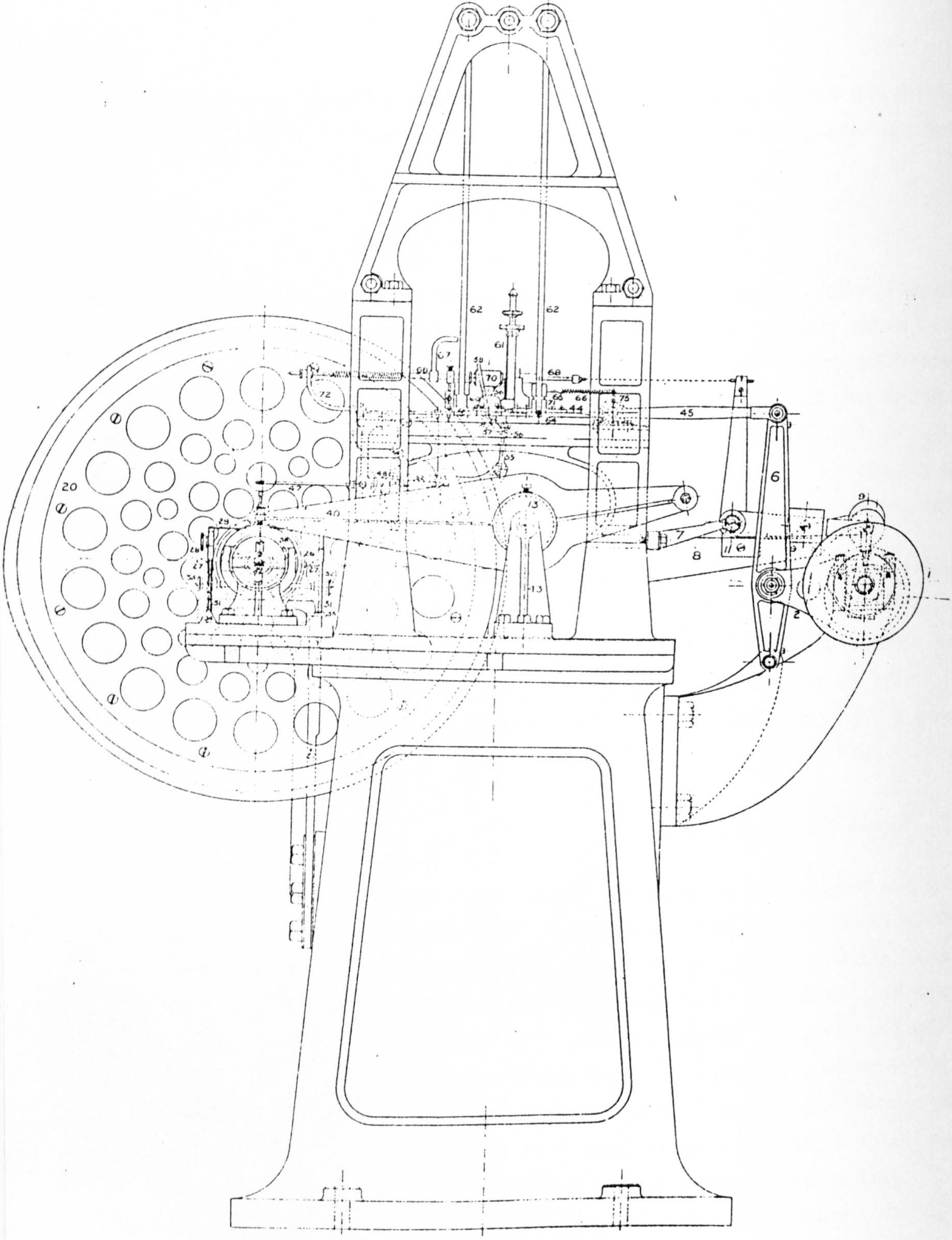
4.4.7 Hilger's 'Blythswood' Ruling Engine:

Despite the fact that an extensive description of the Blythswood diffraction grating engine is extant (Scoble: 1912) relatively little is known about its origins. It was begun by Adam Hilger in 1888 and appears to have been almost continuously modified to improve its performance up to the time of Scoble's description.[1] Thus it is difficult to date the appearance of specific features. The mechanism is not substantially different from other engines of its type being completely automatic with the dividing controlled by a reciprocating mechanism. To avoid temperature changes and vibration of any kind, the engine was erected in a small building of its own isolated from other buildings. The machine was also enclosed in a case to further reduce temperature effects and was mounted on a massive pier isolated from the building itself. A number of measures were taken to control the temperature including an electric thermometer attached directly to a gas stove, and to fan blades on one of the pulleys driving the machine.

The machine (Fig. 4.4.6) was of course designed to make gratings on concave glass blanks with the vertical path of the diamond being generated by the arms of a pendulum type mechanism. The precise length of the radius of curvature was controlled by a micrometer acting in the vertical plane. This micrometer is of Hilger's standard design

---

[1] Some alterations are documented by J.E. Sears in Appendix I of Scoble's paper (p.248-9).



4.4.6b Right-hand plan of the Blythswood engine.

in use in the 1880's and very similar to those of Browning. The cutting apparatus had to lift the diamond during the backward stroke which was accomplished with a cam mechanism acting on claws attached to the micrometer head (identified as 61 in the figures). The cutting weight could be set between 0.5 and 5g but normally was from 1-2g.[1]

The main driving screw is of 20 TPI, 1 7/16in diameter, 12in long and of Whitworth form. According to Scoble, the accuracy of the screw was 0.00001in. The shaft is carried on white metal lined bearings which also carries a large honeycombed steel toothed wheel with brass rim. The screw was made on a Whitworth lathe with a particularly accurate lead screw and was then ground to the proper pitch. However, this original screw was replaced by an improved one; the old screw was used as the lead screw during the process of making the replacement. Scoble (p.236) stated that this new screw was the most accurately made to that time. The nut for grinding was 18in long--i.e. 6in longer than the screw itself. The nut was made with 4 separate, soft, cast-brass pieces which were machined, fitted together and bored. The cutting tool was mounted on a bar which was mounted between the centres of the lathe and the nut was mounted on a saddle attached to the lead screw which was the original screw from the grating machine. For grinding, the four pieces were fitted inside two cone sleeves which could be drawn together by screws and during the grinding an air blast kept the temperature regulated since the screw and nut were of different materials. Oil and bluestone were used for fine grinding. The nut used on the grating machine was prepared in the same manner as the grinding nut.[2]

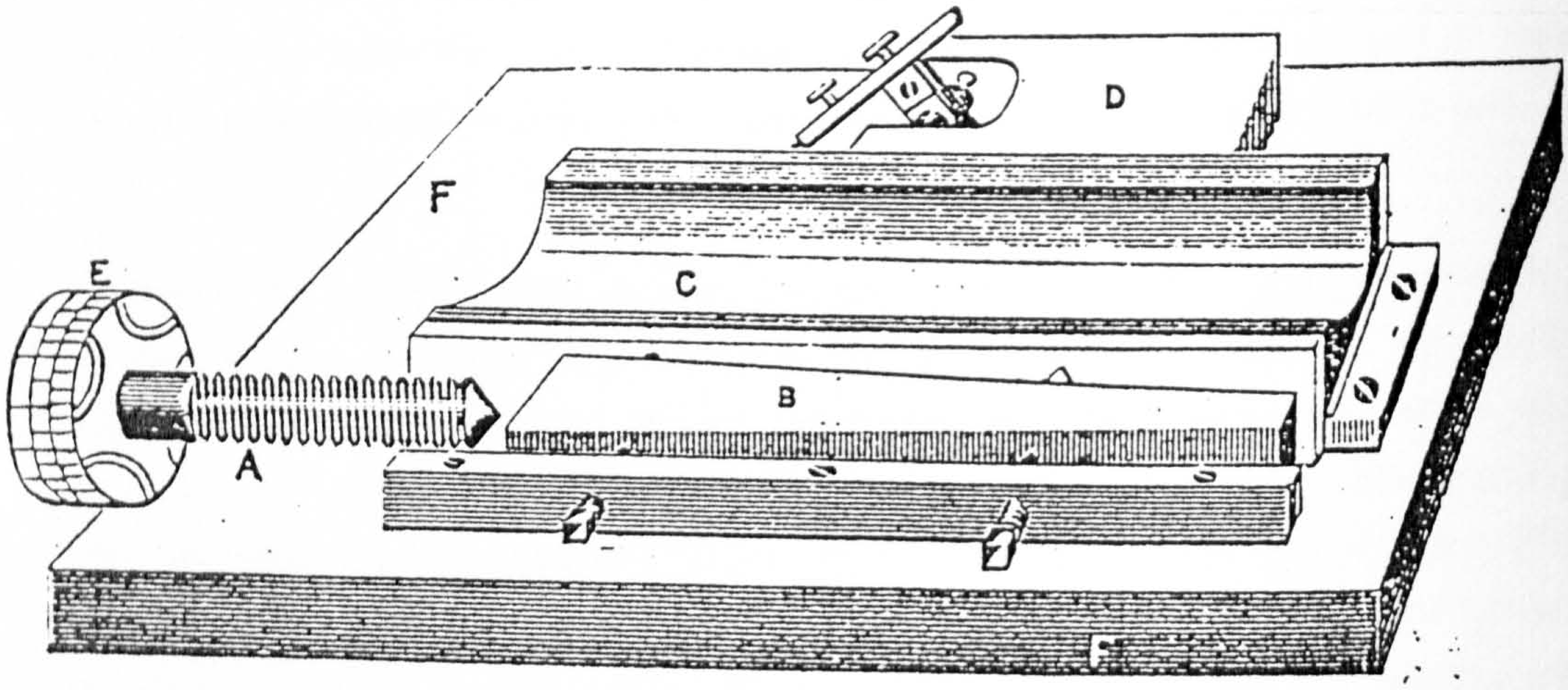
To eliminate the crucial endplay, the shaft of the screw opposite the wheel was slightly tapered and had a hardened and rounded steel pin bearing against a plane agate bearing mounted in a thrust block. The main screw itself was made from the centre portion of a "block of specially pressed, soft, Bessemer steel, a material selected because its structure is particularly uniform." The nut was made in halves of white metal which were bound together with 4 piano wires adjustable in tension by screws; the 4 wires were in fact 'tuned' to a specific note for equal tension. This flexible connection averaged out inequalities in the screw's pitch. To function properly, the nut must float on the screw with respect to the carriage and was thus mounted in a gimbal ring. The ring was mounted between agate channels which permitted the carriage to shift slightly relative to the screw.

Since periodic errors of the screw cause ghosts in spectra, such errors are easy to detect and must be corrected. Testing of gratings from the Blythswood machine was done

---

1 A diamond cutter was replaced when any cuttings were visible on the grating. It was determined that cuttings indicated that the diamond was cutting rather than scratching the glass surface.

2 A number of types of nuts were tried but rejected (see Scoble: p. 244).



4.4.7 Smith's (1898) simple apparatus for ruling lines on glass for microscopical purposes. Some details were omitted for clarity.

by illuminating a grating with monochromatic light and looking for bands running parallel with the grooves. Such bands indicate periodicities in the screw and nut. Grinding of the screw was continued until no bands were visible. Tests with a Michelson's interferometer provided no further improvement. To assist in correcting residual errors, the large wheel attached to the screw was used. It had 720 numbered teeth which "were laid off with the greatest care". Indeed each tooth was optically measured and built up with copper plating or filed down to the correct width. However, a change in one affected all adjacent teeth and the process was one of going around the wheel several times comparing and correcting each tooth individually.

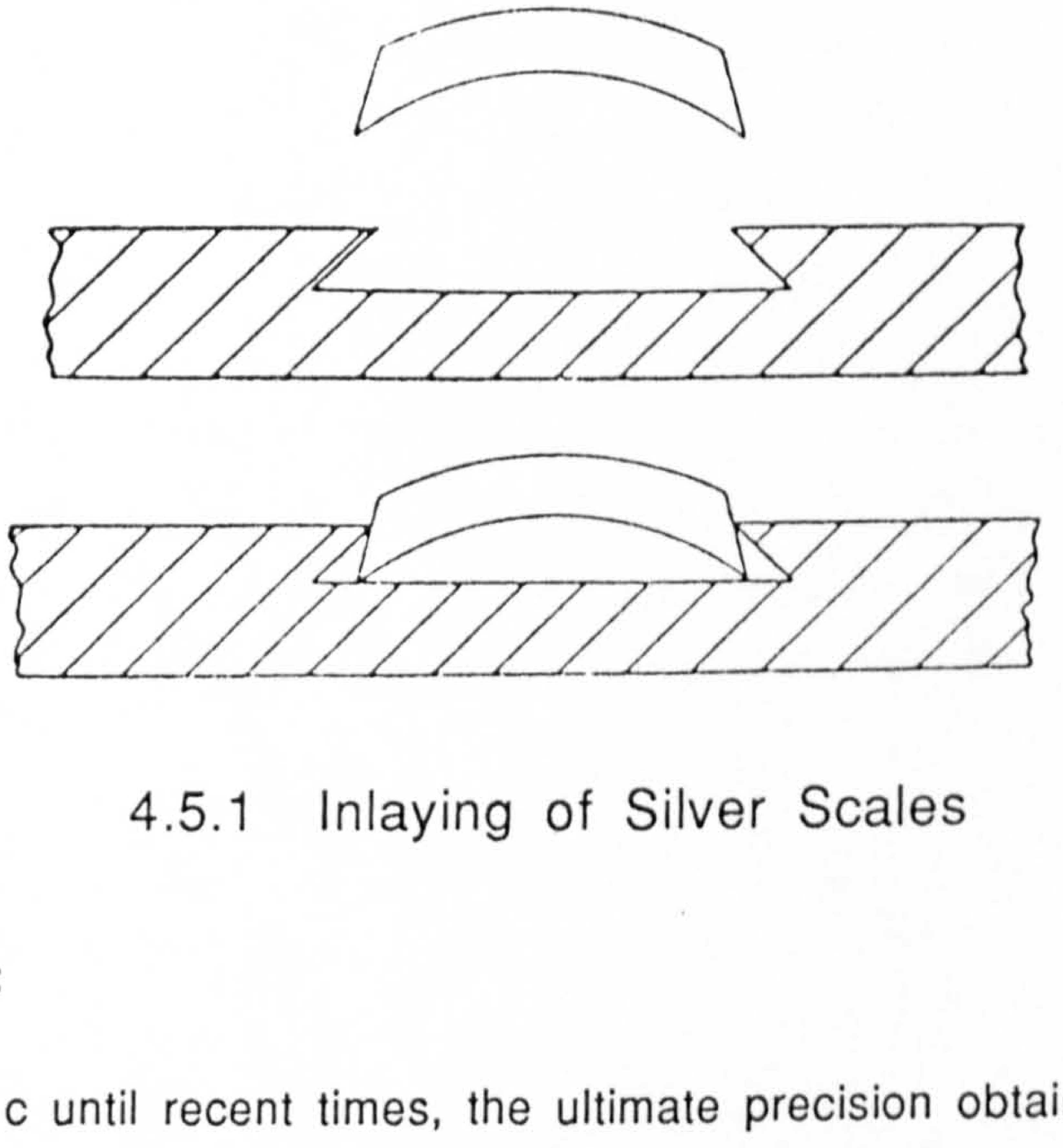
Even with all the care taken in making the screw and wheel, it was necessary to add a cam mechanism to correct the pitch. This was attached to the end screw's shaft which acted through a system of pins, levers and tubes to correct the periodic error of the worm screw. The shape of the cam was determined by photographing a spectrum made with a grating with a known number of lines and being a multiple of the 720 teeth of the wheel. By measuring the lines in the spectrum on a micrometer designed by Lord Blythswood, the bands could be measured and associated with a specific tooth of the wheel or to a particular period. If bands were seen to repeat in each period, then the angular position on the wheel could be determined and defined the shape of the cam. As a further check, two gratings were superimposed at a slight angle and, if equally spaced, the loci were straight lines but curved if not equally spaced. These then indicated where further corrections were necessary and the shape of the cam was adjusted accordingly. Scoble noted that the best gratings were made just after the screw had been cleaned with benzol and this was done after making every 3rd or 4th grating. The very lightest, thinnest layer of lubricant was used on critical components of the machine; in some areas no lubricant could be used since a layer of oil would destroy the precision of the apparatus.

4.4.8 Smith's ruling device:

A very simple device (Fig. 4.4.7) was described by Rev. D.W. Smith of Brooklyn, N.Y. in 1897, which had been exhibited before the New York Microscopical Society. To rule lines finer than 40-50/in he noted that the selection of the diamond point was more important than the machine. The apparatus (for clarity some components were not included in the figure) consisted of a wedge pushed along by a screw with divided drum. The wedge advanced the piece of glass to be divided. With a high quality micrometer screw of 60 TPI, the accuracy was dependent upon the flatness of the wedge and bearing surfaces since a very thin wedge would give an amplification of the pitch of the screw. The wedge pushed against a brass block which in turn advanced the block holding the diamond ruling point and this in turn was held in contact by strong springs. The glass to be ruled was placed under the brass block. It was operated entirely by hand but as Smith observed could be easily automated.

4.5 Note on Inlaying of Silver Scales:

Since the vast majority of scales were divided on inlaid silver during the 19th c, it may be worth noting the procedure by which this was accomplished. First the wheel was roughly turned and an undercut groove formed on its surface as illustrated. The strip of silver was then drawn through a die to shave off the edges to the shape and size of the undercut groove in the wheel. The strip was then run through rollers to give it a curved cross section as shown in the figure. It was next placed in the groove and carefully hammered until level with the surface. The wheel was then mounted in a dead centre lathe and the surface finished off and stoned down with water of Ayr stone at which point it was ready for division. The use of water of Ayr stone left the surface with a slightly matte finish which is desirable since a polished surface is more difficult to read.



4.5.1 Inlaying of Silver Scales

4.6 Summary:

From the 18th c until recent times, the ultimate precision obtainable in mechanical positioning and measurement was obtained by dividing engines. It might be argued that comparators such as those made by Whitworth[1] were more precise, but these did not provide an absolute measure as did the results of the dividing engines. To obtain the maximum performance required sound mechanical understanding on the part of the instrument maker and meticulous care in the handling of errors by the maker and by the

[1] Whitworth's first 'millionth inch' comparator was made in 1856. Examples (MSTB-10) dated 1869 and 1899 are preserved in Birmingham. These later versions had the wheel colinear with the screw while the original used a worm and wheel arrangement for measurement (see Derry & Williams: 1960, p354).

user. By the mid-19th c there was not much further accuracy to be gained in positioning an engraver, but the errors were now more regular and predictable indicating a high level of mechanical stability in the engines. As noted, temperature effects during division of scales began to be the dominant problem after Bessel recognized these effects in 1839 when the instrumental errors had fallen below ≈0.4-5".

A chronological list of known dividing and ruling engines made before ca.1900 is presented in Appendix B. Those which have not been mentioned in the above text have a few comments where warranted. This list is undoubtedly incomplete, but is the first attempt at such a compilation and may be useful for future research.

CHAPTER 5

Measurements of Screw Profiles; the Screws of Micrometers and Dividing Engines

5.1 Acquisition of Thread Samples:

5.1.1 Choice of Samples--Rationale:

Initially the intent of this study was to examine only micrometric screws of the 18th and 19th centuries in order to maintain a homogeneous sample. It seemed unreasonable to expect binding screws to have anything more than general similarities because of the crude modes of manufacture employed, and by the fact that many instruments of the period have screws fitting only one specific hole--i.e. screws presumably by the same maker (or at least from his shop or from his supplier if such were available) were chosen to fit a hole by trial and error. An alternative to this approach was to make the screw to fit an already tapped hole, the latter being the more difficult operation. This changed as techniques of screw production, and ease of cutting threads improved and as standards were developed and adopted during the 19th c. Micrometric screws, however, had to be made to the highest possible standards of the day, and one may assume the master often had a direct hand in making and/or finishing these screws. Thus there would be a reasonable expectation to find micrometer screws from one maker's shop with similar characteristics. If this were born out by detailed studies one could potentially identify relationships between makers and identify the makers of unsigned instruments. From the descriptions of Ramsden and Troughton, etc. we know for certain that the master carried out most of the labour in making the screws for their dividing engines. Detailed knowledge of the attributes of these engines, their scales and screws might provide a means to identify instruments and to provide an assessment of the maker's abilities.

In addition micrometer screws permit investigation beyond simple 'form' studies. Their motion may be measured to determine the precision capabilities of the micrometer, which in turn may, in some cases, be related to measurements made by the scientists who bought and used them. Astronomical micrometers were the most accurately made mechanical devices of the 18th c, were relatively common, and were carefully maintained. However, it became clear early in this study that a sufficiently large sample of astronomical micrometer screws was going to be difficult to acquire. The basis of the study was therefore broadened by acquiring samples of other screws from the micrometers or from the parent instruments. In addition it was felt desirable to acquire samples from non-astronomical micrometers and of adjusting screws, both of which were also more carefully made than most screws.

Thus the majority of screws sampled in this study have been chosen because they may be classed as precision screws used either as micrometric screws or as adjusting, focusing or leveling screws. These functions require them to be finished to a state which (in theory) allowed smooth operation and motion of components. Only a few binding type screws have been studied, these being ones removed from instruments during dismantling in order to obtain access to the precision screws. In addition a small sample of screw threads from telescope and microscope tubes of the 19^{th} c have been included because of their special nature. Examples of screw making tools of the 19^{th} c have been studied because of their special relationship to standards developed by Maudslay and Whitworth. Inevitably the sample range has been affected by limitations of museum collections, by suitability, by inability to dismantle an instrument to a suitable state, or by rust and corrosion which made a number of micrometers on early observatory mural quadrants unsuitable for study. Because of the relationship between scientific instrument makers and clock makers, a few screws from 17^{th}-19^{th} c clocks and clock makers' tools have been acquired. A number of casts of instruments which had survived from the earlier studies by Mills and Maddison were incorporated into this study. The origin of those chosen was the deciding factor on whether they should be used; samples from Newton's reflecting telescope in the possession of the Royal Society (identified as RS-1) and leveling screws from instruments in the astronomy collections of the Science Museum were employed (the latter are identified with the code SML-C092 to C106). The results of the current tests and procedures may be compared with those of Mills and Turvey (1979) for Newton's telescope.

In order of significance for this study's objectives, the following types of screws have been studied:

1) Astronomical micrometers
2) Micrometers used by machinists and used on microscopes
3) Dividing engines
4) Adjusting and leveling screws: e.g. azimuth and altitude adjusting screws from surveying, nautical and astronomical instruments
5) Taps and dies
6) Special instrument screws: e.g. for telescope or microscope tubes
7) Clock and clock makers screws
8) Binding screws

The homogeneity sought initially was not achieved; this made some objectives more difficult to achieve, but the expansion of the sample types has, at the same time, opened up new avenues for consideration, e.g. a determination of working tolerances as a function of time for different classes of screw.

Micrometric screws were the most difficult to obtain from a physical point of view. A wide range of designs of these instruments were encountered and some required considerable time to dismantle the instrument to a suitable state. 19^{th} c instruments with a screw fixed to a moveable frame were the simplest requiring only the knurled knob and one cover to be removed. The other extreme was John Smeaton's micrometer in the Science Museum which was by far the most complex instrument, initially requiring form02

MICROMETER SCREW THREAD REPORT

DATE: MUSEUM: CODE:

INSTRUMENT: Micrometer Parent Inst.

Type:

Maker:

Mus. Acc. No.:

Date/Ser. No.:

PHOTOS: (y/n)
Parent Inst.: Shadowgram No.:
MU Detail: MU Screw:

VISUAL INSPECTION:

Material(s):

General Appearance and Damage:

Anti-backlash mech.: With Without Type

Measure (div. on scale):

MU PROPERTIES:

Inches Centimeters

Scale:

Dia. of Drum:

No. of Div./rev.:

Resolution:

THREAD PROFILE:

TPI/TPC:

Thread Angle (average):

Length of Screw:

Diameter of Screw:

Depth of Thread:

Radius at Crest:

Radius at Root:

Nom. Thread Form:

Number of Nuts:

Length of Nuts:

NOTES (inc. Defects, Machine Tool Markings):

5.1.1 The form used to record information on the instruments, tools, etc. while at the museum along with follow up data.

more than an hour simply to take it apart. This lengthy period was required to ensure that springs and other components were not removed accidently which would later prove difficult or impossible to replace correctly.

5.1.2 Identification:

Instruments were identified by a study code based on the following rules:

1) A 2-4 letter code was assigned to each museum; usually this was simply the initials of the institution with the initial of the city included where necessary to avoid confusion with other well known institutions (q.v. Table 5.1).

2) Each instrument was assigned a consecutive number for the institution.

3) Each screw or nut was assigned a non-capitalized letter to distinguish it from the others. An exception to this rule was applied when tools with specific TPI numbers stamped on them were encountered. In such cases this number is added as a suffix. Also instruments with multiple micrometers were sometimes identified by the maker with a letter; in such cases the maker's identification has been employed for obvious reasons.

4) Occasionally, where a repeat cast of a screw was made, a '-2' was added to indicate that the mould was a replacement. Thus, the code for a particular screw would appear as: SML-12c or occasionally as SML-1c-2

Table 5.1

Museum Codes

IMSS -	Istituto e Museo di Scienza, Florence
ITT -	Istituto Tecnico Toscana, Florence
MCML -	Merseyside Co. Museum, Liverpool
MHS -	Museum of History of Science, Oxford
GMMS -	Greater Manchester Museum of Science & Industry
MSTB -	Museum of Science & Technology, Birmingham
NHM -	Newarke Houses Museum, Leicester
PO -	Observatoire de Paris
RB -	Author's Collection
ROG -	Royal Observatory, Greenwich
RS -	Royal Society of London
SML -	Science Museum, London
WMHS -	Whipple Museum of the History of Science, Cambridge

The identification code was placed on each sample's 'U'-channel with tape prior to the moulding process. Information about the instrument was recorded on Form 02 (Fig. 5.1.1) including maker's name, serial number or museum accession code, date attributed by the museum (if not specifically stated on the instrument), type of instrument, use of screw, etc. Physical parameters of the screw were also recorded, the most important being the diameter measured (accuracy ±0.0002in) with a Moore & Wright micrometer. The length of the actual threaded portion of the screw was measured. Details of the usage, materials and state of the screw were noted as well as any distinguishing factors observed (e.g. whether there was any evidence that the screw was made in a lathe as suggested by a dimple in the end of many micrometer screws).

5.1.3 Sample Preparation:

Once a screw or nut was removed from the parent instrument, oil, grease, dust and loose corrosion were removed. This was carried out with a fine bristled toothbrush followed by cleaning with an even finer small laboratory brush. It should be noted that even the finest toothbrushes have bristles slightly larger in diameter than the troughs of 100 TPI screws and hence will not properly clean the roots of such screw threads. The cleaning agent employed was petroleum ether (with appropriate ventilation) as it both dissolves oil and grease and evaporates quickly allowing the moulding process to proceed with minimum delay. Some problems were encountered with residue left in the threads of very small (<0.5cm diameter) fine pitched nuts. This could be overcome by using a compressed air cleaner with directional nozzle. Initially in the study, all samples, once cleaned, were coated with a release agent consisting of a 5 percent solution of vaseline in petroleum ether. However, its use on very fine threads seemed to adversely affect the separation of the sample from the Silastic, and trials without this solution for screws of ≈60 TPI or finer produced better moulds. Therefore the release agent was used only on larger screw and nut samples. After removal of screws from the moulds the screws were cleaned, and any remaining traces of silastic removed with a brush. The samples were then given an application of the release agent to prevent rust forming, the vaseline residue providing the necessary protection.

5.1.4 Moulding and Casting Techniques:

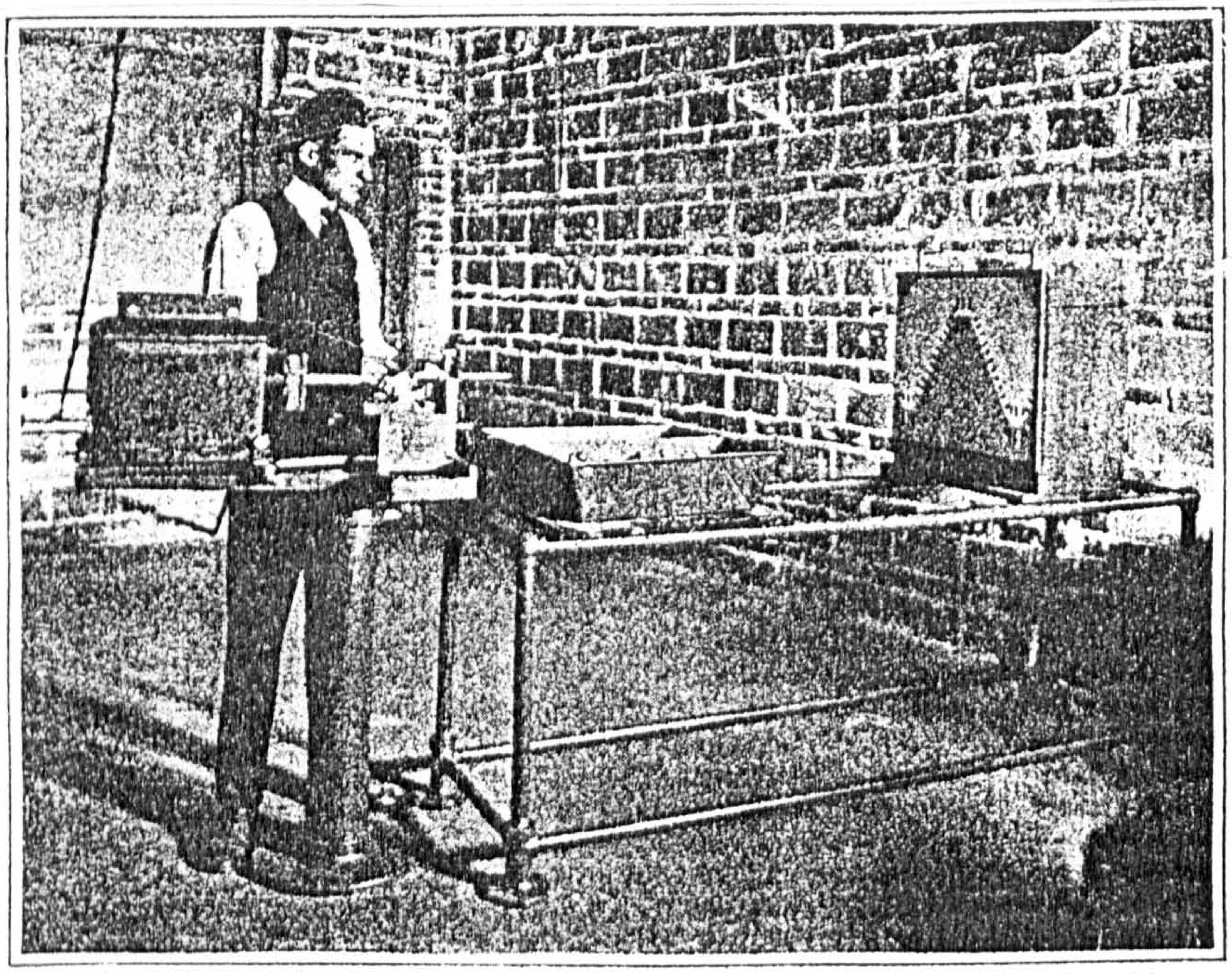
The majority of moulds were made in 1/4in or 5/8in aluminium 'U'-channels cut to 11/2 or 2in lengths. Each channel was identified with the study code prior to actually making the mould, and the inside of the channel was 'painted' with Silcoset Primer (ICI). This is a special fluid to promote adhesion of the moulding material--Silastic 3110 RTV (Dow-Corning). The primer takes 15-20 minutes to dry, but may actually be applied up to an hour prior to use of the channels. In most cases, one end of the channel was taped over with a dam of plasticene placed at the other end. This dam also acted as a support for the screw while the mould was setting. The Silastic 3110 RTV was mixed with the hardener and a small amount poured into the prepared trough. The screw was then pressed into the plasticene dam and into the moulding material so that it covered half the diameter. If small diameter screws were pressed down too far, the moulding material 'crept' up over the screw in the threads which then required more care in their removal after the material had set. Fortunately, bubbles trapped in the threads were rarely a problem.

For larger diameter screws and for some screws which could not be removed from the parent instrument, sections of aluminium sheet were used in place of the 'U'-channel troughs. The sheeting was cut into 5 or 8 cm long strips with a variety of widths ranging from 1/2cm to 3cm; thus a piece was chosen and bent around a pen, film canister or other suitably sized round object and primed with Silcoset. Dams of plasticene were applied to each end and a layer of Silastic 3110 RTV applied. The screw was then placed in the moulding material as previously described.

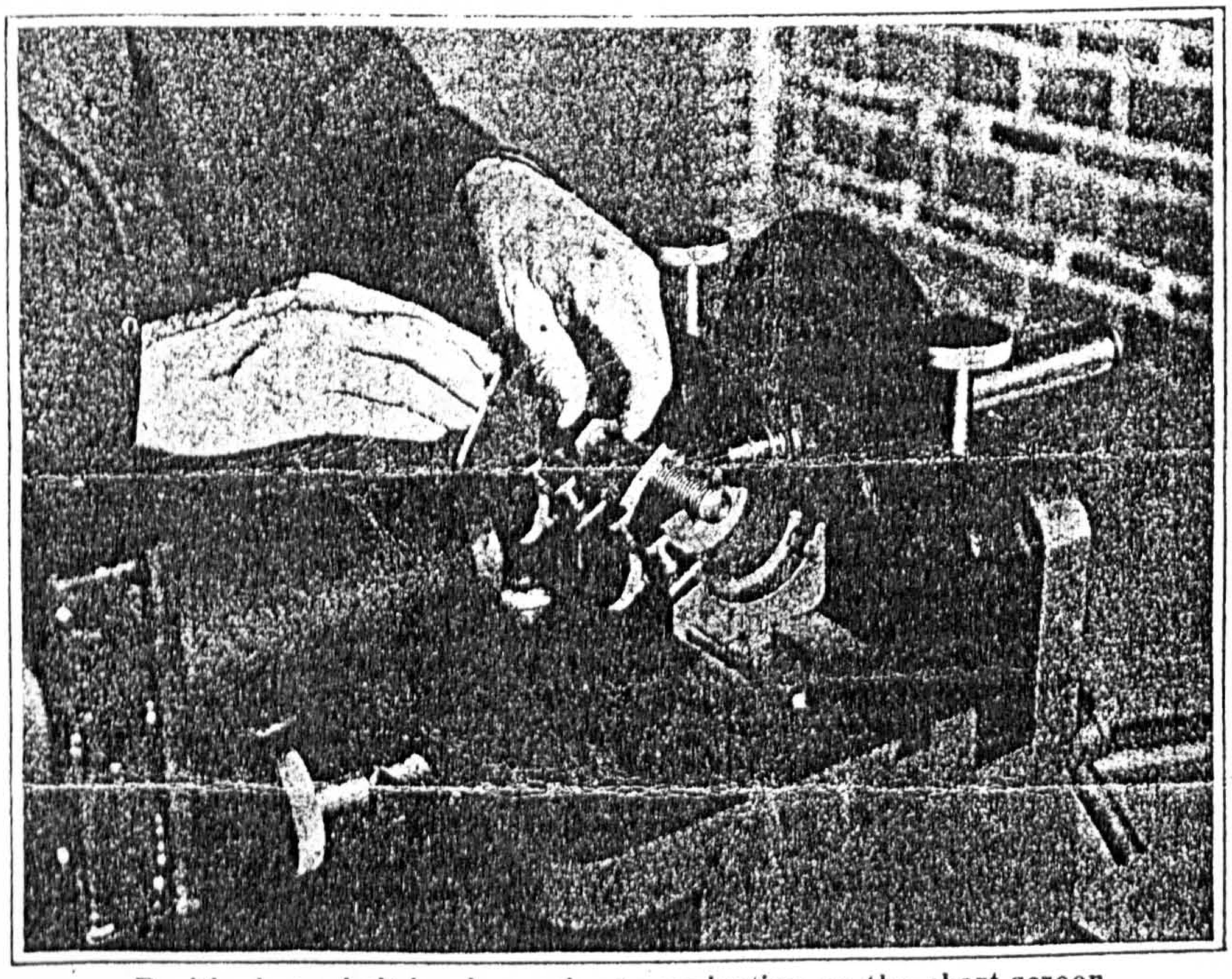
5.1.5 Casts:

Once back in Leicester, the moulds were prepared to make the casts, i.e. the ends of the channels containing the moulds were taped over. Araldite (Ciba-Geigy CY 1301 GB with hardener HY 1300) was employed as the casting medium. To ensure that the cast would cast a dark shadow, lampblack was added to the Araldite, but this appeared to delay the hardening process. On advice of the U.K. agents, (B & K Resins) a black colouring pigment was substituted, with somewhat improved results. However, it was found that the hardener caused an exothermic reaction when first added to the resin, and that the best results were obtained when the mixed resin was allowed to sit for an hour, stirred and then poured into the moulds. Dependent on the ambient temperature, this time could be longer or shorter, so it was thus necessary to stir the mixed resin, hardener and pigment from time to time to ensure that it was placed in the moulds before the Araldite began to set. To avoid bubbles at the bottom of the moulds, the resin mixture was poured into one end and allowed to flow the length of the channel. To ensure that the Araldite set to the required hardness, the casts were set aside for a minimum of 2 or 3 days--longer in cool weather. Each cast was identified by placing a piece of tape with the study code on the back of the casts.

Precautions are necessary in the handling and storage of the casts. If not completely hardened, removal of the casts sometimes resulted in their bowing when a screwdriver was used to extract the cast from the channel. Likewise, the backs of the casts were not always flat and soft casts may bow after sitting for long periods. In early attempts, some contamination from dirty screws was found in the troughs of the casts and acetone was employed (not recommended) in an attempt to 'clean' them. This resulted in the Araldite becoming soft and susceptible to abrasion--in fact care should be taken to avoid contact with the thread crests at all times. Some casts had to be repeated from the same moulds because of the setting problem. Some of these moulds were contaminated with the unhardened resin and these were cleaned with acetone. To do this, the moulds were held vertically and acetone was flushed over the thread form and quickly blown dry with a forceful puff of air. It was noticed that the Silcoset shrank slightly if the acetone remained in contact for an extended period, although it returned to its previous size and



This special projection lamp and chart screen enable accurate and rapid screw-thread inspection by means of the screw's shadow



Positioning a bolt in place prior to projection on the chart screen

5.2.1 The screw thread projector made by Hartness as illustrated in Scientific American (1920).

shape once the acetone had evaporated. It was felt expeditious not to permit absorption of the acetone any more than necessary.

The casts were stored in sample boxes (by museum) next to the mould channels. In most cases, shadowgraphs were made as soon as the casts were removed from the channels to avoid any deterioration or accidental damage to the thread profiles. Of course, not all casts were perfect and the extent of defects was directly related to the size and pitch of the screw sample; finer screws suffered more serious defects and, fortunately, only a handful of moulds had to be repeated at the museums.

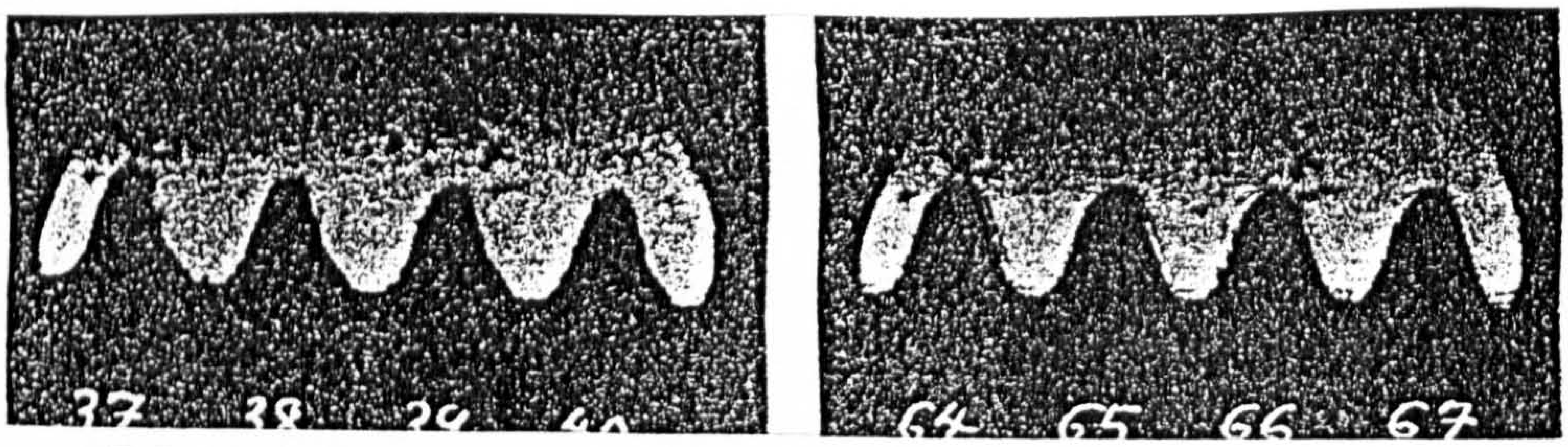
5.2. Shadowgraphs and Digitized Profiles:

The method of gauging screw threads employed in this thesis, i.e. shadowgraphs, originated with Taylor, Taylor & Hobson of Leicester when they were developing screw threads for optical components in the 1880's (q.v. §2.5.3) (Taylor: 1894, pp.58,568 and 1926, 594-603). Col. Watkins advocated the method in 1896 (Brooks: 1988 I, pt.2, p.49) when the British Association for the Advancement of Science was attempting to find means of making gauges for the BA screw thread. His intent was to check the accuracy of mechanical gauges rather than the screws themselves. Sample profiles of gauges were made on a sheet of photographic paper and presented to the BAAS Committee and were included with the Committee's 1899 Report (Reports, BAAS 1899: p.467). They were reproduced at ≈37.5x rather than the 50x advocated by Taylor. However, it was some years before a special device was developed commercially to exploit the shadow of threads. M.M. Hunting (1920, p.215) reported on the comparator designed by James Hartness (Fig. 5.2.1).[1] Such a machine would have evolved earlier as a result of Watkins' application had the BAAS Small Screw Thread Committee adopted the concept of tolerances. However, it was not until 1915 that tolerances and clearances became an accepted concept--at least for BA screws--and was finally incorporated into BS: 93 (1919). Hartness recognized the advantage of comparing the projected thread profile against a test card with the outline of the permitted tolerances and clearances. Such a procedure eliminated the need for gauges for testing most screws thereby eliminating wear of the test gauges and necessary tests of such gauges. The Hartness machine had interchangeable lenses and charts depending upon the particular screw under test and accuracy desired.

Ikeda (1937, p.305) reported on the use of the shadowgraph as a means of testing the micrometer screw of the Wanschaff zenith telescope at the International Latitude Observatory (ILO) at Mizusawa, Japan. The micrometer had been put into use in 1899 but by 1927 had increasingly large errors due to the wear of the micrometer screw

---

1 Hartness was from Springfield, Vt. and is best known among astronomers as the designer and builder of the Hartness turret telescope which is the centrepiece of the annual meeting of amateur telescope builders at Stellafane near Springfield.



5.2.2a Ikeda's Shadowgrams of the micrometer screw of the ILO zenith telescope showing worn (left) and unworn segments. These were measured point by point on a 2-axis measuring engine to produce the data for the plots below.

5.2.2b Profiles determined by Ikeda from the shadowgraphs of the male and female threads. It is interesting to note that the steel male screw was worn more than the brass female thread.

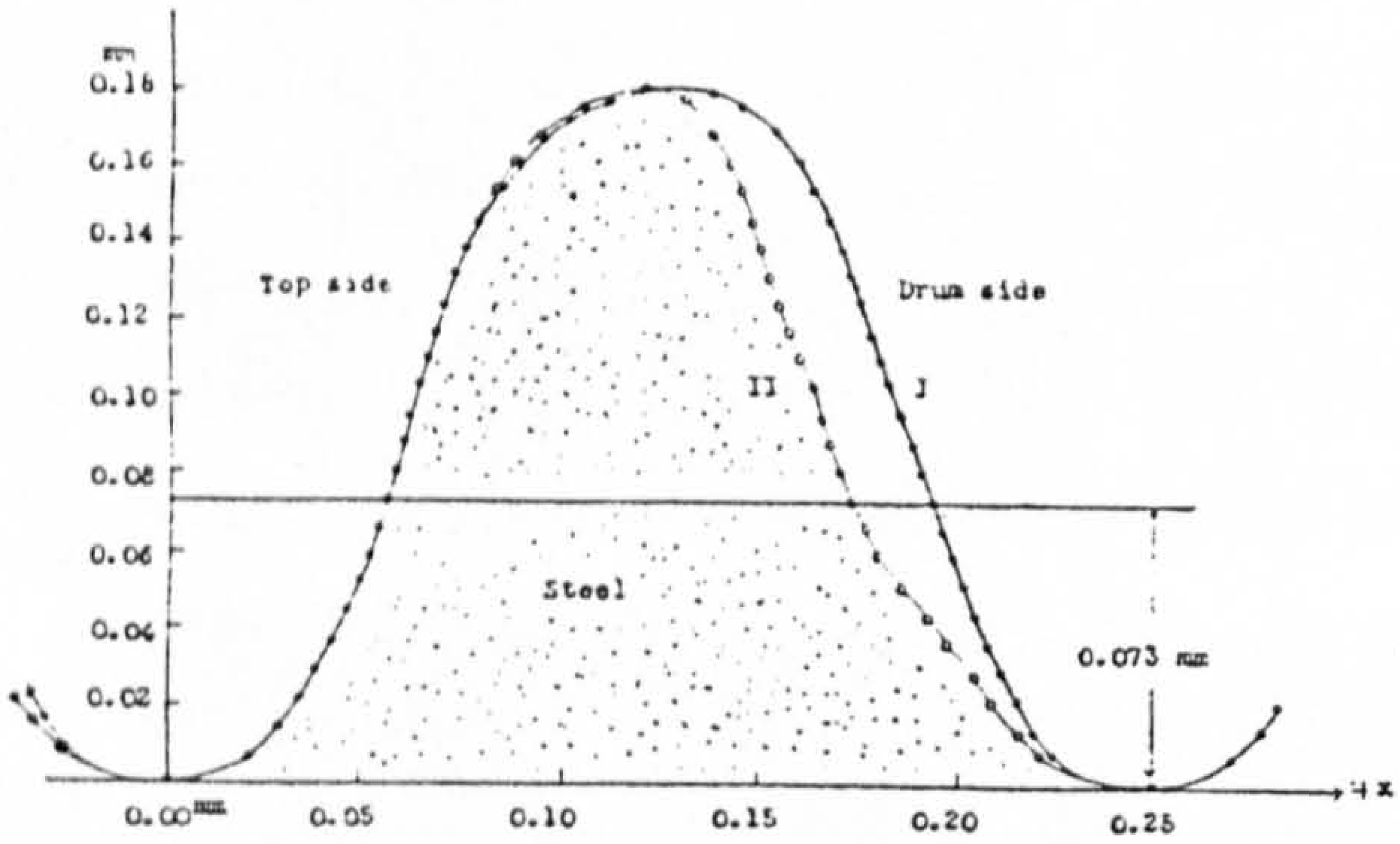


Fig. II. Mean Shapes of the Male Screw Threads.

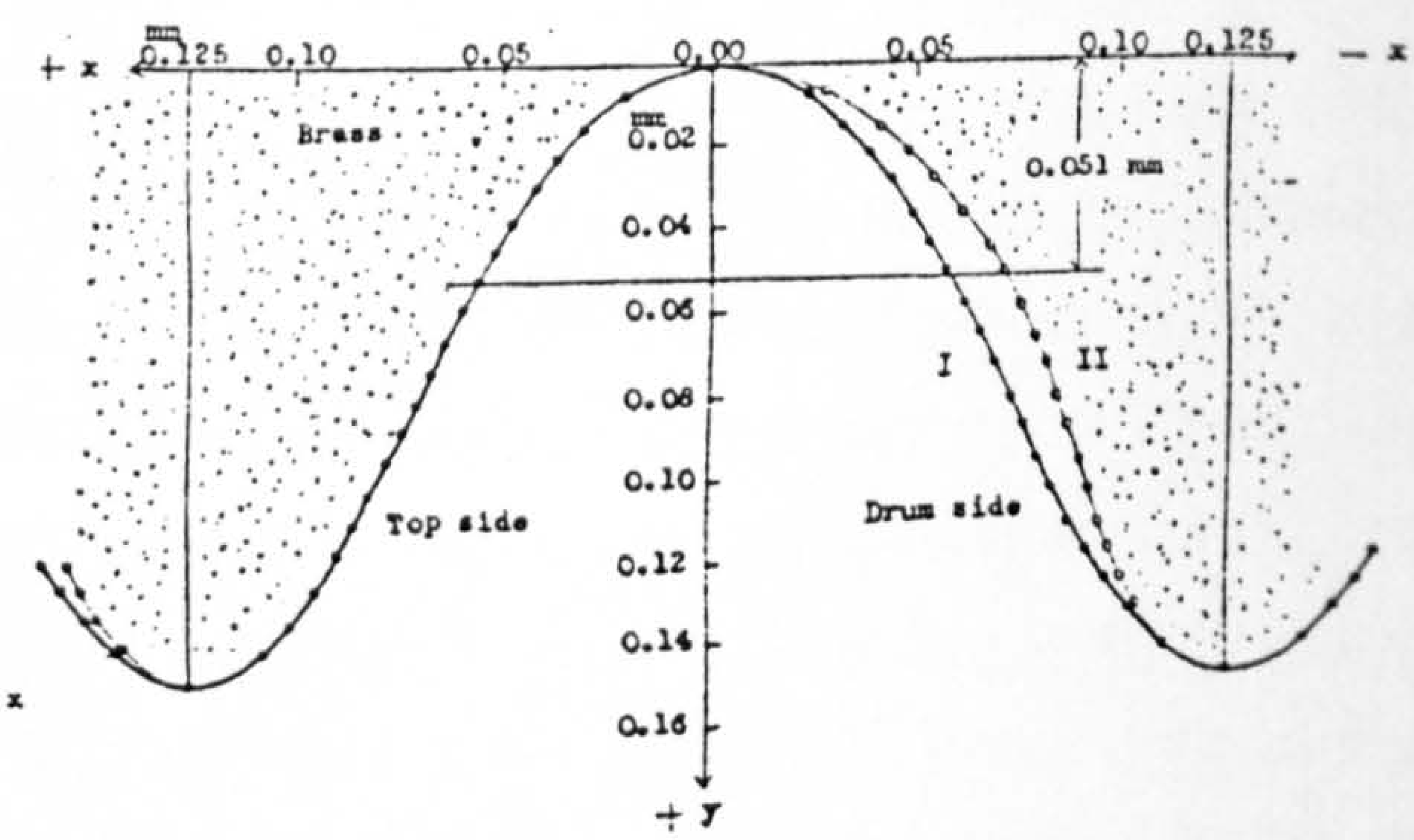
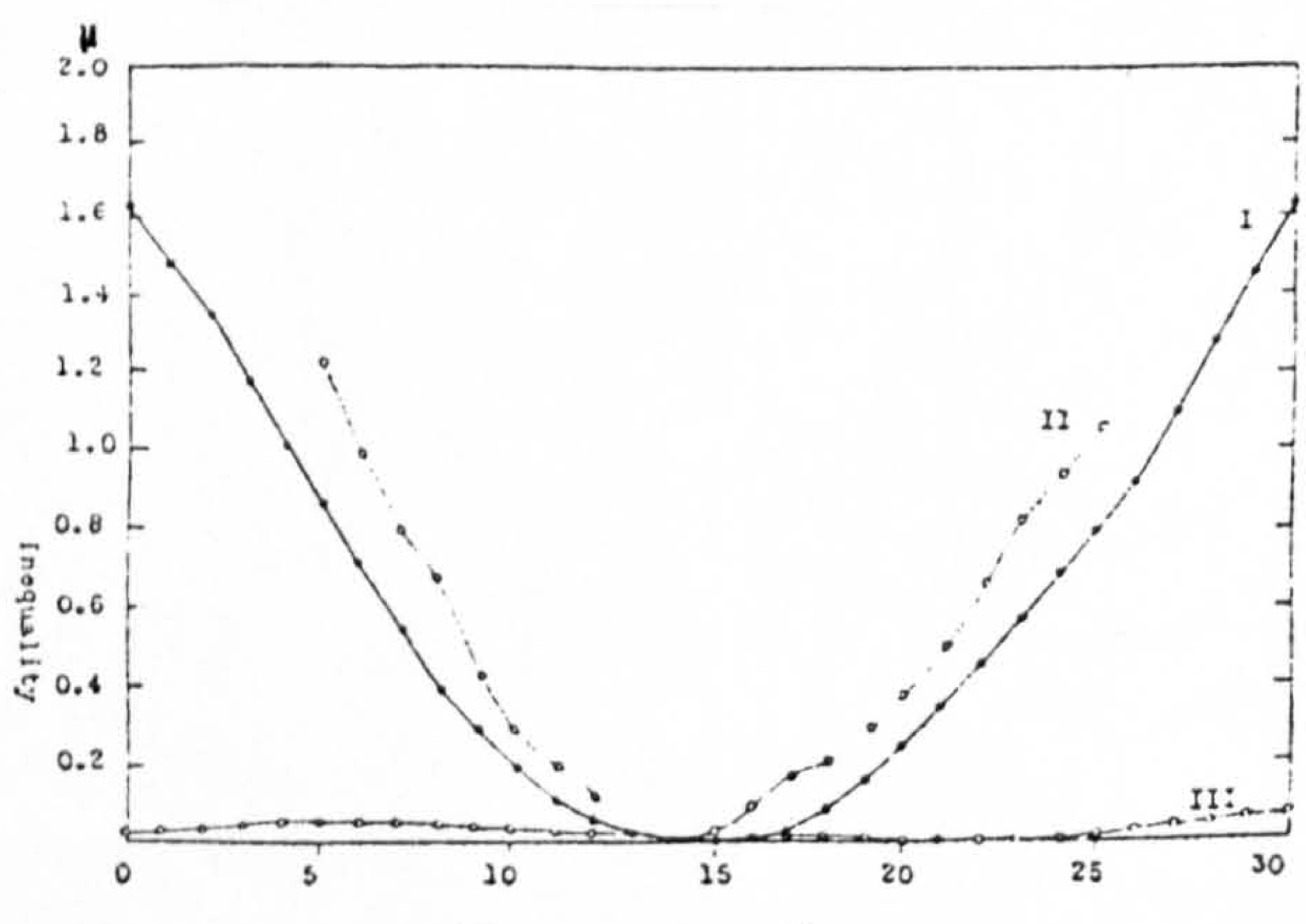


Fig. III. Mean Shape of the Female Screw.



5.2.2c Error curves for the ILO zenith telescope micrometer screw. Curve I is for 1937; II for 1922-7; III for 1899.

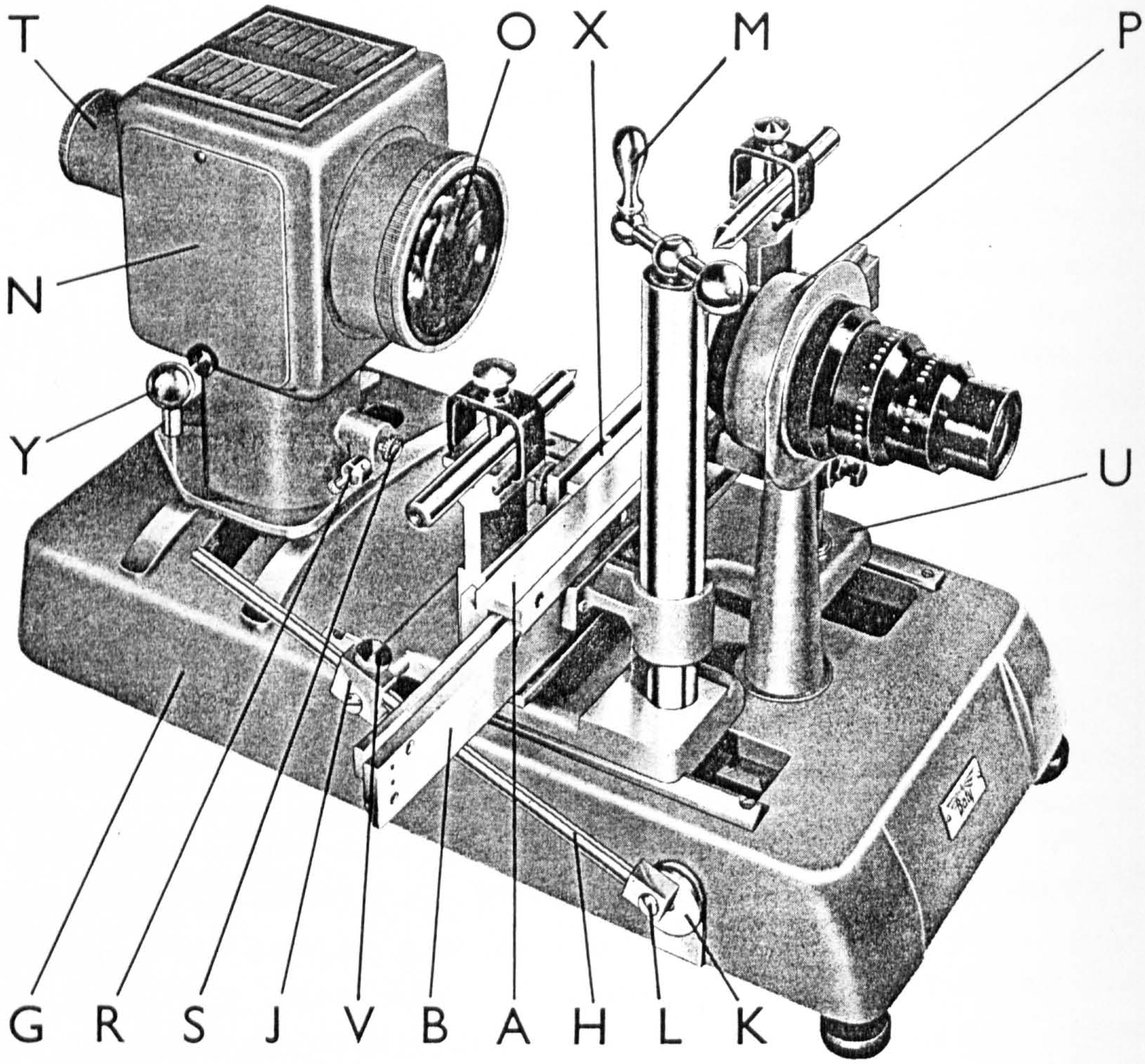
thread. The male screw was directly projected onto photographic plates at 44x magnification while the female thread was copied with dental surgeon's modeling compound and the mould projected. The plates were then enlarged and printed on photographic paper at 136x natural size and measured by hand. The extreme ends of the male screw gave the unworn profile against which the worn parts could be compared. Fig. 5.2.2a shows shadowgrams of worn and unworn portions of the thread while Fig. 5.2.2b shows the extent of the wear which was mainly on the leading flank as one would expect. The accumulated error is illustrated in Fig. 5.2.2c by the curve marked I. Curve II is the errors observed between 1922-7 and III the error measured in 1899.

In this research work, it was not an objective to inspect the running error of a few micrometers in detail, but rather to estimate the mean errors of the screws from the perspective of manufacture and the mean errors users were encountering in their observations, which were directly attributable to micrometers. No micrometers demonstrated the extreme wear of the ILO micrometer although, of course, if the micrometers were used for a long period, wear will have affected the profile. Hand measurement was initially carried out on the shadowgraphs for approximately 100 samples to determine pitch, flank angles and rounding of the crests and roots. However, this approach did not yield an estimate of the errors one encountered in the pitch which for screws used for measurement purposes is the most fundamental error.

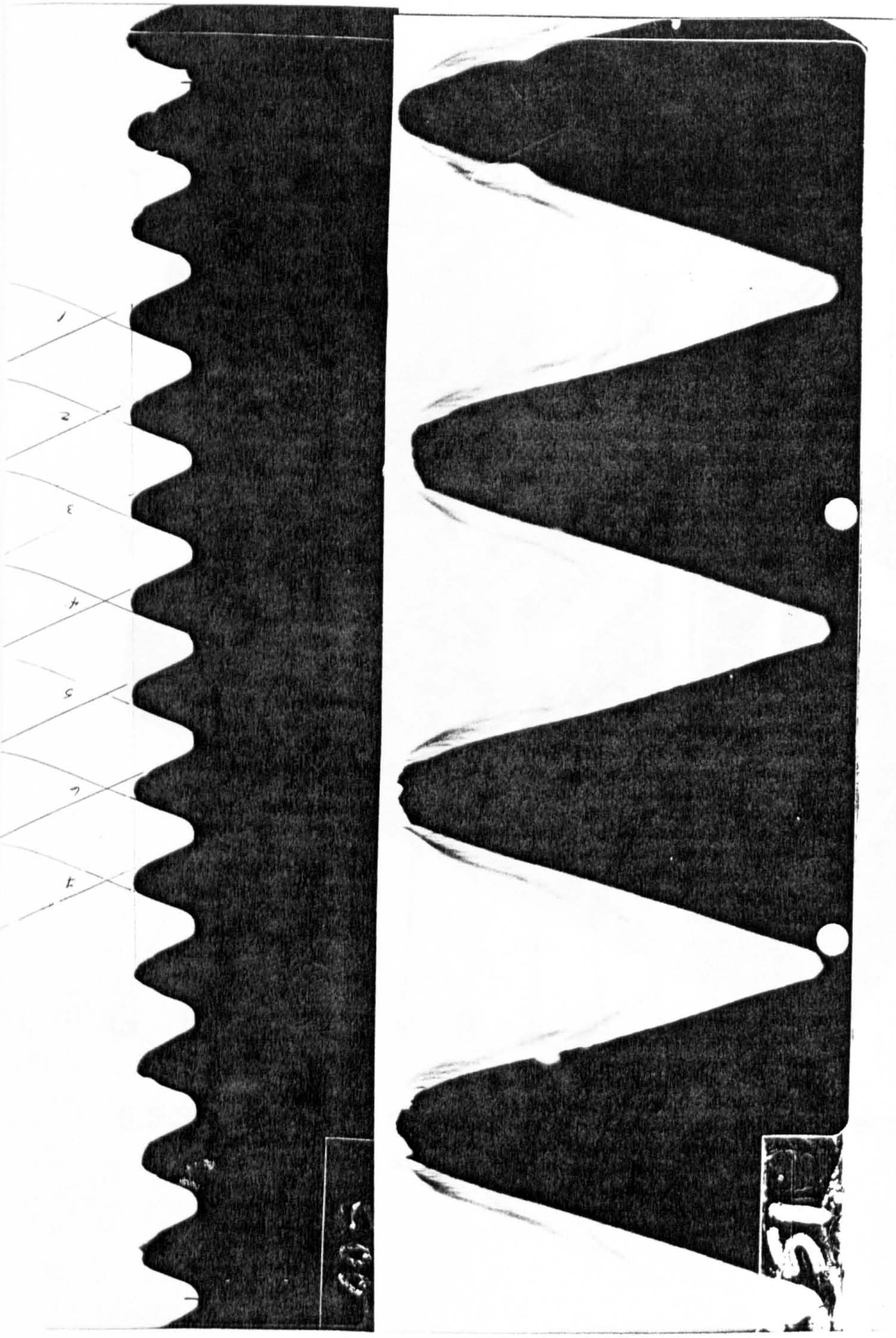
The approach therefore adopted for this research was to digitize the profiles of the shadowgraphs and to determine the mean pitch via a modified Fourier transform technique--the Jurkevich-Swingler method (Swingler: 1985, p.675-9). The determination of the pitch is based on not less than 200 points with the majority based on 500-800 points and with some based on as many as 1200 points. Once the pitch was determined accurately, the profile of several threads could be 'stacked' by assigning a 'phase' of 0-1 to each data point and then plotting as one would do in plotting the velocity curve of a spectroscopic binary star. Once the profiles were stacked, one has a 'mean' profile for the thread and the errors of pitch could be determined from the scatter in the flanks. Although it has not been attempted in this project, an analysis of the digitized profiles could be carried out by the method of Ikeda since a mean profile could be computed and deviations from the mean determined as a function of 'phase'. Such a procedure would be used if one were interested in correcting the results of observations made with the particular instrument.

5.2.1 Preparation and Equipment:

The most straightforward means of analyzing the screw profiles is from a permanent record such as obtained from shadowgraphs--an image obtained on photographic paper from the enlarged shadow of the screw's profile. To facilitate the rapid production of the shadowgraphs, a frame was made to hold a sheet of photographic paper up to 15 x 25cm.



5.2.3 The type of Baty screw thread projector employed to make the shadowgrams.



5.2.4a (right) The shadowgram of the Barton ruling engine (SML-34a) illustrating the symmetric 'fringes' from a properly aligned screw thread and projector lamp housing (screw is white). Note the debris in the roots.

5.2.4b The effect of a misaligned thread--the non-symmetric appearance of the thread root and crest and the difference in focus on the flanks indicate that the thread was poorly aligned with the light source.

2.5a - 351
5.2.5b

A tab overlapping one corner of the paper was left so an identification code could be recorded on the shadowgraph in the bottom left hand corner. The majority of shadowgraphs were made on 6.7 x 25 cm strips but larger (≈15 x 25cm) paper could be used for large screws with deep profiles.

A Baty Screw Thread Projector (Fig. 5.2.3) was employed to make the shadowgraphs. This instrument was loaned by the Physics Workshop of the University of Leicester. After some initial attempts it was found that the profiles were poorly focused, and that it was necessary to collimate the projector as described in the instrument's manual. The reflecting mirror behind the lamp bulb was found to be both too far from the lamp and decentred. Once corrected the high magnification images were improved but still showed 'chromatic' fringes. These were minimized by use of a Wratten blue-green filter placed over the objective lens when using Ilfospeed semi-matt paper (grade 4) or, even more effectively, with a MG5 filter (as used for multigrade photographic papers) when using Ilfospeed or Ilfobrom Multigrade paper.

The projector was placed at a distance to give 50X magnification. This magnification was chosen since micrometer screws were the prime interest and were expected to have fine pitches; high magnification was necessary to get suitable resolution. A scale reticule from an eye loupe was mounted between the sample pins and the distance of the projector adjusted until 0.5cm was magnified close to 25cm. The actual magnification when measured on the shadowgraphs was 49.8. [This reticule was initially measured on the Astronomy Department's measuring engine made by Precision Tool Instrument Company, and was found to be correct to the accuracy of the engine (0.001 cm)]. The projector was not moved throughout the period of its use; nevertheless, before each run, the reticule was rephotographed as a check.

5.2.2 Exposure of the Shadowgraphs:

The casts were inspected with an eye loupe to locate the best segments for projection and then placed between the projector's mounting pins and held in place with plasticene. The projector lamp housing was moved from side to side to align the light beam with the rake angle of the screw to avoid 'shadowing' effects of one thread by another. Focusing was then carried out using the projector's remote paddle when observing the shadow at close proximity. This also showed if the housing was correctly aligned since, if not, reflection fringes appeared more prominently on one flank (Fig. 5.2.4a). If not correctly aligned, distortion of the form results (Fig. 5.2.4b). The housing and focus were successively readjusted until the profile was acceptable.

Once the shadow was satisfactory, the line voltage to the projector was reduced to 70% by use of a Variac; this was the level at which exposure times of 5s resulted. The shadowgraph ID was written on the tab on the paper frame with a black marker. This form3

THREAD MEASUREMENTS

DATE: SHADOWGRAM :

INST CODE: MAKER:

SCALE: INST DATE:

THREAD ANGLE MEASUREMENTS:

	L	R	T		L	R	T
1				11			
2				12			
3				13			
4				14			
5				15			
6				16			
7				17			
8				18			
9				19			
10				20			

LFA ± MEAN ±

RFA ± FAE ±

LENGTH FOR ___ THREADS = ===>PITCH ===> TPI

OD OF SCREW:

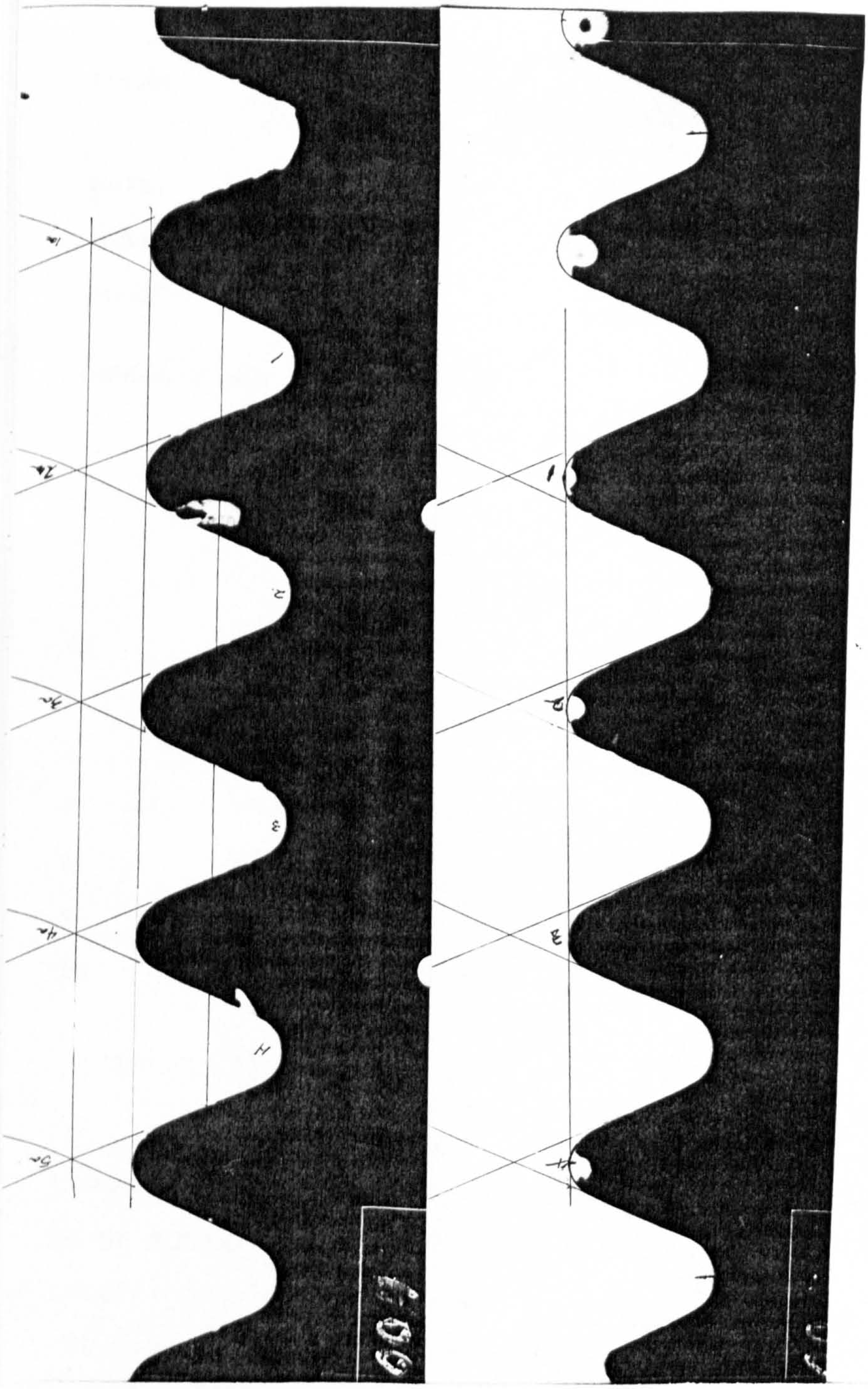
CREST-TROUGH DEPTH (Dct) = ===>

(OD-CTD) = R (OD/CTD) =

DIAMETER OF CREST = ===>

TROUGH = ===>

5.2.5 Form 03 used to record the measurements made from the shadowgraphs and the resulting calculated thread parameters.



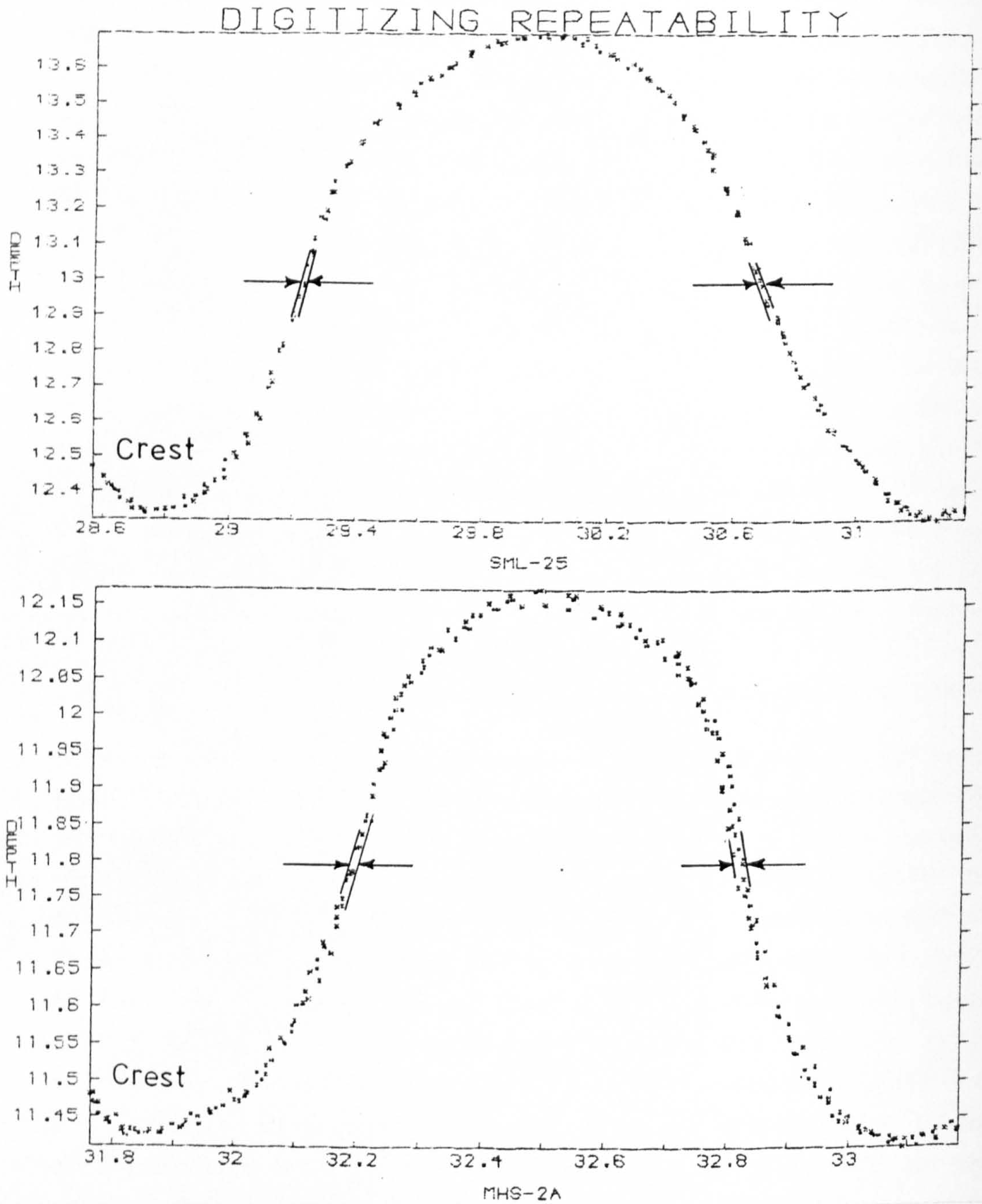
5.2.6 Lines drawn to make the measurements of flank angles, pitch and truncation (upper) of a 2BA tap. This is the profile of the tap itself while the lower shadowgram is of a cast made from the tap's mould. This was one of the first samples processed and shows flaws in the root of the cast due to bubbles that were trapped during the moulding process. Initially, the Silastic 3110 RTV moulding material was poured around the screw which had been positioned in the 'U'-channel. This trapped the bubbles observed; after this experience, the Silastic was first poured into the 'U'-channel and the screw slowly pressed into it thus eliminating the majority of such flaws. Lines drawn in the dark regions do not appear in these reproductions.

tap cast 5.2.7.

number and the sample's study code were recorded in a logbook and the photographic paper then inserted into the frame. During these procedures room lighting was limited to 3 photographic darkroom lamps placed for convenience but at an appropriate distance from the photographic paper. Timing of the shadowgraph exposures was simply done by counting off seconds. The paper used was Ilfospeed semi-matte/multigrade paper. This was chosen for its fast processing time, because one can write on the image with a pen or pencil and because it is a resin based paper which remains flat once dried--very desirable attributes for this study. Processing of the paper used standard developing procedures: D-76 for 2 to 3 minutes, stopbath for 30 seconds, fixer for 5 minutes and running water wash for 10 to 15 minutes. Once dry, the shadowgraph numbers were recorded on the instrument data sheets (Form 2). The majority of shadowgraph prints were made on Ilfospeed semi-matte paper (grade 4 and later multigrade) but when this ran out, Ilfobrom pearl multigrade paper had to be substituted because of difficulty getting the original paper in a small quantity in a short time. However the multigrade paper required that a MG 5 (Ilford) filter be substituted for the Wratten blue-green filter. The exposure times remained at 5 seconds. The Ilfobrom paper is not recommended, however, since it is susceptible to curling of the edges which creates problems during the digitizing procedures.

5.2.3 Shadowgraph Measurements--Direct Measurement:

The first 125 or so shadowgraphs were subjected to direct measurements in order to determine pitch, flank angle, rounding of crest and root, and depth of thread. 'Form3' (Fig. 5.2.5) was devised to record the measurements and relevant data. It soon became apparent that this technique had limitations and was a tedious procedure, especially for 100 TPI micrometer screws. At 50x magnification only 0.5cm of the screw thread is projected onto the shadowgraph, yet this means 20 thread profiles to measure, i.e. 40 flank angles, many of which--because of flaws, etc.--are difficult to decide what the angle should be. In general, lines were drawn across the crests and roots then a third line was drawn midway between these and the angle where this 'mean depth' (MD) line cut the flank was the measured angle (Fig. 5.2.6). This assumes that contact was made by the screw and nut at this depth; this is not necessarily the case, but the choice of this MD line provided some homogeneity in the sampling scheme. A serious drawback for one objective of this study was that the assembled numbers from the measurements did not provide an easy and suitable means of comparing profiles and characteristics of large numbers of screws. Thus direct measurement of the shadowgraphs was dropped in favour of digitizing, computing and plotting of mean profiles. However, the data determined by direct measurement is given in Table 5.2 and illustrates the difficulty of comparison. It is also provided as a means of comparing the results by this technique and by the digitizing and plotting procedures to be described in the following section.



5.2.7 The profiles resulting from repeated digitizing of a single thread on the shadowgrams of micrometer screws SML-25 (50 TPI) and MHS-2a (100 TPI). The scatter is due to the manual positioning of the digitizing cursor and since all shadowgrams were made at the same magnification (50x) the errors are proportional to the pitch of the sample.

5.2.4 Digitized Profiles and Digitizing Precision:

Each screw profile has been digitized on the Leicester University Computer Centre's Calcomp 9100 digitizing table using library program **DIG**. **DIG** is a menu driven program which allows choice of parameters such as coordinate system, sampling rate and type, etc. Default parameters were used except for the coordinate system. This was chosen to be the 'table' coordinates given in cm. The table has an accuracy of 0.001cm, well within the setting accuracy estimated by the manufacturers to be approximately 0.005-0.01cm.

The setting accuracy for high and medium TPI threads was checked by choosing a single 'clean' thread profile and repeatedly digitizing its form. This data was then plotted at the same scale as its entire 'stacked' thread profile. Plots of MHS-2a (100 TPI) and SML-25 (50 TPI) (Fig. 5.2.7) digitized profiles for the single and stacked shadowgraph profiles show the size of these errors. For the latter, the error is minimal being about equal to the size of the plotted points. However, for the 100 TPI example the error is larger and must be corrected. The mode of handling this error will be dealt with later.

5.2.4.1 Digitizing procedures:

The shadowgraphs were placed on the digitizing table with the mean line roughly horizontal although this is not critical as it is corrected in the analysis. **DIG** is the software package provided by the Computer Centre to operate the digitizing table and begins by requesting a file name. A separate file was created for each shadowgraph with each file identified by the instrument code. In digitizing a 100 TPI thread, ≈700+ points were created taking 10-15 minutes. Once digitizing was completed, each file was edited to delete header lines created by **DIG** and to remove unnecessary codes for each digitized point. The number of digitized points was determined and a new first line inserted as required for **PROFIL1**[1] and **DATAGRAF**. One very important note of caution is required in digitizing. Because **PROFIL1** first fits a linear least square fit to the digitized data, the starting and end points for digitizing must be either near the top of a crest or bottom of a root, otherwise a slope will be introduced into the data resulting in unsatisfactory composite thread profiles and systematic errors in the calculated pitch and periodograms. In practice it was found expedient to start just before the bottom or top of a crest or root and to end a similar distance past the bottom or top. This is particularly critical for shadowgraphs with less than 4 complete thread profiles. The reason will be explained in the description of the 3 programs used.

---

[1] A second program, **Profil2** is identical except for the order the x and y data sets are read in.

5.2.4.2 Production of digitized shadowgraphs:

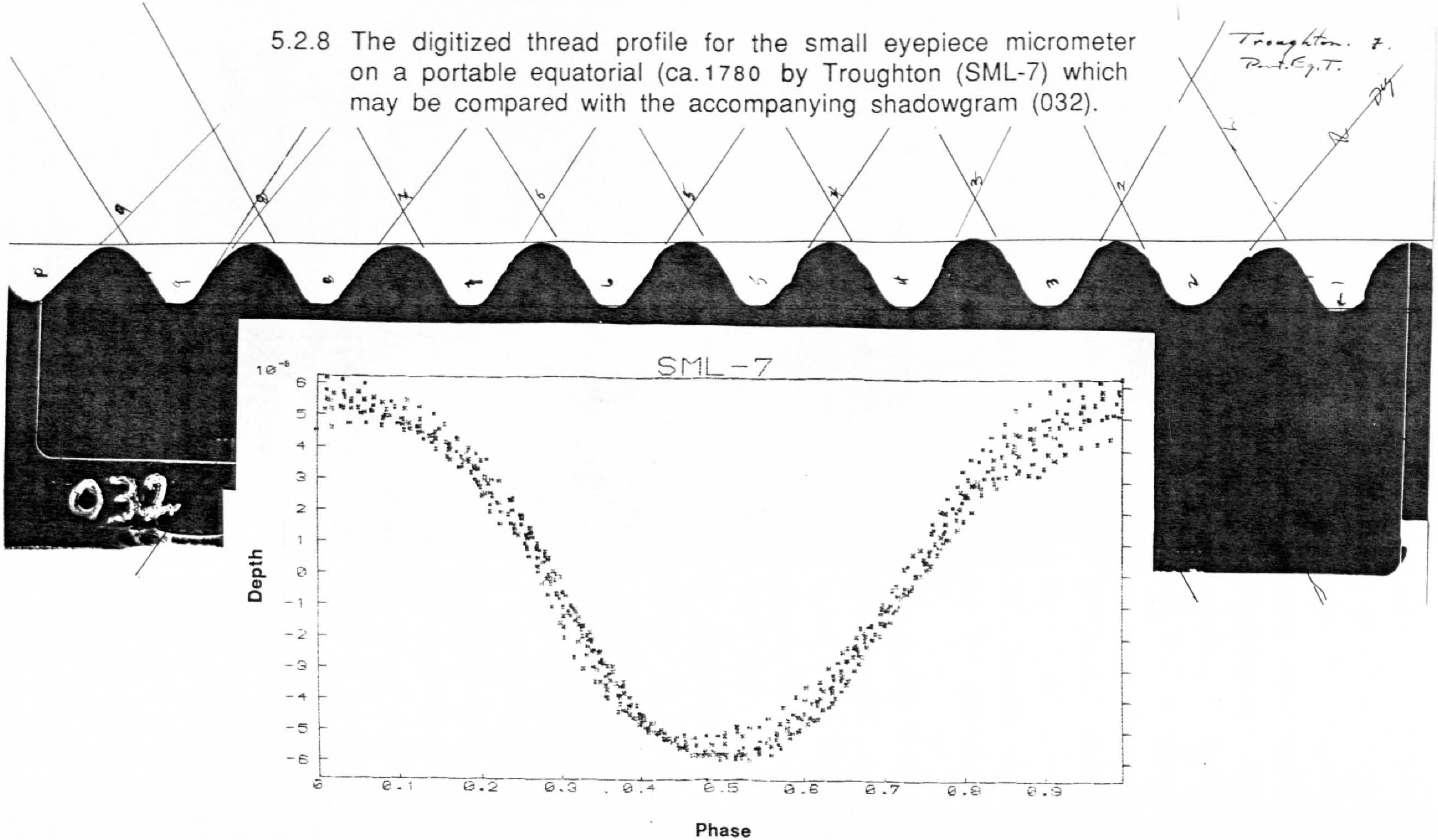
The files of digitized data were each processed using **PROFIL1**. After rotating the data via the linear least square section (program **LSQ** incorporated in **PROFIL1**), and creating a file of the rotated data, the starting and ending points for the range of the period search were entered. These were determined by measuring the thread period on the shadowgraph with the starting period chosen about 1mm less than and the ending period 1mm more than the period. The Jurkevich/Swingler method was chosen for period searching for several reasons, but primarily because it is a technique which is particularly suited to searching data spaced randomly and which may have large gaps between series of data points. The original Jurkevich method has been successfully used for searching for periods of Delta Scuti variable stars by Morris (1979). But the modified method proposed by Swingler (1985) was even more successful and easier to use as demonstrated by Reed and Welch (1987) in a similar study of Delta Scuti stars.

PROFIL1 created a file of 500 data points of period vs. Jurkevich value--an index of the accuracy of the period. This data was searched by **PROFIL1** for the maximum 'Y' value (Jurkevich value) and a new period range determined--first for periods less than the primary, P, and secondly for periods above the primary. The respective ranges searched were 0.0909P - 0.85P and 1.20P -11P. These ranges were specifically chosen to exclude P which predominates with a very prominent Jurkevich value. For each of the 2 period ranges, a file was created compatible for plotting with **DATAGRAF**. Following this stage, the data which was initially rotated by the least squares procedure was processed to calculate the phase of each point. This phase data was also placed in a data file for plotting with **DATAGRAF**. **PROFIL1** permits bypassing several of these steps if desired, and also permits the phase data to be calculated with a user incremented period. This latter feature was found necessary after a few profiles exhibited systematic 'runs' in the plotted data due to a slightly too small period. This occurred only for large pitched screws which had <5 threads on the shadowgraph and resulted from the Jurkevich/ Swingler period search which is sensitive to the resolution of the searched range; resolution which is too fine results in a flat topped period vs. Jurkevich value curve. The first maximum point of this flat topped curve is the one chosen and thus may be slightly low. The increments, when required, were approximately 0.1mm or less in shadowgraph coordinates or 0.02mm in actual pitch.

5.2.4.3 Plotting digitized profiles:

Once the necessary files had been created with **PROFIL1**, **DATAGRAF** was employed to plot the data using the Astronomy Department's Pericom graphics terminal. The rotated least squares data and primary period data were first plotted to insure that the rotation and primary period had been correctly determined. The high and low period search data were then plotted with the horizontal and vertical scales adjusted for a plot of the desired

5.2.8 The digitized thread profile for the small eyepiece micrometer on a portable equatorial (ca. 1780 by Troughton (SML-7) which may be compared with the accompanying shadowgram (032).



size. Plotting of the profiles, however, required the vertical/horizontal scale to be altered by an appropriate amount since **DATAGRAF** defaults to plots to the full scale permitted by the particular plotting device. The proper scaling factor was obtained using the following formulae:

For profiles where depth of thread < pitch:

$$S_y = 1 - \frac{|Y1| + |Y2|}{P}$$

For profiles where depth of thread > pitch:

$$S_x = 1 - \frac{P}{|Y1| + |Y2|}$$

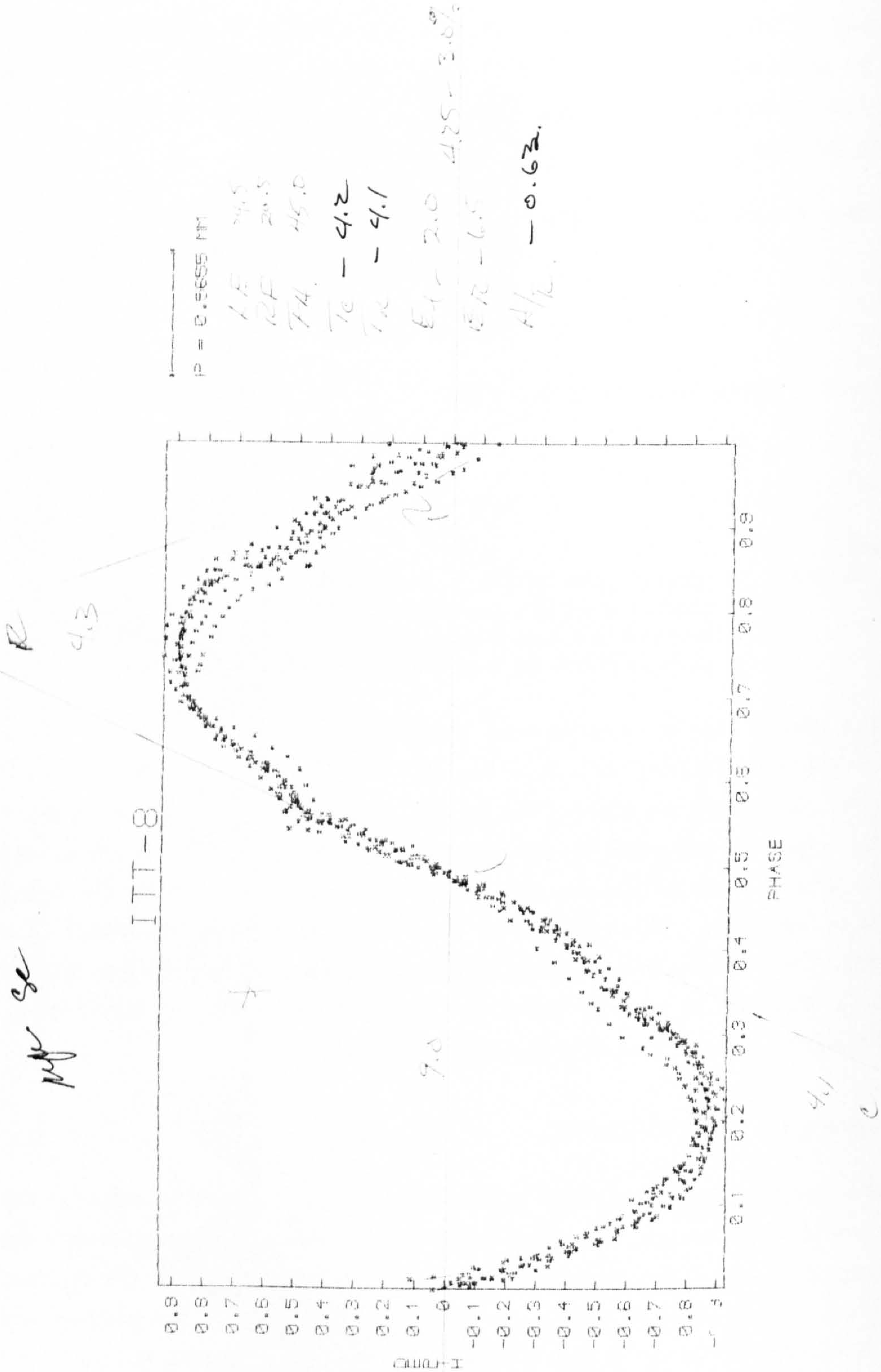
where:

S_x and S_y = scaling factor for x or y coordinates
Y1 = positive maximum y value as determined by **DATAGRAF**
Y2 = negative maximum y value as determined by **DATAGRAF**
P = period (in cm) as determined from **PROFIL1**

In practice, pitch P must be recorded when calculated by **PROFIL1** and Y1 and Y2 are the values called up by **DATAGRAF**. S_y is entered in **DATAGRAF** as value Q1 or S_x is entered as P1. Essentially this changes the ratio of vertical : horizontal size of the graph to match the original 'aspect ratio' (a term adopted from computer lingo) of the screw's thread. The ratio of depth of thread : pitch will hereafter be referred to as the aspect ratio or A/R of the thread. This ratio will be used as a discriminating characteristic of screw threads. Once the physical parameters of the graph were entered, the title, x and y labels and Y1 label (actual pitch of the screw in mm) were entered as called for by **DATAGRAF** and the plot was produced in duplicate (Fig. 5.2.8).

5.2.5 Measuring the Digitized Profiles:

Two hard copies of the thread profile were drawn, one for the 'Atlas' of Vol. II of this thesis and one to be measured. The 'mean depth' (MD) line was once again used in the measurements and was drawn midway between the roots and crests of the digitized profiles. Next, best fit straight lines were drawn along each flank; the position and orientation were adjusted by eye to give a mean fit. One could, of course, compute such lines but it was felt that the programming would take considerable time and would not allow for adjusting the line for data points which should have low weight; it was simply not practical to assign weights to the individual points. A program to calculate a mean for



5.2.9 Measuring the parameters of the digitized profile of a scale reading micrometer screw on a manometer by F. Miller of Innsbruck (3rd q 19th c).

all the data points is still a desideratum and would be useful for the highest quality shadowgraphs.[1]

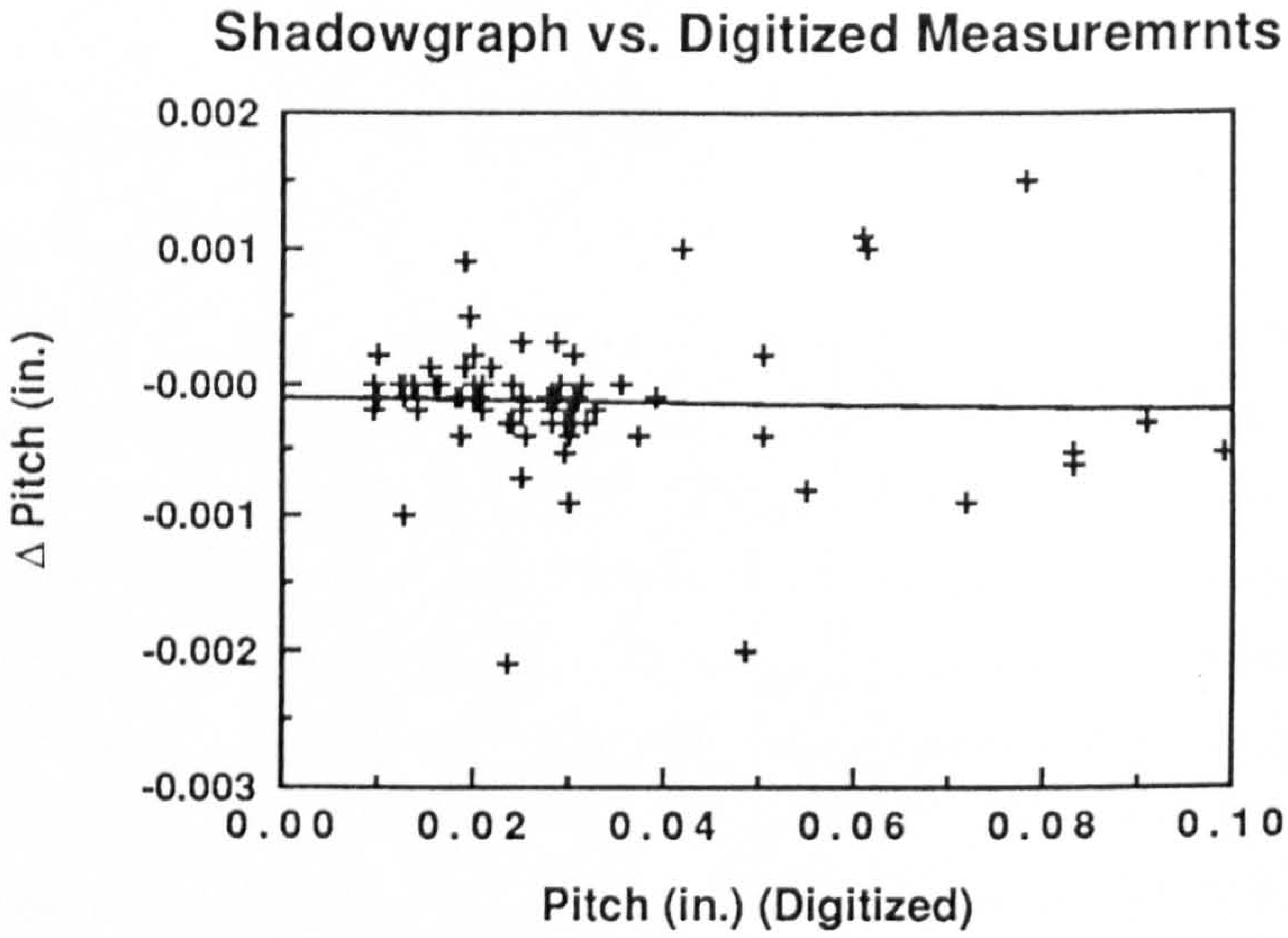
The lines for the flank angles were then measured with respect to the MD line. There being only one line for each flank, no standard deviation could be obtained. To fill this deficiency, the width of the scatter of each flank was measured at the MD line. This scatter, less the digitizing error, is the variation of the pitch of the screw. This scatter in fact gives a better and more direct measure of the machining capability of the instrument maker, being easily converted to actual 'thous' since these flank errors are calculated as percentage of the pitch. Thus the scatter of points on the flanks is also a direct and simple indication of the magnitude of the various periodic and non-periodic errors of pitch.

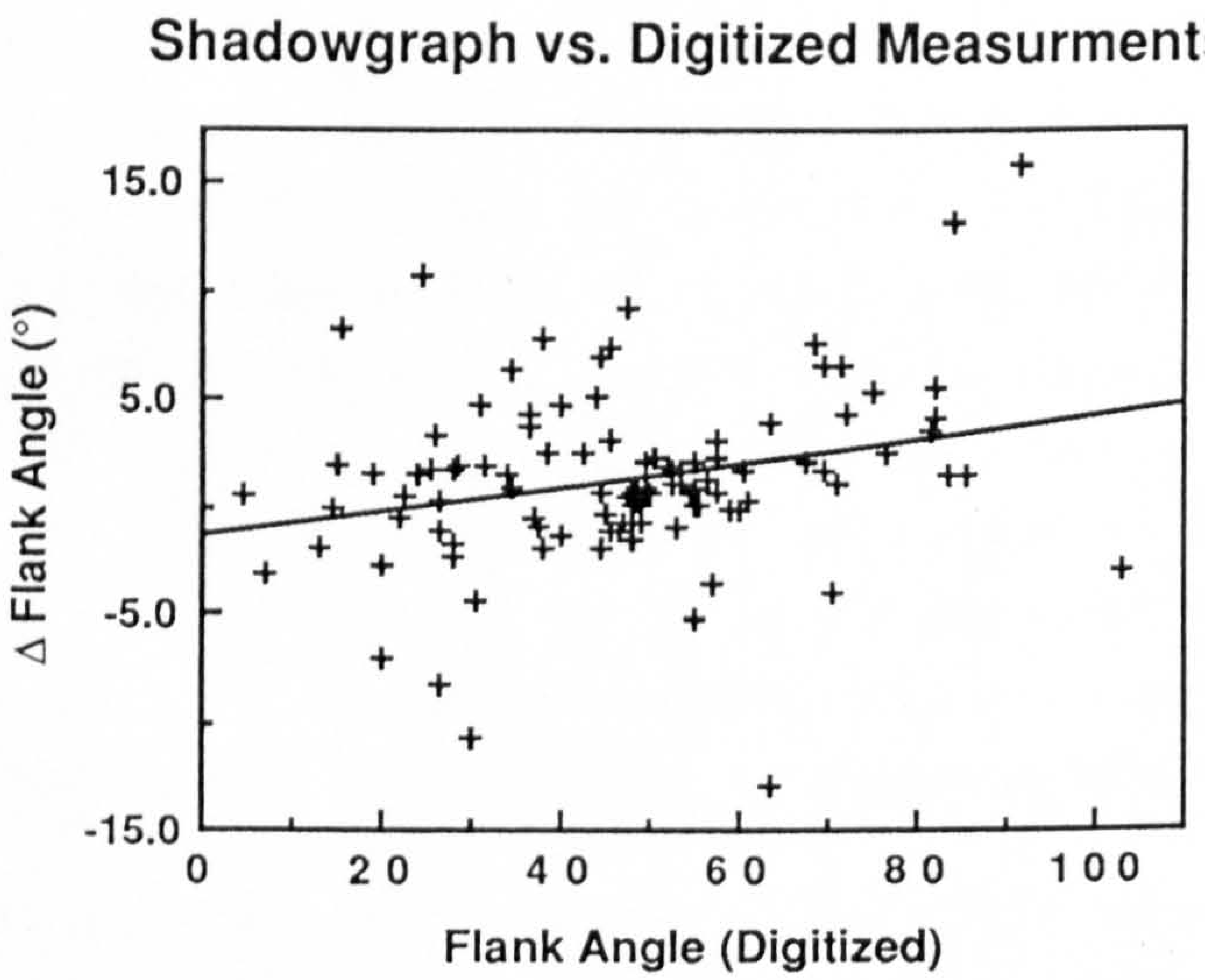
Since modern screw thread gauges are partially defined as a function of the truncation of the profile, the truncations of the crest and root were also measured. The lines along the two flanks were extended and a third line drawn parallel to one of these to give the other truncated point. Unfortunately these points have an error proportional to the cotangent of the flank angle which, for small flank angles, can be quite large. In addition, the exact point of the truncated thread can be ill-defined, especially for the root; in earlier screws substantial variation in the depth is found. Therefore the truncation, calculated as a fraction of the untruncated profile, has errors arising from errors in the measured flank angle and from an inability to define precisely the root of the thread. The usefulness of the root and crest truncations as discriminants will be discussed later.

Each working copy of the profile was measured for flank angles, truncation, and errors in spread of each flank at the effective (mean) diameter (Fig. 5.2.9). It was decided not to attempt automated generation of mean lines since 'hand' drawing of the curves could take into consideration obvious problems in digitizing (infrequent) or casting problems (most prevalent in rusted forms). Comparison of results from measurement of the shadowgraphs--i.e. measuring each thread and taking the mean--and results obtained by measuring the digitized profiles showed little difference, with the flank angles agreeing within the standard error of the mean determined from hand measurements of the shadowgraphs. To measure, record the data, and reduce a shadowgraph of a 100 TPI thread required more than an hour when carried out directly from the shadowgraph. To digitize the shadowgraph and edit the file required 10-15 minutes, while running the data through **PROFIL1** and **DATAGRAF** took an additional 10-20 minutes. Thus time was saved but the greatest advantage was that, once completed, one had a standardized mean profile and also a graphical analysis of periodic errors which provides additional clues to the mode and precision of production.

---

1 The software package, **CricketGraph**, has been discovered to have the facility to do this although it has not been attempted to discover what problems may arise.





5.2.10 Comparison of results of pitch and flank angles of screw samples as measured directly from the shadowgraphs and as measured from the digitized profiles.

It should also be noted that direct shadowgraphs of certain screws as well as their casts were run through this procedure to ensure the casting procedure was not introducing unrecognized effects. Some deterioration in the quality of profiles and period search data should be expected and was found, but was minimal for good quality casts (q.v. Fig. 5.2.6). Fig. 5.2.10 shows a comparison of the results derrived from direct measurment of the shadowgraphs and by measurement of the digitized profiles for pitch and flank angle. In both cases the digitized measurments are the more reliable.

5.2.5.1 Extracting instrumental errors:

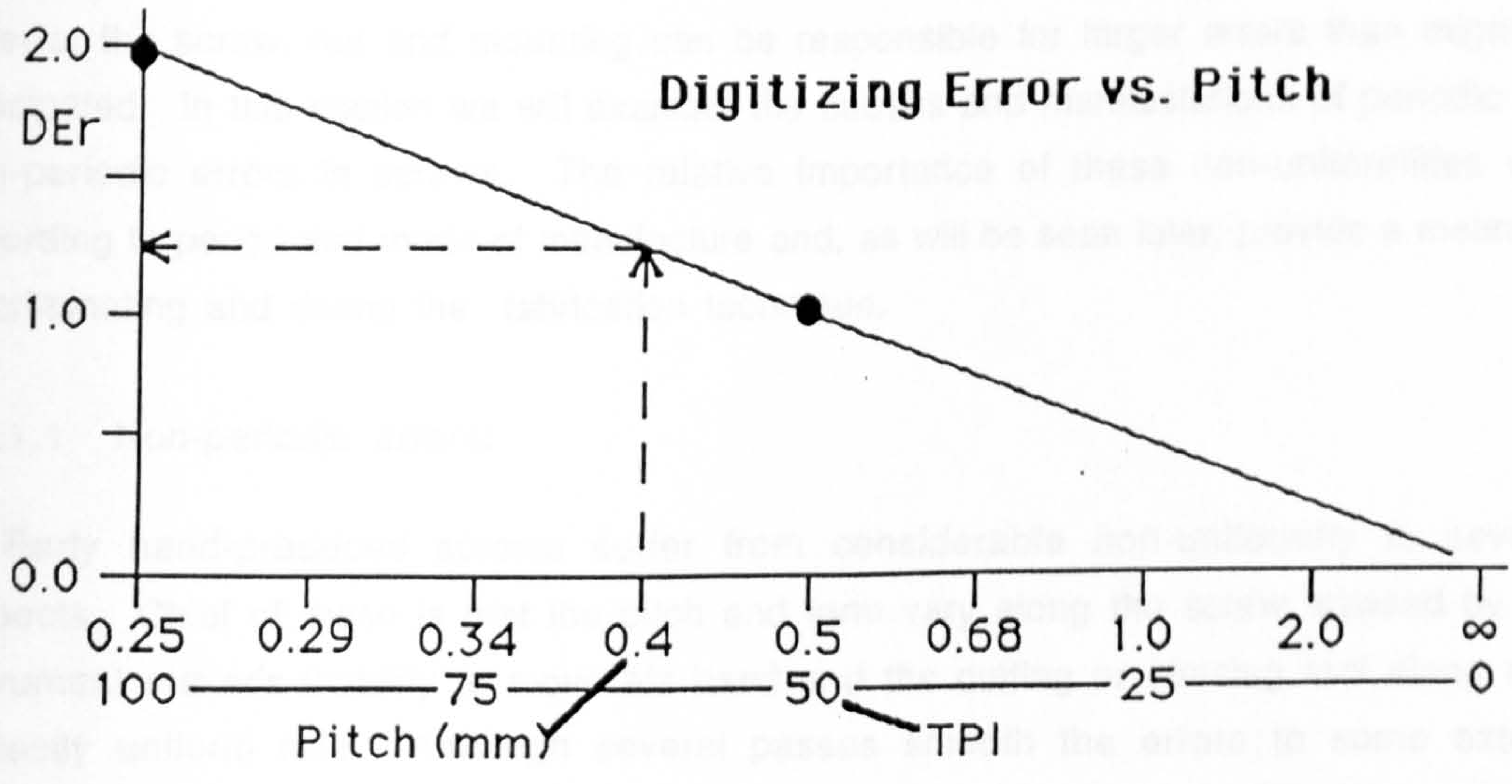
The shadowgraphs of screw threads reflect the precision of the original screw reasonably well (as will be demonstrated) and may be used to estimate the precision of the maker and/or his equipment as well as the precision with which a given micrometer might be expected to operate. This technique is particularly useful where an instrument is damaged (e.g. micrometer MHS-4 by Bird) or seized (zenith sector MHS-7 also by Bird). However, the fixed magnification (50x) employed to produce the shadowgrams was a problem for coarse-pitched screws as are found on dividing engines. At the other end of the spectrum, great care is needed to remove very fine-pitched samples from the cast or mould. However, gross problems are easily detected and can be passed over in the digitizing phase. More subtle problems, such as warping of the araldite moulds once removed from the cast, can create larger errors in the crest or root of the thread. To minimize this source of error, shadowgraphs were made from the casts immediately upon removal from the moulds.

To estimate the error of a screw, one could compute a statistical error for the digitized points after fitting a polynomial. However, a simpler and more straightforward procedure was adopted. Since a screw bears against the nut only on the flanks, the scatter on the flanks represents a good measure of the precision of the screw and, ultimately, the micrometer itself. The width of the scatter of the points on the flank was determined at the mid-point of the depth of the thread, and was measured parallel to the axis of the screw. The value thus measured will, of course, be slightly larger than a statistical error measured along the flank. The tables in Chapter 6 summarize the data for the different classes of screws investigated, with the exception of dividing engine screws where the large pitch did not permit a fit of sufficient confidence. The main problem with these was fitting a mean line through the points--if even slightly sloped, the profiles are skewed causing false measures in the flank measures. Problem screws are immediately apparent as the stacked profiles are plotted, and although the mean line can be adjusted by deleting points at either end of the profile, this was minimized as far as possible. Where 5 or more thread profiles appear on the shadowgraph, little problem is encountered so long as the digitizing begins and ends at the same 'phase' of the screw profile as has been explained in §5.2.4.1. For profiles with 3-5 threads, adjustment by deletion of points works well, though time consuming, while with less than 3 threads, considerable effort is required to correct the slope. In general, it was felt that the dividing engine screws were of much higher standard than the other classes of screws and that the quality of the results would be unfairly compromised by 'adjusting' the data. The best solution, if this procedure is to be employed on dividing engine screws, would be to produce a longer shadowgraph on which 5 or more thread profiles appear. Alternatively, the magnification could be reduced in producing the shadowgraph, but this would proportionately increase the digitizing error and lower the accuracy of the technique (q.v. §5.2.4).

5.2.5.2 Correcting for the digitizing error:

The digitizing error is linear with respect to the pitch or TPI of a screw as measured on the shadowgraphs since the magnification employed was the same in all cases. As has been described, a single thread on two profiles was carefully and repeatedly digitized. These were of 50 (SML-25a, P=0.5mm) and 103 TPI (MHS-2a, P=0.25mm) respectively. The errors for each were measured and found to be 1.0 and 2.0mm respectively from which the following figure was prepared. Since the relation will be linear, we can extrapolate and use the line to determine the digitizing error for screws with pitch 0.25 to 2mm. However, since some of the shadowgrams (i.e. of screws with very deep thread profiles) had to be drawn on a different scale (due to the limitations on the plotting area of the equipment employed), it is necessary to adjust for this. A formula relating the X dimension of the shadowgram (normally 143mm), pitch (P), measured error (ME expressed as a fraction of 1--e.g. for 1.4% error on the flank, ME = 0.014) and digitizing error (DEr) to the Pitch Error was developed. This is:

$$\left\{ \frac{[(X) \; * \; ME] \; - \; DEr}{143} \right\} \; * \; P \; = \; \text{Pitch Error}$$



5.2.11 Plot used to determine the appropriate correction for digitizing error.

The most useful result of this digitizing and computing exercise was the acquisition of 'normalized' thread profiles. With the exception of the few profiles with an A/R >1, (where an additional step of photographic adjustment of scale is required) each profile can be directly compared with any other simply by superimposing them on a light table. This allows a simple and efficient means of finding similar-looking profiles, and can be used to identify potential makers, screw type, or period of manufacture. This is a major step beyond what has been attempted by other studies of instrument screws, where the investigators appear to have given up hope of being able to identify makers of instruments by the screws.

5.3 Micrometric Measurements:

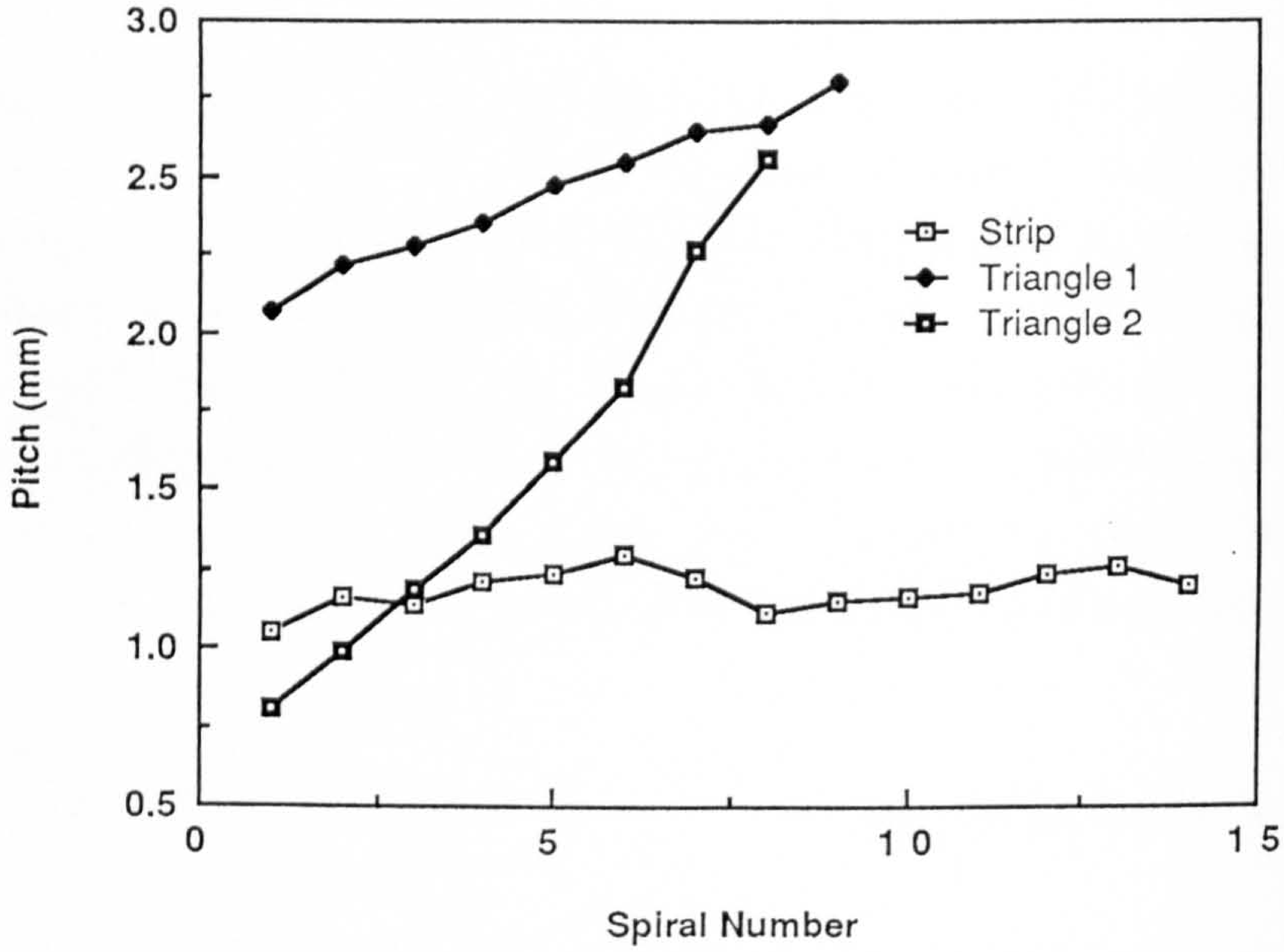
In this section we will discuss the application of a dial indicator to measure the errors of sample micrometers of various classes as an alternative means of determining the errors which would have been experienced by their users. The shadowgraph method of the previous section provides information on the screw itself, but the technique to be outlined yields information on the overall operational performance of the micrometer as a piece of mechanism. The two errors should of course be related and that will be demonstrated in the next chapter.

5.3.1 Types and Causes of Non-Uniformity in Micrometric Screws:

It is a truism to say that no screw can be made which is absolutely perfect--although some made for use on modern ruling engines for spectrum gratings come close enough that limiting factors and errors caused by other elements are of the same order of magnitude. It is important to recognize that, in most measuring instruments employing micrometer screws, the screw, nut and mounting can be responsible for larger errors than might be anticipated. In this section we will examine the causes and manifestations of periodic and non-periodic errors in screws. The relative importance of these non-uniformities vary according to period and mode of manufacture and, as will be seen later, provide a means of discriminating and dating the fabrication technique.

5.3.1.1 Non-periodic errors:

Early hand-produced screws suffer from considerable non-uniformity in several respects. Chief of these is that the pitch and form vary along the screw, caused by the instrument maker's inability to move his hand and the cutting or chasing tool along at a perfectly uniform rate. Although several passes smooth the errors to some extent, variation in the hardness of the metal accentuates (or at least make it difficult to remove) errors made on early passes. Micrometric screws of the 17th c and first half of the 18th



5.3.1 Results of an experiment to test the effects of wrapping ruled paper around a screw blank as a means of generating a thread. Using a triangle of paper causes the pitch to increase as the thickness of paper increases. The better method is using a narrow strip wrapped in a helix form. The pitch for 'Triangle 2' has had 8mm subtracted; thus the first point is ≈8.6mm and the last ≈10.5mm. Both Triangles 1 and 2 have an ≈20% increase in pitch.

c are generally larger (about 5-8mm) in diameter than later examples (2-3mm) and, although the evidence has been removed in the production, micrometric screws made in the period would have employed the wrapped spiral method to lay down the line of the thread. A punch was employed to mark out the line, or alternatively a sharp nicking file was employed to file through the paper making an initial groove in the screw blank.

To test these methods, a simple experiment was attempted in which a right triangle was cut out using a good straight edge. This triangle was then wrapped around a rod of 6.35mm diameter which was then placed on a Gaetner measuring engine and the width of the 'thread' measured with the results tabulated in Table 5.2. Even though thin onion skin paper was used, the multiple layers cause the effective diameter of the screw to become larger and to affect the pitch. An alternative exercise was attempted in which a thin strip of paper (Case 1) was carefully cut with its width as uniform as possible and approximately equal to the desired pitch. This was then wrapped around the rod and measured. This is simply a variation of the old technique of wrapping a wire of uniform diameter around a rod to make a simple screw. As observed in Fig. 5.3.1 the uniformity of pitch by this technique is not too bad. Next the 'thread' line laid out on this sample was punched with a sharpened centre punch every 2-3mm along this line. The rod was mounted in a lathe set to rotate at the lowest possible rate and a small triangular file was then employed to file the line of the thread as indicated by the centre punch holes. After a few attempts one can readily appreciate the usefulness of a treadle lathe for such an operation since the speed can be varied at will and at a slower speed than is available on a standard modern change gear lathe. Maudslay insisted that his apprentices should be able to achieve good results by similar methods before being permitted to use a screw lathe. However, this exercise was instructive in that an upper limit of pitch which could be achieved would have been perhaps 35-40 TPI, being largely a function of the size of file which could be acquired, the slowness with which the lathe turned and, of course, one's manipulative skill in advancing the tool. The screw made during this experiment was of brass, but all the micrometric screws and many of the adjusting screws sampled in this study were of hardened steel; the hardening process was performed last and introduced warping and associated periodic errors. Holtzapffel (1854, p.579ff.,635ff.,655ff.) deals with errors induced by screw making tackle, and it was

Table 5.2

Thread Generating Experiment

Case 1 Reading (mm)	Case 1 Difference (mm)	Case 2 Reading (mm)	Case 2 Difference (mm)	Case 3 Reading (mm)	Case 3 Difference (mm)
60.660		-1.488		7.342	
	1.053		2.072		7.812
61.713		0.584		15.154	
	1.162		2.214		7.992
62.875		2.798		23.146	
	1.134		2.275		8.191
64.009		5.073		31.337	
	1.215		2.348		8.356
65.224		7.421		39.693	
	1.240		2.467		8.592
66.464		9.888		48.285	
	1.297		2.546		8.825
67.761		12.434		57.110	
	1.226		2.650		9.268
68.987		15.084		66.378	
	1.117		2.667		9.553
70.104		17.751		75.931	
	1.146		2.806		
71.250		20.557			
	1.157				
72.407					
	1.174				
73.581					
	1.234				
74.815					
	1.256				
76.071					
	1.194				
77.265					

Case 1: thin strip of onion skin;
Case 2 & 3: triangle of standard typing paper for small and large pitch threads respectively.

not until precise grinding techniques were developed that variations created during hardening could be adequately corrected.

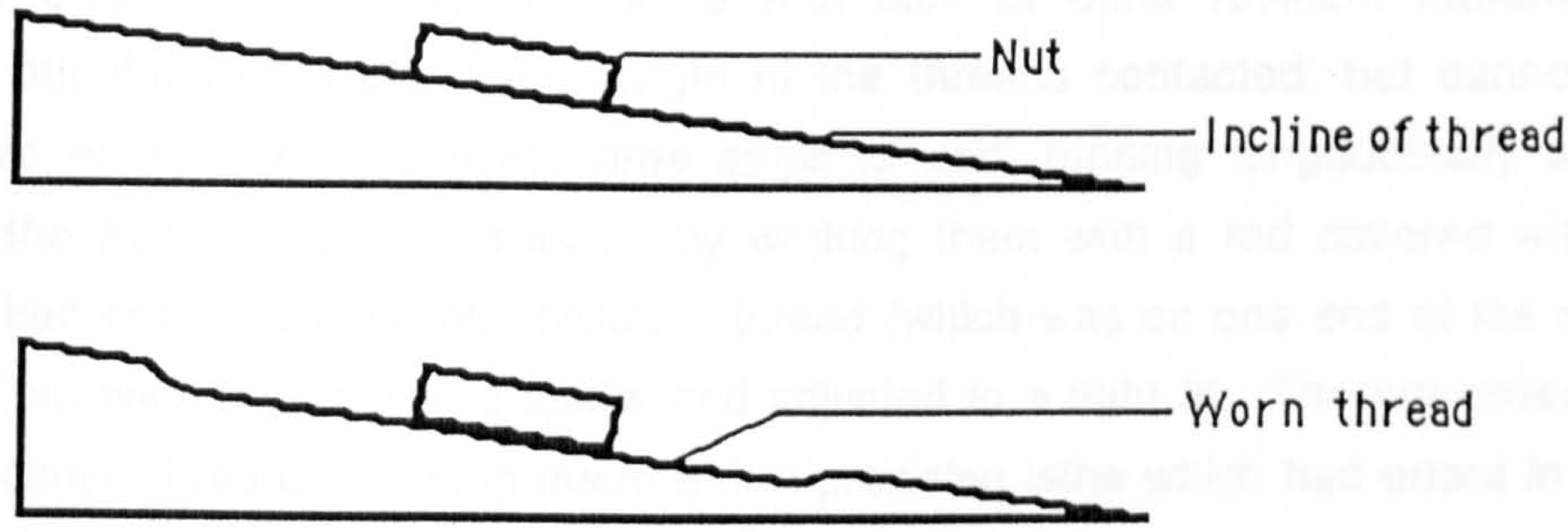
To summarize, we can identify several sources of non-periodic errors in screws, viz.:

1) Diameter of the screw varying along the length of the screw blank thus leading to an effective change in pitch.
2) Errors of pitch caused by 'hand' manufacture either because the line of the thread is not followed accurately or because the angle at which the cutting tool or chaser is held alters during a 'run' of the tool.
3) Errors of form caused by variations in the hardness and structure of the metal screw blank.
4) Errors of pitch caused during the hardening process.
5) Variations in the depth of thread which can be caused by error types 1,2 or 3 or combinations thereof.

5.3.1.2 Periodic errors:

Errors of pitch are the most important in micrometric applications on scientific instruments. There are in fact 4 types of pitch error: progressive error, periodic error, drunkenness and irregular error (Elliott, Dickson: 1959 pp.140-3).

Progressive error in micrometer screws results from a slightly long (or short) pitch in each turn with this small error accumulating as the screw is rotated. Ramsden (1765) solved this problem with a sine bar compensation which is still usefully employed. Correction is achieved by keeping the non-rotating nut in contact, through a radial arm, with a guide bar parallel to the screw axis. If a progressive error is present, the guide bar may be set non-parallel to the screw. This then allows the nut to rotate slightly and to correct the progressive error. If the errors are known, one can, in theory, make a guide bar shaped to correct each of the observed errors. Progressive error can also result from wear of the screw in the central, more heavily traversed parts of the screw. This is seen graphically below where the thread is illustrated as having been rolled out. Careful measurements can be made to determine errors due to wear but these were not adopted until well into the 19th c.



5.3.2 Error due to worn micrometer screw thread.

Periodic errors are most prevalent in screws made with screw lathes which, in normal workshop practice, began to appear after Ramsden's successful screw lathe of 1765. This was not the first such lathe, but his lathe, having been described in the *Philosophical Transactions*, was the impetus for others to copy and improve upon. The most prevalent errors are those with a period of one revolution and can arise from:

1) screw blanks which are out of round either prior to threading or after hardening;
2) screw blanks that are not centred before the thread cutting process on the lathe;
3) by motion of the cutting tool longitudinally as a result of an off-center lead screw; or
4) mounting the finished screw between thrust bearings where the bearing faces are not parallel.

The last is a frequent problem in 17th and 18th c micrometers where the bearing surfaces are simply the instrument case walls. A similar error results from a bent screw blank, or slide surfaces on the lathe which are not flat as a result of poor manufacture or wear. It should be pointed out that Maudslay was the first to pay proper attention to making flat surfaces on his tools, e.g. the ways on his lathes; errors in the heights of screw crests and troughs can often be traced to the lack of flat lathe ways though in older hand-made screws the errors are a function of the steadiness of the hand-held chaser. Errors with periods greater or less than 1 revolution can arise from change gears, which themselves may have periodic errors due to the way the teeth were cut, or because the wheels are out of round or eccentricly mounted. The periodic error introduced into the precision or micrometric screw is dependant on the order of the errant gear in the drive train; the closer the gear is to the workpiece, the stronger the effect will be since errors further up the train will be masked to some extent in the backlash of the system. In 1901 the National Physical Laboratory began building a special lathe to make lead screws of exceptional accuracy for lathes. One precaution was to dispense with change gears and mount the lead screw (6ft long and accurate to 0.0001in) coaxially with the screw blank (*American Machinist:* 4 March 1905, p.231).

In 1950 Merton (1950, pp.190-1) introduced the 'Merton nut' to correct periodic errors by employing a long[1] nut lined with cork or other resilient material. This averages out the errors along the length of the threads contacted, but cannot correct progressive errors. Merton used three strips of cork running longitudinally along the length of the nut; these were dressed by working them with a rod covered with emery paper. When mounted over the specimen thread (which was on one end of the rod to be ruled) the nut was coated with graphite and adjusted to a tight fit. The nut covered 4000 of the specimen threads (2in long made with a precision lathe which had errors in the lead screw) and moved the diamond cutting point which ruled a thread on the unruled end of the same rod. The Merton nut is applicable only in equipment requiring light thrust, such as in the production of gratings. Using the elastic nut was found to make a very substantial improvement in the quality of gratings. The periodic errors detected by **PROFIL1** are of these types, but the computer analysis also picks up periodicities from multiple thread screws and from screws which were finished with multiple toothed chasers. Analysis of micrometer data with **Profil1** will find errors from faulty bearings, progressive errors, errors due to eccentricity of the screw and/or graduated scale as well as periodic errors in the engraving of the scale.

Drunkenness arises from periodic errors which occur at intervals equal to the screw's pitch. Drunkenness results in screws made with dies if the dies are not perpendicular to the rod at all times, from faulty end bearings on a lathe's lead screw or headstock, or if the pitch of the fabricated screw equals that of the lead screw. Thus we might speculate that Maudslay's small screw lathe of 1800 (SML-18) was not of the best possible design, since the gears could be of the same size and the chosen lead screw could be directly duplicated thus making drunkenness a distinct probability.

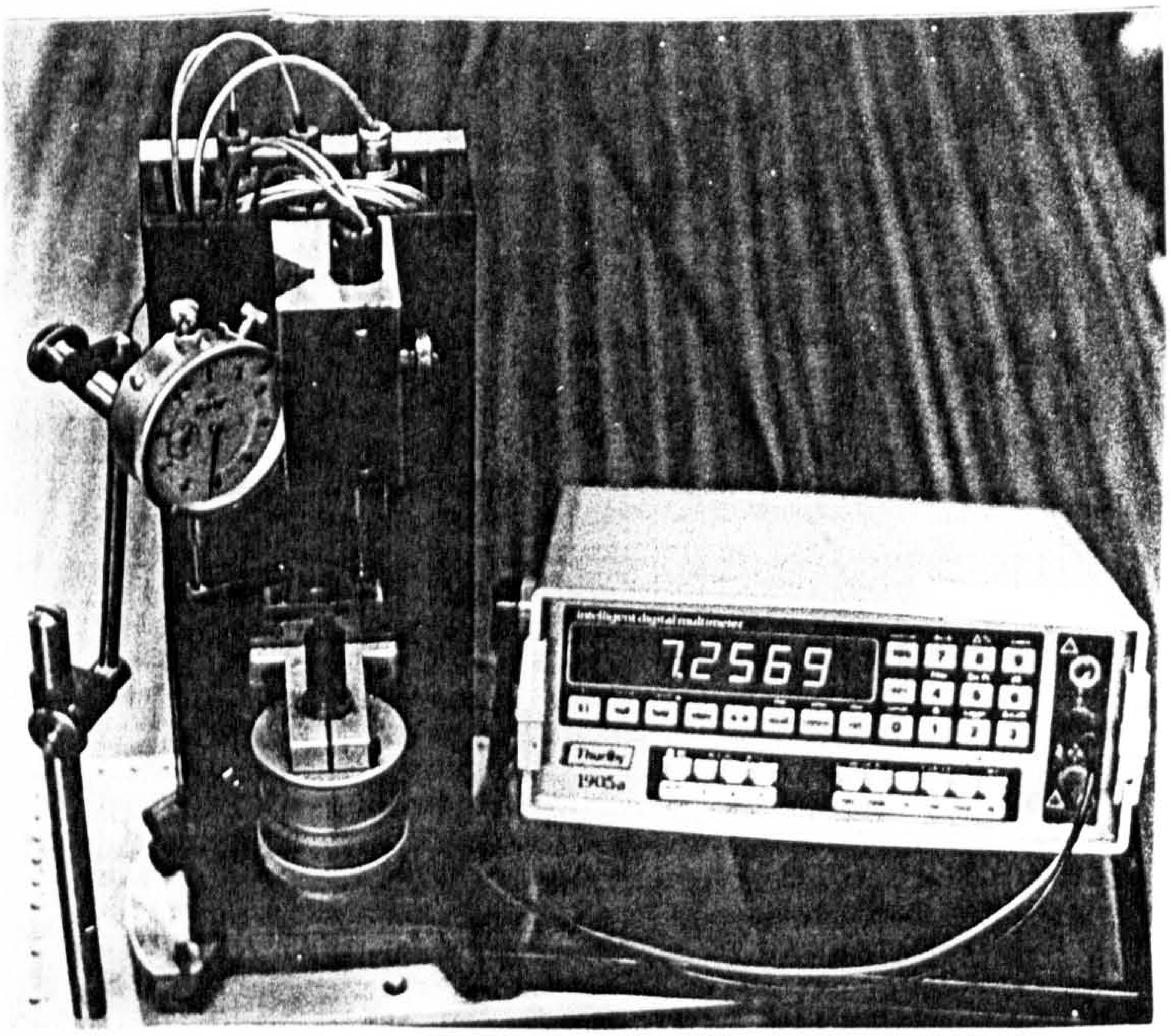
Irregular errors can arise from a multitude of sources: Uneven heating in the screw blank during cutting, uneven yielding of lathe parts, 'built-up ends' on the threads, etc. However, these can be largely eliminated by grinding the screw on the nut as initiated by Rowland (Rogers: 1884, p.258).

5.3.2 Selection and Calibration of the Dial Indicator:

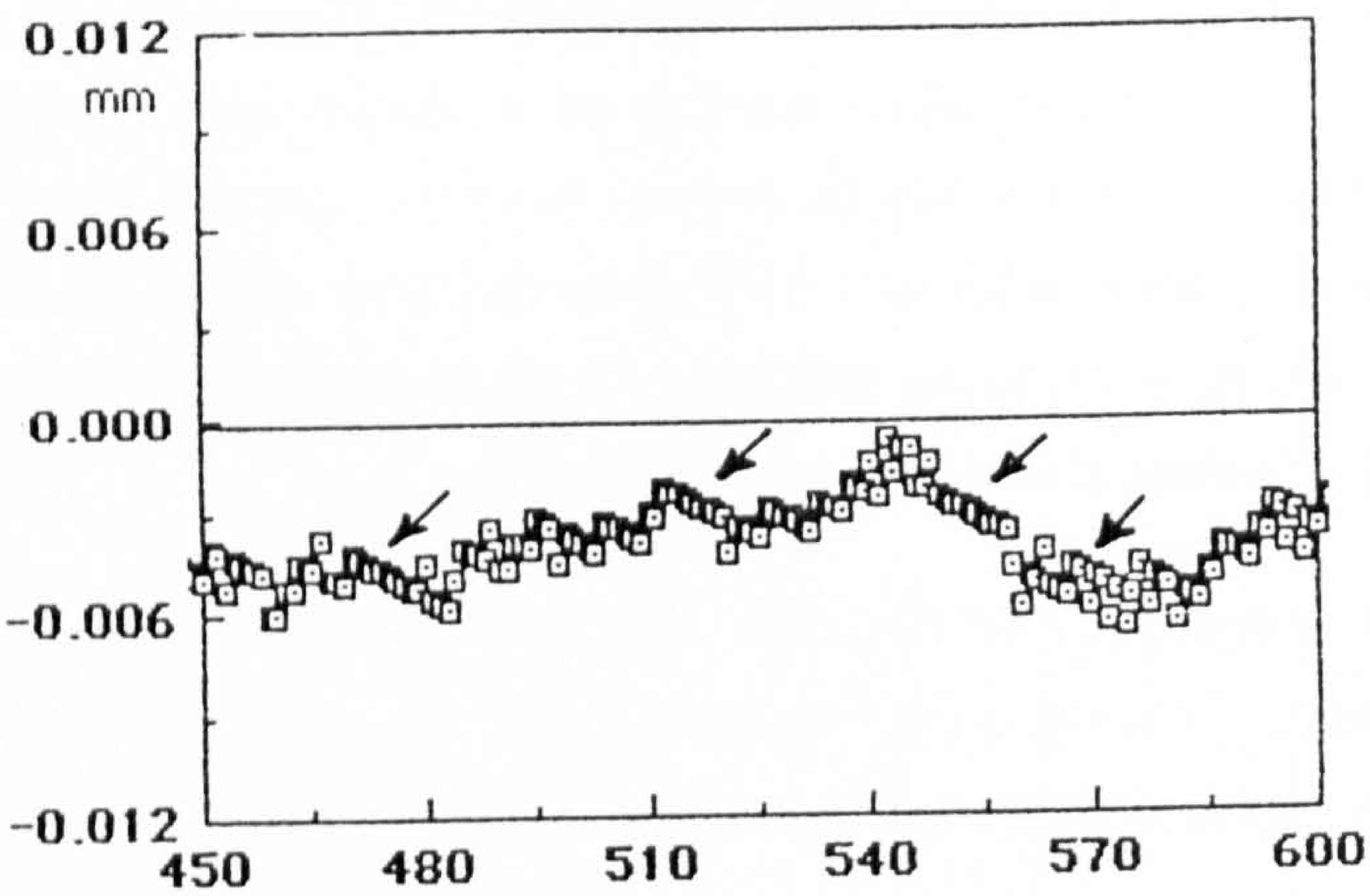
Although the error of micrometers will be estimated from the screw errors, this does not give the overall precision achieved with an instrument. Empirical knowledge of errors of scientific instruments of the 18th and 19th centuries comes mainly from estimates by the scientists who used the equipment, Chapman (1976 I,1983 I) has estimated the precision of a limited number of astrolabes and quadrants while Ward (1961) and Howse (1980) has reviewed the accuracy of clocks as a function of time. G.

---

[1] Long with respect to the pitch. In his test apparatus, the nut was 2in long but covered 4000 threads.



5.3.3 The capacitance comparator test rig for determining the calibration curve of the Mitutoya dial indicator.



5.3.4 Part of a calibration curve of the Mitutoya dial indicator illustrating the hysteresis (arrows) due to binding of the plunger. This could be due to the plunger of the capacitance comparator but more probably results from the dial indicator itself because of the right-angled extension that was necessary due to the geometry of the components.

L'E. Turner has investigated the resolution of microscopes. The objective here is to confirm the validity of the techniques adopted for this research while adding to this empirical knowledge.

The test instrument finally selected was a dial indicator made by Mitutoyo. This was selected in favour of a Mercer Type 41 dial indicator after repeated tests of both instruments against Moore & Wright English and Metric micrometers and a Hilger & Watts measuring engine belonging to the Astronomy Department. These tests showed that the Mitutoyo suffered less backlash and produced highly repeatable data.[1] Further calibration was attempted using a set of Grade 1 Johannsen slip gauges[2] belonging to the Physics Department Shop. However, the results did not attain the precision desired, although in theory they were capable of accuracy of the order of 0.0001in or 0.0025mm.

Recourse was then made to a test rig belonging to the Leicester University Engineering Department. The capacitance comparator (Fig. 5.3.3) employs a plunger moving within a block in a finely machined hole. The dial indicator was mounted parallel to the motion of the plunger which is itself controlled by a micrometer (the precision of the latter does not affect the results of the test of the dial indicator, this being a function of the stability of the amplifier and DVM only). The capacitance of the block varies according to the length of the plunger within the hole, and is measured by a sensitive amplifier/DVM combination. The relationship is highly linear and, with a 5 1/2 digit voltmeter, an accuracy equivalent to ≈0.001mm is achieved for the motion of the plunger. To test the Mitutoyo dial indicator, it was placed on the mounting designed to be employed to test the museum micrometers. A right-angle extension arm was attached to the plunger of the dial indicator so that motion of the plunger was transmitted to the dial indicator. (It should be pointed out that the geometry of the capacitance comparator and most of the micrometers to be measured in museums would not allow the dial indicator to be employed directly on the axis of the plunger.) Two off-set arms were made to mount on the dial indicator plunger and provided off-sets of ≈2.75cm and 5.75cm. The former was used in the majority of cases. Use of the arms compromises the attainable accuracy in that a rotational torque is applied to the plunger. This causes slight sticking and a hysteresis effect which manifests itself as diagonal 'runs' in data points on the calibration curve as illustrated in Fig. 5.3.4. With the 2.8cm arm, the overall error of the dial indicator is ≈0.0015mm. Comparison of two calibration runs made with the capacitance comparator and dial indicator is shown in Fig. 5.3.5. By comparing the graphs point by point, the

---

1 Good results were obtained when operating in both directions although such instruments are intended to be used by advancing so that the plunger is pushed into the indicator. However, it was anticipated that measurements would have to be made in both directions, so this feature of the Mitutoyo dial indicator was very welcome. The tests on the dial indicators also indicated a fault in the thrust bearing of the measuring engine which was duly repaired

2 Made by Coventry Gauge Co., ser. no. 87719.

repeatability becomes obvious and reaches ≈0.001mm[1]--well within the limits required for the majority of instruments tested with it. This is the level at which changes in temperature begin to perceptibly affect the apparatus. Unfortunately, there was no means of controlling the temperature during the testing of instruments. For future measurements of dividing engines it will be necessary to monitor this effect, especially if the measurements cannot be made within a few minutes. During the current tests the data were obtained in ≈1/2 hour per instrument, so temperature effects were not of great concern. Body heat was minimized by limiting contact with the test equipment as far as possible.

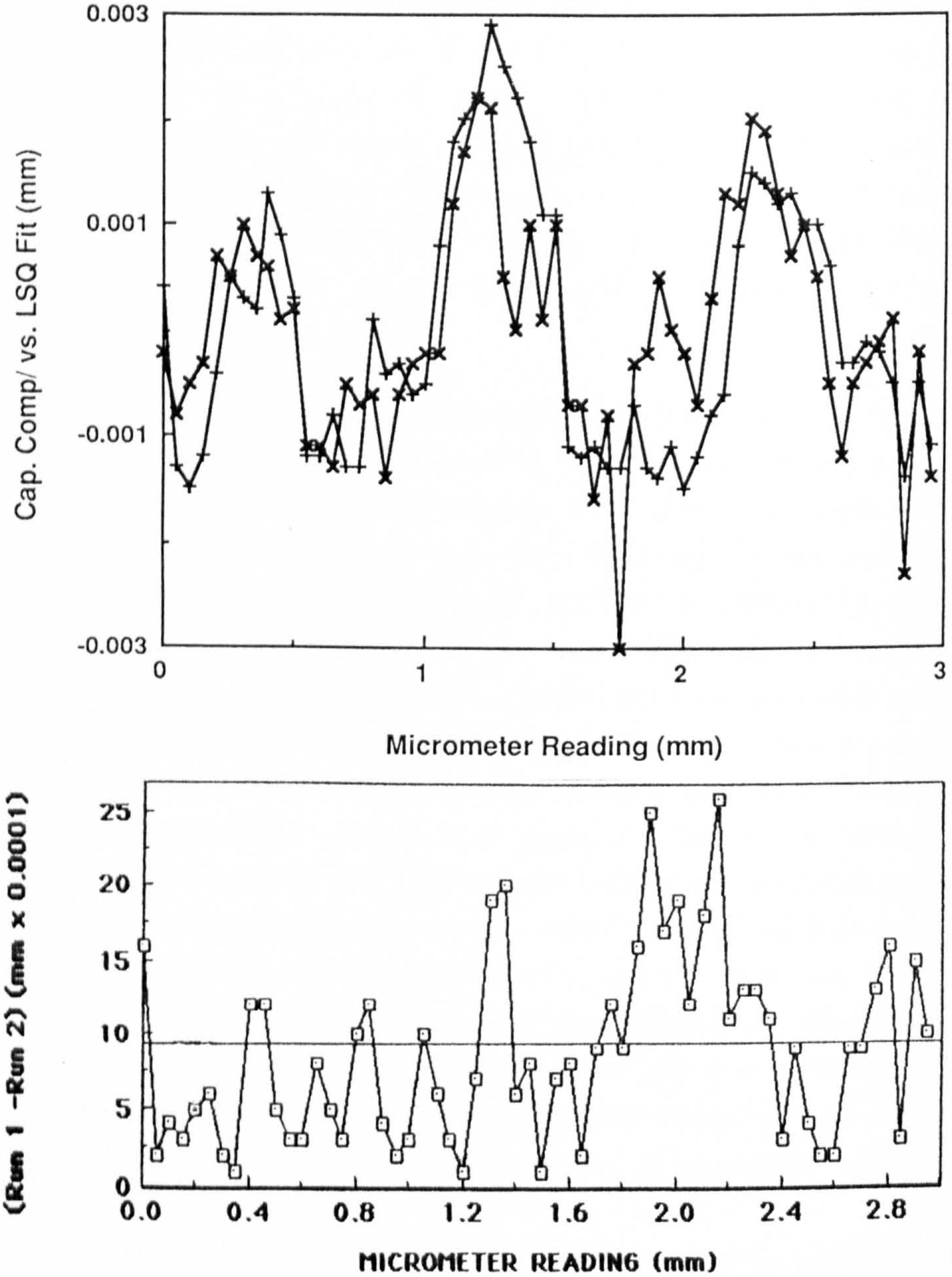
The final calibration run was carried out with position increments of 0.01mm over the 20mm range of the dial indicator. This was done in order that the curve could be subtracted from the measured data using an interpolation program **CALBRAT**. However, to make this procedure useful, the zero reading of the micrometer is required. Unfortunately this was not recorded at the outset since the early calibration attempts did not demonstrate the potential repeatability and the fact that such a precise calibration curve would be useful in beating down the errors in the measurements. In the end, the only instruments where this procedure would have been desirable was in the measurement of the 19th c dividing engines; otherwise the dial indicator error was substantially less than the micrometers measured. Only in a very few cases did the dial indicator error exceed 15-20% of that of the tested device. The features of **CALBRAT** now allows this procedure to be carried out with minimal effort, and would be carried out as a matter of course in the future. To ensure that data for all types of micrometers and dividing engines are directly comparable, subtraction of the calibration curve has not been carried out. However, in a few cases, measurements and reduction with the calibration curve subtraction procedure has been applied for demonstration purposes to attest to its usefulness for measurements of the highest precision instruments under test.

5.3.3 Data Handling and Reduction:

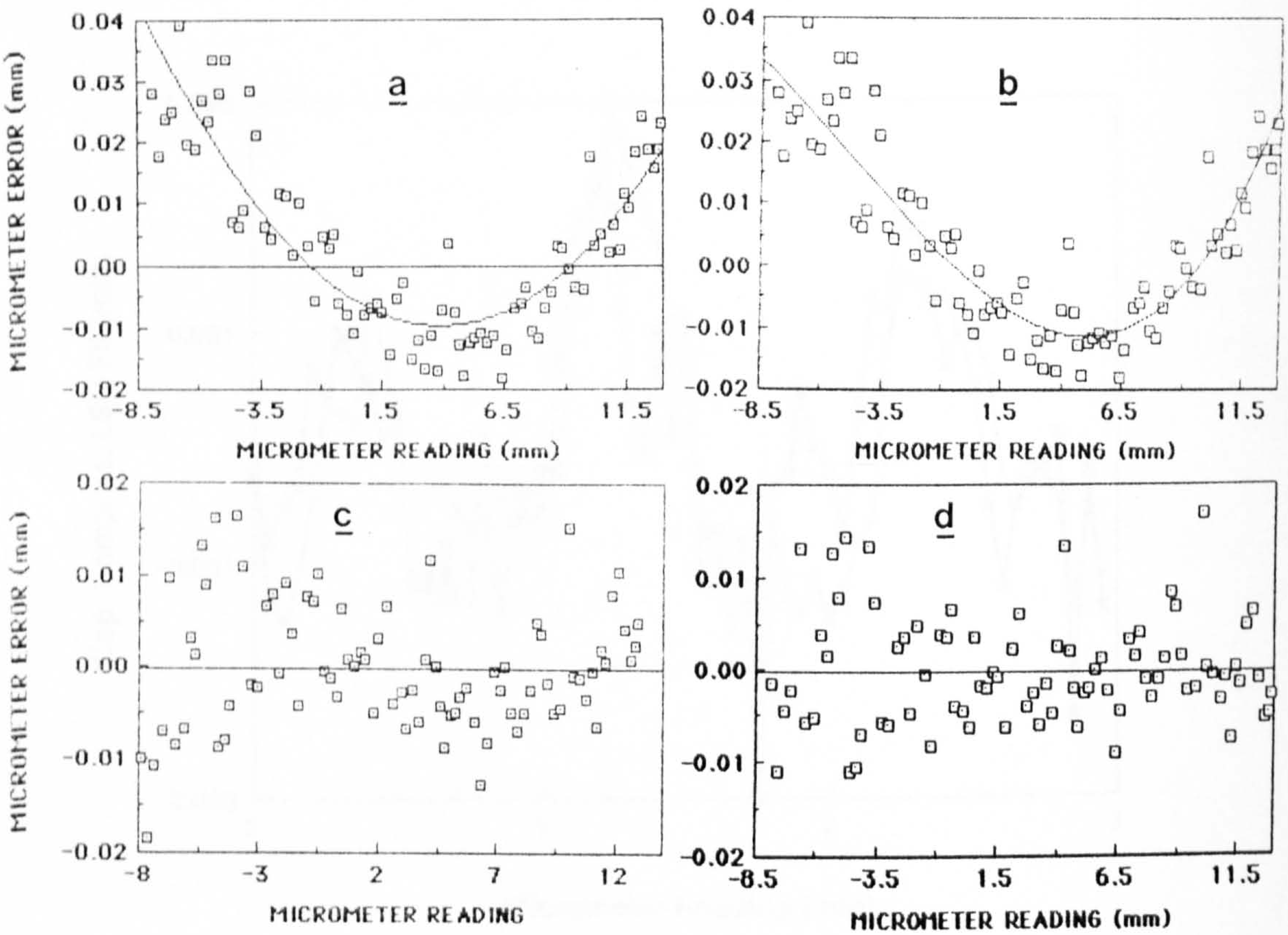
The micrometer data was processed on a VAX 11/780 using a Fortran program, **PROFIL1**. This produced a linear least squares fit to the data which, after organizing the file, was transferred for plotting and further analysis to a MacIntosh Plus computer with 20 megabyte hard disc via a software package called **KERMIT**. After some further restructuring of the data (necessary due to the direct incompatibility of the two computers) the micrometer data was plotted using another software package, **CRICKET GRAPH**. This permitted easy identification of mistyped or misrecorded data points which were checked against the original data sheet, and corrected or deleted as appropriate. Once the data was corrected on the Mac, **CRICKET GRAPH** was used to fit a 2nd-5th degree polynomial to the micrometer data. This is necessary for two reasons. First, if the

---

[1] The mean difference between these two curves is 0.00095 (±0.00085mm).



5.3.5 Two calibration curves for the 0.0-3.0mm range of the Mitutoyo dial indicator (total range 20mm). The difference between each run averages <0.001mm.

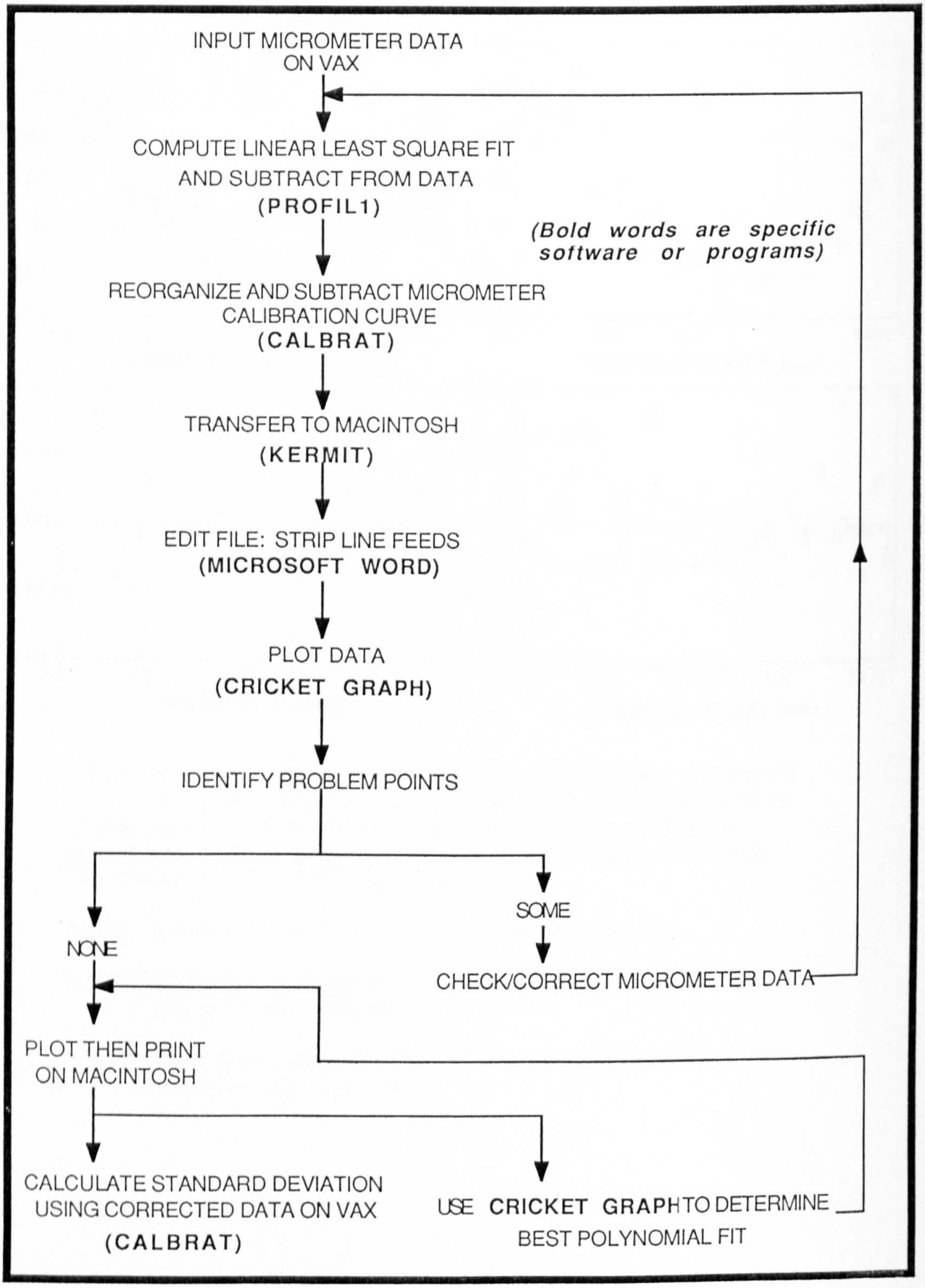


5.3.6a Measurements of one of the scale micrometers of Langlois' 6ft sextant made in 1738 (PO-1b). The curved appearance of the data is due to the fact that the micrometer is fitted to a curved scale and is being measured by a linear measuring device. The fitted curve is a 2nd degree polynomial.

5.3.6b Same data fitted with a 3rd degree polynomial.

5.3.6c Data after subtracting the 2nd degree polynomial. (mean error = 0.0065mm).

5.3.6d Data after subtracting the 3rd degree polynomial (mean error = 0.0059mm).



5.3.7 Flow chart showing the steps required to produce the graphs (e.g. 5.3.5) and to determine the errors of the micrometers from the micrometer measurements.

micrometer measured was a scale micrometer on a quadrant with pivoted index and alidade, then the dial indicator was providing a linear measure of a curved motion. Subtracting a second degree polynomial removes this instrumental error. Secondly, other errors of pitch can appear due to poorly made screws or other mechanical problems. The latter problem manifests itself as a periodic error corresponding to one turn of the index handle, while errors of pitch of greater length appear as longer period functions. One should be able to draw a correspondence with errors that appear in this data with errors identified by testing the digitized thread profile or micrometer data using the Jurkevich-Swingler period searching function of program **PROFIL1**.

An appropriate polynomial was determined for the micrometer data (for scale micrometers the 2nd degree polynomial was first subtracted). The selection was done simply by looking for the lowest order polynomial giving a good visual fit and only reached a 4th degree in 1 case. 3rd degree polynomials were fitted in 13 cases and a 2nd degree polynomial in 11 cases. In the majority of cases no polynomial fit appeared necessary. In all cases **PROFIL1** was again used to fit the corrected data and **CALBRAT** gave the standard deviation, which is a useful error to extract for comparison purposes. In cases where a 2nd or higher order polynomial was desired to fit the data, **LSQ** was employed to provide the fit and to subtract the fitted curve from the data. Again **CALBRAT** yielded the standard deviation which is recorded for later comparison. The outputs from **CALBRAT** were transferred to the Mac and replotted. These are the figures which are provided in Appendix E with the data, profiles and information on the screws and micrometers. Examples of profiles are inserted here (Fig. 5.3.6). A flow chart of the steps required to produce these diagrams is provided in Fig. 5.3.7

For clarification, **CALBRAT** serves three purposes: 1) to subtract the dial indicator calibration curve from the micrometer data, if desired; 2) to calculate the standard deviation, sigma, of the data whether corrected or not; and, 3) to create a data file more easily handled by the MacIntosh computer. Data can be read from files created by **LSQ**, **PROFIL1**. The structure of the output files of these programs is ideally suited to calculation of the standard deviation. **LSQ** is employed when a straightforward polynomial fit is desired for degrees 1-10, but can also be used to subtract the fitted curve from the original data. **PROFIL1** (or **PROFIL2** which is identical except the input file is read reversed, i.e. y,x instead of x,y; both outputs create a file with x,y) automatically fits a linear least square to the input data, allows subtraction of the fitted line, but also carries out functions required for the analysis of the digitized thread profiles which were discussed in §5.2.4.2.

Chapter 6

Analysis of the Results

6.1 Introduction:

Here we investigate relationships between the various classes of screws and seek relationships for the accuracy of screws. Because of the amount of data accumulated in Appendix E, the most expedient method for finding these relationships would seem to be graphical. As will be seen, there is considerable scatter in the figures. This is not unexpected since the sample of screws is neither perfectly homogeneous nor in pristine condition. Also, the makers were not always producing screws to the limit of their capability. Reference to the accuracy of measurements will be made when appropriate, since the accuracy affects the results differently for the various comparisons and occasionally differentially within a graph. An example of the differential effect is the varying accuracy of the measurements of errors of progressively finer-pitched screws.

Before proceeding, it is appropriate to provide a listing of all the instruments studied and relevant information since this will not be repeated when reference to a specific instrument is made. The date given is usually that provided by the museum, but where an obvious error has been made, that is corrected. Where no date is available, a 'best' estimate is given based on available information and on design considerations. Where the instrument is signed but no date provided, reference has been made to the author's unpublished "Index to Scientific Instrument Makers to 1935" which contains information on some 7,000 makers.

TABLE 6.1: LIST OF INSTRUMENTS STUDIED

MUSEUM CODE	ACQUISITION NUMBER	SIGNED MAKER	INSTRUMENT	DATE
MUSEUM: **Greater Manchester Museum of Science and Industry**				
GMMT-				
- 1		Dancer, Manchester	Large Dumpy Level	1860-70
- 2		Harvey & Peak, London	Spherometer	ca.1900
- 3	1970.3	Watkins	Gregorian	ca.1770
- 4	1984.168.1	Dancer, J.B.	Microscope	ca.1860
- 5	1986.3	John Cuff, Fleet St.[1]	Gregorian	ca.1740
- 6		J. Casartelli, Manchester	Survey Level	m-l.19th c
- 7	1986.242.1	Rothwell, Manchester	Survey Level	1850-75?
- 8	1972.5	G. & M. Simons, 49 King Sq	Everest Pattern Theodolite	1896?
- 9	1968.15	W. & S. Jones	Y-Level	ca.1840

[1] Belongs to Manchester Astronomical Society at UMIST.

MUSEUM: **Istituto e Museo de Storia Della Scienza, Florence**

IMMS-

- 1	Duc de Chaulnes[1]	Circular Dividing Engine	1762
- 2	Duc de Chaulnes	Linear Dividing Engine	ca.1762
- 3	probably Amici	Circular Dividing Engine	ca.1825
- 4	possibly Chaulnes	Linear Dividing Engine	18th c

MUSEUM: **Istituto Tecnico Toscana (Istituto Salvemini), Florence**

ITT-

- 1		Perreaux de l'Orne à Paris	Circular Dividing Eng..	1855-78
- 2	A177	Perreaux	Linear Dividing Engine	1855-78
- 3	B48	Duboscq, Paris	Mutipurpose Micrometer	1855-78
- 4	B79	Secretan	Adjustable Spectroscope Slit	1855-78
- 5	B166	(Kohl?)	Micrometer to measure interference from slits	1855-78
- 6	131	(Fuess or Koristha?)	Microscope Micrometer	ca.1890?
- 7	321	Fuess, Berlin	Crystallography Microscope	1855-78
- 8	B214	F. Miller, Innsbruck	Manometer Scale Reading Micrometer	1855-78
- 9		F. Miller, Innsbruck	Manometer Scale Reading Micrometer	1855-78

MUSEUM: **Merseyside County Museum, Liverpool**

MCML-

- 1	1976.537.6	Troughton & Simms	Biflar Micrometer from Bidston Observatory	ca.1870
- 2	1976.537.2	(Troughton & Simms?)	Filar Micrometer from Bidston Observatory	ca.1870
- 3		Not Signed	"Fast set" Micrometer	l.19th c

MUSEUM: **Museum of the History of Science, Oxford**

MHS-

- 1	7	Simms	Filar Micrometer	ca.1850
- 2	79-23	Thomas Jones, 62 Charing Cross	Filar Micrometer	ca.1820
- 3		John Bird	Filar Micrometer	ca.1770
- 4		John Bird	Portable Quadrant	1770
- 5		(German)	Gunner's Level	1736
- 6		John Bird[2]	8ft Quadrant (Radcliffe Obs.)	1773
- 7		John Bird[3]	12ft Zenith Sector	1773
- 8		John Bird	32in Quadrant	ca.1767
- 9		Powell & Leyland 170 Euston Rd., London	Wenham Microscope with micrometer	1864
- 10	32-29	Thomas Wright	Surveyor's Level	1724
- 11		Gourdin, Paris	Ellipsograph	ca.1790
- 12		"I·D" F. (F=fecit)	Gunner's Sight	1621

---

1 See Daumas: 1972, f.110,111 for Chaulnes' dividing engine of 1768 and Clay & Court: f.131 for Chaulnes' microscope micrometers.

2 See Bennett: 1987, f.111. Bennett dates 1772 but this and next instrument were not put into operation until 1773.

3 See Bennett: 1987, f.114; A. Turner, 1987, f.236.

-13 95	Edward Scarlett	Screw Barrel Microscope	<1738
-14 92	Edmund Culpepper	Screw Barrel Microscope	ca.1710
-15 RAS #19	Lenoir	de Borda Circle	ca.1790

MUSEUM: **Museum of Science and Technology, Birmingham**

MSTB-

-1	83-3663	Maudslay	Lathe	ca.1800
-2		Maudslay	Screw Lathe	ca.1800
-3		Not Signed (Tickenhill Coll.)	Thread Rolling Machine	1878/9
-4	Ser #1461	Babbage	Lathe	1823-7
-5	59-1064	Humpage, Jacques & Pederson Bristol	Bench Micrometer	ca.1890
-6		Holtzapffel	Thread Gauges	3rd q. 19th c
-7	67-2201	Brown & Sharpe Mfg. Co., Providence, R.I.[1]	Bench Micrometer	ca.1877
-8		Holtzapffel & Co., London	Tube gauge-internal diameter	l.19th c
-9	64-1372	H.J.W. King & Co., Glasgow	Bench Micrometer	ca.1850
-10		Whitworth, Manchester	12in Comparator	1869
-11		Whitworth, Manchester	24in Comparator	1899

MUSEUM: **Newark Houses Museum, Leicester**

NHM-

-1	1233/1951/15	Not signed	Screw Plate	e-m.19th c
-6	1233/1951/24	J. Deacon	Die Stocks	m.19th c
-7	49-1949	PS Stubs	Screw Plate with PS rotated 90° CCW	e-m.19th c
-8		Not signed	Pendulum Bob	19th c
-9		Not signed	Pendulum Bob	19th c

MUSEUM: **Observatoire de Paris**

PO-

-1	1A 1811	Langlois "Paris aux Galleries du Louvre"[2]	Portable Sextant	1738
-2	237/964=9.6	James Short	Gregorian+Heliometer	ca.1757
-3		Richenbach[3]	Vertical/Altitude Circle	ca.1810
-4	5/778=49-2.9	James Short	Gregorian + Micrometer	ca.1753/4
-5		Foucault/Secretan[4]	Reflecting Telescope	1860
-6		Fortin	Repetition Circle	1831
-7a		Langlois	Portable Sextant	1746
-7b		Berthet[5]	Scale Micrometer	ca.1770
-8		Rogaud à Paris	Altazimuth Instrument	1770/80

---

1 US Patent awarded 23/04/1878.

2 Used by LaCaille at the Cape of Good Hope in 1751.

3 A similar instrument is in the Deutches Museum, Munich and is illustrated in Bennett: 1987, f.187.

4 First telescope with silver on glass mirror.

5 This is a later replacement micrometer on the Langlois sextant.

MUSEUM: **AUTHOR'S COLLECTION**

RB-

-1	Charles P___s	Quintant	ca.1860
-2	Van der Voodt	Sextant	ca.1860
-3	Spencer, Browning & Rust	Octant	ca.1840
-4	Yeates & Son, Dublin	Dumpy Level	l.1840's
-5	Not Signed	Gregorian	>1790
-6	Hartnack, Potsdam	Bar Limb Microscope	1890/1
-7	Leitz	Microscope Objective	1892/3
-8	Zeiss	Microscope Objective	1892/3
-9	Broadhurst, Clarkson	Refracting Telescope	ca.1865
-10	Omer "late Harris", London	Spyglass	ca.1848-50
-11	(French)	Spyglass	l.19th c
-12	Harris & Co.	Spyglass	m.1840's
-13	(probably Cooke & Son(s))	Telescope Eyepiece Set	ca.1890
-14	Eugene Deitzgen & Co.	Proportional Dividers	1912
-15	Troughton & Simms [1]	Surveyor's Cross	ca.1850

MUSEUM: **Royal Observatory, Greenwich**

RO-

-1	OL-76	(Herschel?)	Filar Micrometer	ca.1780
-2	OL-79	(Herschel?)[2]	Filar Micrometer	ca.1780
-3	OL-17	Dollond	Filar Micrometer	ca.1840
-4a/b	OL-18	Troughton & Simms	Filar Micrometer	ca.1840-5
-4e	OL-18	Troughton & Simms	Dynameter	ca.1840-5
-5	OL-16	Not Signed (possibly Simms)	Airy's Divided Eyelens Micrometer	ca.1840
-6	00/R6	Haupois	Mount for Refractor (RO-7)	1787
-7	00/R7	Dollond	Refractor	ca.1780
-8	00/RF26	Dollond & Son	Heliometer	1753-5

MUSEUM: **Royal Society**

RS-1	Newton/Heath & Wing[3]	Newtonian	1670/ca.1760

MUSEUM: **Science Museum, London**

SML-

-1	1938-719	Heath & Wing	Filar Micrometer	ca.1760's
-3	1880-57	(Italian?)	Micrometer	ca.1700
-4	1984-174	John Browning	Filar Micrometer	>≈1878
-5	1986-377	(French)	Filar Micrometer	ca.1875
-6	1929-979	Ramsden[4]	Shuckburgh Equatorial	1787-1800
-7	1912-221	Troughton	Portable Equatorial	ca.1780
-8	1931-347	Smeaton[5]	Filar Micrometer	1745-70
-9	1928-1329	Ramsden	Portable Equatorial with Filar Micrometer	1775

---

1 See Christie's Catalogue, 4 June, 1987.
2 On loan to Herschel House, Bath.
3 See Mills & Turvey: 1979; Turner & Wynter: f.238; A. Turner: 1987, f.128.
4 See Bennett: 1987, f.125.
5 See Hawkes: 1981, f.67; Bennett: 1987, f123.

-10	1950-246	Ertel & Sohn	Geodetic Theodolite	ca.1840
-11	1948-128	Thomas Jones	Altazimuth Theodolite	ca.1830
-12	1876-1206	Thomas Jones	Transit Theodolite	ca.1830
-13	1981-111	Ramsden[1]	Geodetic Theodolite	1790
-14	1876-1204	Troughton & Simms[2]	Geodetic Theodolite	1828
-15	1925-164/5	Maudslay	Taps	<1830
-16	1857-8	Whitworth	Taps	1857
-17	1938-529	Whitworth	Clamp Type Screw Die	m.19th c
-18	1900-19	Maudslay	Screw Lathe	1800
-19	1929-881	Siemens	Bench Micrometer #152	1881
-20	1876-1370	James Watt	Bench Micrometer	ca.1770
-21	1900-75	Maudslay	Bench Micrometer	ca.1800
-22	1928-719	John Barton	"Atometer" Micrometer	1806
-23	1911-214	Dollond[3]	Portable Quadrant	ca.1767
-24	1937-600	John Bird	Quadrant	ca.1770
-25	1900-138	John Bird[4]	Quadrant	ca.1767
-26	1927-1491	Sisson[5]	Filar Micrometer	ca.1780
-27	1986-1697	Jan van Call, Neomagens[6]	Pendulum Clock	1657
-28	1925-468	(Herschel?)	Filar Micrometer	ca.1780
-29	1925-469	(Herschel?)	Filar Micrometer	ca.1780
-30	1963-120	Not Signed	Fusee Engine	2nd h.19th c.
-31	1938-15	Not Signed	Fusee Engine	ca.1800
-32	1900-21	Maudslay	Screw Originating Machine	ca.1800
-33	1958-224	Hilger/Blythswood	Circular Dividing Engine	1888-97
-34	1926-32	John Barton	Linear Ruling Engine	ca.1820
-35	1978-?=RAS4	Dollond	Divided Eye-glass Micrometer	ca.1825
-36	1932-22	John Troughton[7]	Circular Dividing Engine	1778
-37	1953-446	Frederick Cooke	Circular Dividing Engine	1872
-40		Edward Troughton	Groombridge Transit Circle	1806
-42	1938-713	James Short	Gregorian with heliometer	ca.1757
-C092	1900-138	John Bird	12in Quadrant	ca.1767
-C093	1911-283	Benjamin Martin[8]	Gregorian	ca.1750
-C094	1912-204	Dollond	Equatorial Telescope	
-C095	1913-281	Ramsden	Cassegrain on Universal Equatorial	
-C096	1918-1651	Sisson	6in Quadrant	3rd q.18th c
-C097	1918-168	Sisson[9]	6in Quadrant	
-C098	1920-439	Thomas Wright	8.5in Gunter quadrant	1715-40
-C100	1931-95	J & E Troughton	12in Sextant on pillar	l.18th c
-C101	1937-118	Benjamin Martin[10]	Quadrant	3rd q.18th c

From Charles Maddison's casts taken at SML and identified as:

-C103	#11-2	No identification found
-C104	#10-2	"

---

[1] See Daumas: 1972, f.109; Bennett: 1987, 143.

[2] See Bennett: 1987, f.232.

[3] This instrument was used by Samuel Holland in the Survey of Quebec from ca.1767-73.

[4] See Bennett: 1987, f.117.

[5] From the King George III Collection.

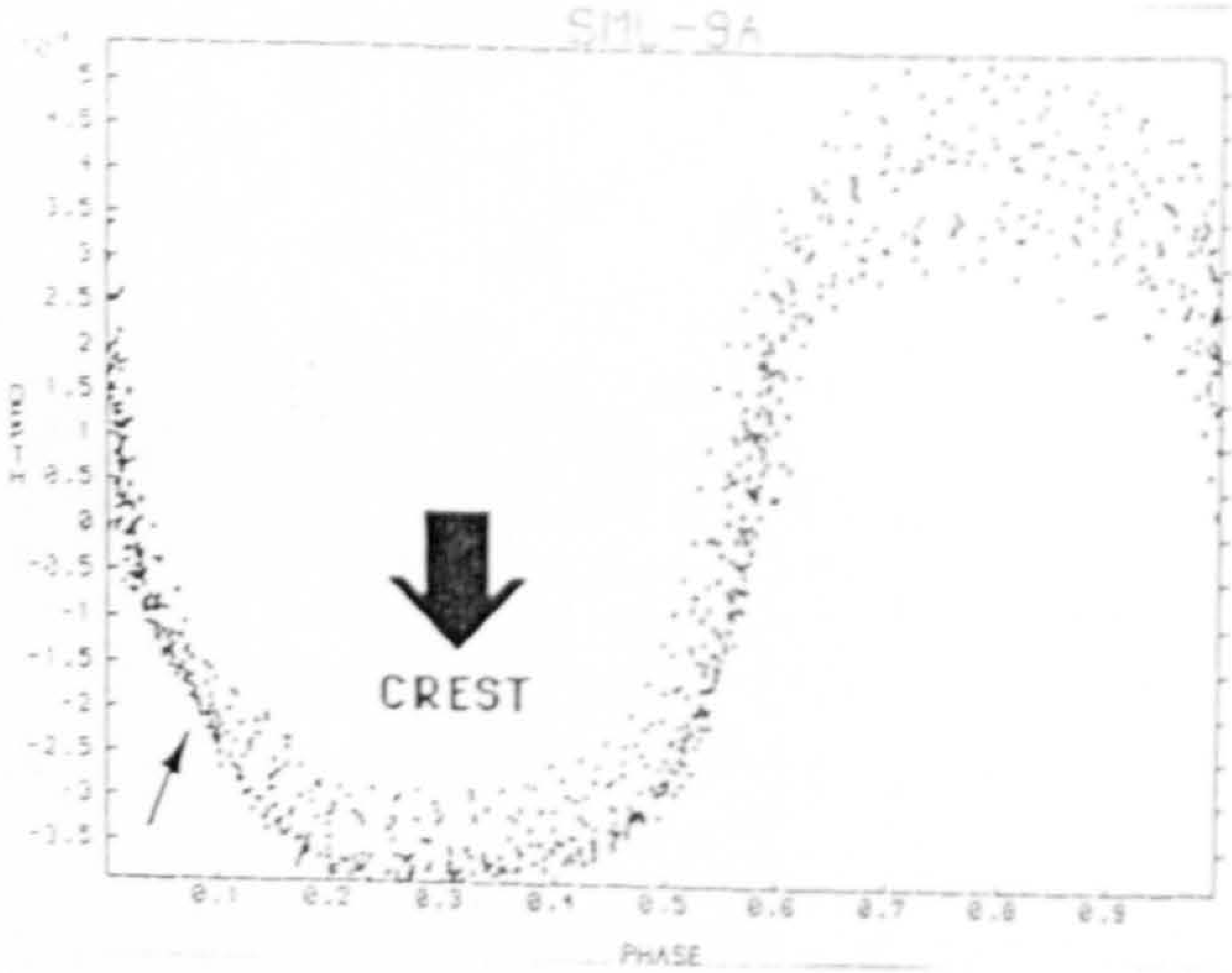
[6] See Christie's Cat., 17 April, 1986.

[7] See A. Turner: 1987, f.231.

[8] Telescope used by Winthrop of Harvard for observations of the Transit of Venus in 1769.

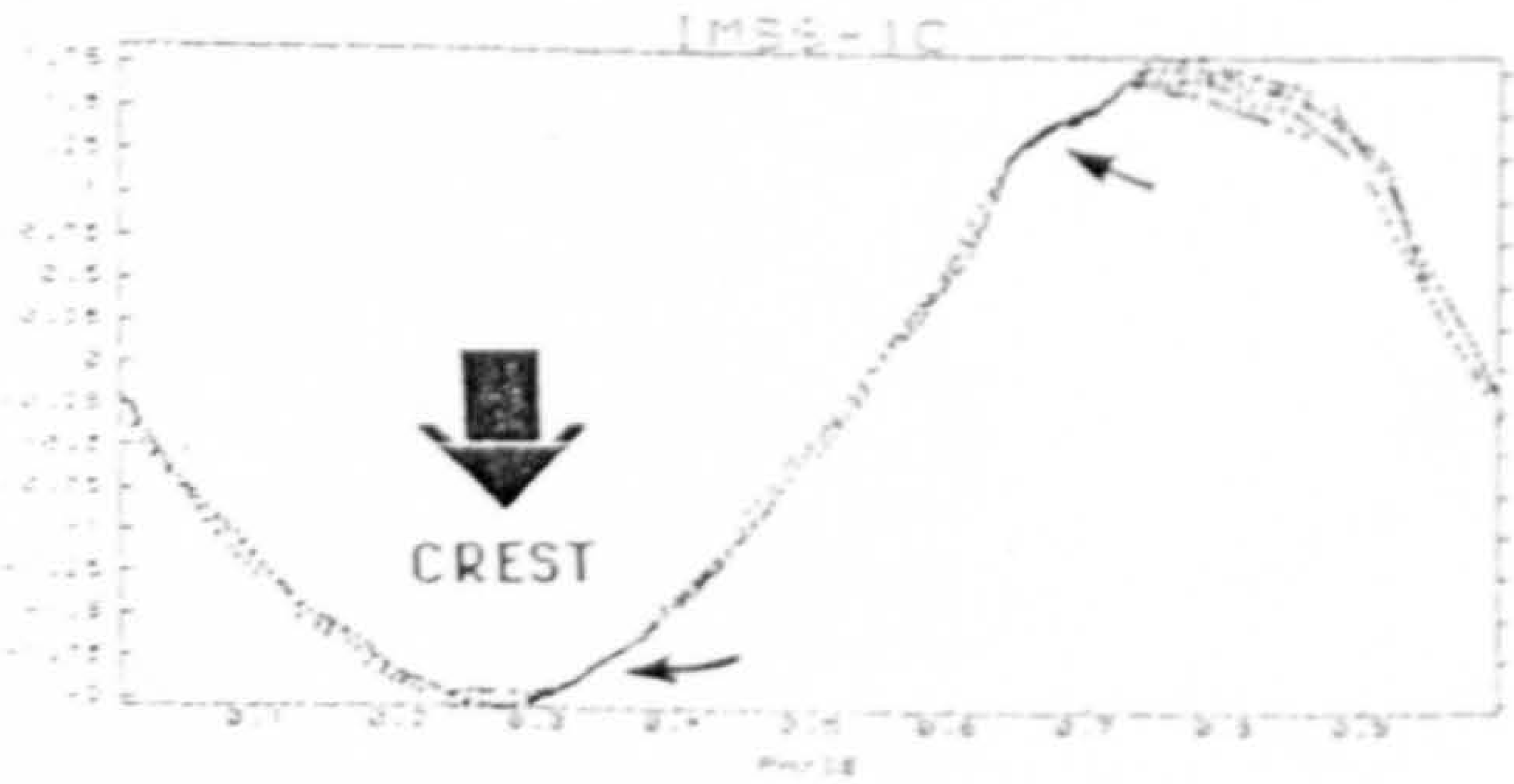
[9] See A. Turner: 1987, f.130. One screw has a very prominent error equal to twice the pitch.

[10] See Millburn: 1986, p.46.

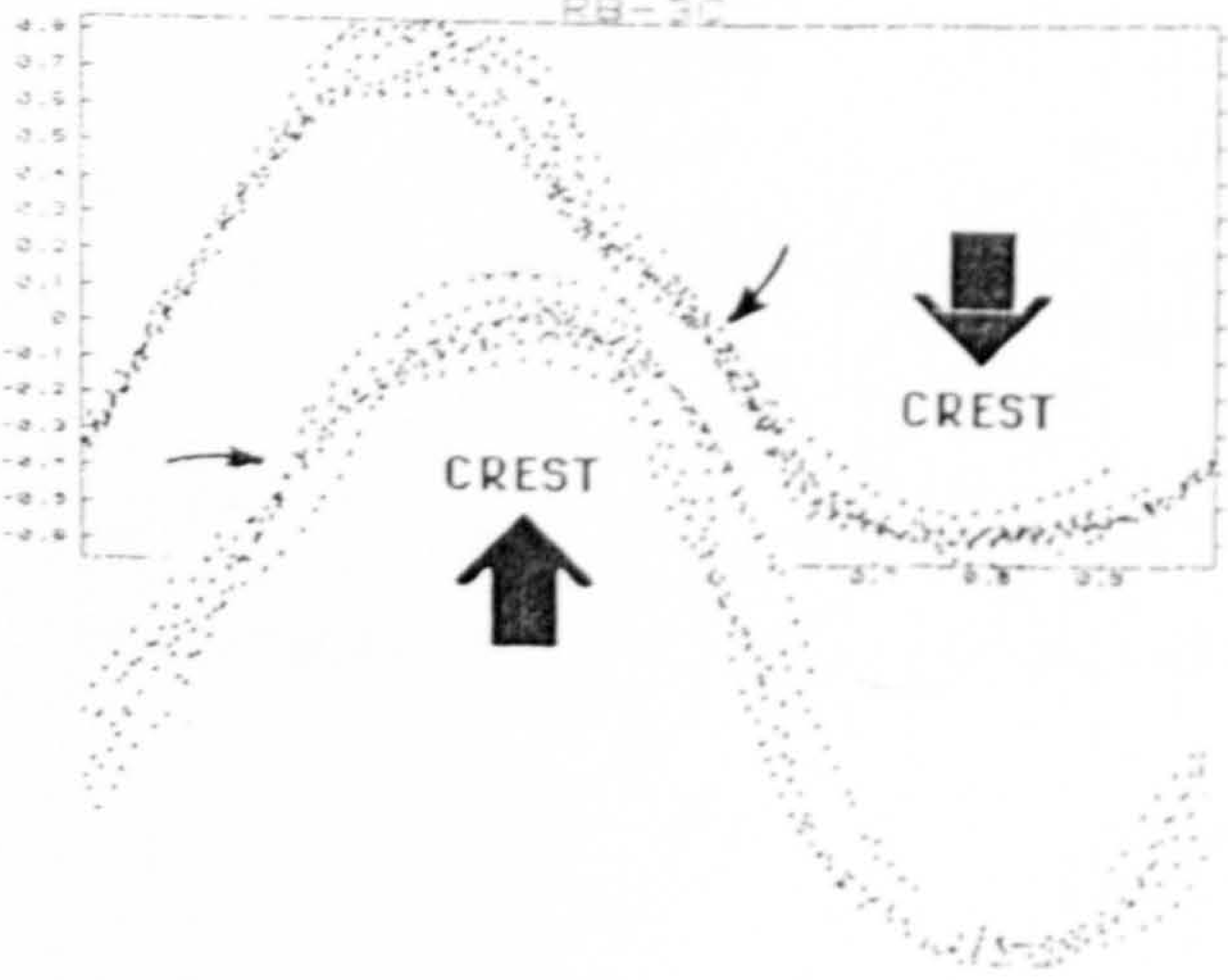


6.2.1a Wear on a Ramsden filar micrometer screw.

6.2.1b Wear on the crest and root of an adjusting screw by Chaulnes.



6.2.1c Wear on the nut (above) and screw of the index clamp on a Spencer, Browning & Rust octant.



-C105 #9-2	"
-C106 "Sundial"-2	"

MUSEUM: **Whipple Museum of the History of Science**

WMHS-

-1	2118	Troughton & Simms	Bubble Level Tester	
-2	1616	Baradelle	Beam Compass	ca.1775
-3	2122	Ramsden	Sextant	ca.1790
-4	2175	Utzschneider/Fraunhofer[1]	Universal Instrument	ca.1825
-5		William Cary	Altazimuth Instrument	1800
-6	2135	Ertel & Sohn[2]	Altazimuth Instrument	ca.1840
-7	1004	Rowley[3]	Filar Micrometer	ca.1703
-8		John Bird[4]	Quadrant	ca.1765

MISCELLANEOUS

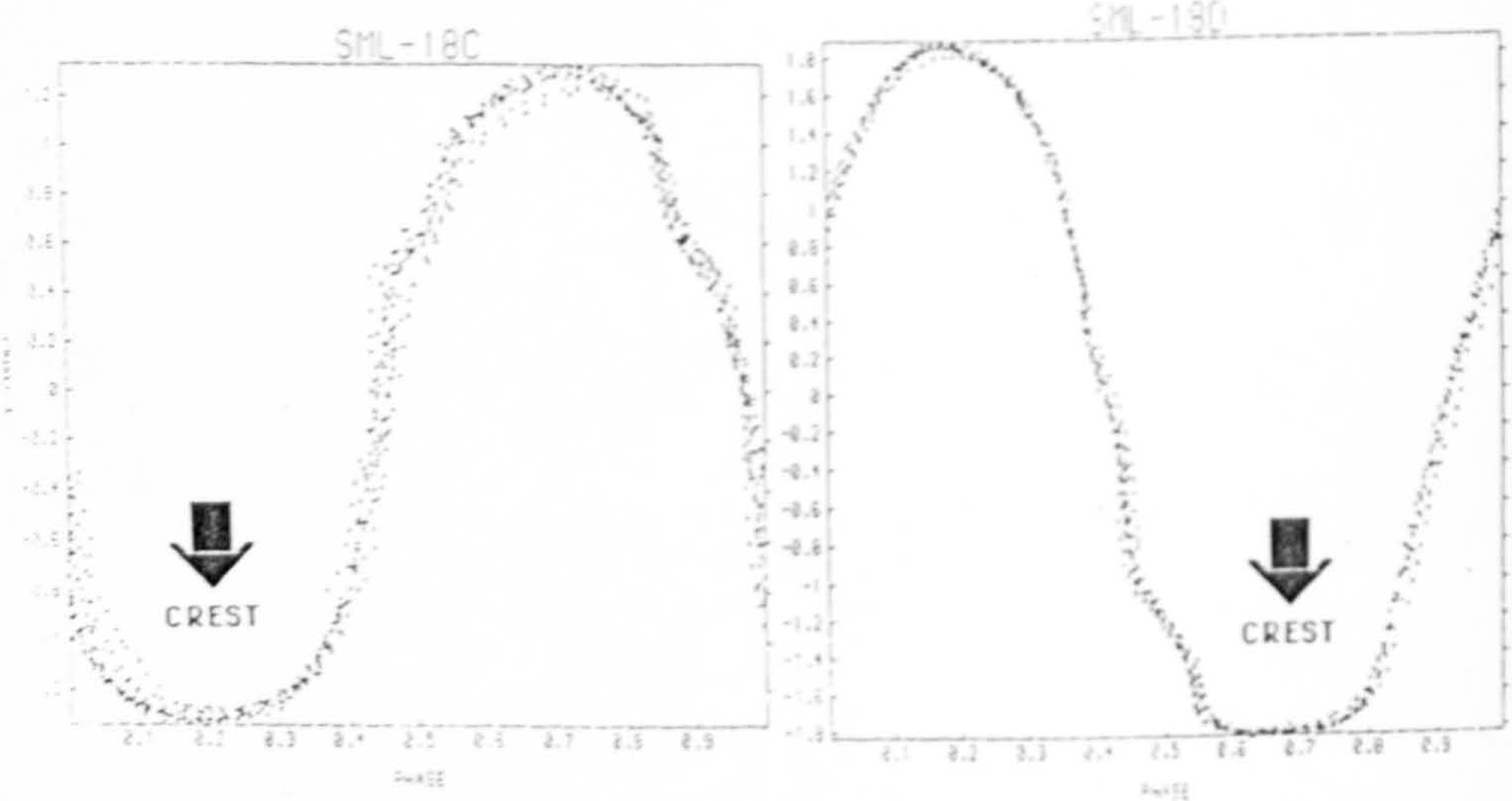
BAAS-	Pratt & Whitney	Screw and Nut Gauges[5]	1899
	Moore & Wright	Metric Micrometer	ca.1965
	Moore & Wright	English Micrometer	ca.1965
	Baty	Screw Thread Projector	ca.1970
		Micrometer[6]	
	Hilger & Watts	Measuring Engine	ca.1970

6.2 Interpretation of the Digitized Profiles of Appendix E:

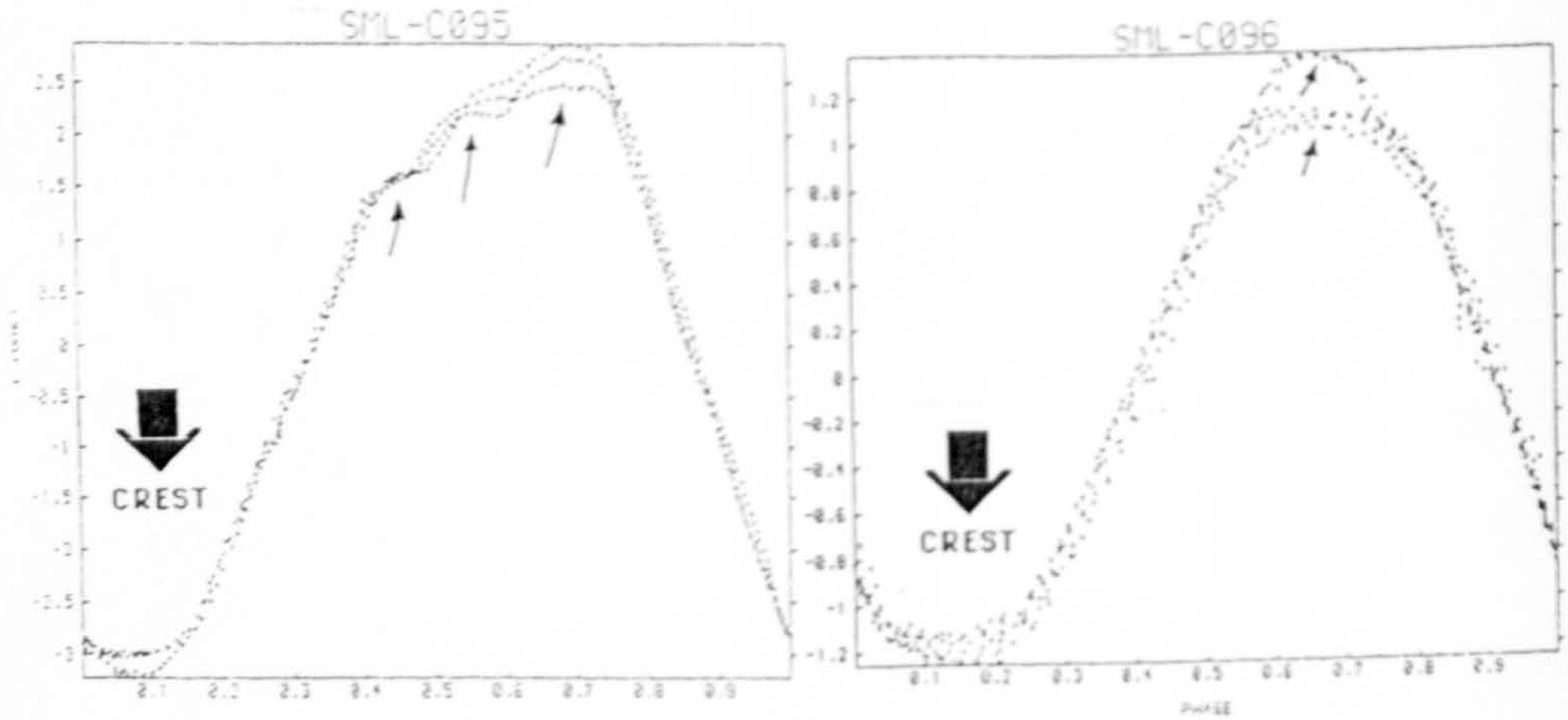
A description of the various parameters on the summary figures of the screw profiles is given at the beginning of Appendix E. There are a number of effects which may be recognized in the shape of the profiles given there. Fig. 6.2.1a illustrates the profile of a micrometer screw by Ramsden in which the left side of the crest has been worn by use, while Fig. 6.2.1b illustrates an adjusting screw from Chaulnes' dividing engine which has spots worn on both the root and crest: this is uncommon. A few samples had a concentration of digitized points on the outer edge of a section of the profile indicating a degree of wear. This is demonstrated in RB-3c, the nut of an index clamp on a Spencer, Browning & Rust octant. In Fig. 6.2.1c the upper profile is the nut while the profile of the screw is below. The zone of contact for the nut is obvious due to the wear on its right side though there is no corresponding wear on the opposite flank; the wear on the screw is on its left side but is not so obvious. The profile of Ramsden's micrometer screw also illustrates an almost universal characteristic of pre-20th c screws--the root is more poorly defined than the crest. In a few cases this may be due to grease or dirt in the root

---

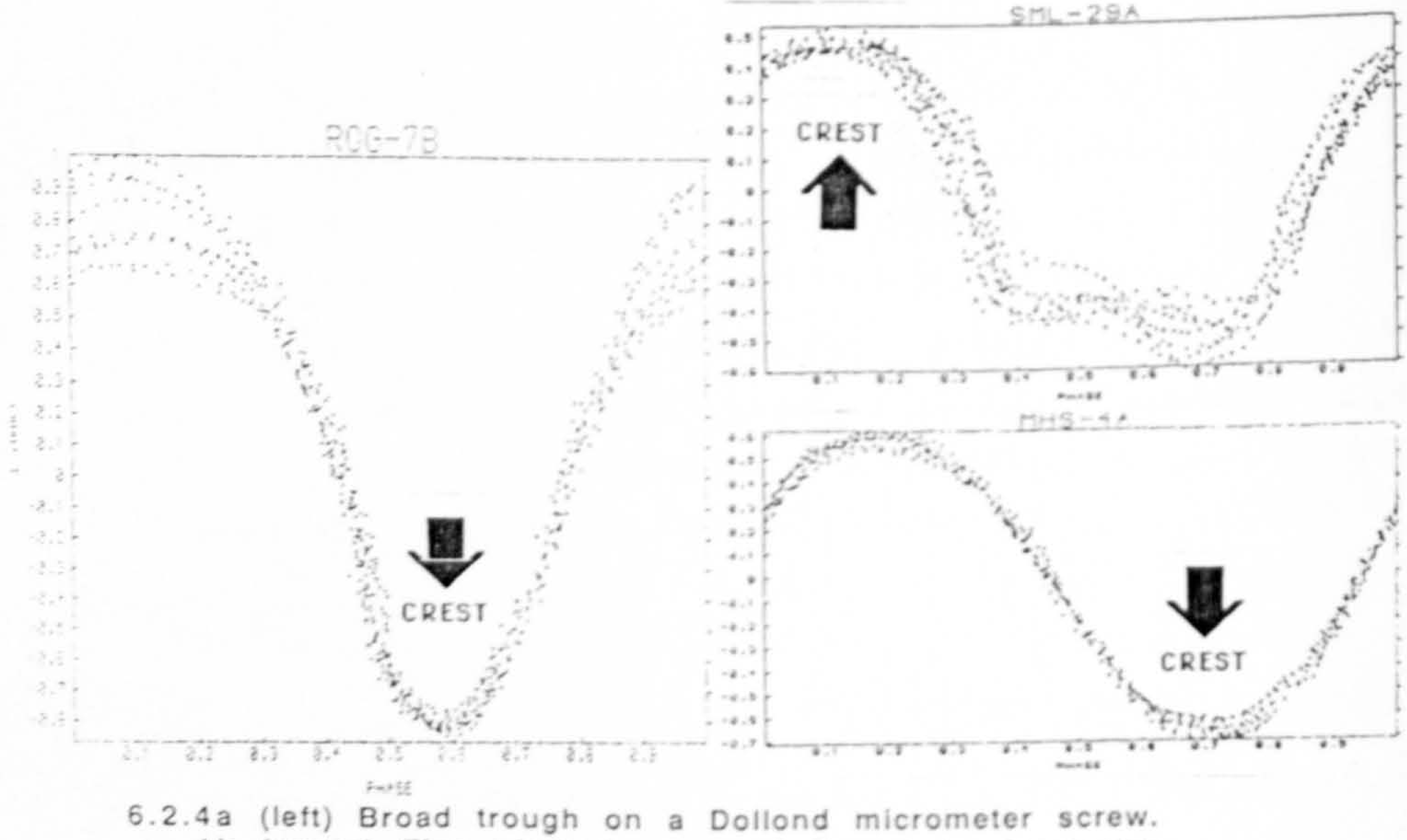
1 See Bennett: 1987, f.176/7.
2 See Bennett: 1987, f.195.
3 See Price: 1952, p.1; Bennett: 1987, f.58.
4 See Bennett: 1987, f.96.
5 Profiles were obtained from a photograph reproduced in the BAAS Reports for 1899 (p.467).
6 The micrometer on this instrument is not signed but was probably made by Moore & Wright.



6.2.2 Maudslay screws showing 'good' or well defined thread roots.



6.2.3 Cutting tool markings on a Ramsden (left) and Sisson leveling screws.

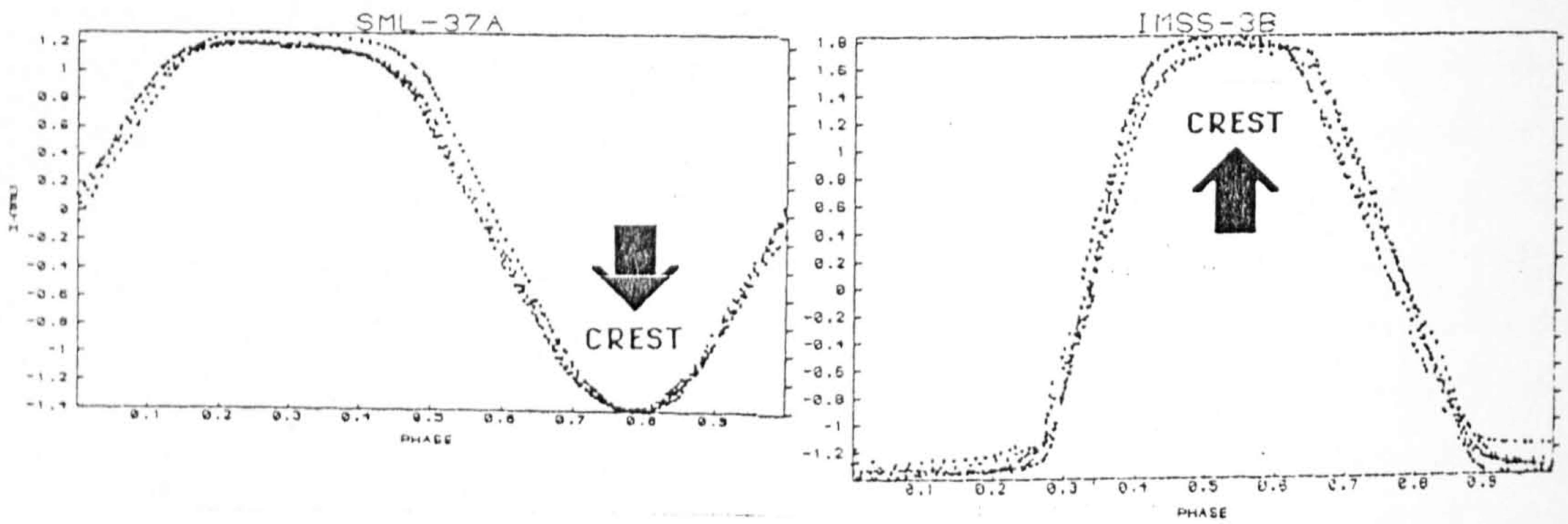


6.2.4a (left) Broad trough on a Dollond micrometer screw.
4b (upper) Fine pitched screw of Herschel micrometer.
4c Bird scale micrometer screw of relatively course pitch.

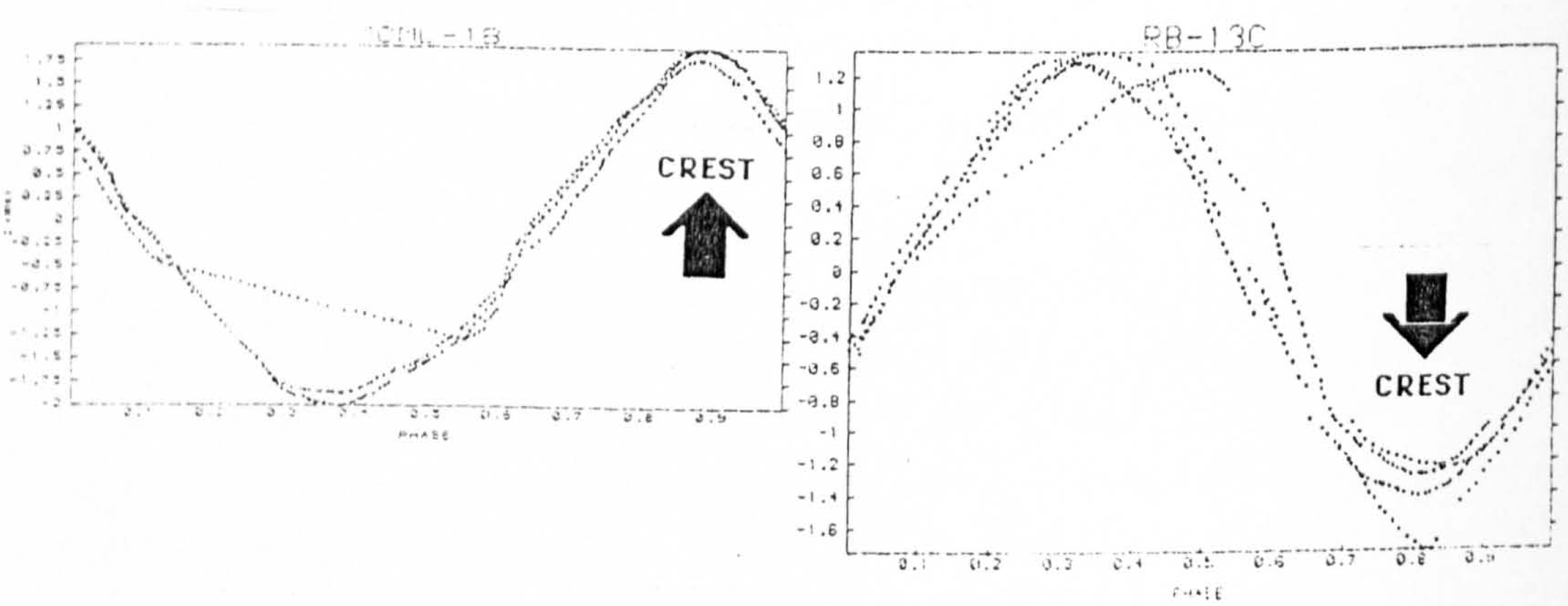
but this explanation does not apply to the majority. Thus one might estimate the accuracy of the ways on lathe beds for those screws made with slide-rest lathes from the late 17th c. For comparison, the roots of the screws from Maudslay's instrument lathe (Fig. 6.2.2) are of almost equal accuracy to the crests. It will be remembered that Maudslay was the first person to take particular care to use flat test surfaces, and one result was improved lathe bed ways and in turn improved accuracy of his screws. The screws from Chaulnes' dividing engines (IMSS-1,2) are more precisely made than those of his contemporaries, and suggest he had taken great care in designing amd making his lathe. The screws for moving the plates of his dividing engines were more accurate than any previously made (≈0.9%) The accuracy found here refutes Daumas' (1972: p.201) claim that Ramsden was the first person to make screws with better than 1% accuracy. In considering progress in the accuracy of adjusting screws, those made in Germany after ca.1820 show an abrupt improvement from those made in France and Britain. This illustrates the effects of adopting better machinery which was to fuel Germany's growing industrial reputation.

Some profiles (Fig. 6.2.2, 6.2.3) also show clues to the shape and size of the cutting tools, and one may infer the depth of cuts taken on each pass of the cutting tool. A superb example of this effect is shown in Fig. 6.2.3 which is a leveling screw from a reflecting telescope by Ramdsen. The root of a leveling screw by Sisson shows the effects of cutting the root with two different cutting tools (or one which had been reground); this effect was found in several samples.

If one is attempting to confirm the date of a screw, one must take a number of factors into consideration. The most sensitive indicators are the overall scatter of the digitized profiles, the aspect ratio (A/R) and the amount of material left in the thread at the mid-depth line. Fig. 6.2.4a shows the profile of an early screw where the trough is much wider than the remaining part of the thread; modern screws have very little difference, this being defined by the allowable tolerances. These factors are not infallible however, since given the form of the micrometer screw thread in Fig. 6.2.4b one would not have expected it to have been made in the late 18th c--but it was indeed used by William Herschel in his early double star work ca.1780. Using these criteria one might also not recognize the date of screws by John Bird. Fig. 6.2.4c is a screw from a portable quadrant dated 1770 and is typical of those found on Bird quadrants. They are, for the period, finely finished with profiles that are modern in appearance though with a slightly low aspect ratio. Going somewhat against the grain, Bird used more coarsely pitched screws and was able to finish them better than Ramsden who was leading the way among younger makers with his 100 TPI screws. In the end the absolute precision of the finer pitched micrometer screws was better but certainly in comparing the appearance of contemporary screws, Bird's look much the better.



6.2.5 Effect of the curvature of dividing engine wheels. With sufficient threads covered by the shadowgraph, these problems can be eliminated.



6.2.6a (left) Effect of a tapered thread on an eyepiece.
6b Poorly finished thread of a short filter mounting thread.

One type of thread with which the profile method has problems is that on the circumference of dividing engine wormwheels--i.e. the threads on the dividing plate. The reason is that the wheels are curved and, as the profile plotting is presently carried out, it is not possible to correct for the curvature (Fig. 6.2.5). Correction is simple given a sufficient number of threads since one can then subtract a second degree polynomial fit, as was done in measuring the motion of scale micrometers with the dial indicator. But as was noted in the previous chapter, more threads are required in the profile studies of dividing engines which have a very coarse pitch compared to micrometer screws.

Other threads which prove difficult to deal with are those on tubes and eyepieces. This is because these are only a few threads long, sometimes with the end threads tapered to permit them to be more easily assembled. Fig. 6.2.6a shows the appearance of a tapered thread profile. Fig. 6.2.6b shows the profile of a thread for mounting a filter on a late 19th c eyepiece. The form is very variable from thread to thread and one crest is quite pointed suggesting that the maker did not go over the entire thread with his chaser in the final finishing. Tube screws on spyglasses and other thin walled tubes, as one might expect, have a lower aspect ratio (A/R) than for other types of screws.

6.3 Summary and Comparison of Results:

The following tables summarize the most important results of the measurements taken from the profiles and made with the dial indicator. The only thing which may need explanation are the numbers in brackets in the last column. These are the errors of the device after subtraction of the periodic errors which can be matched with a polynomial fit; the degree of the polynomial is in brackets.

Table 6.2

RESULTS OF MEASUREMENTS OF SAMPLES

Table 6.2a

FILAR MICROMETERS

MAKER	YEAR	CODE	PITCH (mm)	DIAMETER (mm)	ERRORS PROFILE	MICROMETER	
N/S (Italian)	ca.1700	SML-3	0.761	5.33	0.023	0.057	0.053
Rowley	ca.1703	WMHS-7a	0.7507	5.46	0.039	0.035	
		WMHS-7b	0.7781	5.46	0.033		
Langlois	1738	PO-1a	0.672	6.62	0.009	0.0147	0.0078(2)
		PO-1b	0.633	6.47	0.016	0.0110	0.0059(3)
		PO-1d-n	0.663	6.62N	0.022		
		PO-1e-n	0.644	6.48N	0.028		
Langlois	1746	PO-7a	0.637	6.58	0.019	0.0218	0.0206(3)
		PO-7b-n	0.628	6.58N	0.025		
Short	ca.1757	SML-42	0.626	7.153	N/A	0.0340	
Berthet	ca.1775	PO-7c	0.404	3.879	0.017	0.0104	0.0085(3)
(on Langlois' 1746 quadrant)		PO-7d	0.392	3.89	0.021		
Dollond & Son	ca.1755	ROG-8a	0.6501	6.955	0.010	0.0279	
		ROG-8b	0.6509	7.03	0.009		
Short, James	1753	PO-2a	0.653	7.16	N/A	0.0148	
		PO-2b	0.650	7.14	N/A	0.0174	0.0170(2)
Heath & Wing	ca.1760	SML-1a	0.769	5.56	0.010	0.0116	0.0104(3)
		SML-1b	0.756	5.56	0.028		
		SML-1c-n	0.755	5.56N	0.057		
		SML-1d-n	0.762	5.56N	0.041		
Bird	ca.1770	MHS-3a	0.640	7.14	0.012		
		MHS-3b-n	0.632	7.14N	0.026		
Ramsden	1775	SML-9a	0.250	2.64	0.009	0.0096	0.0079(2)
Dollond	ca.1780	ROG-7a	0.3866	2.88	0.012		
		ROG-7b	0.3894	2.91	0.008		

Herschel(?)	ca.1780	ROG-1	0.5022	3.627	0.052		
Herschel(?)	ca.1780	SML-28a	0.2767	1.381	0.010		
Herschel(?)	ca.1780	SML-29a	0.4125	1.829	0.021	0.0165	0.0081(2)
Sisson, Jeremiah	ca.1780	SML-26	0.6449	6.35	0.023	0.0105	
Smeaton	ca.1780	SML-8a	0.394	5.79	0.019		
		SML-8b	0.395	5.79	0.014	0.0111	
Ramsden	1791	SML-6a	0.2379	3.891	0.008	0.0056	0.0055(2)
		SML-6b	0.2385	3.941	0.005		
Troughton	1806	SML-40	0.446	6.634	N/A	0.0034	0.0017(4)
Reichenbach	ca.1810	PO-3a	0.310	3.05	0.028	0.0066	0.0026(2)
		PO-3b-n	0.3165	3.05	0.007		
Jones, Thomas	ca.1820	MHS-2a	0.246	3.84	0.005	0.0210	0.0090(3)
		MHS-2b	0.245	3.84	0.010	0.0051	0.0041(3)
Dollond	ca.1820	SML-35a	0.5125	2.357	0.033	0.0076	0.0042(4)
		SML-35b	0.5137	3.523	0.027	0.0049	0.0040(2)
Dollond	ca.1840	ROG-3a	0.2532	3.96	0.009	0.0081	0.0062(2)
		ROG-3b	0.2441	3.96	0.019	0.0198	
Troughton/Simms	ca.1840	ROG-4a	0.2523	4.493	0.011	0.0047	
		ROG-4b	0.2545	4.511	0.016		
		ROG-4c	0.2541	4.521	0.011		
		ROG-4d	0.2543	4.542	0.008	0.0216	0.0197(2)
		ROG-4e	0.2470	2.451	0.013		
N/S (Simms?)	ca.1843	ROG-5	0.5110	3.96	0.010	0.0115	0.068(2)
Wm Simms	ca.1850	MHS-1a	0.2439	3.96	0.008		
		MHS-1b	0.2436	3.96	0.006		
Fuess or Koristka	1855-74	ITT-6	0.5012	4.11	0.009		
Powell & Leland	1864	MHS-9	0.499	3.92	0.024	0.0082	0.0059(3)
		MHS-9-2	0.5002	3.92	0.030		
(French)	ca.1875	SML-5	0.398	8.92	0.008		
Browning	ca.1878	SML-4	0.255	3.96	0.014	0.0060	
Rigaud	ca.1880	PO-8a	0.240	4.732	0.014		

Notes: n=nut

TABLE 6.2b

SCALE MICROMETERS

MAKER	YEAR	CODE	PITCH (mm)	DIAMETER (mm)	ERRORS PROFILE	ERRORS MICROMETER	
Bird	CA.1767	MHS-8	0.473	0.188N	0.038		
Bird	ca.1767	SML-25a	0.5003	0.1676/92	0.018	0.0057	0.0047(3)
Dollond	ca.1767	SML-23c	0.3590	0.1841	0.013	0.0092	0.0089(3)
Bird	1770	MHS-4a	0.504	0.1288	0.012	0.0286	0.0131(3)
		MHS-4d-n	0.499	0.128	0.022		
Bird	ca.1770	SML-24a	0.4704	0.1734	0.030	0.0204	0.0190(2)
Bird	ca.1770	WMHS-8	0.5054	0.1602	0.016		
Bird	1773	MHS-6	0.530	0.281	0.023	0.0060	0.0058(2)
Bird	1773	MHS-7	0.487	0.188	0.032		
Ramsden	ca.1790	SML-13a	0.3559	0.1416	0.012		
Cary	1800	WMHS-5	0.3617	0.1820	0.013		
Troughton/Simms	1828	SML-14a	0.2451	0.1616	0.014		
		SML-14d	0.2439	0.1628	0.010		
		SML-14g	0.2436	0.1628	0.013		
Duboscq	1855-78	ITT-3a	0.5093	5.265	0.030		
		ITT-3b-n	0.5076	5.23	0.019		
Kohl?	1855-78	ITT-5a	0.5004	0.416	0.020		
Miller, F.	1855-78	ITT-8	0.5655	0.666	0.017		
Secretan	1855-78	ITT-4a	0.5020	0.1553	0.015		
Rigaud	ca.1880	PO-8b	0.260	0.1701	0.016		

Notes: n = nut; N = nominal

Table 6.2c

BENCH MICROMETERS/COMPARITORS

MAKER	YEAR	CODE	PITCH (mm)	DIAMETER (mm)	ERRORS		
					PROFILE	MICROMETER	
James Watt	ca.1770	SML-20a	1.397	0.375	0.027		
	ca.1770	SML-20b-n	1.425	0.375	0.046		
Baradelle	1775	WMHS-2	0.8403	0.1739	0.028		
Maudslay	1797	SML-21	0.2537	0.156	0.012		
Barton	1806	SML-22a	0.2739	0.984	0.029	0.0204	0.0193
		SML-22b	0.2484	0.984	0.038		
Troughton/Simms	>1850	WMHS-1	0.5033	0.2402	0.036	0.0472	0.0136
King & Co	ca.1850	MSTB-9	2.550	0.6189	0.008	0.0075	0.0059
Whitworth & Co	1869	MSTB-10	1.269	0.3729	0.032	0.0018	0.0017
Holtzapffel & Co	ca.1870	MSTB-8a	0.6394	0.175	0.013		
Browne/Sharp	1877	MSTB-7	0.6339	0.244	0.013	0.0201	
Siemens Bros.	1881	SML-19a	1.127	0.313	0.018	0.0141	
	1881	SML-19b	1.278	0.344	0.026	0.0087	
Humpage et al.	1890	MSTB-5	2.520	0.3403	0.023	0.0040	
Harvey/Peak	ca.1900	GMMT-2	0.2552	0.1875	0.014	0.0314	
Moore & Wright	ca.1970	- - -	0.6350	7.58	0.006		
Moore & Wright	ca.1970	- - -	0.6360	7.52	0.007		
Moore/Wright	ca.1970	- - -	0.5001	0.3022	0.007		
(Baty)	ca.1970	- - -	0.6363	0.2993	0.005		

Notes: n = nut

Table 6.2d

DIVIDING ENGINES

MAKER	YEAR	CODE	PITCH (mm)	DIAMETER (mm)	ERRORS PROFILE	ERRORS MICROMETER
Chaulnes	1762	IMSS-1a	1.3428	0.720	0.012	0.0051
		IMSS-1b-w	1.3762	0.720N	0.010	
Chaulnes	1762?	IMSS-2a	1.3764	≈0.750	0.012	0.0294[1]
		IMMS-2b-r	1.2199	0.75n	0.020	
French?	ca.1765	IMSS-4	1.213	0.40	0.005	
Troughton	1778	SML-36a	1.709	1.156	0.007	0.0039 0.0026(3)
		SML-36b-w	1.681	1.16N	0.013	
Barton	ca.1820	SML-34a	1.269	0.3115	0.005	0.0041
		SML-34c-r	1.2625	N/A	0.011	
Amici?	ca.1830	IMSS-3a	1.025	0.350	0.011	
		IMSS-3b	1.030	≈0.35	- - -	
Perreaux	1855	ITT-1a	1.242	0.621	0.052	0.0109
		ITT-1b-w	1.430	N/A	0.064	
Perreaux	1855	ITT-2a	0.5009	0.669	0.036	0.0024
Cooke	1872	SML-37a	1.009	1.0058 -1.0117	0.021	
		SML-37b-w	1.007	1.01N	0.023	
Hilger/Blythswood	1887/8	SML-33	1.268	1.438	0.014	

Notes: w = wheel; r = rack; N = nominal

1 This dividing engine exhibited a severe eccentricity in the rotation of the crank which is responsible for this large error.

Table 6.2e

Results of Measurements of Adjusting Screws

MAKER	YEAR	CODE		PITCH	DIAMETER	ERROR
'IDF' (German)	1621	MHS-12	S	0.7287	3.96	0.024
Newton(?)	1671/ca.1760	RS-1b	S	1.020	4.57	0.028
N/S (German)	1736	MHS-5a	S	0.6110	3.18	0.016
		MHS-5b	N	0.6027	3.15N	0.018
Langlois	1738	PO-1c	S	0.9625	7.061	0.017
Langlois	1746	PO-7e	S	0.9538	7.856	0.025
Short	1753/4	PO-2d	S	0.6891	5.535	0.016
Chaulnes	1762	IMMS-1c	S	1.569	11.41	0.013
		IMMS-1d	S	0.7620	5.537	0.018
		IMMS-1e	S	0.7651	5.329	0.007
Chaulnes(?)	1762(?)	IMMS-2c	S	1.000	5.56	0.020
Bird	ca.1767	SML-25b	S	0.6199	3.96	0.029
Dollond	ca.1767	SML-23a	S	0.6044	4.636	0.013
Bird	1770	MHS-4b	S	0.6048	4.338	0.019
Smeaton	ca.1770	SML-8c	S	0.8277	4.37	0.009
Haupois	1787	ROG-6	S	0.5611	7.031	0.028
Gourdin	ca.1790	MHS-11	S	0.4353	1.895	0.013
Lenoir	ca.1790	MHS-15b	S	0.5723	3.332	0.052
Ramsden	ca.1790	SML-13b	S	0.6124	4.750	0.031
		SML-13c	S	0.6169	4.699	0.024
		SML-13d	S	0.6158	4.696	0.013
Ramsden	ca.1790	WMHS-3	S	0.5091	3.581	0.009
Ramsden	1791	SML-6c	S	0.6504	7.264	0.017
Barton	1820	SML-34b	S	0.6360	7.912	0.003
Thomas Jones	ca.1820	SML-11a	S	0.7374	5.390	0.014
		SML-11b	S	0.7149	5.380	0.019
Thomas Jones	ca.1820	SML-11c	S	0.6351	5.822	0.015
Utzschneider/Fraunhofer	ca.1825	WMHS-4	S	0.5166	3.838	0.034
Thomas Jones	ca.1830	SML-12a	S	0.7209	4.582	0.012
		SML-12b	S	0.5256	3.673	0.023
Fortin	1831	PO-6	S	0.4973	3.312	0.020
Ertel & Sohn	ca.1840	SML-10a	S	0.3217	3.983	0.015
		SML-10b	S	0.3205	4.028	0.015
		SML-10c	S	0.3211	4.214	0.019
		SML-10d	S	0.3229	4.018	0.007
Ertel & Sohn	ca.1840	WMHS-6	S	0.3617	3.485	0.011
W. & S. Jones	ca.1840	GMMT-9a	S	0.8020	6.304	0.029
Troughton/Simms	ca.1840	ROG-4f	S	0.6582	4.882	0.043
Spencer, Browning & Rust	ca.1840	RB-3b	S	0.6306	3.637	0.046
		RB-3c	N	0.620	3.63N	0.014
Perreaux	1855	ITT-2b	S	0.9596	6.721	0.025
Duboscq	1855-78	ITT-3c	S	0.5100	3.802	0.018
Miller	1855-78	ITT-9a	S	0.9466	6.00N	0.018
		ITT-9b	S	0.6657	7.00N	0.008
		ITT-9c	S	0.3615	5.00N	0.003
		ITT-9d	N	0.9498	6.00N	0.040
Secretan	1860	PO-5	S	0.5962	5.212	0.044
Dancer	ca.1865	GMMT-1b	S	0.7870	4.674	0.024
Holtzapffel	ca.1870	MSTB-8b	S	0.9894	7.214	0.026
Casartelli, J.	ca.1880(?)	GMMT-6a	S	0.6355	5.944	0.017
		GMMT-6b	S	0.6321	5.926	0.019
G. & M. Simms	ca.1896	GMMT-8	S	0.5117	3.668	0.012
Dietzgen	1912	RB-14	S	0.4975	4.445	0.044

Table 6.2f

Results of Measurments of Leveling Screws

MAKER	YEAR	CODE		PITCH	DIAMETER	ERROR
Thos. Wright	ca.1715?	SML-C098	S	1.131	4.67	0.028
Thos. Wright	1724	MHS-10a	S	0.5709	3.962	0.020
Martin, Ben.	ca.1750	SML-C093	S	1.255	9.50	0.014
Short	1753/4	PO-2c	S	0.7011	6.134	0.047
Martin, Ben.	<1760	SML-C101	S	0.9287	7.061	0.013
(Martin, Ben.?)	ca1760?	SML-C104	S	0.9580	7.01	0.014
Bird	ca.1767	SML-C092	S	1.045	9.19	0.002
Bird	1770	MHS-4c	S	1.058	9.373	0.014
		MHS-4e	S	1.056	9.3N	0.025
Bird	ca.1770	SML-24b	S	1.530	12.7	
Ramsden	1775	SML-9b	S	0.9440	6.96	0.023
Dollond	ca1775?	SML-C094	S	1.054	6.60	0.023
Ramsden	ca.1775?	SML-C095	S	1.337	12.9	0.018
Sisson, Jeremiah	ca.1775?	SML-C096	S	0.6032	4.75	0.015
Sisson, Jeremiah	ca.1775?	SML-C097	S	0.6115	4.78	0.017
?	<1800?	SML-C105	S	0.5782	4.14	0.015
?	<1800?	SML-C106	S	0.7531	5.89	0.010
Troughton, J. & E.	<1806	SML-C100	S	0.8422	5.23	0.020
Troughton, J. & E.?	<1806	SML-C103	S	0.7515	5.28	0.011
Jones W. & S.	ca.1840	GMMT-9b	S	0.6455	8.47	0.031
Ertel & Sohn	ca.1840	SML-10e	S	0.7576	7.978	0.009
Thomas Jones	ca.1830	SML-12c	S	0.7684	8.428	0.016
		SML-12d	S	0.7757	8.357	0.031
Dancer	ca.1865	GMMT-1a	S	0.4669	8.938	0.024
Rothwell	ca.1870	GMMT-7a	S	0.5261	4.636	0.031
		GMMT-7b	S	0.9120	6.731	0.039

Table 6.2g

Results of Measurements of Focus Screws

MAKER	YEAR	CODE		PITCH	DIAMETER	ERROR
Edward Scarlett	ca.1730	MHS-13a	S	0.9293	21.82	0.018
		MHS-13b	n	0.915	21.8	
Edmund Culpepper	<1738	MHS-14a	S	0.8508	21.9N	0.022
		MHS-14b	n	0.8835	21.9N	0.047
Short	1753/4	PO-2e	S	0.4813	4.653	0.014
Watkins	ca.1770	GMMT-3a	S	1.359	9.225	0.022
John Cuff	(unused)	ca.1780	GMMT-5d		S	0.5458
3.909	0.009					
(used)		GMMT-5d	S	0.5424	3.988	0.009
N/S	>1800	RB-5a	S	0.8435	3.548	0.038
Fuess	1855-78	ITT-7	S	0.5001	11.86	0.009
Dancer, J.B.	1880(?)	GMMT-4	S	0.3190	3.576	0.008
Hartnack	1890/1	RB-6a	S	0.4760	3.533	0.021

Table 6.2h

Results of Measurements of Eyepieces

MAKER	YEAR	CODE		PITCH	DIAMETER	ERROR
Newton?	1671/ca.1760	RS-1c	S	1.019	19.0	0.050
		RS-1d	S	1.008	19.0	0.037
John Cuff	ca.1780	GMMT-5a	S	0.837	25.4	0.031
		GMMT-5b	S	0.847	27.0	0.032
		GMMT-5c	S	0.783	26.2	0.027
Herschel?	ca.1780	SML-28b	S	1.131	34.9	0.020
Herschel	ca.1780	SML-29b	N	1.523	34.9	0.036
		SML-29c	S	1.587	7.938	0.048
N/S	>1790	RB-5b	S	0.753	15.09	0.036
		RB-5c	N	0.759	14.3	0.045
Harris & Co.	ca.1840	RB-12a	S	0.945	34.51	0.013
Yeates & Son	ca.1848	RB-4b	N	0.625	17.5	0.009
		RB-4c	S	0.628	18.06	0.047
Broadhurst/Clarkson	>1858	RB-9d	N	0.687	30.2	0.032
Troughton/Simms	ca.1860	MCML-1b	S	1.526	34.9	0.042
Troughton/Simms	ca.1860	MCML-3c	N	0.638	34.9N	0.020
N/S	ca.1890?	RB-11a	S	0.844	17.05	0.025
		RB-11b	N	0.8804	17.9	0.010
(Cooke & Sons?)	ca.1895	RB-13a	S	1.504	31.3	0.030
		RB-13b	S	0.6468	25.4	0.022
		RB-13c	S	0.8629	33.7	0.039
		RB-13d	N	0.875	30.2	0.031

Table 6.2i

Results of Measurements of Tubes[1]

MAKER	YEAR	CODE		PITCH	DIAMETER	ERROR
?	e.18th c?	WMHS-C1	S	0.9871	22.2	0.007
?	e.18th c?	WMHS-C2	S	1.090	22.2	0.022
?	e.18th c?	WMHS-C3	S	0.8788	19.1	0.013
Harris & Co.	ca.1840	RB-12b	N	0.9124	30.2	- - -
		RB-12c	S	0.625	34.5	0.026
		RB-12d	N	0.604	42.9	0.061
VanderVoodt	ca.1845	RB-2a	S	0.850	22.2	0.038
		RB-2c	S	0.8236	22.2	0.033
Omer	1848-50	RB-10a	N	0.834	41.3	0.024
		RB-10b	S	0.853	41.7	0.041
Charles P___s?	ca.1860	RB-1c	S	0.7703	23.09	0.029
		RB-1d	N	0.750	30.2	0.046
N/S	ca.1890	RB-11c	S	0.5505	24.12	0.025
		RB-11d	N	0.553	23.8	0.029
Hartnack	1890/1	RB-6b	N	0.6991	19.1	0.011
Leitz	ca.1890	RB-7	S	0.752	20.3	0.009

[1] Includes joints for tubes, mounting threads for eyepieces to tubes and filters used on eyepieces.

Table 6.2j

Results of Measurements of Tools

MAKER	YEAR	CODE		PITCH	DIAMETER	ERROR
N/S	ca.1775	SML-30	S	1.322	8.456	0.018
Maudslay	ca.1797	SML-21	S	0.2537	3.96	0.021
Maudslay	1800	MSTB-1	S	2.591	8.97	0.012
Maudslay	1800	SML-18a	S	0.5083	9.53N	0.022
		SML-18b	S	0.2547	9.53N	0.009
		SML-18c	S	0.5096	9.53N	0.018
		SML-18d	S	0.7252	9.53N	0.015
		SML-18e	S	0.8102	9.53N	0.036
Maudslay	ca.1800	MSTB-2a	S	1.837	6.56	0.020
		MSTB-2b	S	0.5480	9.53	0.023
Maudslay	ca.1800	SML-32a	S	0.8409	8.042	0.017
N/S	ca.1800	SML-31	S	1.518	7.684	0.029
Maudslay	ca.1810	SML-15a	T	0.7202	9.53	0.032
		SML-15b	T	0.508?	11.1N	0.009
		SML-15c	T	1.231	11.1N	0.034
		SML-15d	T	1.27?	6.35	0.041
		SML-15a	D	0.5046	N/A	0.012
		SML-15b	D	0.5046?	8.13N	0.021
		SML-15c	D	0.2526	8.13N	0.019
		SML-15d	D	0.3159	8.13N	0.012
Deacon, J.	ca.1850	NHM-6	S	0.4170	3.843	0.011
N/S	ca.1850	NHM-5a	S	1.051	6.35	0.037
		NHM-5b	N	1.053	6.3N	0.048
Whitworth	1857	SML-16a	T	2.118	15.9	0.020
		SML-16b	T	2.309	15.9	0.009
		SML-16d	T	2.108	12.7	0.020
Whitworth	ca.1857	SML-17b	D	0.5166	2.38	0.032
		SML-17c	D	0.6316	3.18	0.032
		SML-17d	D	0.7841	3.97	0.025
		SML-17e	D	1.059	4.78	0.031
N/S	1878/9	MSTB-3	S	1.562	41.3	0.035
N/S 0-BA	ca.1970	AAM	T	1.006	6.00N	0.013
N/S 2-BA	ca.1970 (original)	AAM	T	0.8092	4.70N	0.011
N/S 2-BA	ca.1970 (cast)	AAM	T	0.8058	4.70N	0.009
N/S 3-BA	ca.1970	AAM	T	0.7312	4.10N	0.008
N/S 4-BA	ca.1970	AAM	T	0.680	3.60N	0.011
N/S 6-BA	ca.1970	AAM	T	0.5301	2.80N	0.006
N/S 8-BA	ca.1970 (original)	AAM	T	0.4300	2.20N	0.009
N/S 8-BA	ca.1970 (cast)	AAM	T	0.4271	2.20N	0.007
N/S 10-BA	ca.1970	AAM	T	0.3496	1.70N	0.006
N/S 1/16-48(Wh)	ca.1970	AAM	T	0.5292	1.59	0.010
N/S 1/16-56(Wh)	ca.1970	AAM	T	0.4390	1.59	0.019
N/S 1/4-25(Wh)	ca.1970	AAM	T	N/A	1.013	0.011

* D = Die; G = Gauge; T = Tap; N = Nominal

Table 6.2k

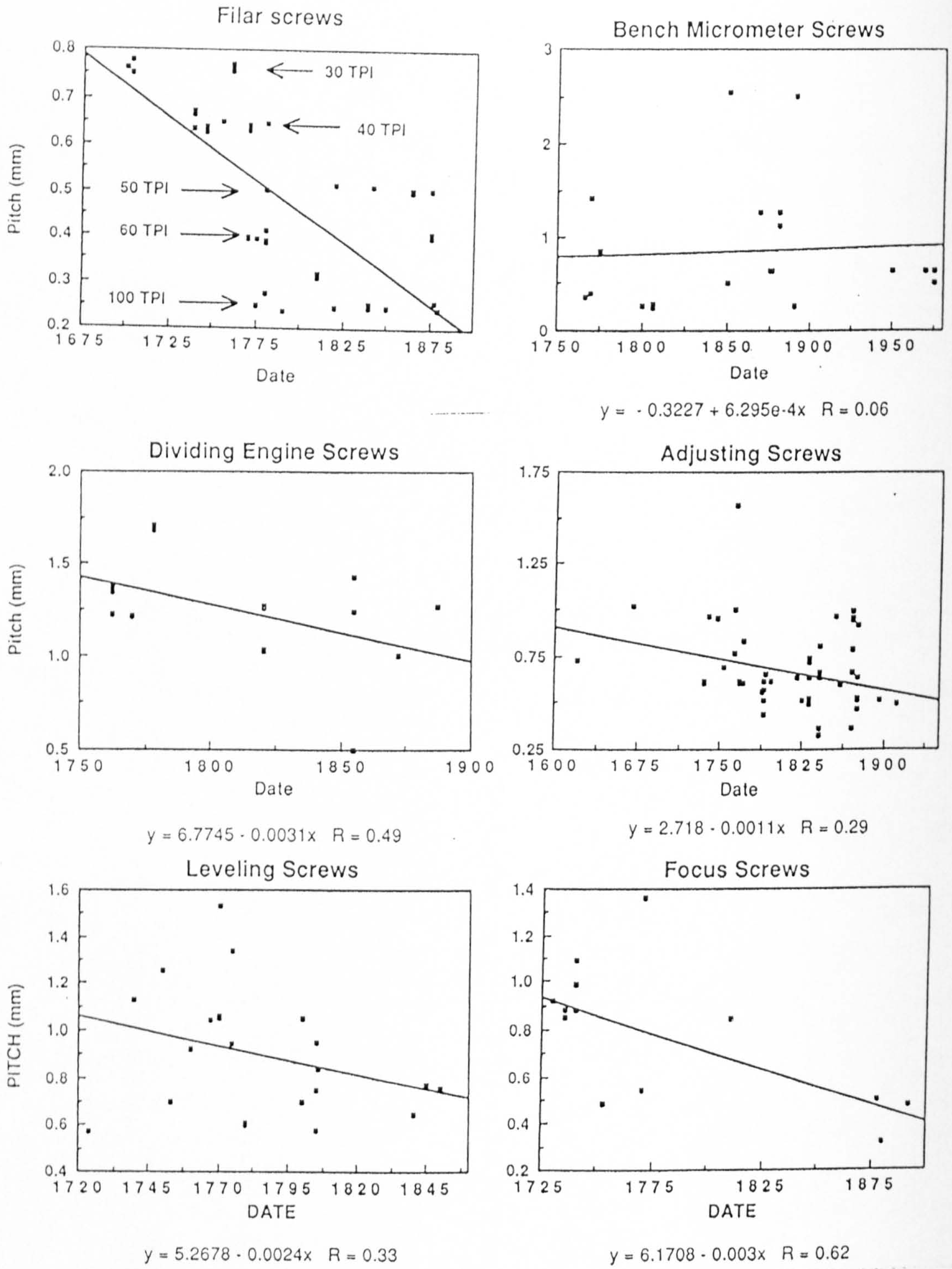
Results of Measurements of Gauges

MAKER	YEAR	CODE		PITCH	DIAMETER	ERROR
Holtzapffel	ca.1870	MSTB-6-2	G	N/A	1.549	0.099
		MSTB-6-4	G	N/A	1.988	0.128
		MSTB-6-6	G	N/A	1.277	0.020
		MSTB-6-10	G	N/A	0.7068	0.021
		MSTB-6-11	G	N/A	0.6391	0.025
		MSTB-6-12	G	N/A	0.4642	0.012
Pratt & Whitney	1899	BA-3	Nut-G	N/A	0.7293	0.010
		BA-3	Sc-G	N/A	0.7210	0.017
		BA-7	Nut-G	N/A	0.4823	0.005
		BA-7	Sc-G	N/A	0.4798	0.010
		BA-13	Nut-G	N/A	0.1883	0.003
		BA-13	Sc-G	N/A	0.1874	0.002
Moore/Wright(Wh)	ca.1970	AAM	G	N/A	0.644	0.008

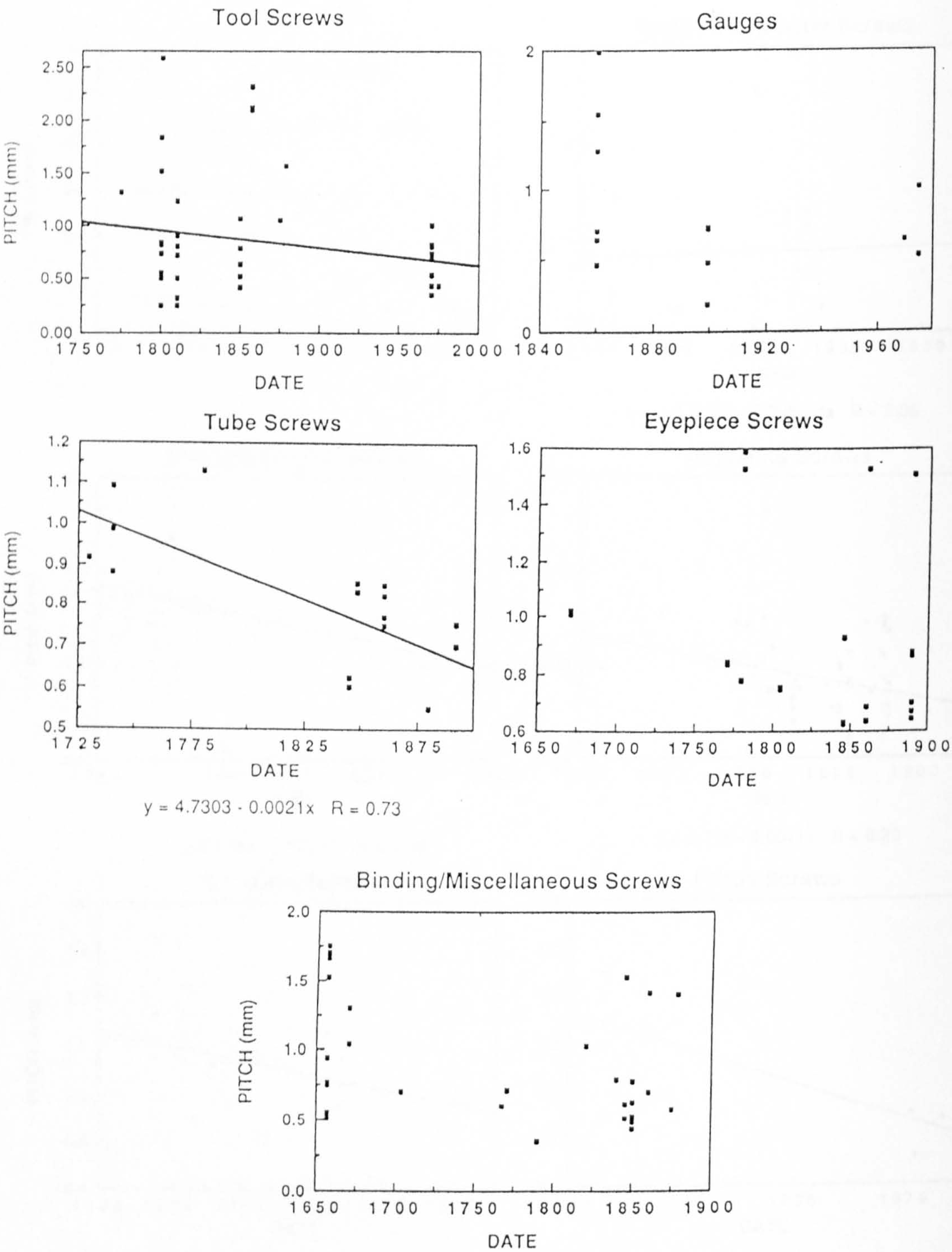
Table 6.2l

Results of Measurements of Binding and Miscellaneous Screws

MAKER	YEAR	CODE		PITCH	DIAMETER	ERROR
van Call	1657	SML-27a	S	1.70	7.706	0.060
		SML-27b	S	1.75	7.836	0.074
		SML-27c	S	1.66	7.805	0.050
		SML-27d	S	1.52	7.805	0.173
		SML-27e	S	0.556	6.213	0.014
		SML-27f	S	0.941	6.193	0.066
		SML-27g	S	0.551	5.418	0.016
		SML-27h	S	0.763	3.493	0.026
		SML-27i	S	0.749	3.112	0.048
		SML-27k	S	0.518	2.281	0.027
Newton(?)	1671/1760	RS-1a	S	1.1297	58.8	- - -
		RS-1e	S	1.042	19.1	0.043
Rowley	ca.1703	WMHS-7c	S	0.7027	3.548	0.029
Dollond	ca.1767	SML-23b	S	0.6068	4.719	0.014
Watkins	ca.1770	GMMT-3b	S	0.7173	5.850	0.035
Ramsden	ca.1790	SML-13e	S	0.3498	2.680	0.013
Deacon, J.	ca.1800?	NHM-2	S	0.4351	2.29	0.075
Deacon, J.	ca.1800?	NHM-3	S	0.783	3.07	0.024
Deacon, J.	ca.1800?	NHM-8	S	0.6312	1.925	0.017
Deacon, J.	ca.1800?	NHM-9a	S	0.5288	1.920	0.011
Thomas Jones	ca.1820	MHS-2c	S	1.031	0.125	0.019
	ca.1820	MHS-2d	N	1.036	0.130	0.012
Troughton/Simms	ca.1840	ROG-4g	S	0.7927	5.685	0.044
Spencer,Browning Rust	ca.1845	RB-3a	S	0.5210	3.564	0.021
Yeates & Son	ca.1845	RB-4a	S	1.528	28.2	0.020
Troughton/Simms	ca.1850	RB-15a	S	0.5769	3.774	0.014
		RB-15b	S	0.5787	3.777	0.016
Chas P___s?	ca.1860	RB-1a	S	0.4903	4.128	0.014
van der Voodt	ca.1860	RB-2b	N	0.7028	18.9	0.029
Broadhurst	ca.1978	RB-9a	S	1.400	6.236	0.012
Clarkson	ca.1865	RB-9b	N	1.405	7.793	0.058
N/S	19^{th} c	NHM-4	S	0.775	tapered	0.033



6.4.1a Date vs. Pitch(mm) for the 'Precision' screw groups.



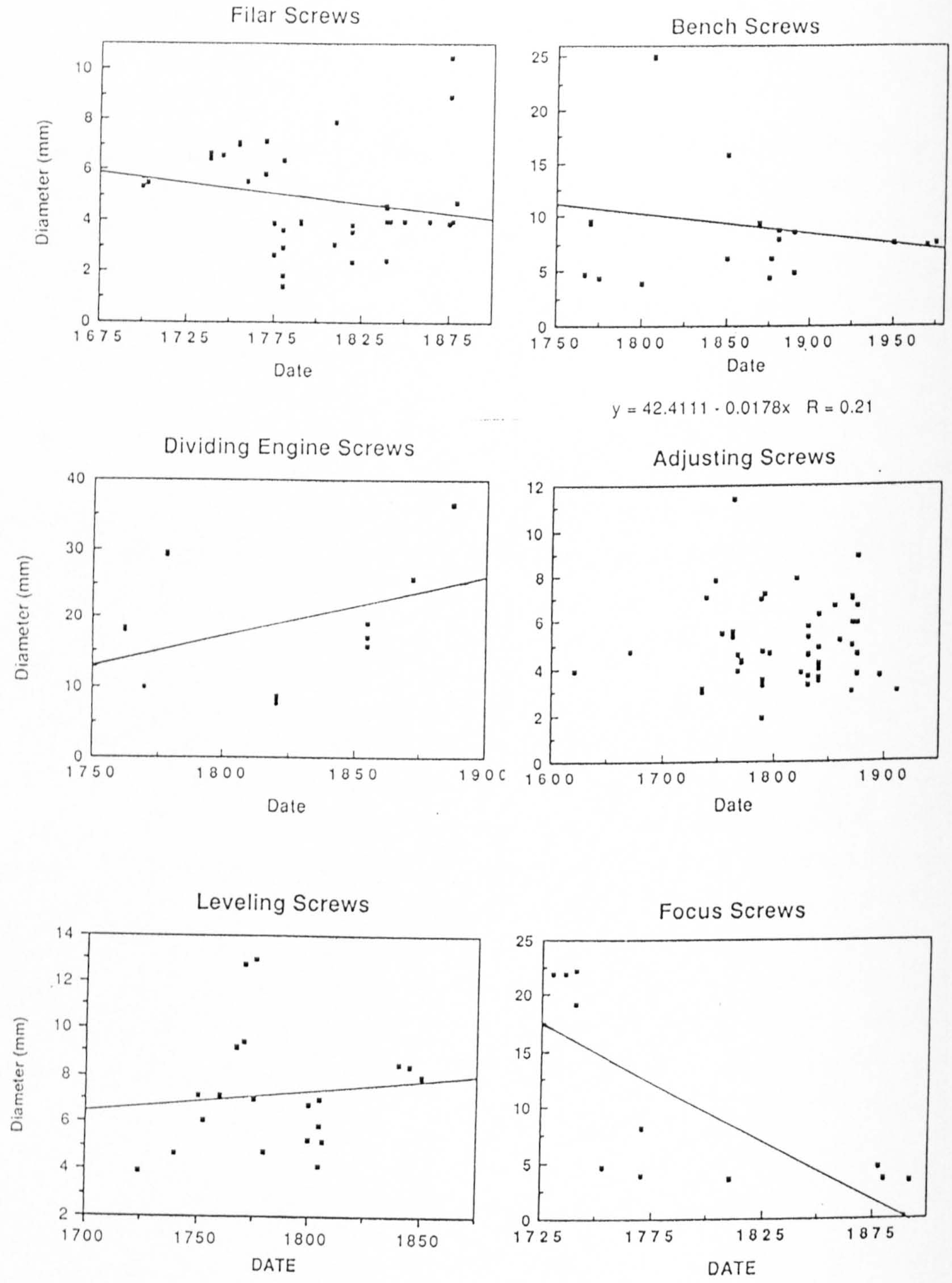
6.4.1b Date vs. Pitch(mm) for the 'Standard' screw groups.

6.4 Graphic Comparisons:

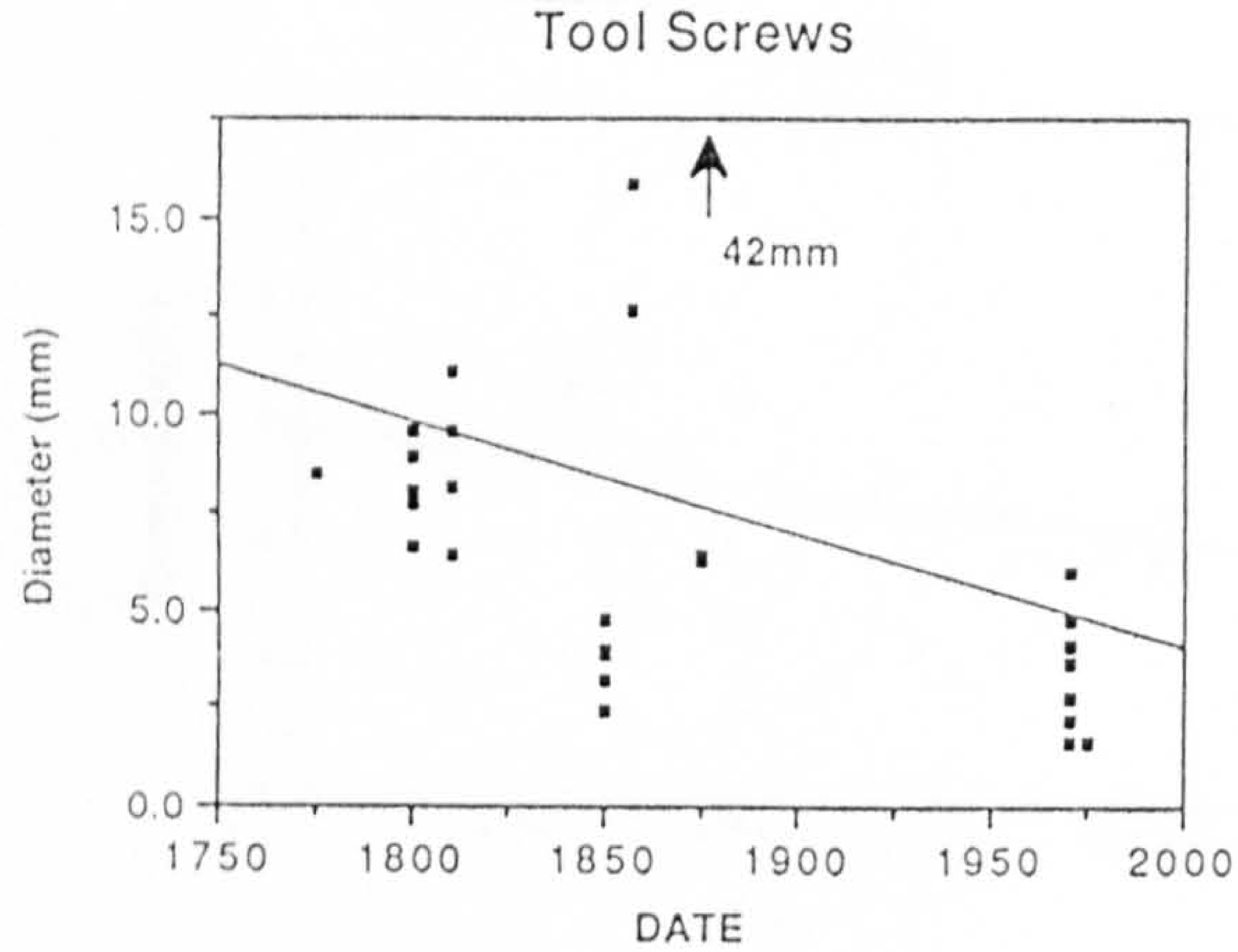
In these graphic comparisons the figures have been grouped in the same positions and in two groups. The first group (Fig. Xa) have 'precision' screws placed together, while in the second group (Fig. Xb) the 'standard' classes have been grouped. A few of the tools and gauges could be placed in the 'precision' category, but the relatively small sample of these classes weakens ones confidence in the results. In the various graphs, the fits to the data are linear least square fits and are provided where there is sufficient data and where it is meaningful. In a few cases a lower limit of the data points is also included and has been plotted parallel to the least square fit. In most cases the formula for the fit is provided below the figure. For the final comparisons the data from filar, scale, bench and dividing engine screws have been combined (Fig. 6.4.12) and designated 'Precision Screws'. Adjusting, focus and leveling screws have also been combined for further comparisons.

6.4.1 Date vs. Pitch (Fig. 6.4.1a/b):

For this relationship the pitch is seen to decrease with time with the exception of bench micrometers. The filar and scale micrometers, which have been combined for these comparisons, show preferred pitches--as one would expect. The 30 and 60 TPI threads are almost invariably scale micrometers; those of 50 and 100 TPI almost invariably filar micrometers. 40 TPI screws were hand made, being about the finest which could be accurately made by that means, and were used for both filar and scale applications. The appearance of 50 TPI and finer micrometer screws coincides with Ramsden's application of the screw lathe. In these graphs the error is primarily in the abcissa though it will be rare for the date to be in error by more than $\pm$10-15yrs. The availability of screw gauges is poor and the results here are basically for only two sets made prior to 1900.

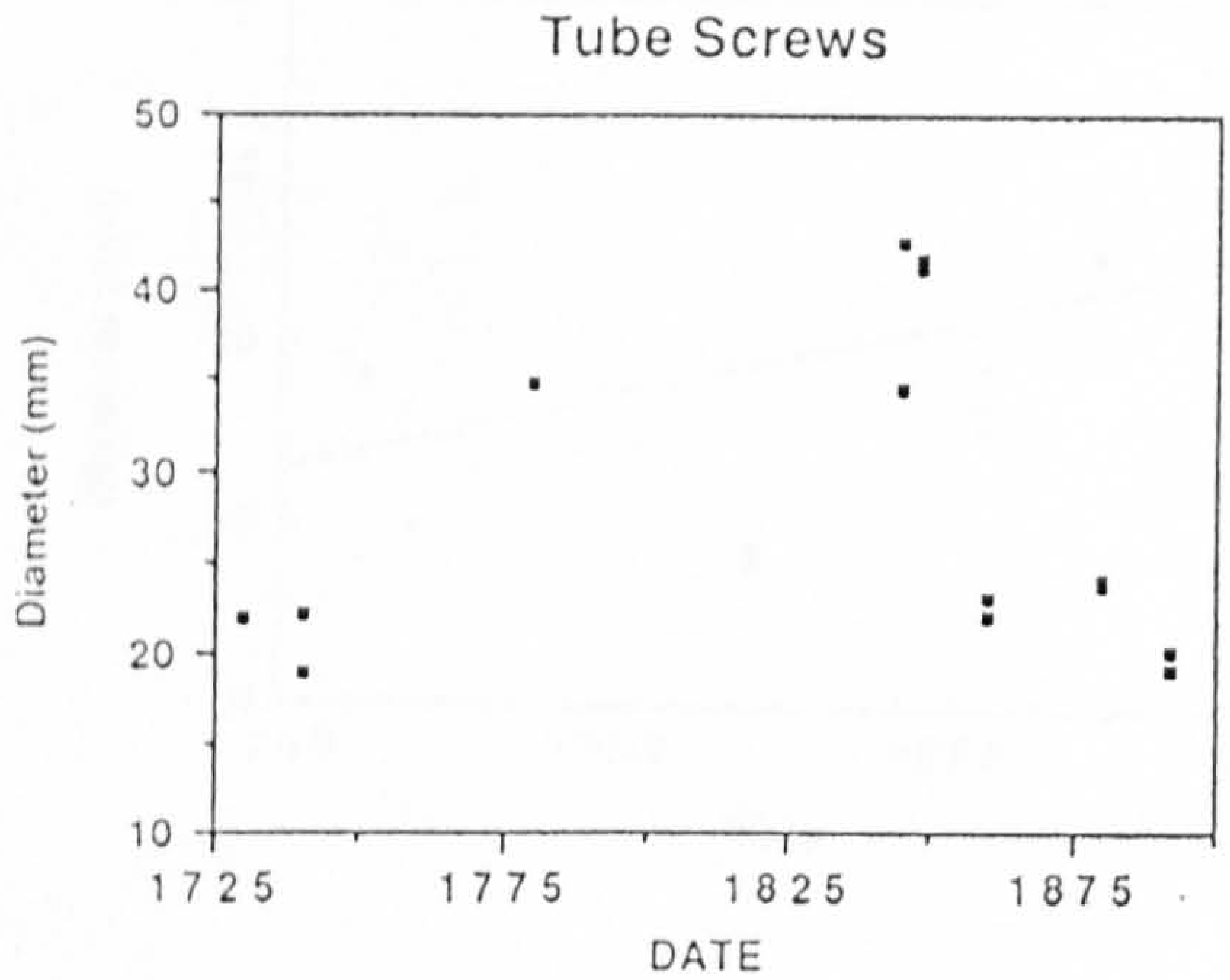


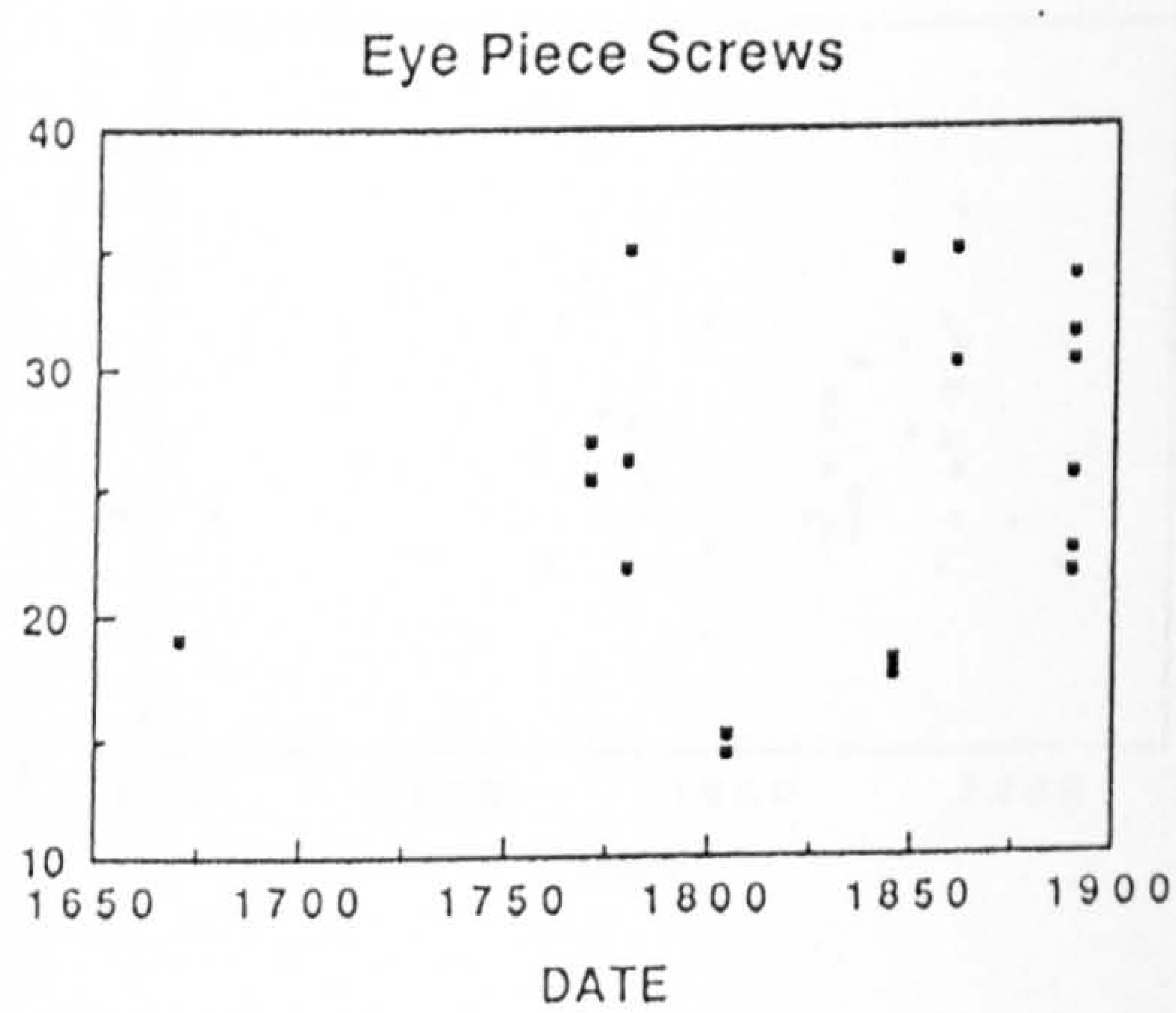
6.4.2a Date vs. Diameter(mm) for the 'Standard' screw groups.

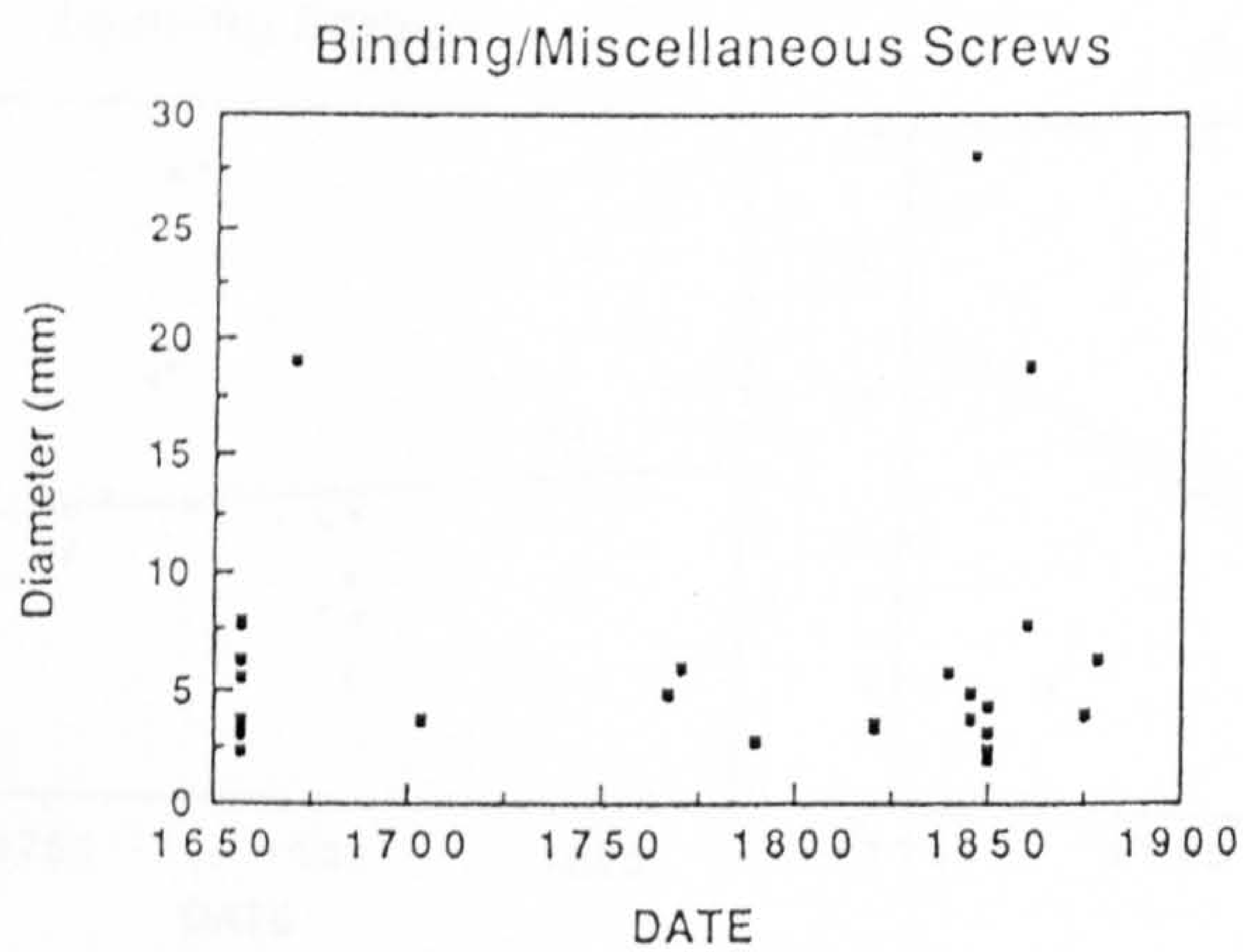


$y = 2.4231 - 0.0011x \quad R = 0.31$

N/A



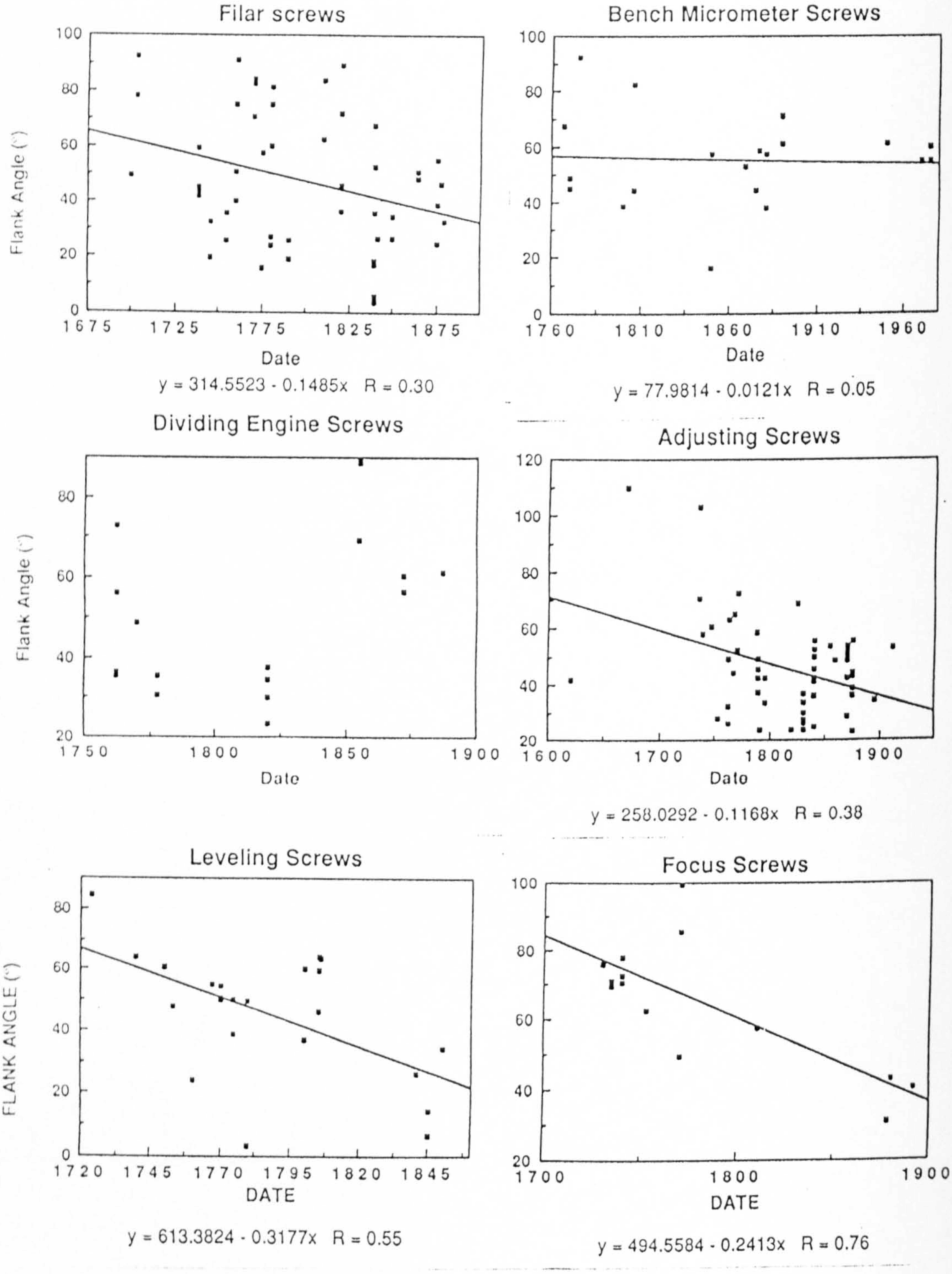




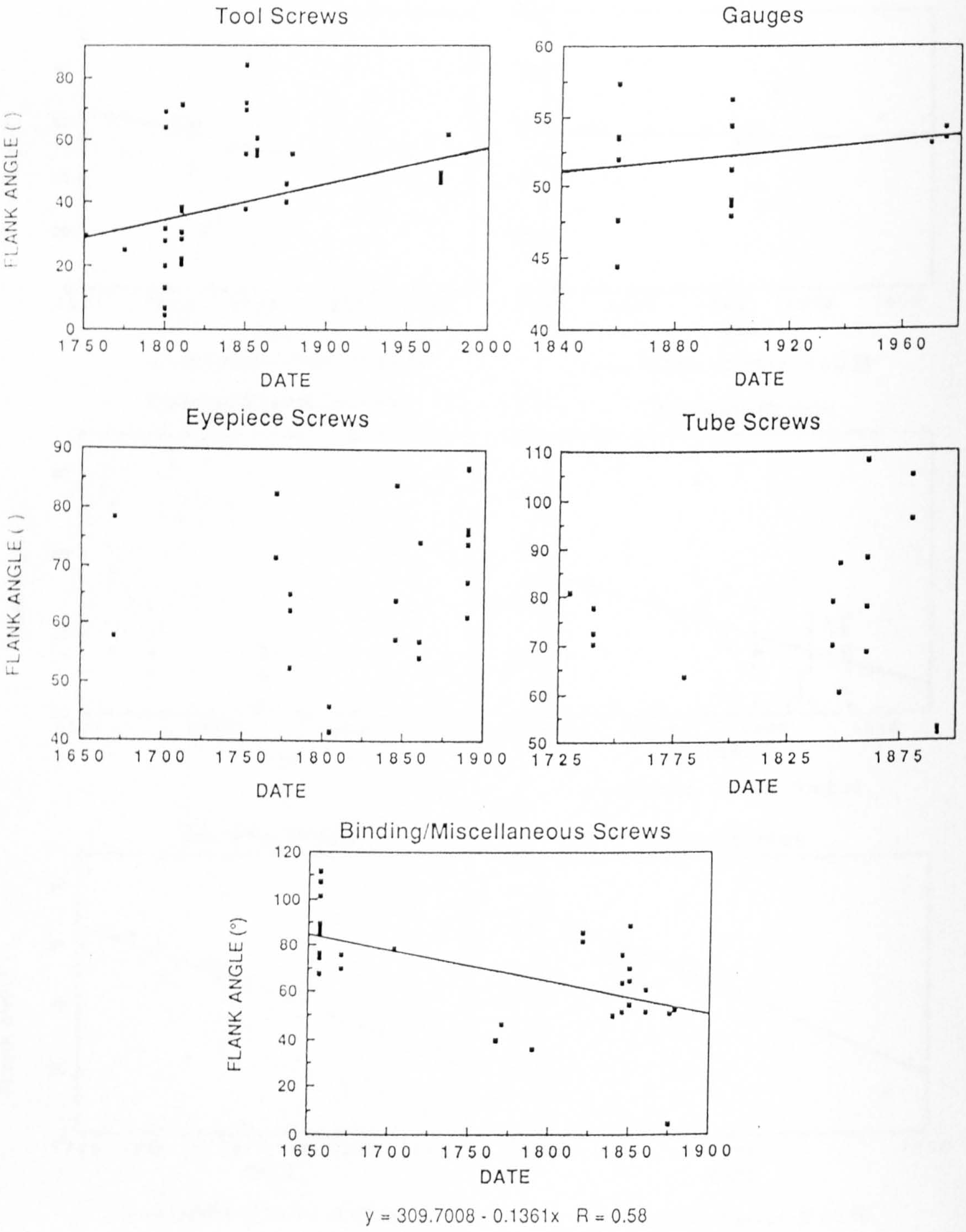
6.4.2b Date vs. Diameter(mm) for the 'Standard' screw groups.

6.4.2 Date vs. Diameter (Fig. 6.4.2a/b):

Date vs. diameter graphs show a wide range of diameters being used for a given application. Again makers of filar and scale micrometer screws showed a preference for diameters of 5-7mm up to ca.1775 and thereafter the diameter dropped to 2-4mm. With a couple of exceptions, bench micrometers have employed 5-10mm diameter screws. Dividing/ruling engine screws started with diameters less than an inch, but the diameter increases with higher precision machines. The largest would have been Ross' screw (§4.3.6) with adjustable faces which was several centimeters in diameter. Leveling screw diameters show a slight increase in diameter reflecting the heavier loads they were designed to carry as time progressed. The apparent dichotomy in eyepiece focus screws is illusory since the large diameter threads in the first quarter of the 18th c result from the inclusion of threads from Wilson screw barrel microscopes. Rods on focusing mechanisms for telescopes were 4-5mm in diameter with little variation.



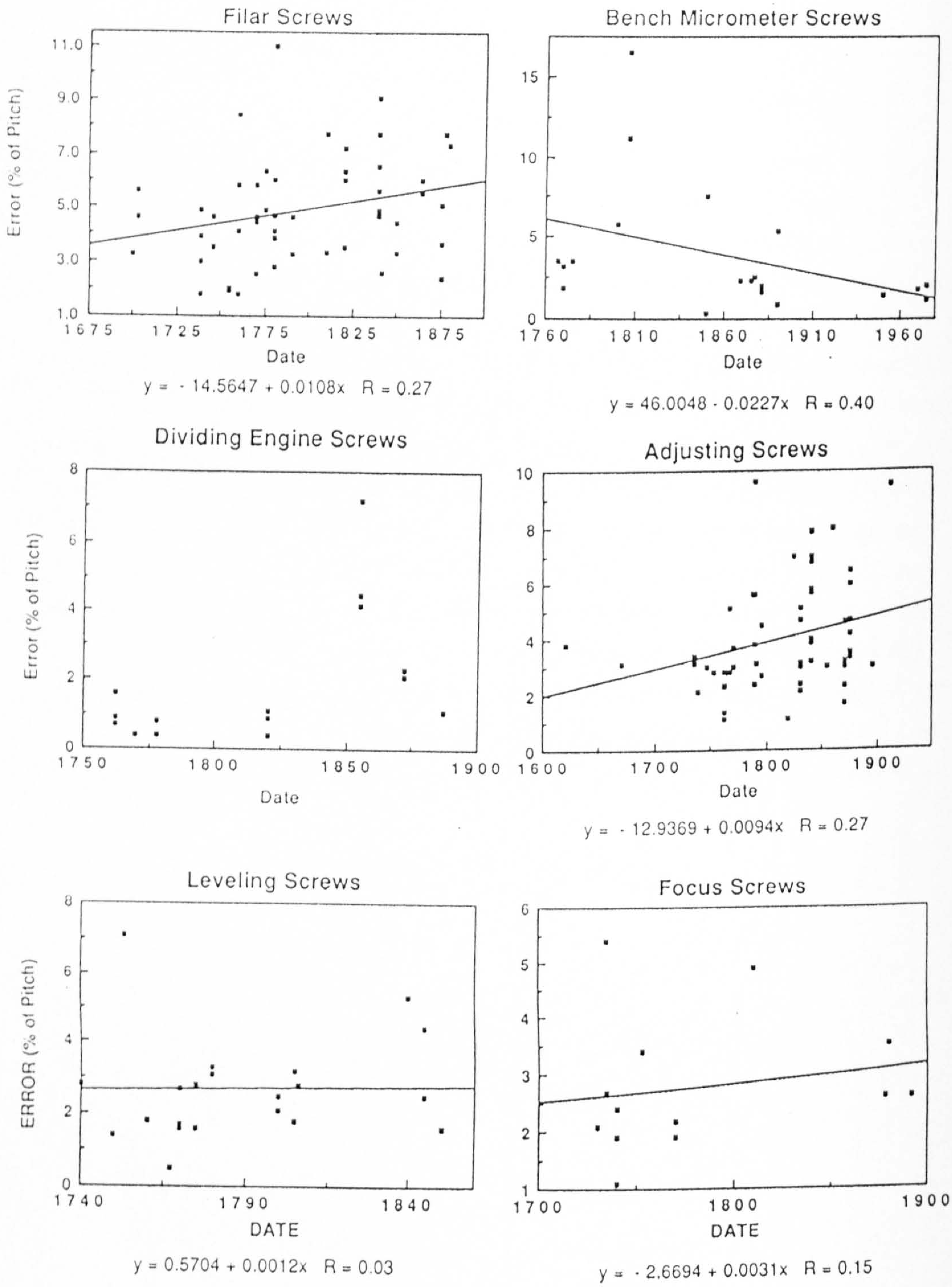
6.4.3a Date vs. Flank Angle(°) for the 'Precision' screw groups.



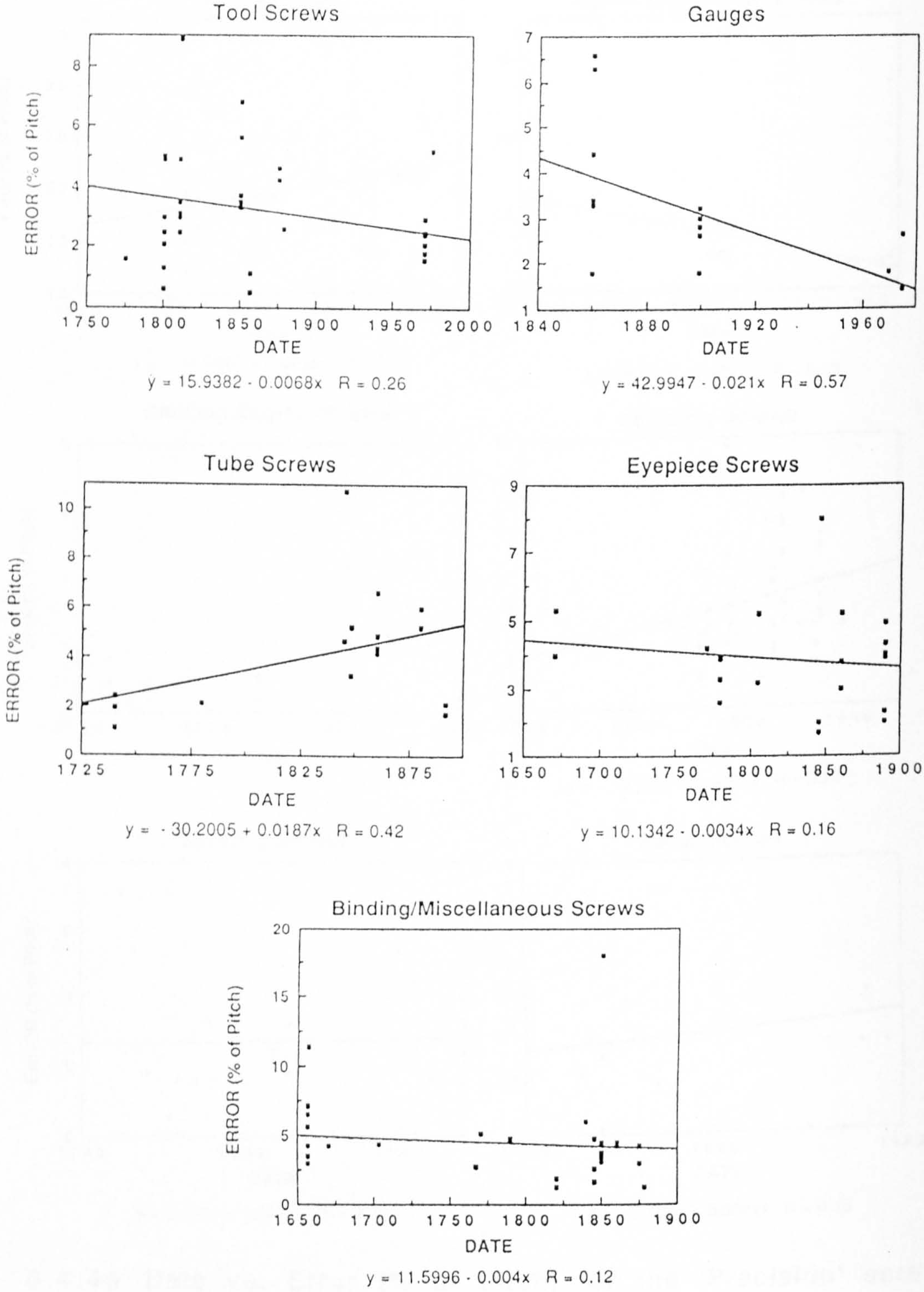
6.4.3b Date vs. Flank Angle(°) for the 'Standard' screw groups.

6.4.3 Date vs. Flank Angle (Fig. 6.4.3a/b):

Flank angles of the various classes of screws appear to have decreased in a temporal manner. The impact of standardization of flank angle (ca.1850's) is best seen in the bench micrometer, tools and binding/miscellaneous screws. The scatter in these classes is a good indication of the precision with which screws were being made late in the 19^{th} c. Tube and eyepiece screws have large angles but this is to be expected since the allowable depth of the thread in thin walled tubes is small. The small angles employed later in leveling screws can again be attributed to load factors. Other than 'fashion', it is difficult to understand why there was such a preference by some makers for small flank angles in filar and adjusting screws from ca.1825; one answer may be that makers were following Maudslay's use of square threads on his lathes but on a smaller scale on the assumption that they could be more precisely made. Early hand-made screws are likely to have large ($\approx$70°+) flank angles; if they are consistently less than 60° on a given instrument, then an early origin should be considered suspect. As in the previous set of graphs the larger error is due to dating of the instruments, though the flank angles of fine pitched screws can only be considered to be accurate to $\pm$5° (see Fig.5.2.10).



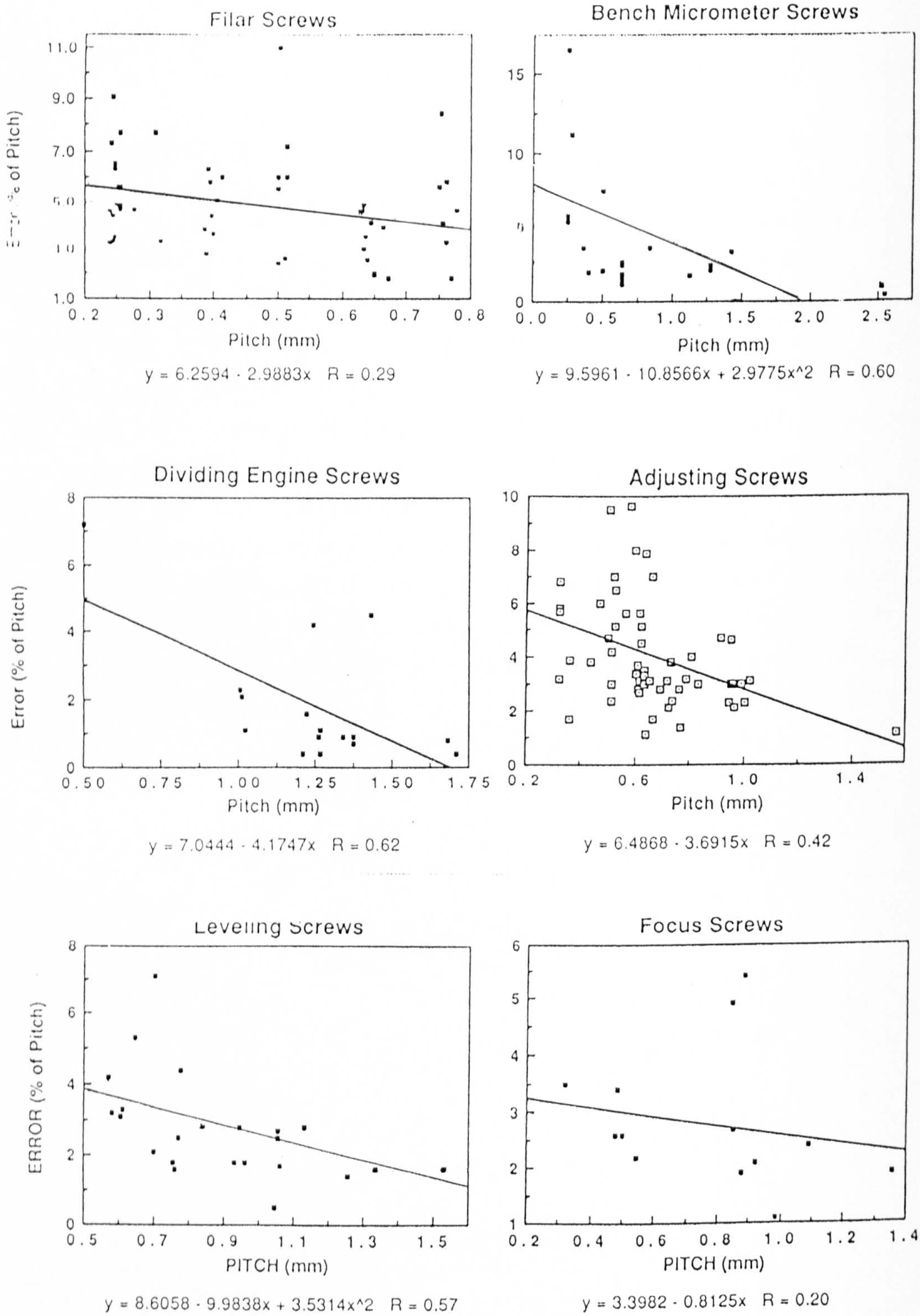
6.4.4a Date vs. Error (% of Pitch) for the 'Precision' screw groups.



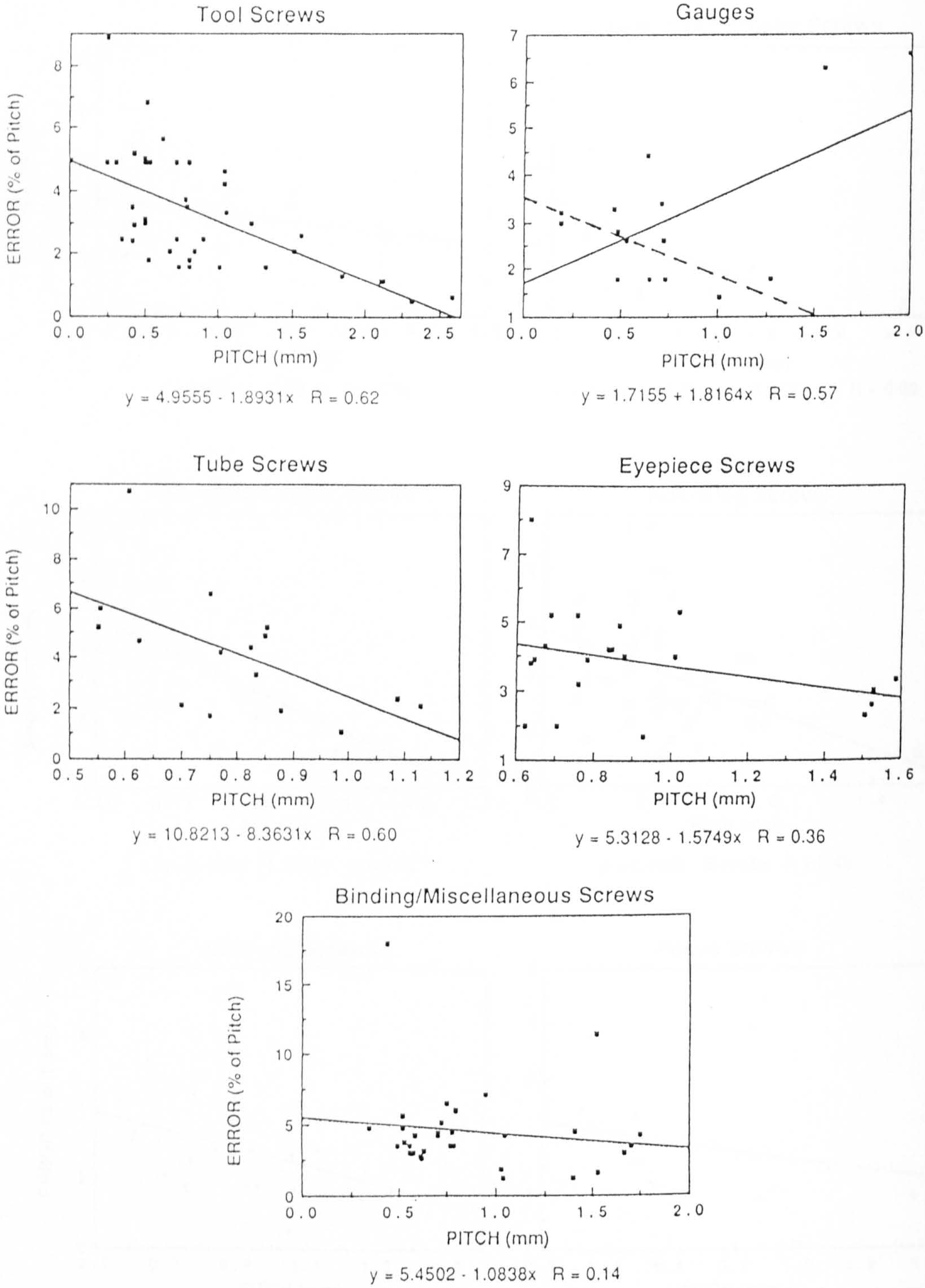
6.4.4b Date vs. Error (% of Pitch) for the 'Standard' screw groups.

6.4.4 Date vs. Error (% of Pitch) (Fig. 6.4.4a/b):

This set of graphs provided the most unexpected results. It was anticipated that the error expressed as a percent of the pitch would decrease in all classifications. However, the decreasing diameter and pitch for some classes obviously affected the accuracy of production. The overall accuracy was increasing but by adopting smaller diameter and pitch, makers were being counterproductive since, the smaller the screw, the less accurately it could be produced. In bench micrometer screws, where the diameter was more or less constant, the error decreased. This was also true of binding/miscellaneous screws but not of adjusting screws. What is surprising is the large error found for filar screws, for which (other than wear which was not particularly prevalent) the reason is not immediately obvious. Clearly, makers of such screws were under the illusion that finer was more accurate--a trap that Varrell (1982) fell into more recently. Wear can be invoked as the cause in the Cooke dividing engine (1872) since the samples were obtained from the part of the thread where contact was made, and this engine is set up to demonstrate the operation at the push of a button by museum visitors. The large errors in the Perreaux machines is probably due to lack of care by the maker--these machines do not appear to be intended for high-precision work.



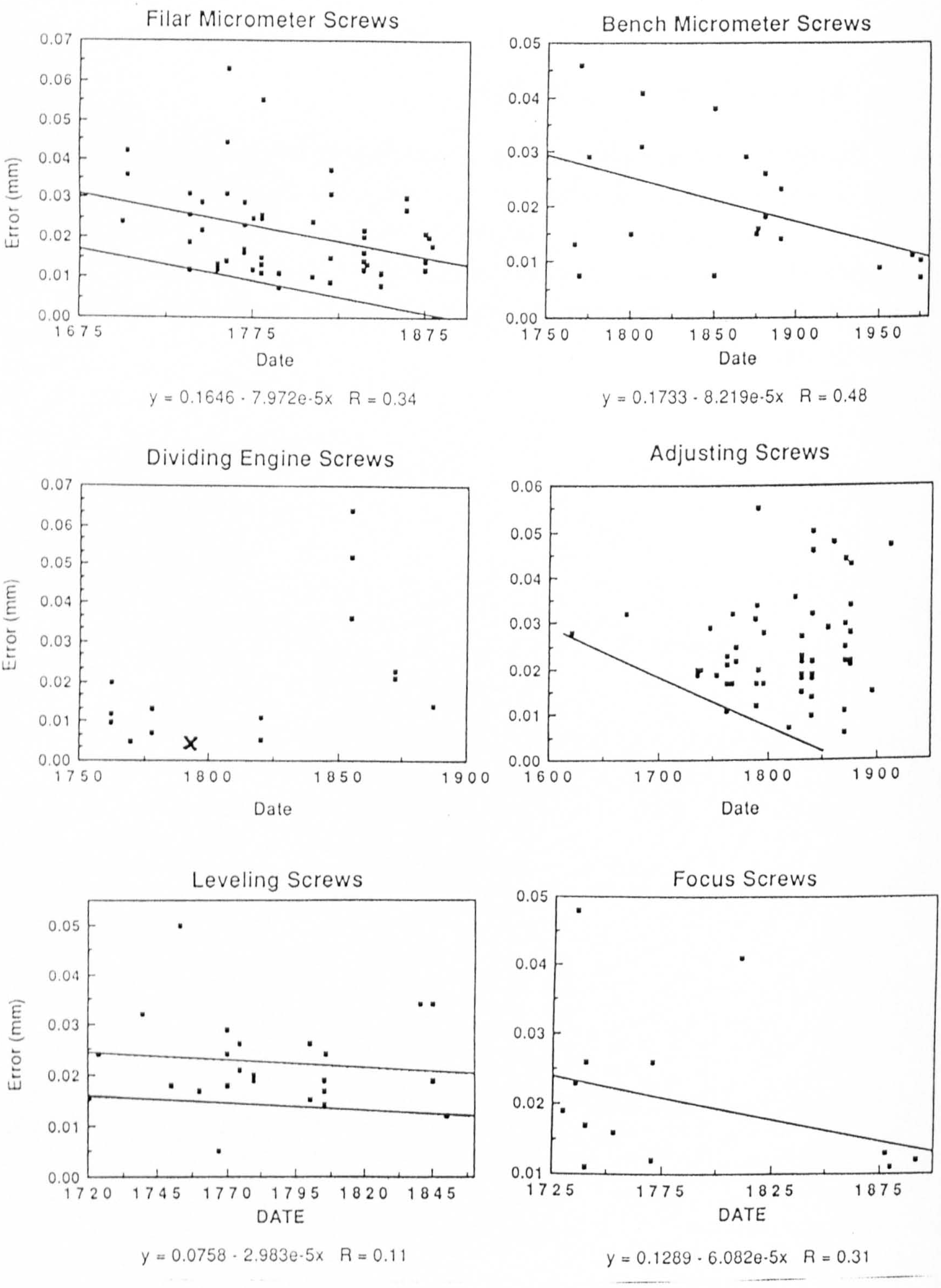
6.4.5a Pitch(mm) vs. Error (% of Pitch) for the 'Precision' screw groups.



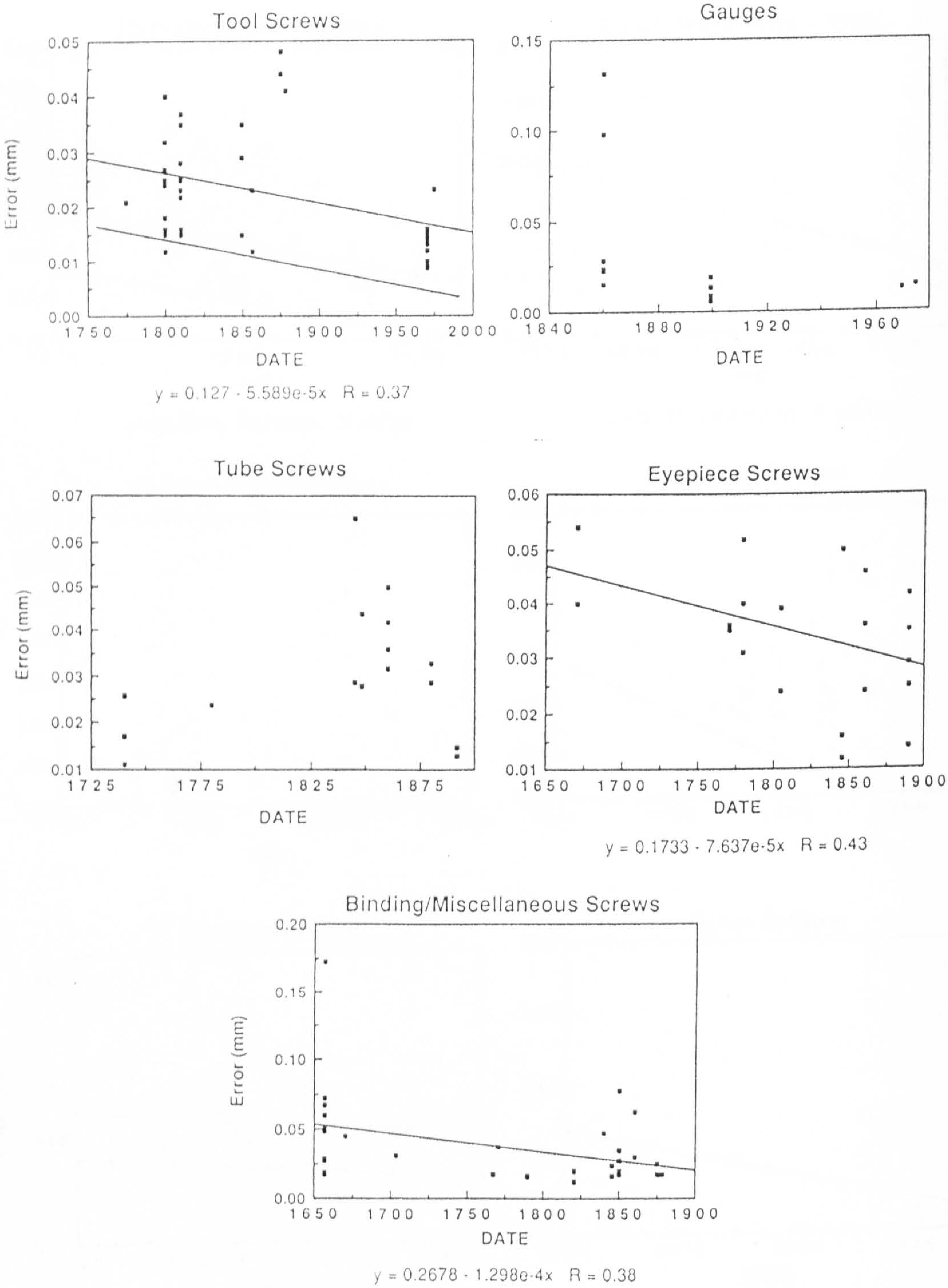
6.4.5b Pitch(mm) vs. Error (% of Pitch) for the 'Standard' screw groups.

6.4.5 Pitch vs. Error (% of Pitch) (Fig. 6.4.5a/b/c):

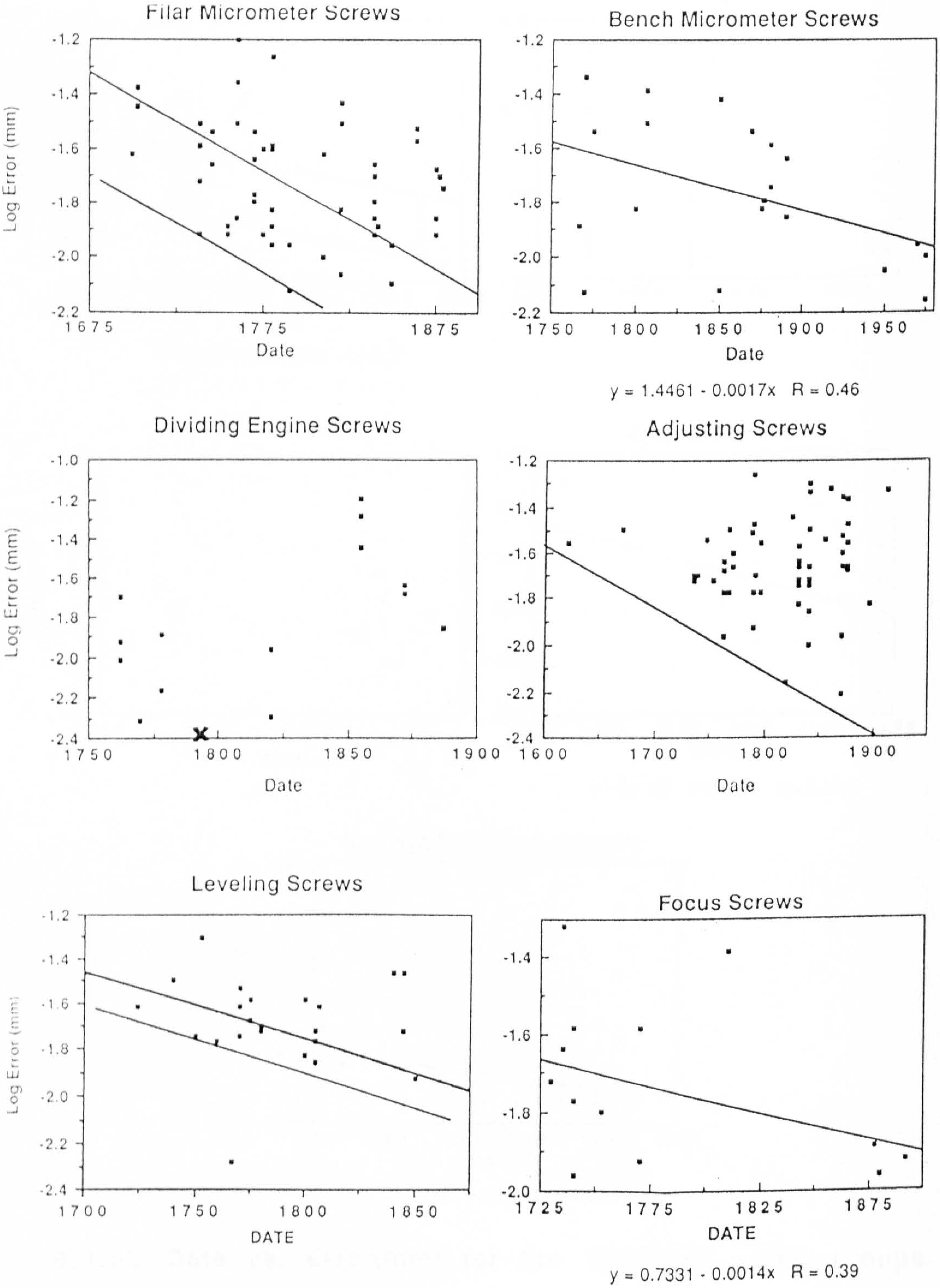
To counter the concerns raised by the findings of the previous comparison, the error as a percentage of pitch is as one would expect, i.e. decreasing as a function of increasing pitch. The one exception is the gauges and here the fit is adversely affected by two points which are for early (1850's or 60's) Holtzapffel gauges which leave something to be desired in their precision. Leaving these two points out the fit (dotted line) has the decreasing slope anticipated.



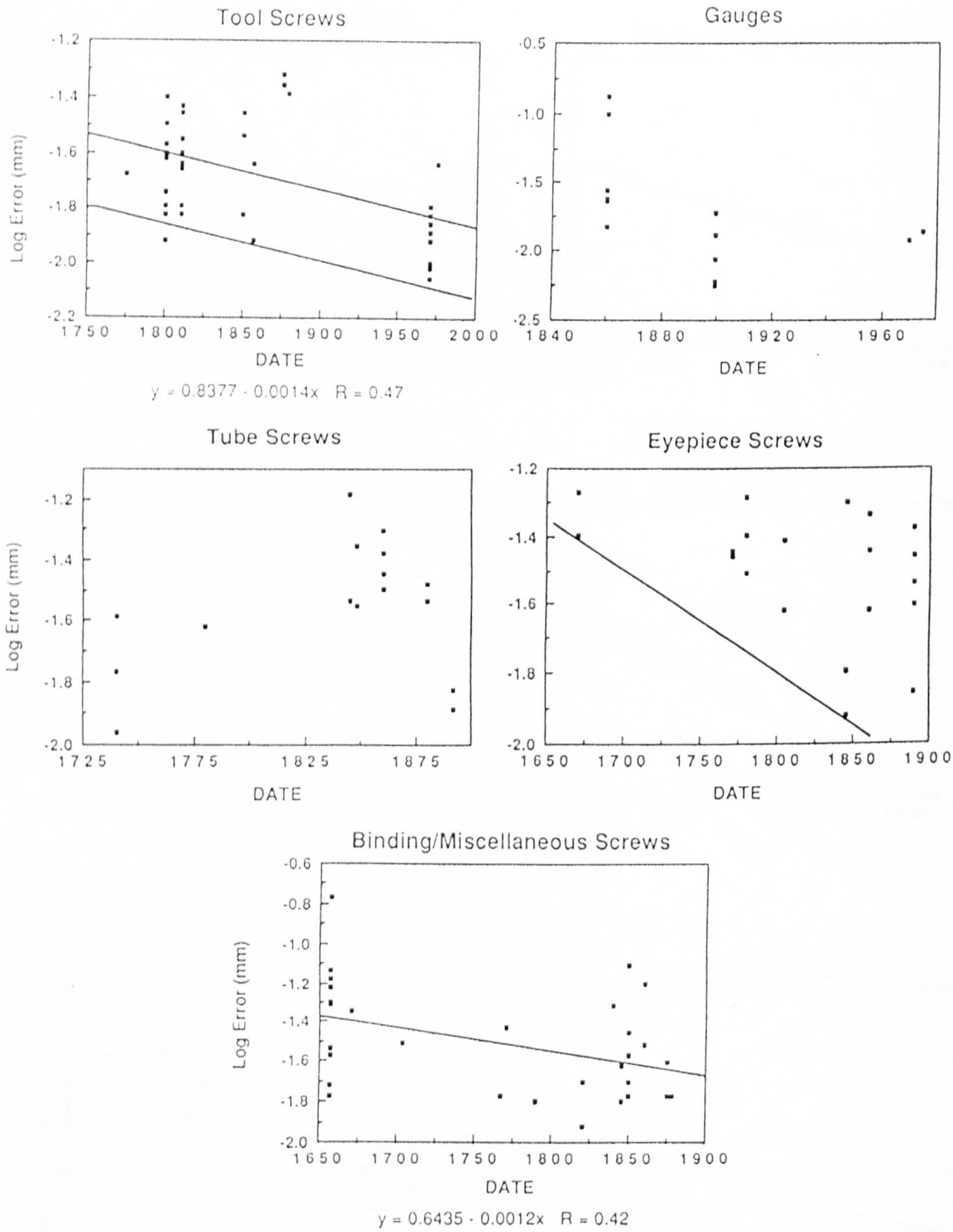
6.4.6a Date vs. Error(mm) for the 'Precision' screw groups.



6.4.6b Date vs. Error(mm) for the 'Standard' screw groups.



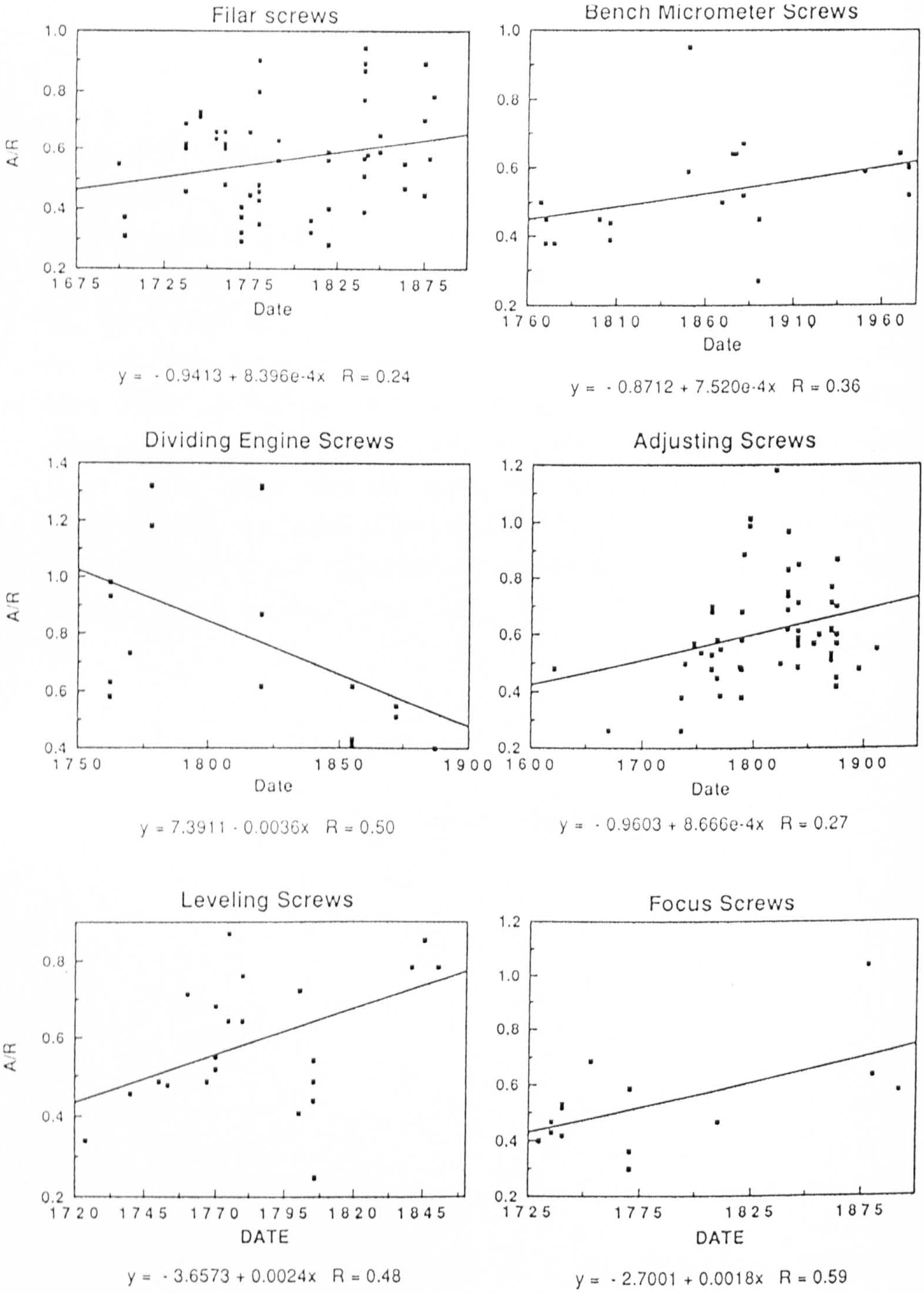
6.4.7a Date vs. Log Error(mm) for the 'Precision' screw groups.



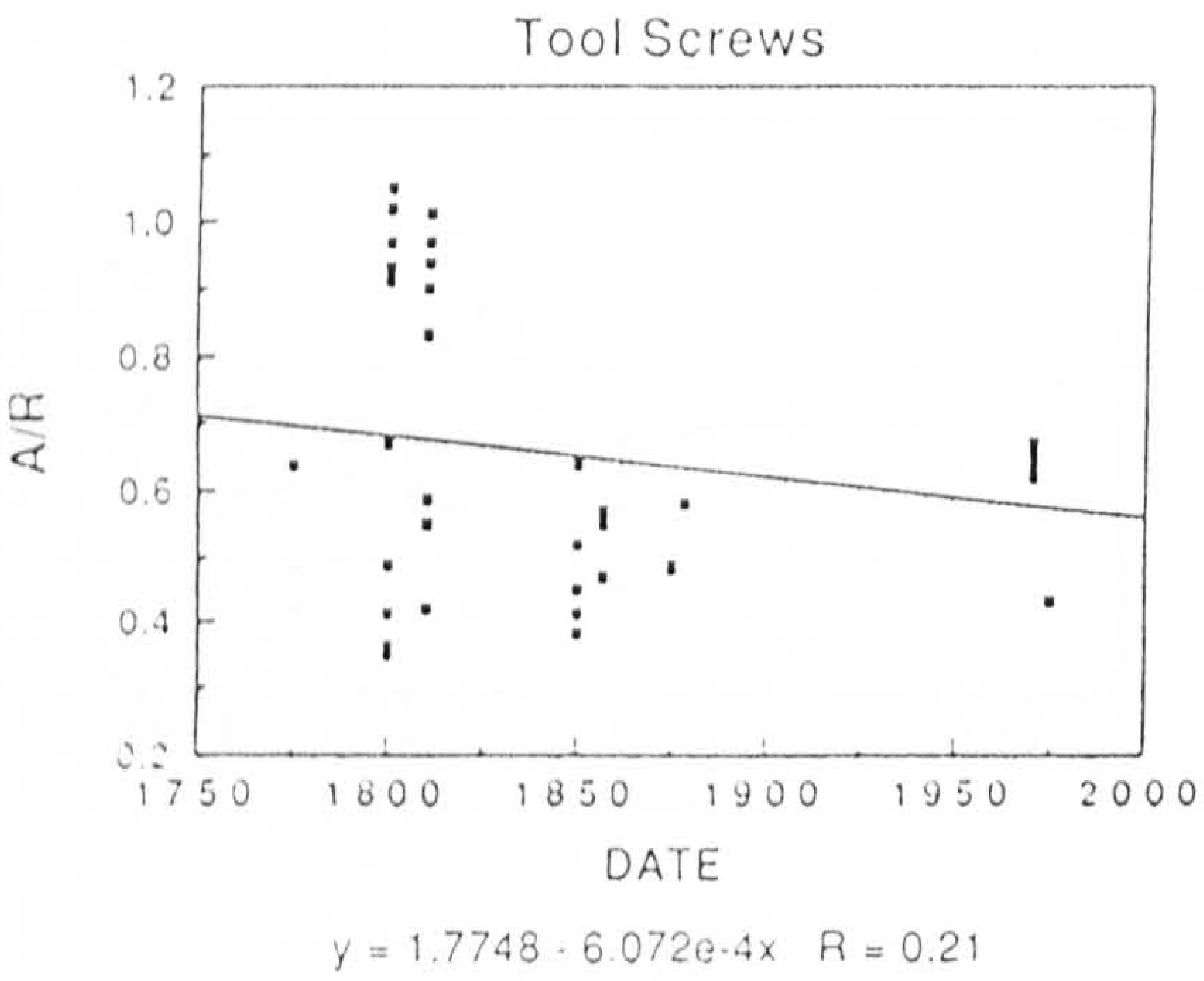
6.4.7b Date vs. Log Error(mm) for the 'Standard' screw groups.

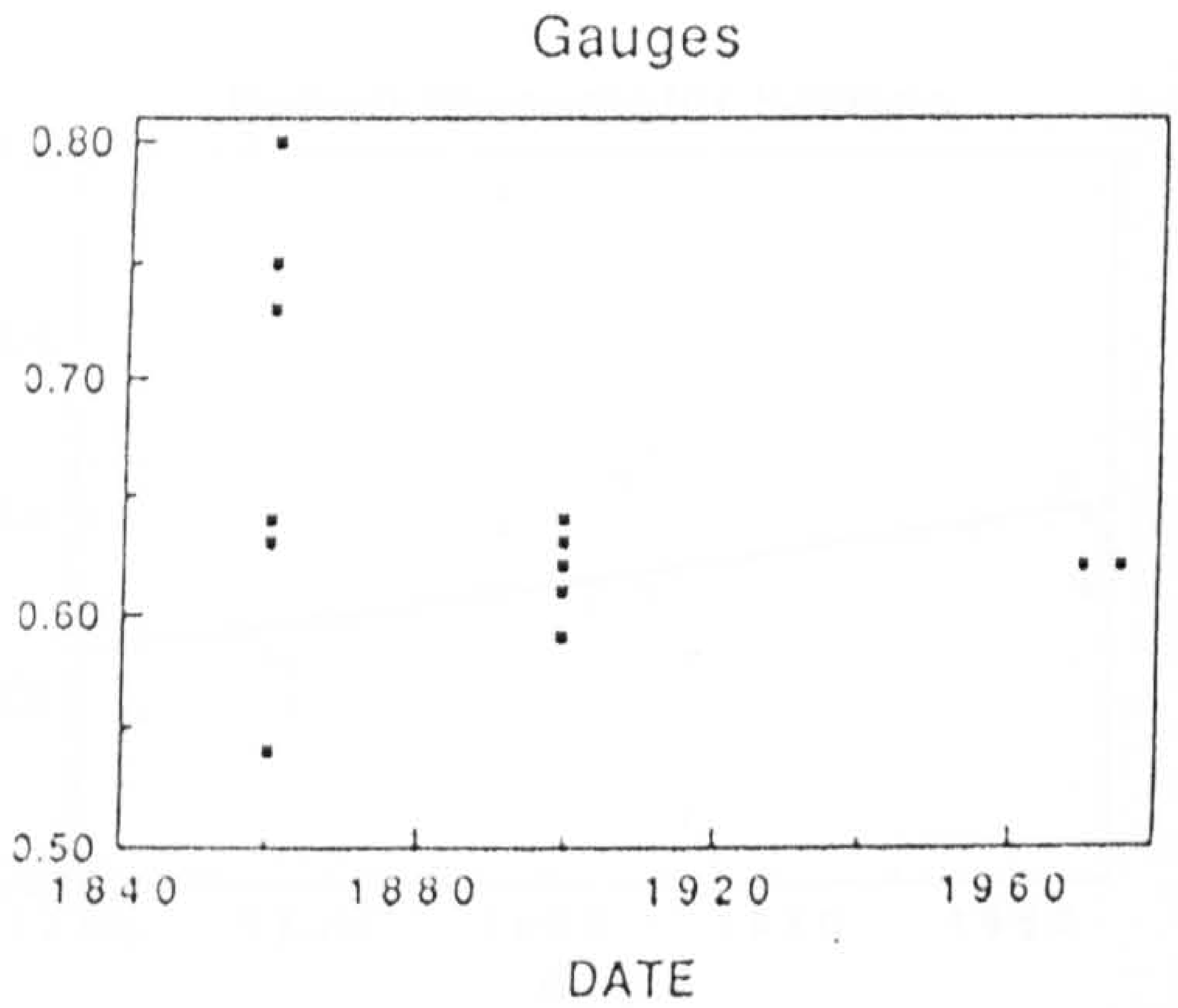
6.4.6 Date vs. Error (mm) (Fig. 6.4.6a/b/c) and Date vs. Log Error (mm) (Fig. 6.4.7a/b/c):

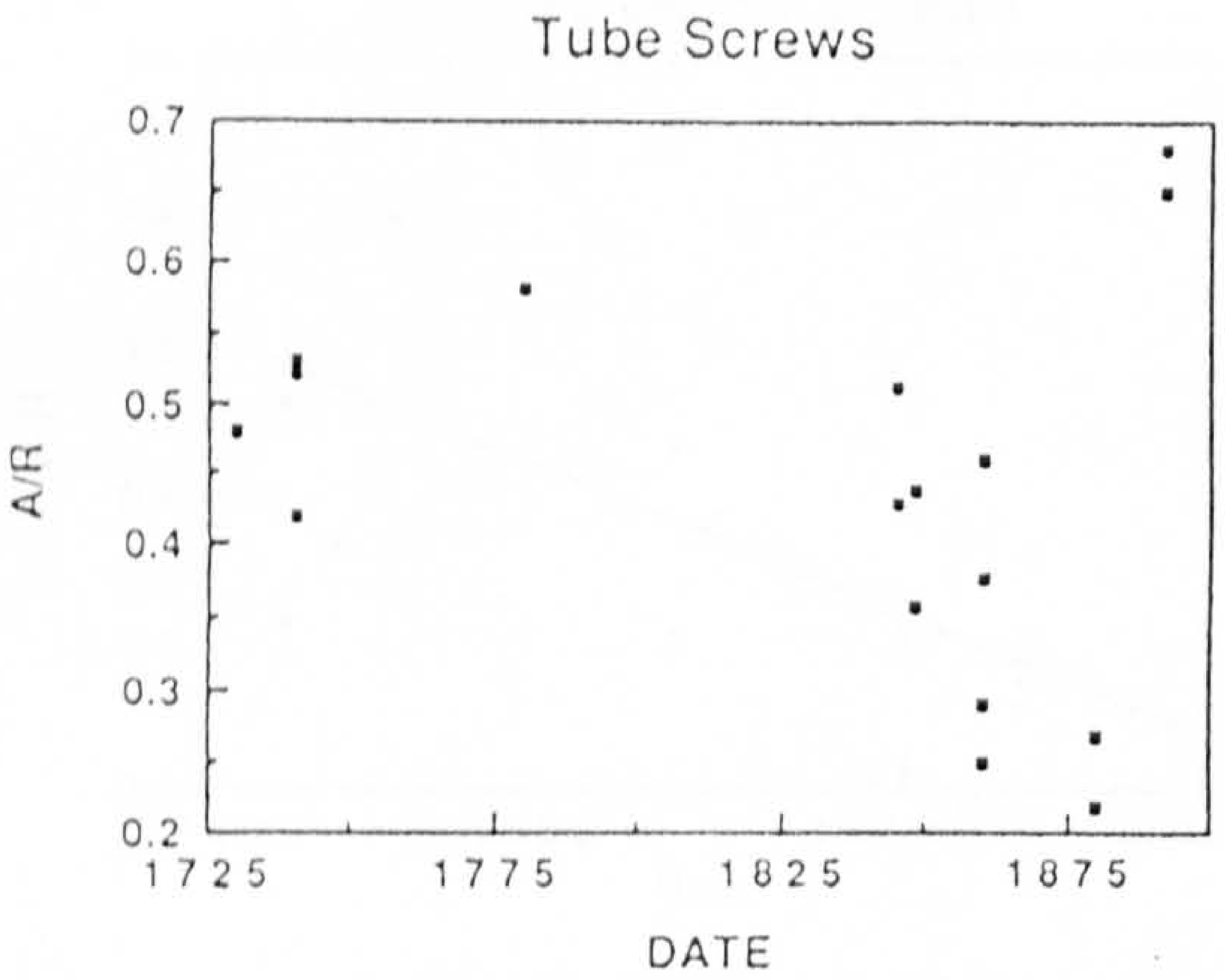
The graphs of date vs error and log error are probably the most useful results of this work since they provide an estimate of the best accuracy obtainable at a given time and can be compared with the results of Chapman, Turner, etc. The lower envelope (drawn parallel to the linear fit) of the filar and scale micrometer screws is interpreted to be the limit of accuracy obtainable with precision tools. This limit is occasionally exceeded in dividing engines for the period studied, but they must be considered as exceptional pieces of apparatus. With an occasional exception, few mechanisms made before 1900 exceeded an accuracy of 0.008-9mm. The log error plot--particularly for filar/scale micrometers, adjusting, leveling and tool screws--shows the linear nature of this lower envelope and agrees with the suggestion of Lienhard (1979) that there is a logarithmic relation between time and rate of improvement of mechanisms. The 'X' marked on the Dividing Engine Screws graphs is the error claimed by Troughton for his circular dividing engine (1793) discussed in §6.7.1.

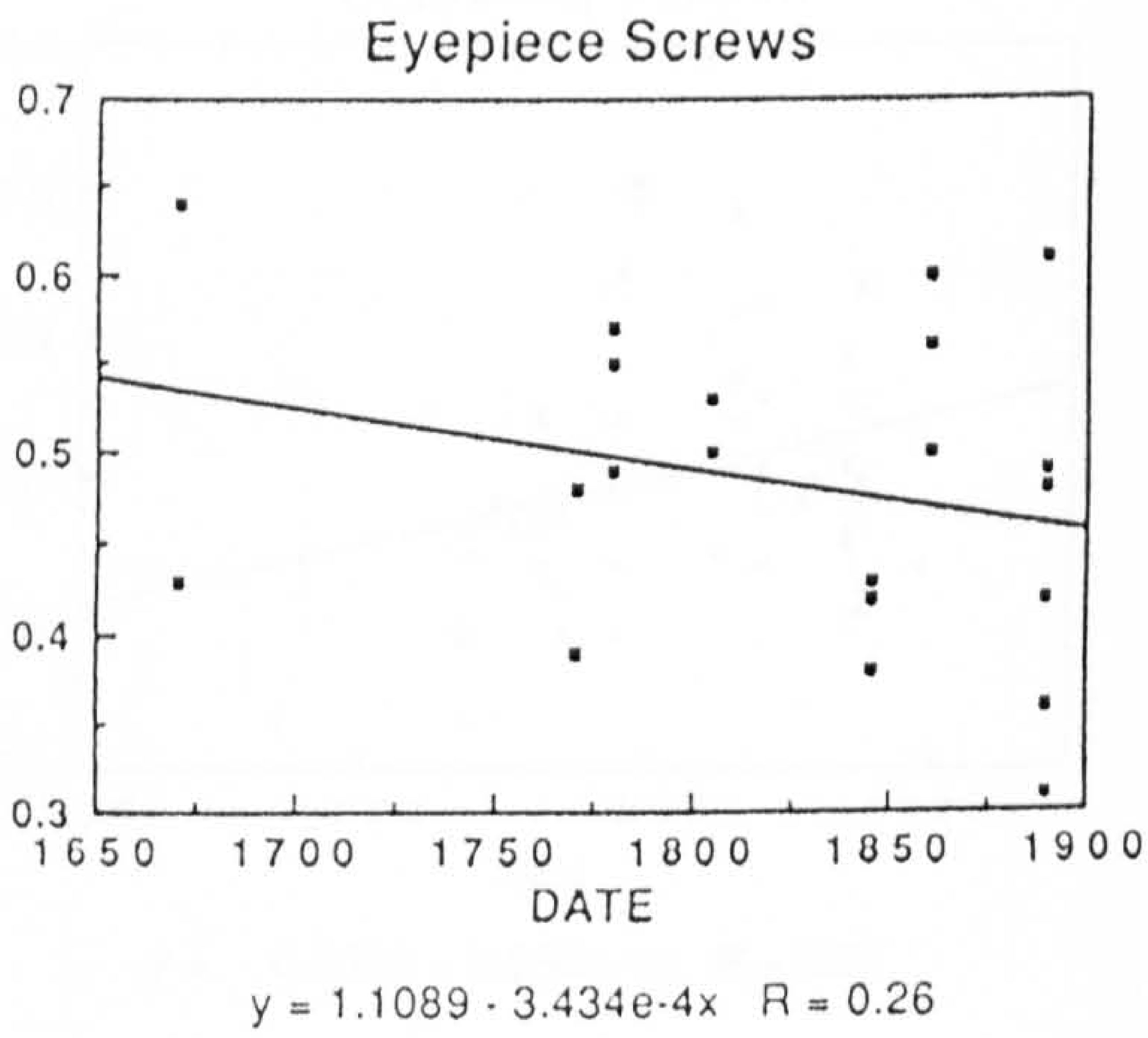


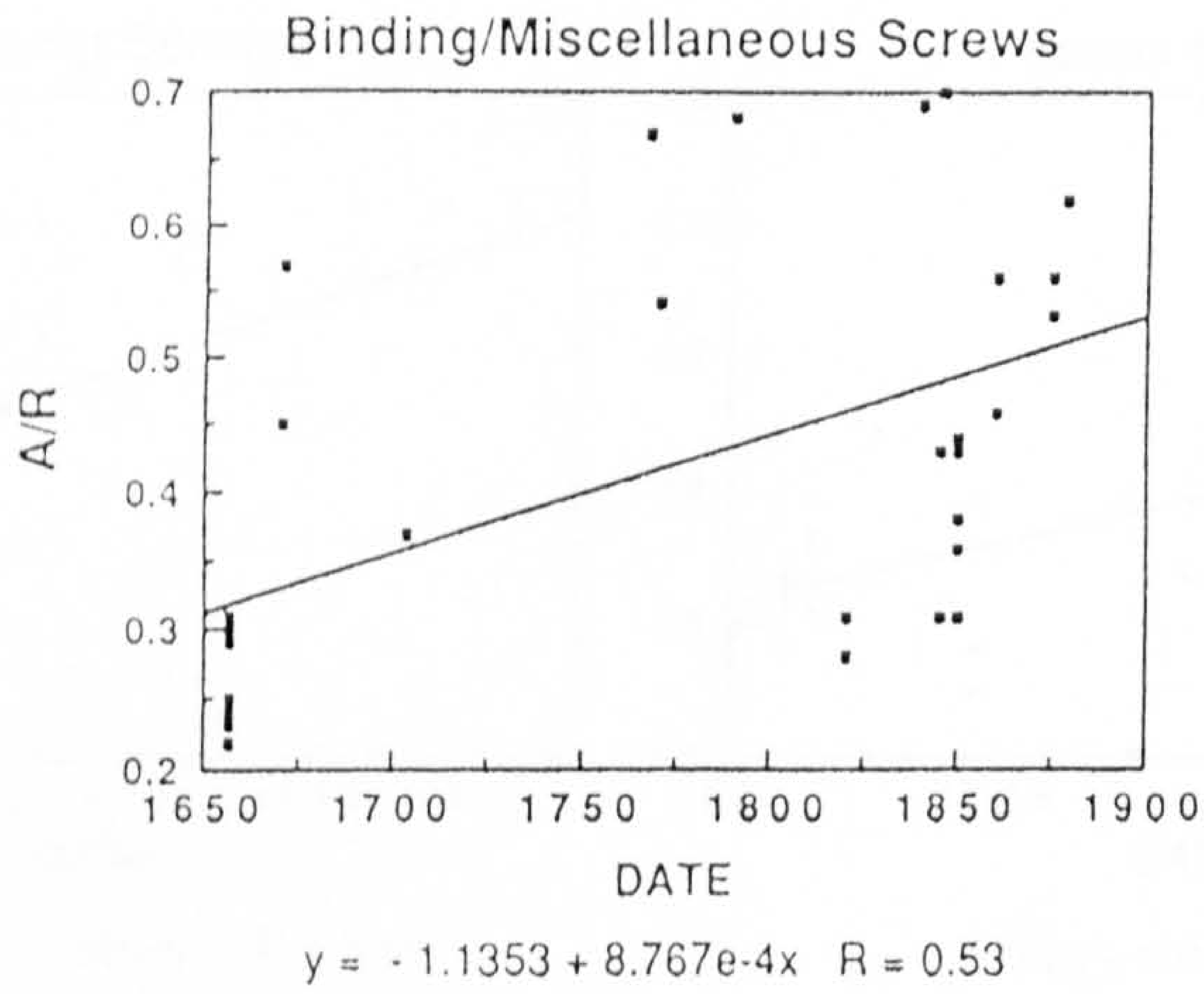
6.4.8a Date vs. Aspect Ratio (A/R) for the 'Precision' screw groups.



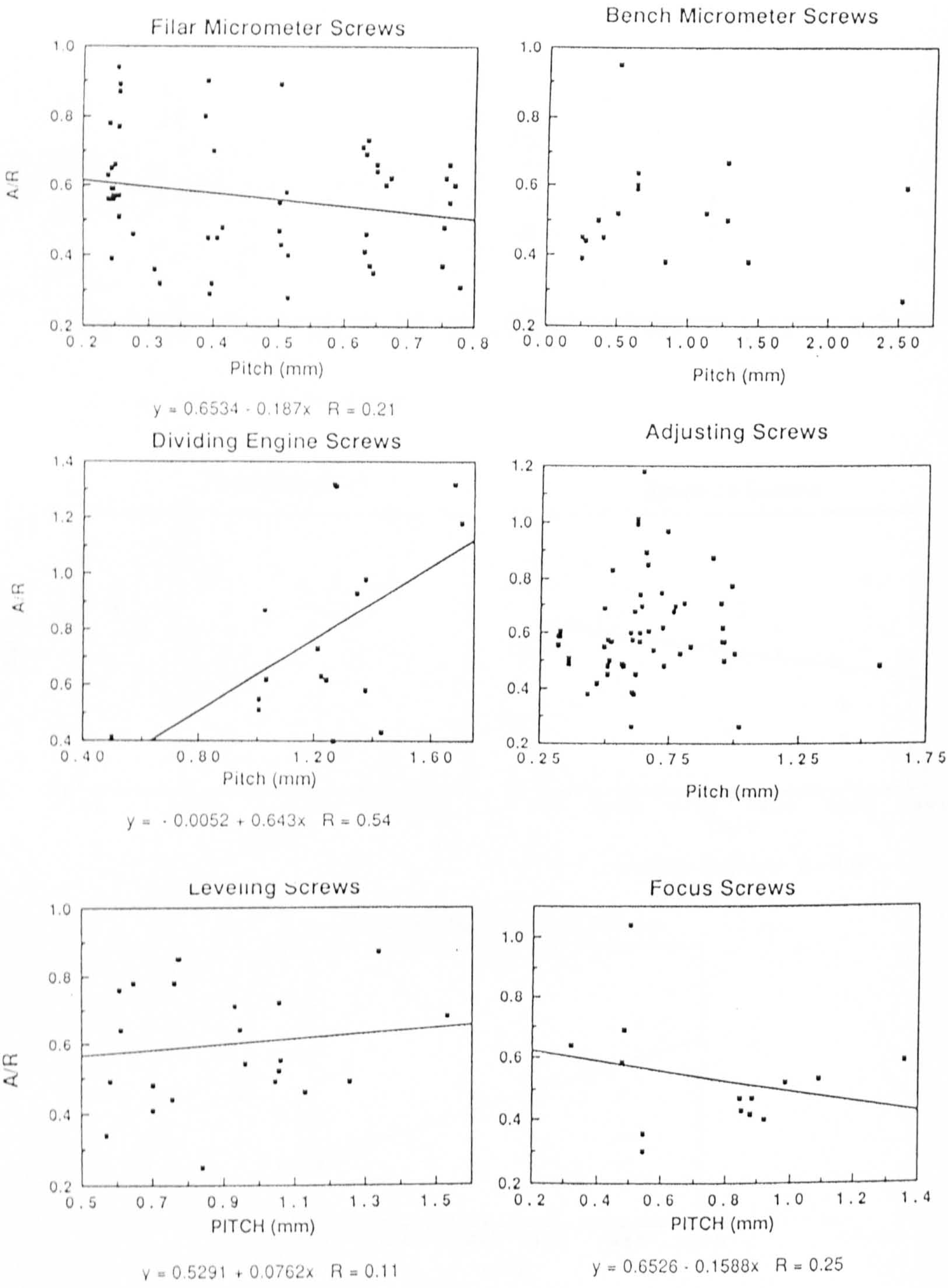




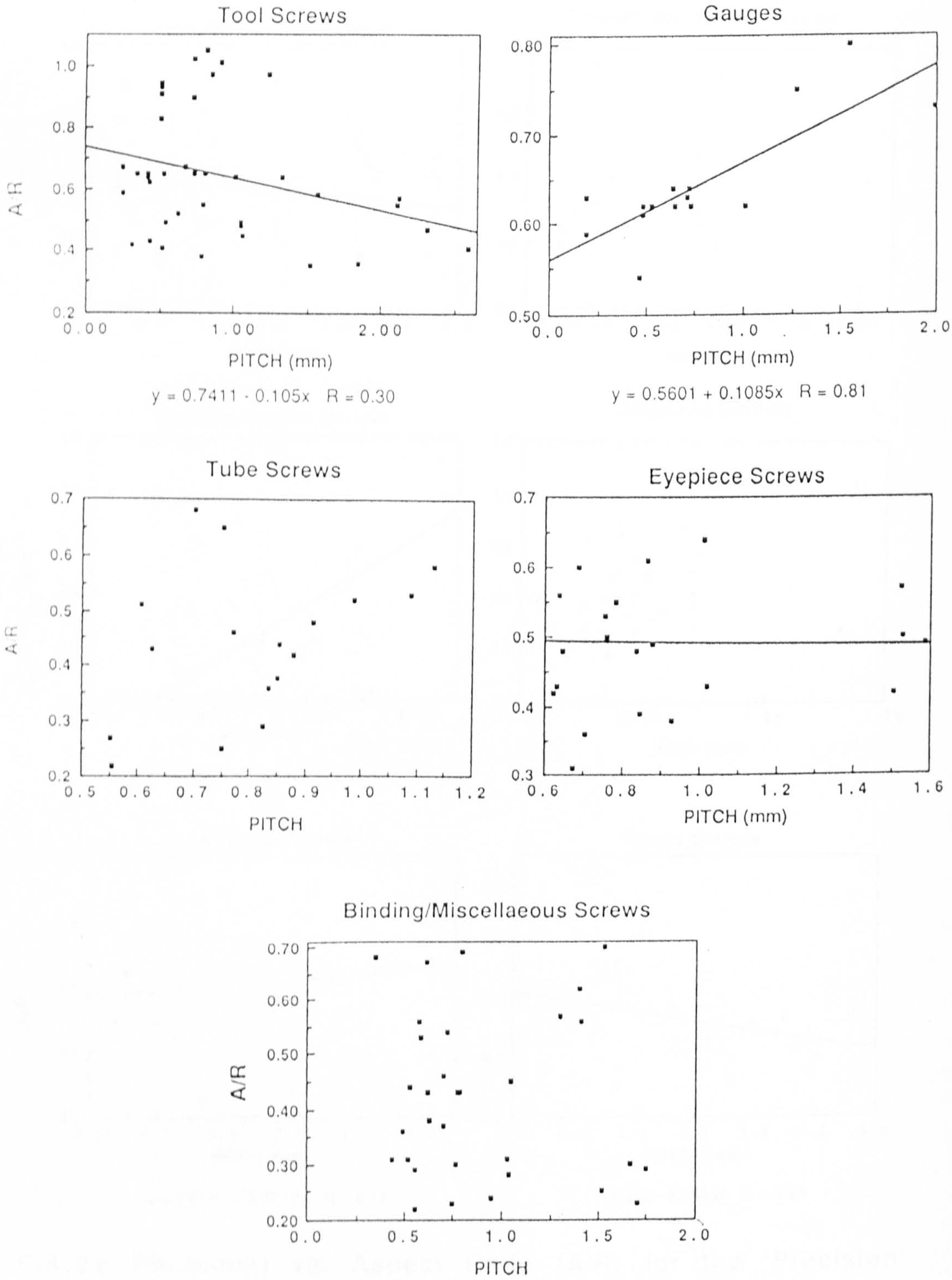




6.4.8b Date vs. Aspect Ratio (A/R) for the 'Standard' screw groups.



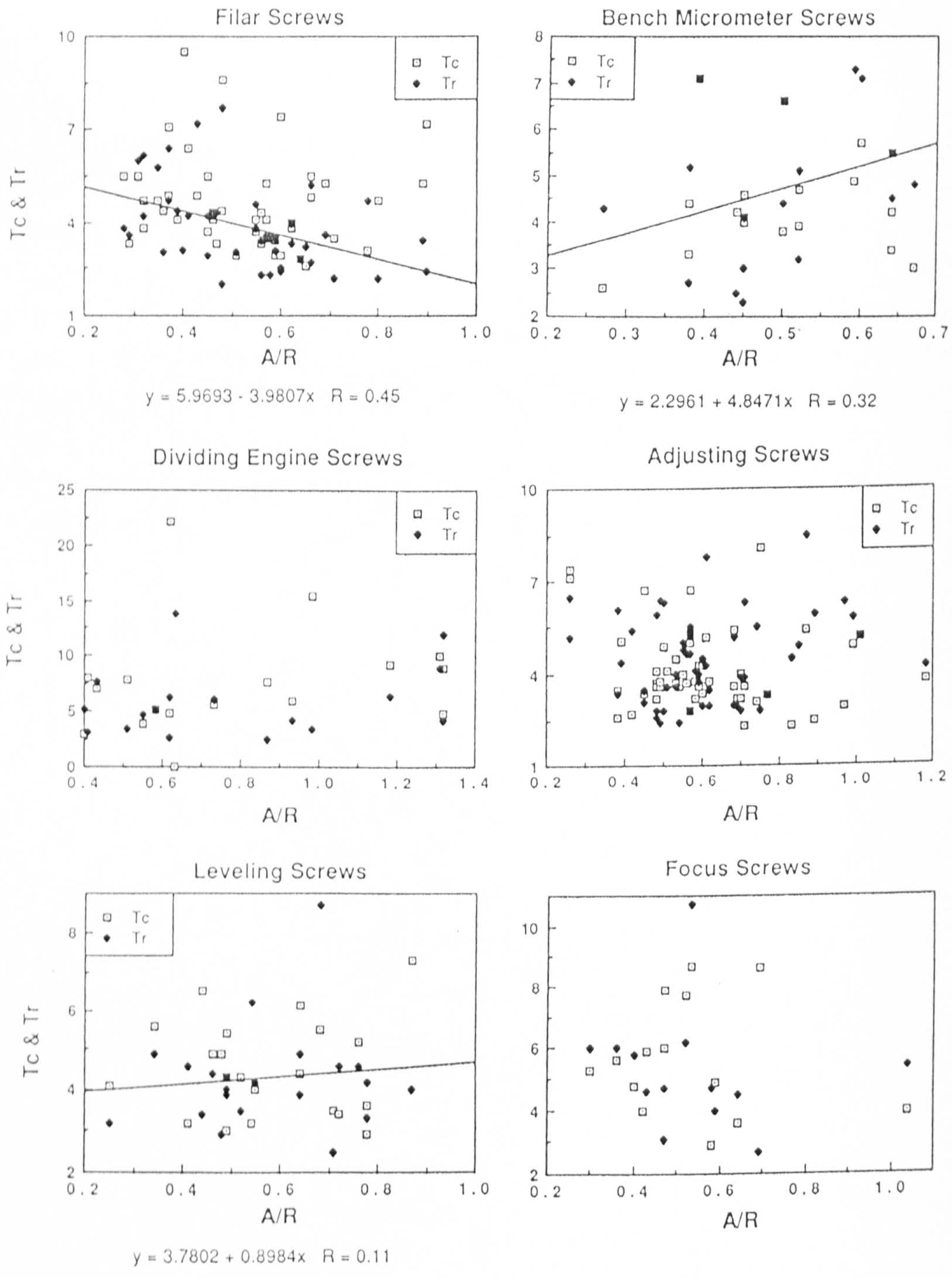
6.4.9a Pitch(mm) vs. Aspect Ratio (A/R) for the 'Precision' screw groups.



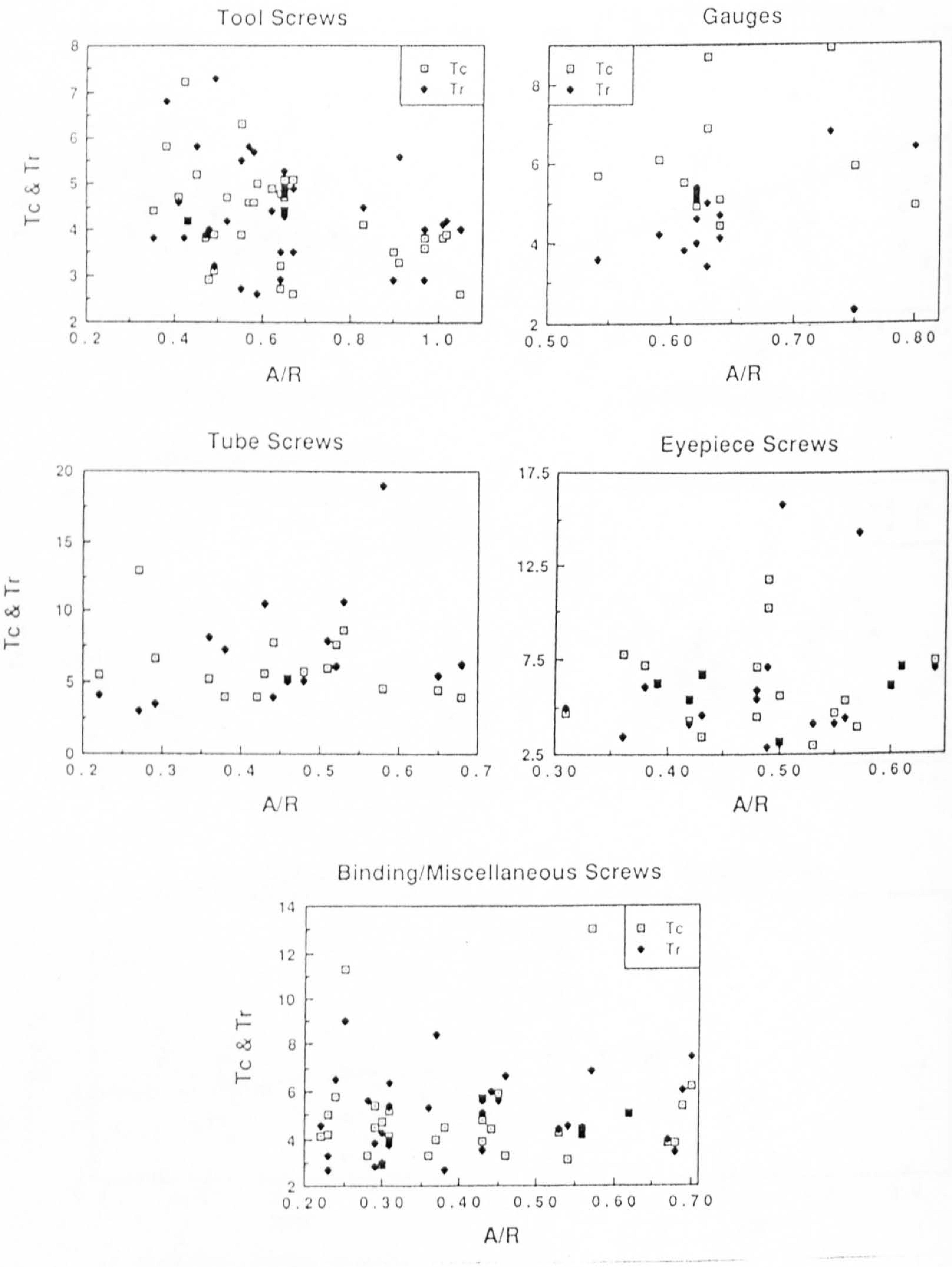
6.4.9b Pitch(mm) vs. Aspect Ratio (A/R) for the 'Standard' screw groups.

6.4.7 Date vs. Aspect Ratio (A/R) (Fig. 6.4.8a/b) and
Pitch (mm) vs. Aspect Ratio (A/R) (Fig. 6.4.9a/b):

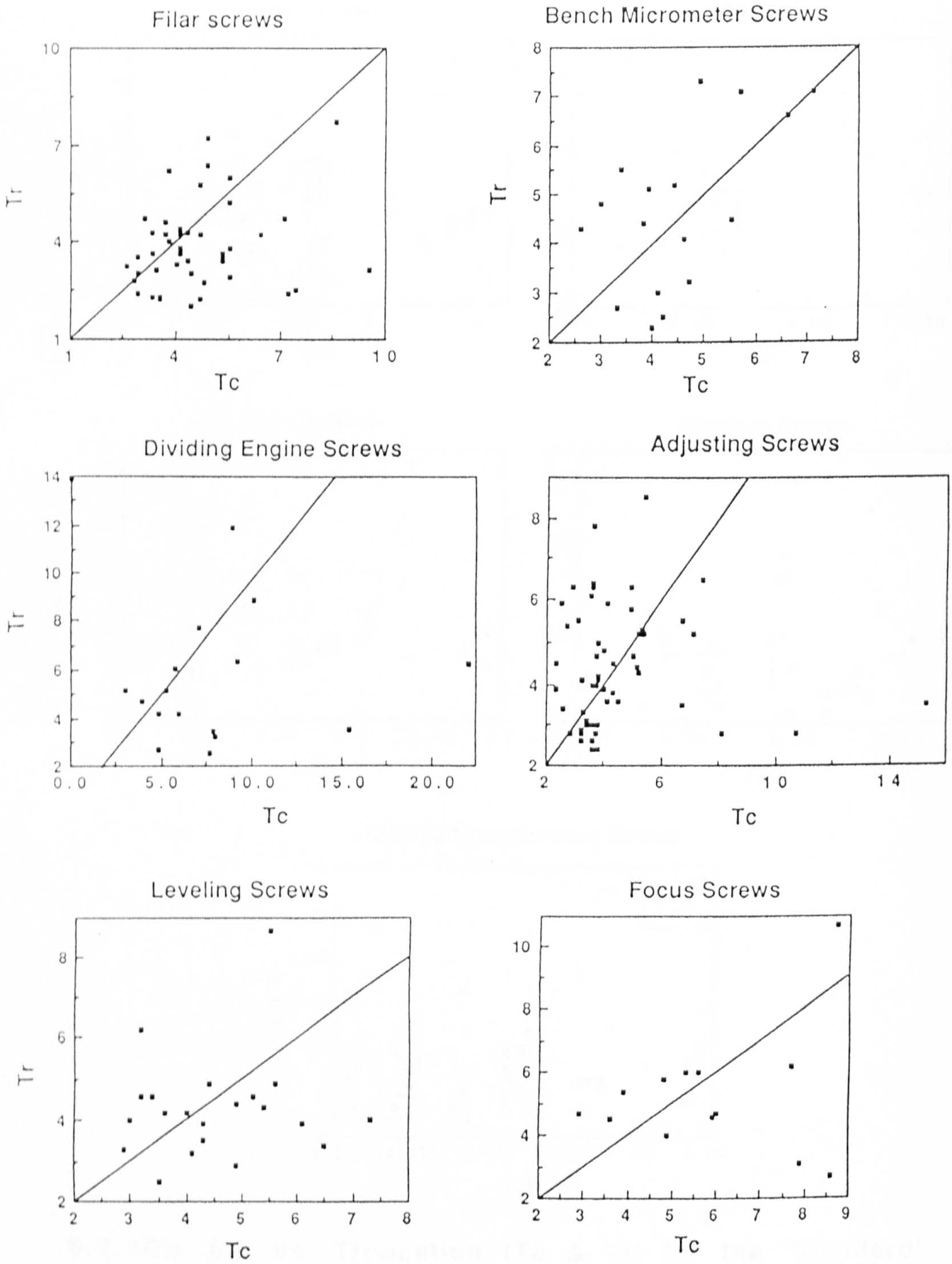
One manner of discriminating between old screws and replacements is to compare the aspect ratio of the thread. This ratio of pitch to depth of thread reflects the range of pitch and flank angles and truncations of the roots and crests. It therefore reflects the 'fashion' of the day for each class of screw. Although the scatter is considerable, this comparison in conjunction with several others may be able to detect relacements or outright fakes. As for flank angles, we would expect bench micrometer, binding/miscellaneous, and adjusting screws and gauges to tend toward an A/R of 0.60-0.65 after the implementation of standardization. Comparison of A/R vs. pitch is not productive as will be seen; with the exception of dividing engine screws there is little variation. The fit for gauges is again illusory due to the form adopted by Holtzapffel for their larger diameter threads, a form which did not conform to standard workshop practice.



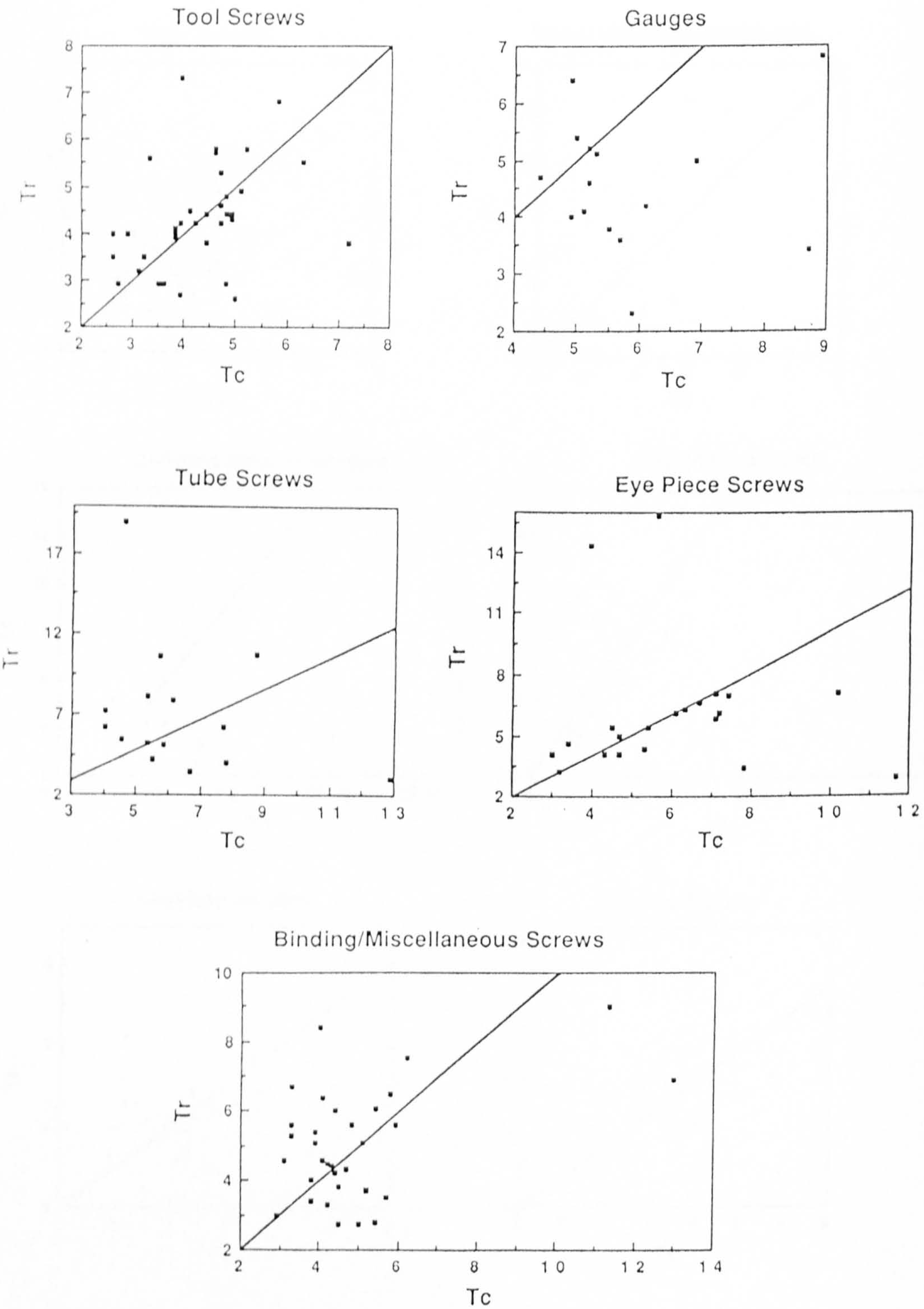
6.4.10a A/R vs. Truncation (Tc & Tr) for the 'Precision' screw groups.



6.4.10b A/R vs. Truncation (Tc & Tr) for the 'Standard' screw groups.



6.4.11a Tc vs. Tr for the 'Precision' screw groups.



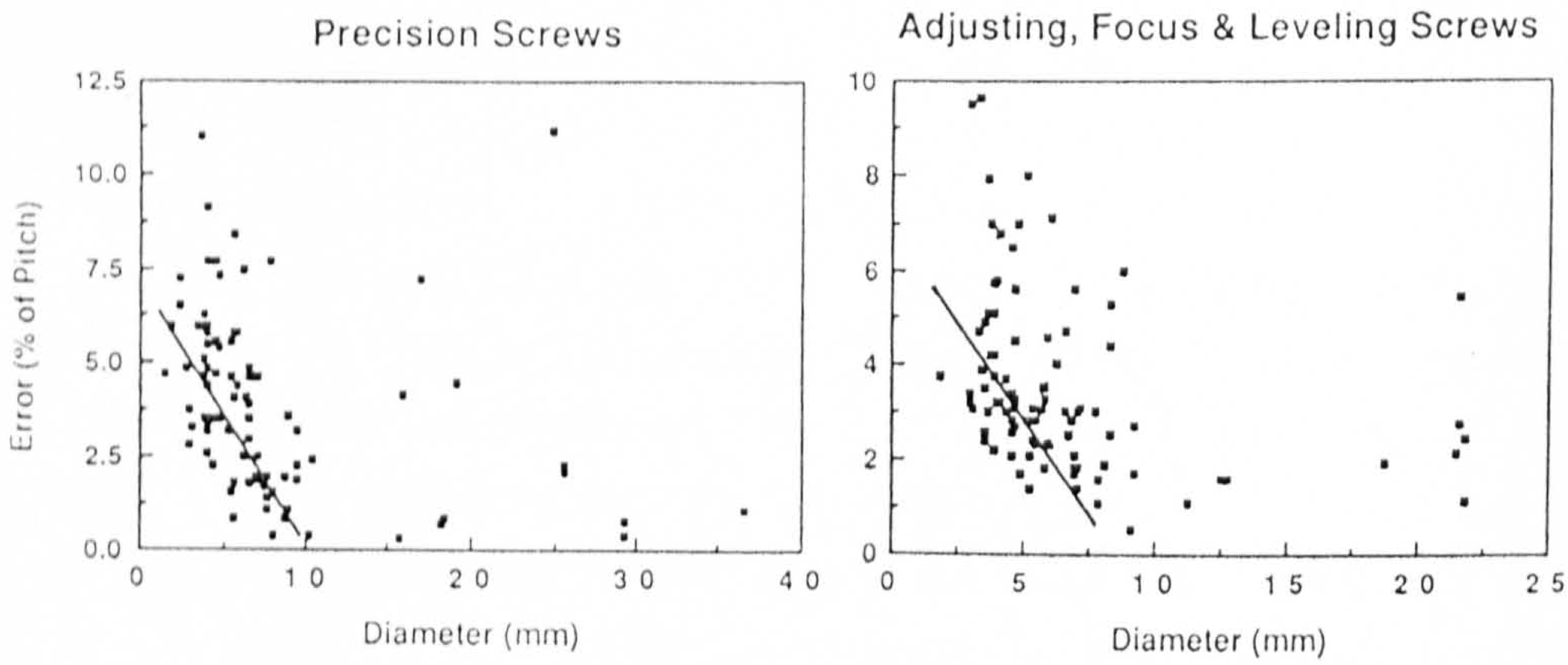
6.4.11b Tc vs. Tr for the 'Standard' screw groups.

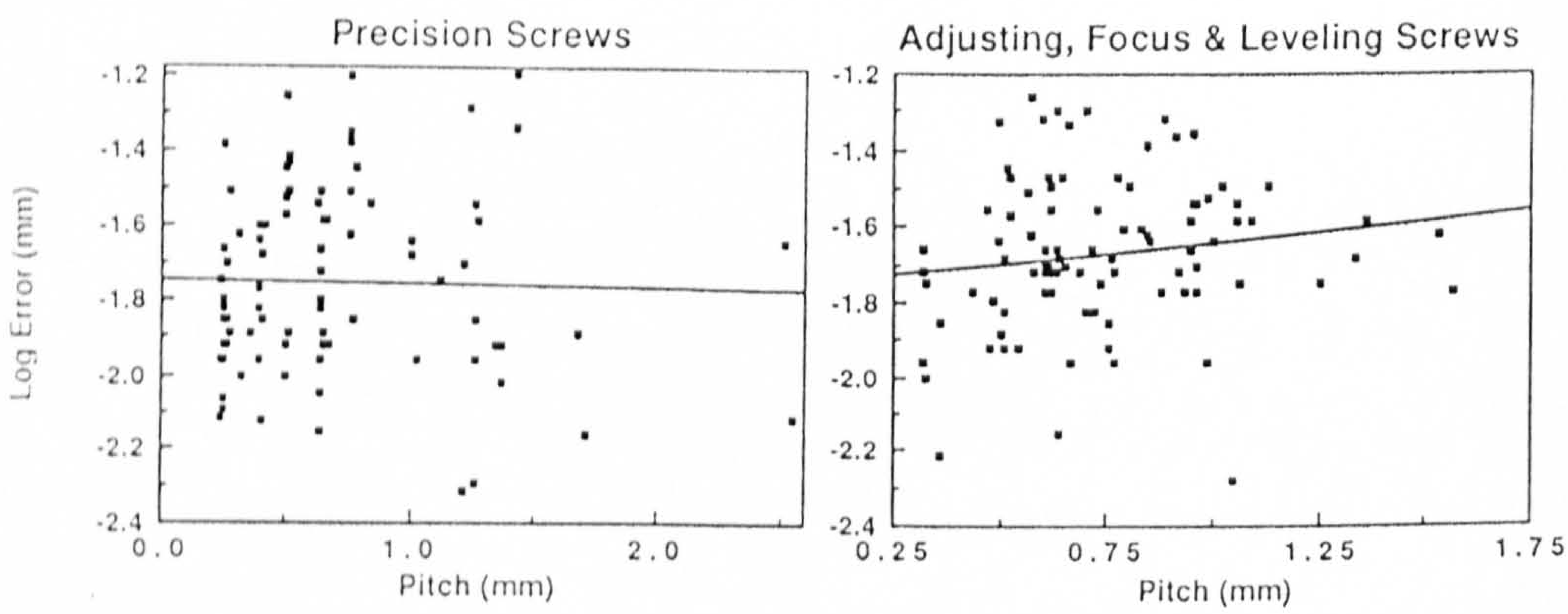
6.4.8 Aspect Ratio (A/R) vs. Truncations (Tc & Tr) (Fig. 6.4.10a/b) and Truncations: Tc vs. Tr (Fig. 6.4.11a/b):

Aspect ratio vs. truncation of the roots and crests is likewise a relatively insensitve discriminator. However, this graph can be used to compare the truncations of root and crest of individual screws by comparing the open and filled squares in direct vertical line. Comparison of the truncations, Tc and Tr, is not useful as a discriminating factor. It is, however, interesting to see how Tc compares to Tr for the various classes since we might expect a linear relation with equal truncations at both the root and crest but as is seen there is again considerable scatter. For the filar scale/micrometer, bench micrometer and tool screws, Tc is proportional to Tr. For adjusting screws there was preference to truncate the crest more than the root perhaps reflecting the fact that the rods on which these threads were made were of relatively small diameter.

6.4.12 Combined results for Precision (micrometer) screws and Adjusting Focusing and Leveling screws.

6.4.12a Diameter(mm) vs. Error (% of Pitch).



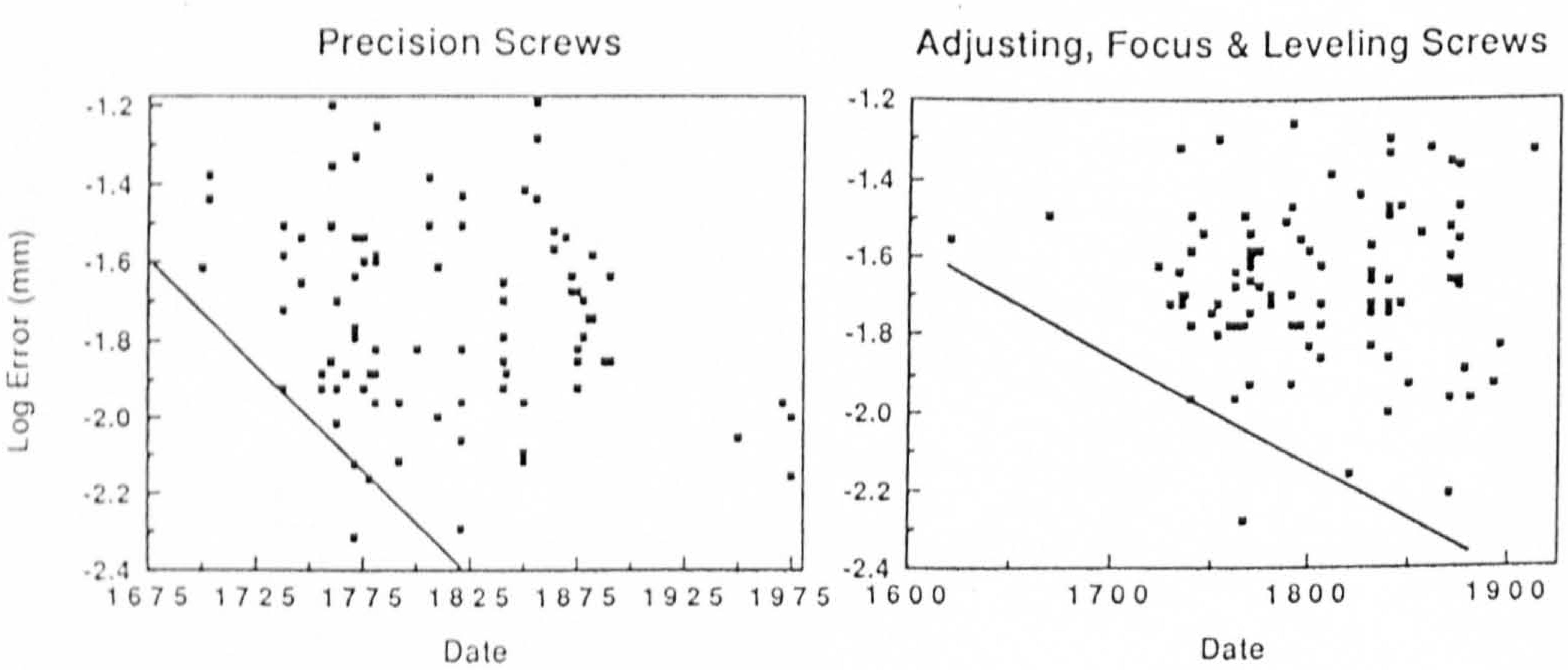


y = - 1.7466 - 0.0074x R = 0.01

y = - 1.7551 + 0.1152x R = 0.15

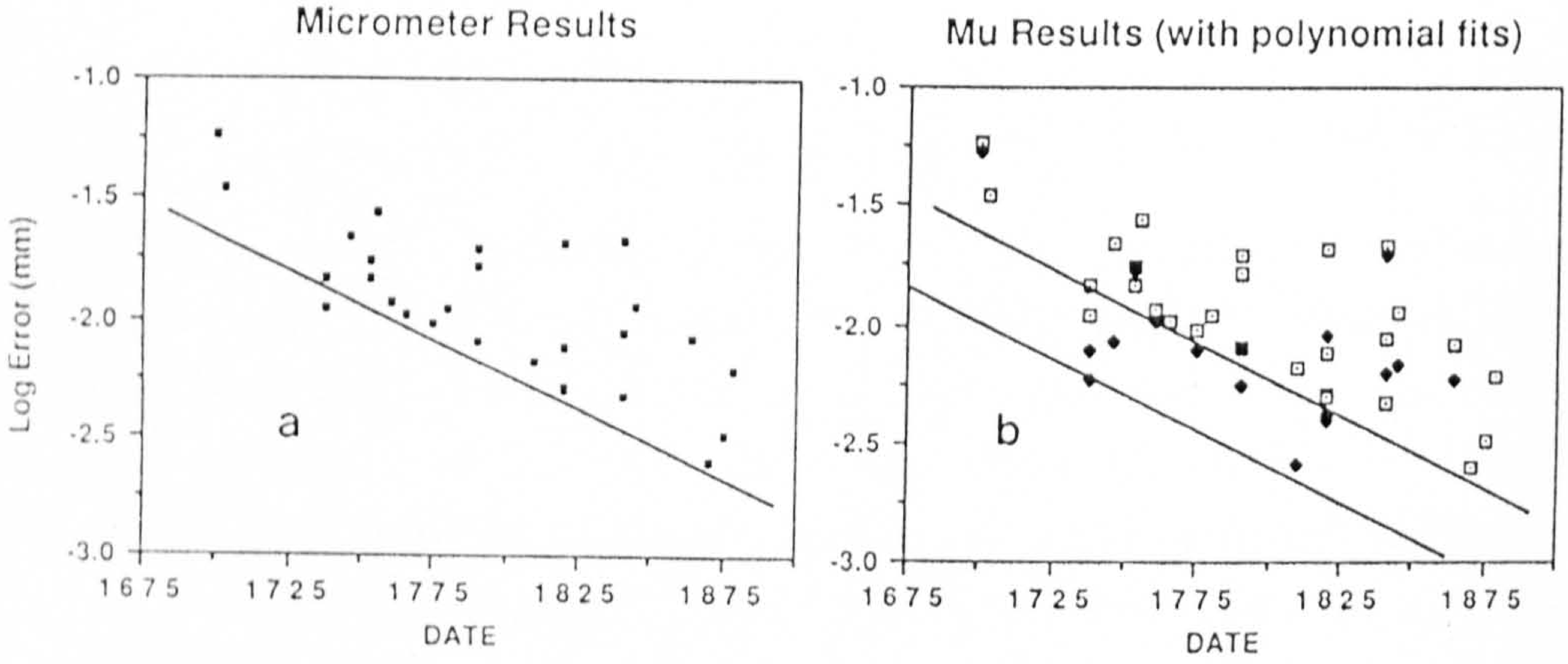
6.4.12b Pitch(mm) vs. Log Error(mm).

6.4.12c Date vs. Log Error(mm).

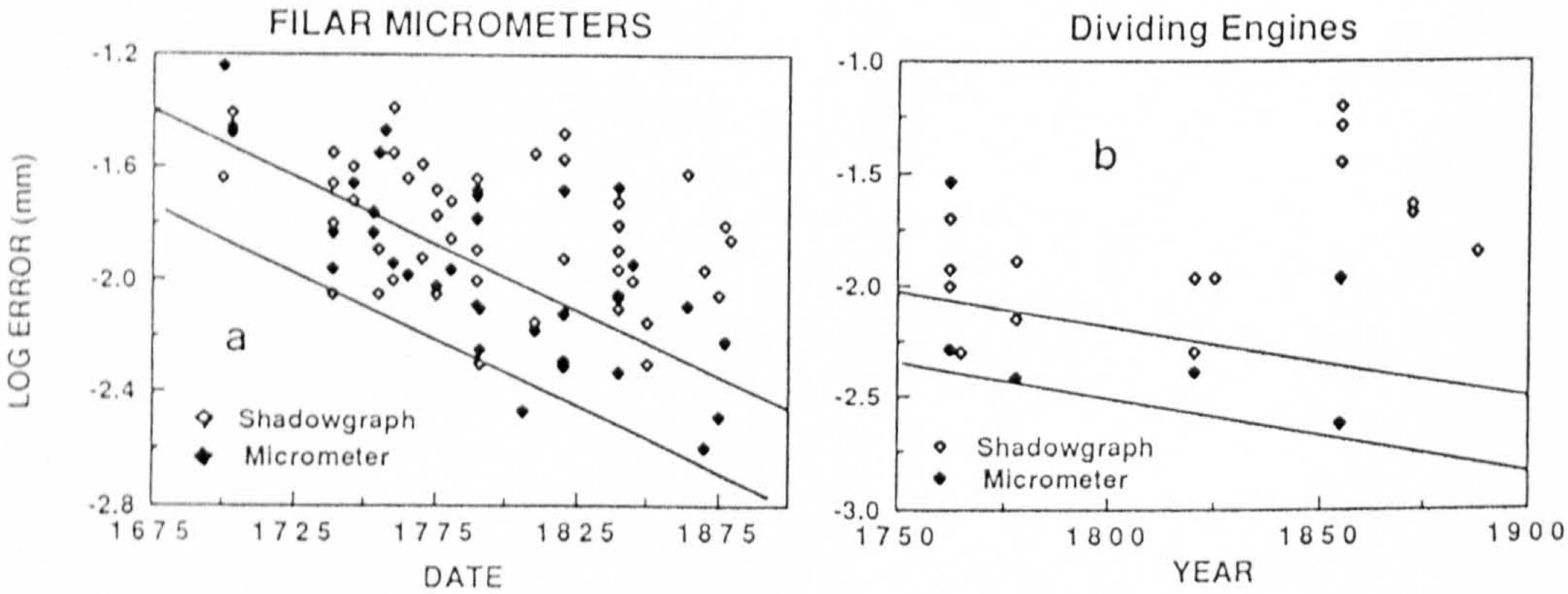


6.4.9 Combined Precision Screw Results (Fig. 6.4.12):

The results for the various micrometer classes and for adjusting, focus and leveling screws have been combined to create the graphs of diameter vs. error (% of pitch), pitch and date vs. log error. It is interesting to see in the diameter vs. error plot (Fig. 6.4.12a) that there was a lower boundary below 5mm where the error increased and that, for both groupings, the increase in error was roughly equal. In Fig. 6.4.12b the log of the errors is seen to be almost independent of the pitch. Finally in Fig. 6.4.12c we can see that the rate of improvement in the precision screws was faster. Before ca.1725 the errors were roughly equal but after 1775 the impact of Ramsden's screw lathe made a new level of precision possible.



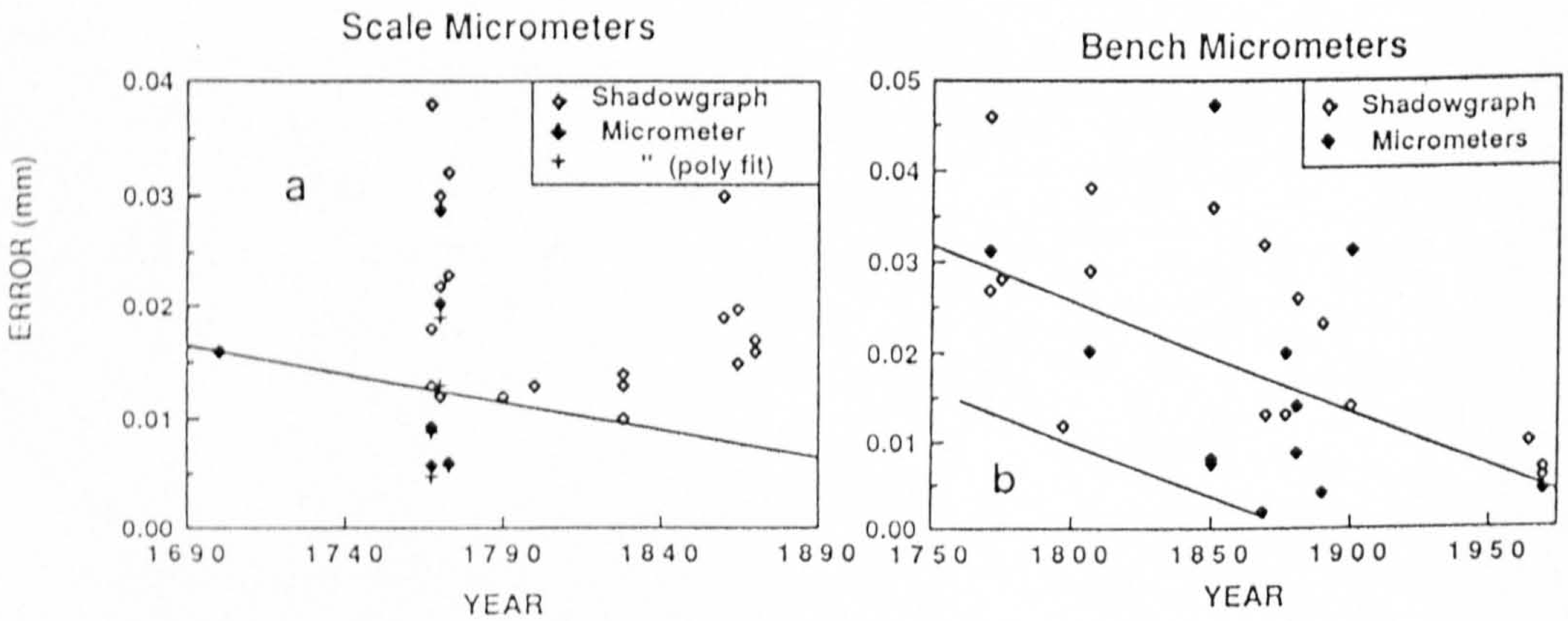
6.5.1 Results of the dial indicator measurements of micrometers. The filled dots in the right graph are the errors after subtraction of the polynomial fit to the micrometer error.



$y = 6.5406 - 0.0047x \quad R = 0.71$

$y = 3.613 - 0.0032x \quad R = 0.36$

6.5.2 Errors determined by the shadowgraph and dial indicator methods compared. The upper line is a linear least sqaure fit and the lower line indicates the lower boundary.



$y = 0.2454 - 1.221e\text{-}4x \quad R = 0.44$

6.5.3 Error(mm) vs. date for the scale and bench micrometers measured by the shadowgraph and dial indicator methods. The points on the scale micrometer graph between 1765 and 1773 are all by John Bird.

6.5 Dial Indicator Results:

The graphical representation of the filar micrometer results by the dial indicator method are given in Fig. 6.5.1a. It will be immediately noticed that the scatter is lower than the results obtained from the shadowgram method: this is understandable since the micrometer results are obtained from the mean of many observations while the shadowgraph technique relies on an estimate of error scatter on the two flanks of the thread. In Fig. 6.5.1b the errors (filled diamonds) which would have resulted had the periodic errors been known and corrected is superimposed on the results shown in Fig. 6.5.1a. Bradley and Chabert took pains to investigate instrumental errors in the mid-18th c; however, it was late in the century before most astronomers took the micrometer screw errors as seriously as they deserved.

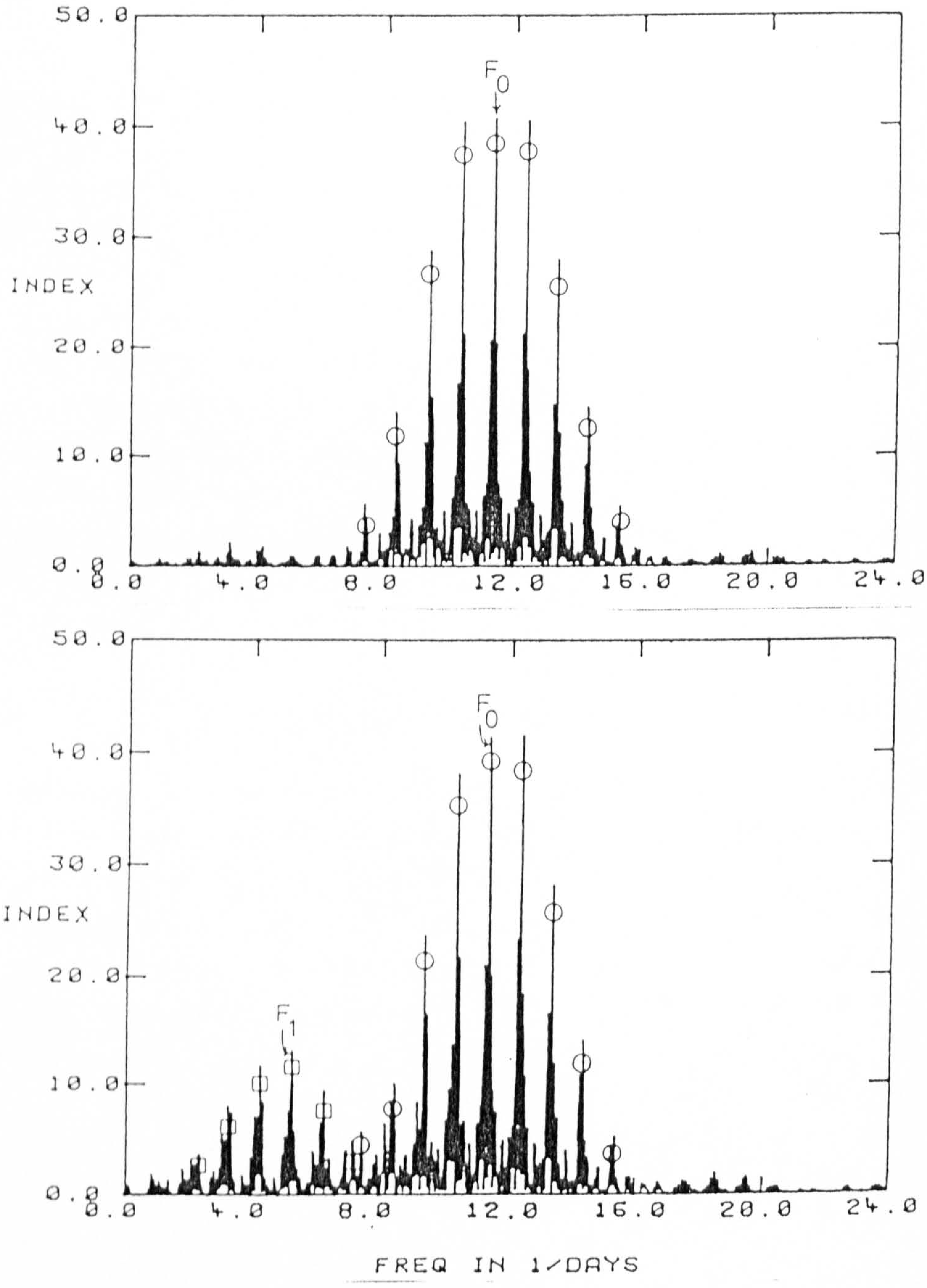
The log error vs date data has been plotted (Fig. 6.5.2a) with the results from the shadowgraph method (open diamonds) for comparison. The least square fit is to the data obtained with the dial indicator (denoted 'micrometer' on the graphs). The lower limit of the envelope is very nearly parallel to the mean fit. As noted previously, the fit is linear as predicted by Lienhard (1979). The fact that the rate of improvement of filar micrometers is more rapid than for the dividing engines (Fig. 6.5.2b) might be attributed to the rapid improvement in machines such as lathes which permitted manufacturing screws closer to the limit of workmanship at later periods. Another explanation--and certainly one which cannot be discounted--is that the methods of measurement employed for this work reached their limit for dividing engines. This is almost certainly true for late 19th c machines, though as noted previously the screws of the two Science Museum dividing engines have suffered wear due to their constant use by visitors. Resort to measurements by the shadowgraph method on sections which are obviously not worn is unsatisfactory since these portions may not have been finished with the same care as the central parts intended for direct contact with the wheel. Many makers would have followed Ramsden's and Edward Troughton's procedure of 'grinding in' the screw on the wheel, with the result that the part of the screw not in contact with the wheel was not fully corrected.

Results (Error vs Date) for scale micrometers (Fig. 6.5.3a) studied by the micrometer method are inconclusive due to lack of samples. These are also difficult to measure accurately because of the problem of relative movement between the dial indicator and the instrument being measured. Because a number of instruments by Bird were studied from ca.1765-73 this warrants a closer look (§7.1.2). At his best Bird was capable of better work than Ramsden during their period of overlapping careers, but there is considerable difference in the performance of his various instruments. For the scale and bench micrometers (Fig. 6.5.3b) the error estimates are smaller when determined by the dial indicator method.

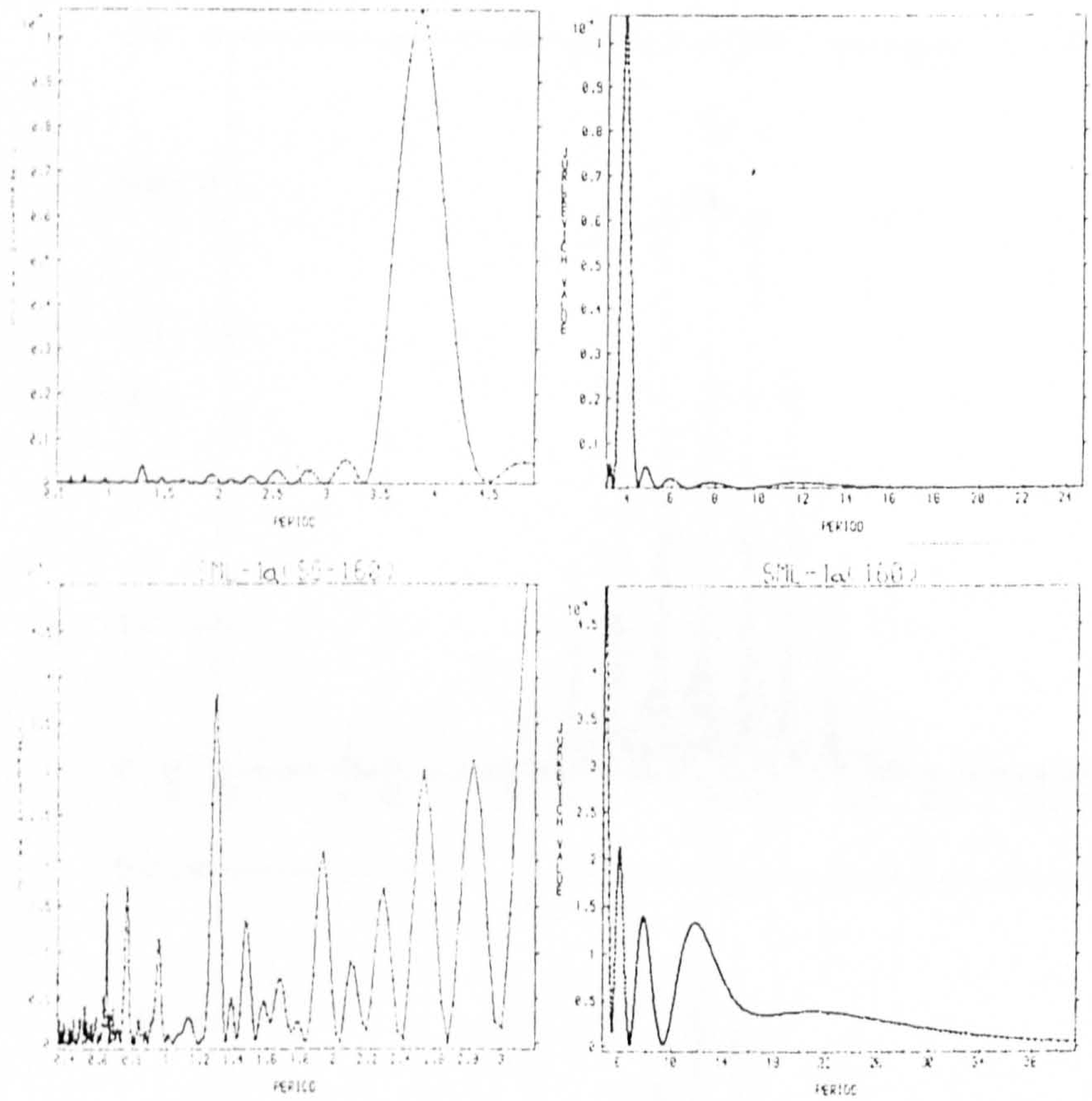
As anticipated the dial indicator results yielded error estimates (excluding other problems!) approximately two-thirds of those from the shadowgraph method; the latter method provides a measure on the maximum error while the dial indicator technique provides a mean error. An overall error could be obtained by simply taking the maximum scatter from the dial indicator graphs included in Appendix E. Given a choice of methods (dial indicator or shadowgraph), the dial indicator method is the less arduous and gives better results if the problem of motion between the test instrument and study instrument can be eliminated, and if the temperature can be maintained fairly constant. The old addage 'simplest is best' applies here. The application of precision optical shaft encoders to driving and reading precision screw motion would be an obvious improvement to this technique, and with appropriate selection of hardware would be capable of measuring even the most precise screws. The advantage of having a digital output to feed directly into a computer would add a degree of freedom from accidental errors and facilitate data reduction.

6.6 Interpretation of the Jurkevich-Swingler Periodograms:

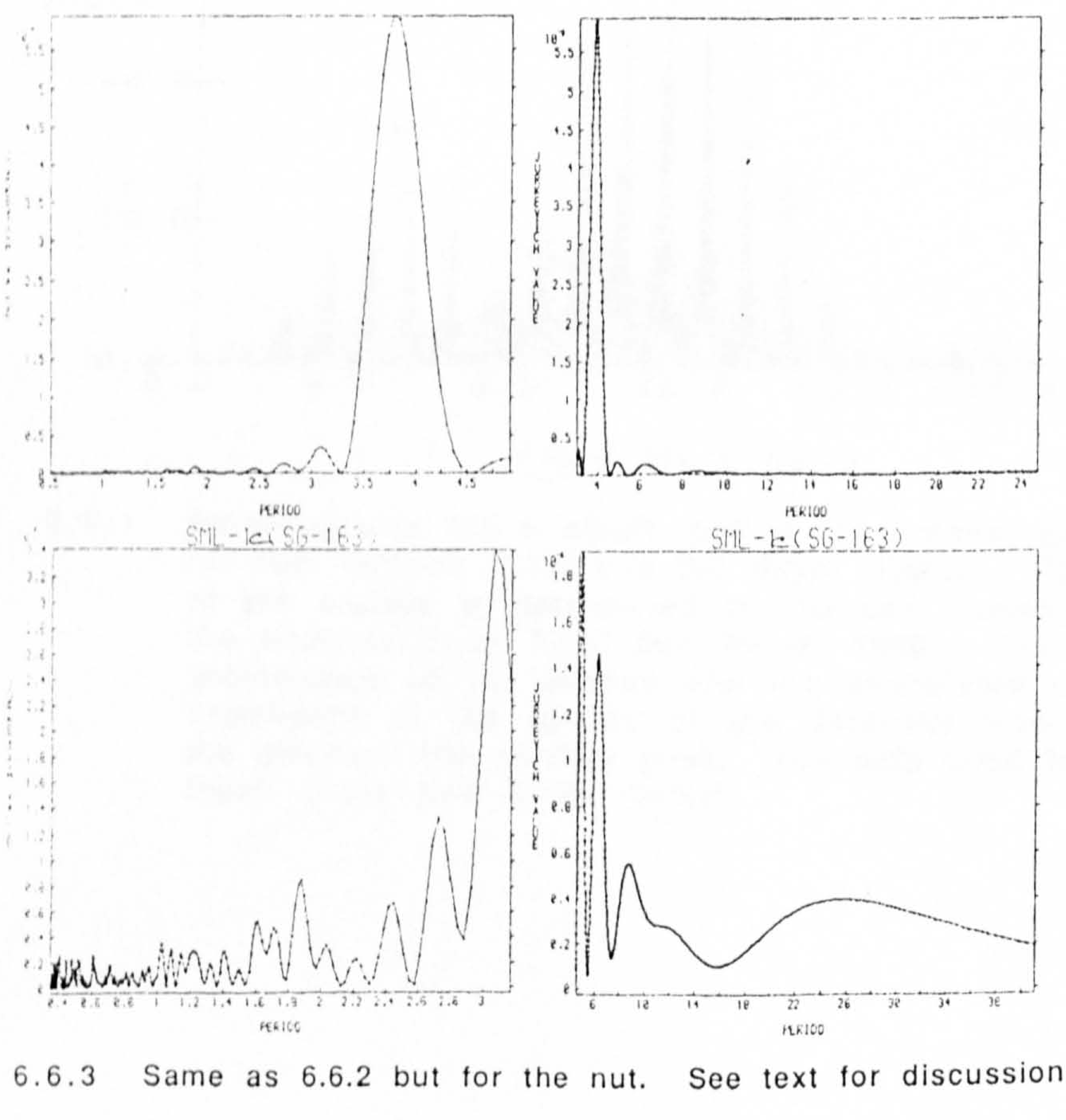
The Jurkevich-Swingler period seaching technique was primarily employed to determine the pitch of the digitized profiles, but a secondary objective was to look for other periods which may appear in the data for the profiles and in the data taken with the dial indicator. These do not have a great deal of immediate importance but the technique has some possibilities for identifying instruments which were made on specific dividing engines or perhaps (though, admittedly, a long shot) on a specific geared lathe. One generalization can be made as a result of these calculations. The periodograms can identify hand made screws from those made on lathes: handmade screws have fewer periods than those made by lathes; however, modern screws have periodograms which are reasonably 'clean' particularly for periods longer than the pitch of the screw. Lathe made screws from the late 18th c through the 19th c show many periods though not of high significance. Some examples will best illustrate the use and interpretation of the periodograms.



6.6.1 Periodograms for a single period (11.5 days) (upper) and for two periods (11.5 and 5.0 days) (lower). The spacing of the aliases is determined by the cell spacing used in the analysis (from Reed and Welch: 1986). The prominence of the aliases and the associated envelope is dependant of the quality of the data--the less scatter, the stronger the primary peak. The data used to make these plots had 100% 'jitter'.



6.6.2 Periodograms for a filar micrometer screw by Heath & Wing (ca.1760). The upper panels include the primary period which is exclude in the lower panels.



6.6.3 Same as 6.6.2 but for the nut. See text for discussion.

6.6.1 Alias Frequencies:

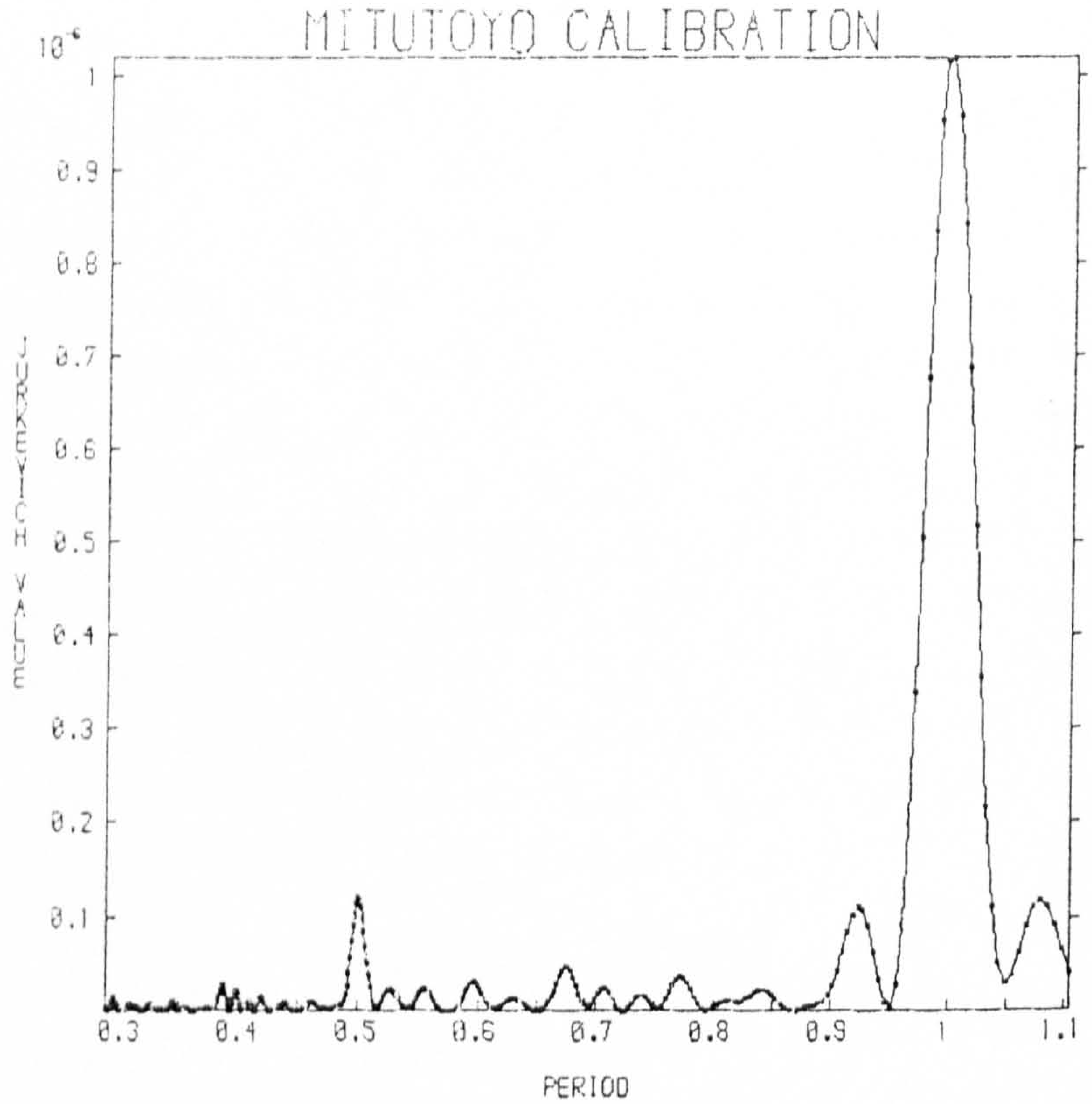
One problem with this technique is that alias frequencies arise from prominent frequencies with a lot of scatter. This is illustrated in Fig. 6.6.1 taken from Reed (1986, p.36/37)[1]. In these figures frequency rather than period is plotted, but the same basic structure appears in a period plot. Reed has used 'Index' rather than 'Jurkevich Value' for the abscissa, but that is unimportant (as is the absolute value of the peaks) as these are dependant on the values of the numbers being subjected to the period search. For each plot, however, the height of the peaks gives an indication of the relative strength of the period. The regular spacing and regular decrease in height of the alias envelope helps pick these peaks out from real peaks. In practice, the alias peaks appear with known relationships to known periods and are thus easily identified. Another problem associated with these aliases is that one appears at exactly one third of the primary frequency (in the results provided here); thus a period of 1/3 the primary period may be masked though if it is strong it may cause the peak to be abnormally high in relation to other aliases or may have aliases of its own.

To overcome this difficulty of a secondary peak being masked one 'pre-whitens' the data. This means that once the primary period is found, a sinusoidal curve is subtracted to remove the evidence of the primary period. The data is then re-run through the period search program and the next strongest period determined. This subtraction technique can be used several times if one is still finding significant periods, but in practice one or two periods can usually be subtracted. The pre-whitening procedure is tricky and time consuming because one must make several trials to find the amplitude of the best sinusoid to subtract. It was not felt that these procedures would significantly add to the results of this thesis so have not been attempted. If one were investigating specific dividing engines, and scales potentially engraved with them, then this procedure would be beneficial if not essential.

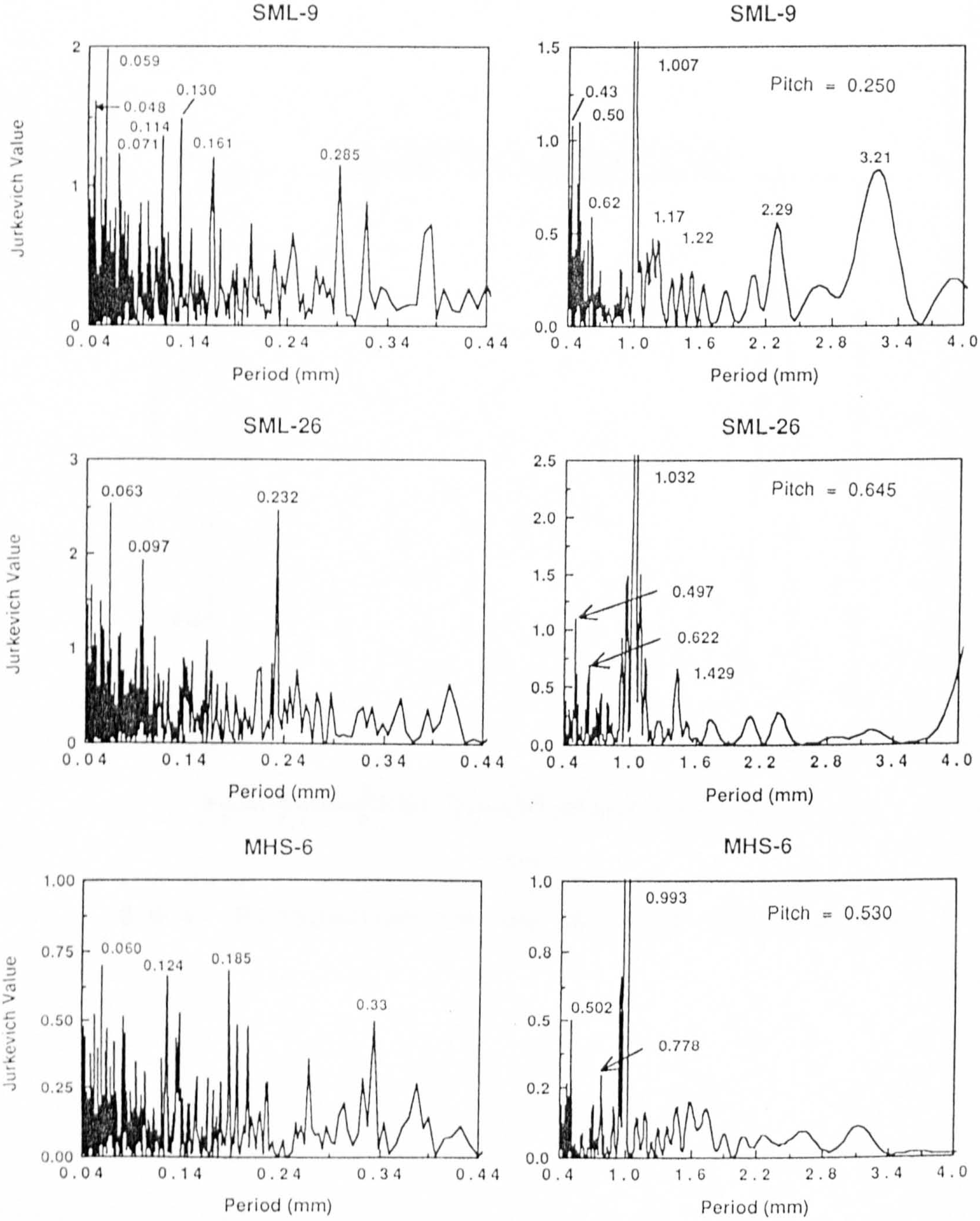
Periodograms for most thread profiles of precision screws have been included in Appendix B. As noted in the previous chapter, the primary period has been omitted from the plots to provide better resolution of the peaks above and below the primary period. Fig. 6.6.2a shows a typical periodogram with the primary included (upper) while it has been omitted in Fig. 6.6.2b. The aliases are identified. Note the alias at 1/3 the primary period (P^1); this appears in all the periodograms due to the number of cells used in the calculations. If the profile has a true period at $1/3P^1$ it may also have a set of aliases. The confidence level rises with the number of points in the curve being tested; the periodogram (Fig. 6.6.3) for the nut of the screw analysed in the above figure has fewer

---

[1] Reed used a primary and secondary frequency with 100% 'jitter' for these tests. The large jitter causes, in part, the alias frequencies.



6.6.4 Periodogram for the Mitutoyo dial indicator.



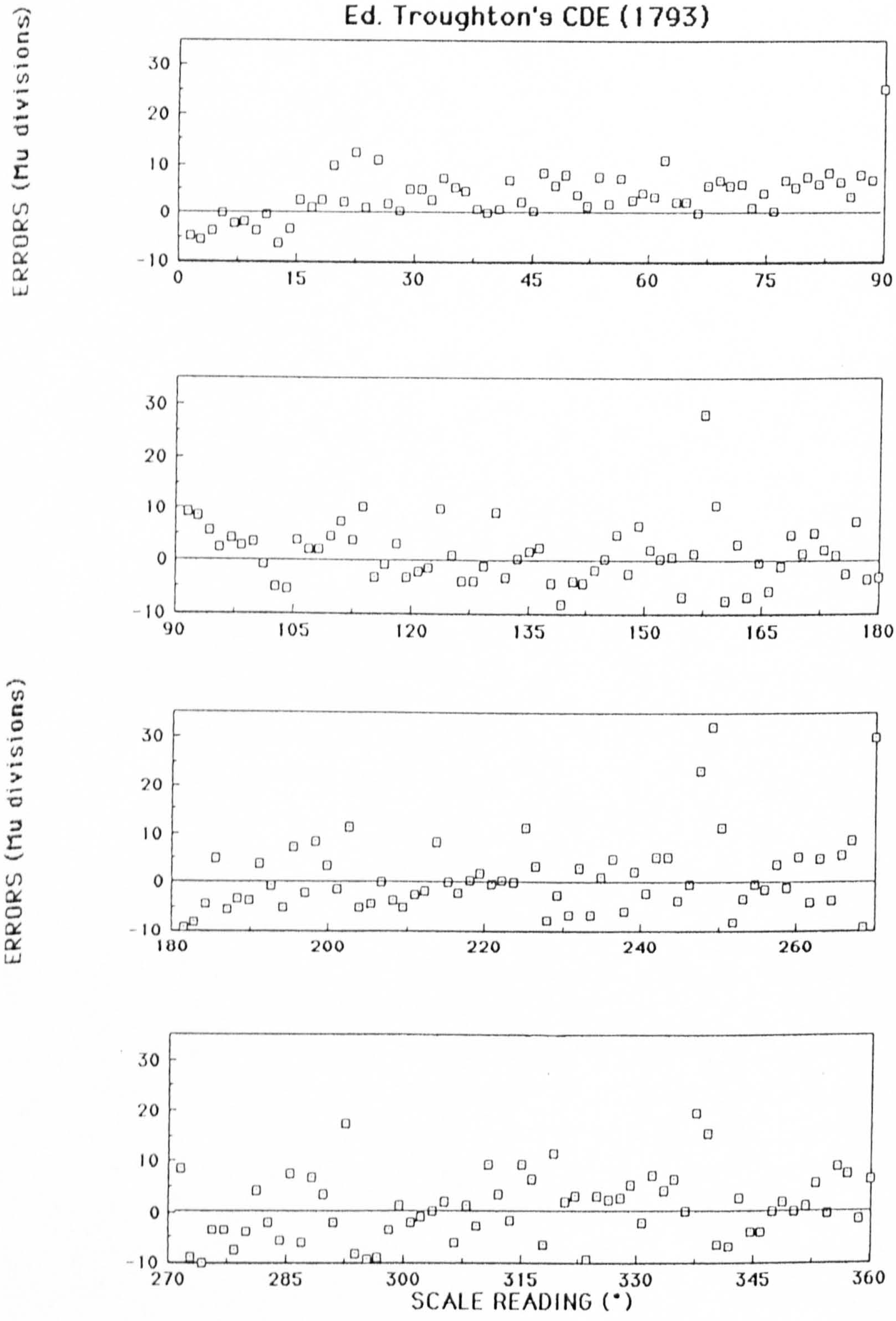
6.6.5 Periodograms for micrometer screws by Ramsden (SML-9), Sisson (SML-26) and Bird (MHS-6). The periods at 0.5 and 1.0mm are artifacts of the Mitutoyo dial indicator's errors.

points and the height of the peaks is not as prominent and indicates lower significance. In this figure, the broad peak centred at ≈25 is simply an artifact of the length of the thread sampled and is not significant. Such peaks appear in many of those plotted. Significant peaks are always narrow. Periods below the primary period include some required to fit the curve of the thread form--the more complex the thread form the more short periods will be generated reaching a maximum for square or acme type threads. The majority of periods generated for this reason are in the lower third of the short period graphs.

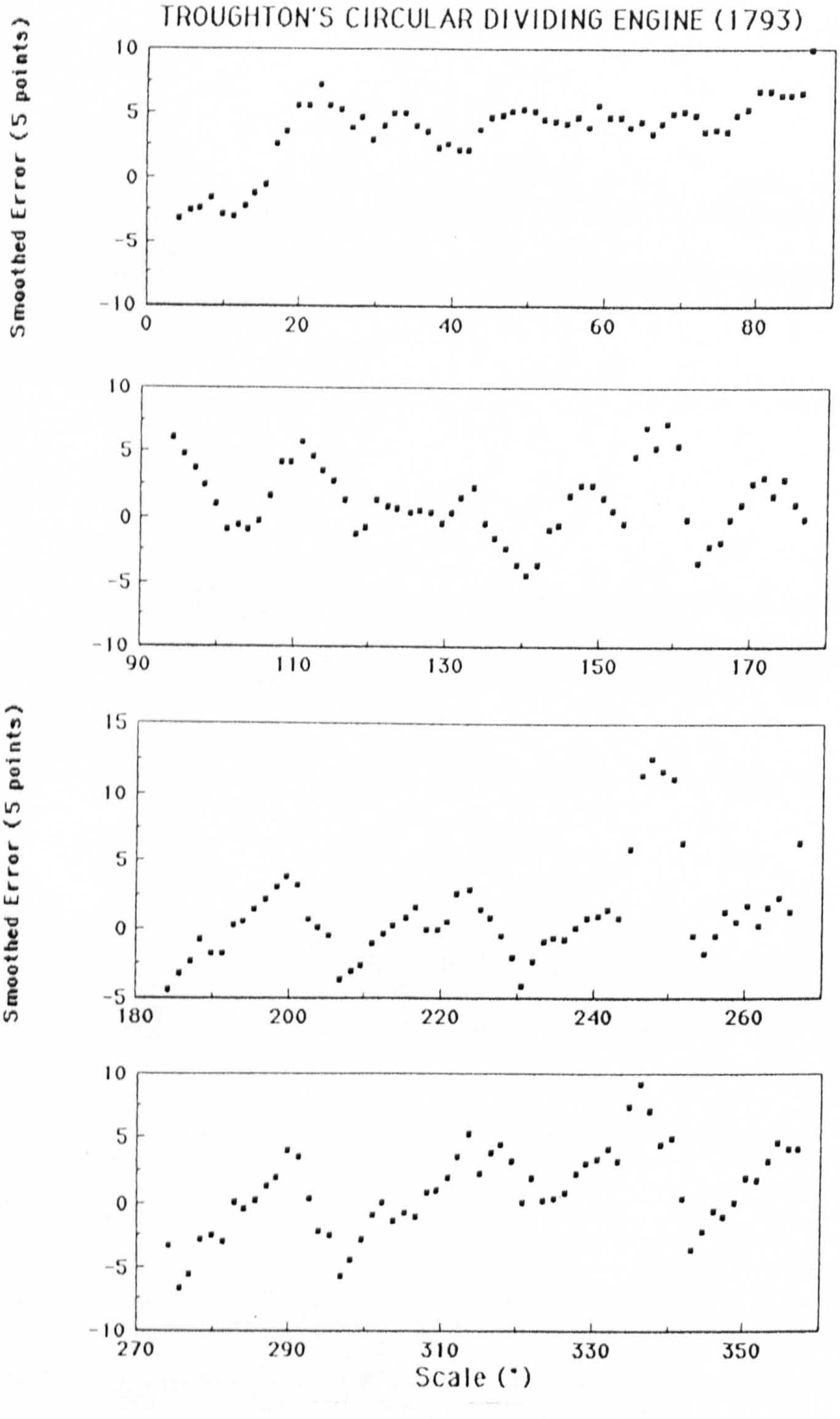
6.6.2 Periodograms Generated from the Dial Indicator Data:

The length or number of thread profiles sampled is not the only factor that affects the appearance of the periodogram. In analysing the dial indicator data, the 'finger print' of the indicator is superimposed on the shadowgram of the instrument being tested in the same manner that the errors of the original dividing engine are imposed on the copy. Fig. 6.6.4 shows the periodogram of the Mitutoyo dial indicator with significant periods (with aliases) at 1mm and 0.5mm. The solution to this problem is simple and follows if the procedure for subtracting the calibration curve as discussed in §5.3.2 is implemented.

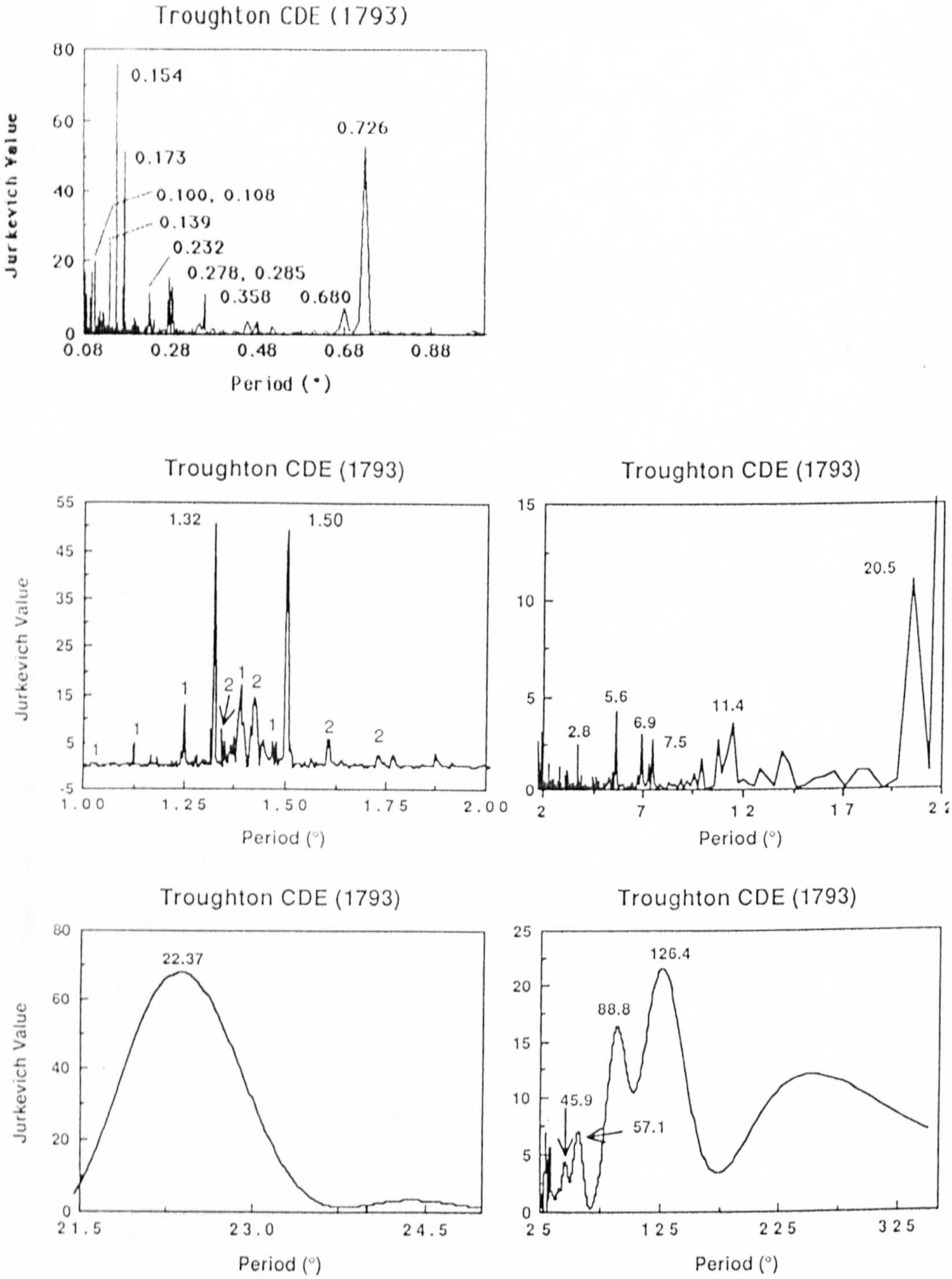
Spacing of the points and gaps in the data (as occurs if one skips over obviously flawed sections of thread profile) can introduce aliases but with the number of digitized points for the profiles, this was not apparent in the graphs presented. However, in analysing the data obtained from the dial indicator measurements, the number of points did not exceed 100 and these sources of aliases can not be overlooked. To avoid spacing problems, the data was taken randomly but the limited number of points lessens the significance of smaller peaks in the results. Samples of periodograms for 3 instruments are given (Fig. 6.6.5). What are believed to be significant periods are identified; this judgement is based on the number of points and the quality of the data. In these figures the primary period has been included but the peak has been truncated to ≈1/4 or 1/5. The periods at ≈1.0 and 0.5mm are those due to the dial indicator. Peaks at the extreme lower end are suspect and may be related to the sample spacing. SML-26 (pitch=0.645mm) and MHS-6 (pitch=0.530mm) were hand made, i.e. without slide rest, while SML-9 (pitch=0.250mm) was made with a screw lathe. In SML-26 and MHS-6 the periods at 0.622 and 0.502 probably result from the pitch of the micrometer screw; in SML-9 the broader peak indicated by the arrow probably results from the screw pitch. Micrometer screws made on a lathe were noted to have larger numbers of and more significant periods above the pitch of the thread presumably due to the errors of the lead screw and change gears.



6.7.1 Errors for Troughton's circular dividing engine (1793).



6.7.2 Smoothed (5 points grouped) for Troughton's circular dividing engine.



6.7.3 Periodograms for Troughton's circular dividing engine.

6.7 Periodograms as a Means of Studying Dividing Engine Ruling Techniques:

One avenue which was contemplated for study was the use of a precision rotary table to determine the errors of circular scales such as are found on surveying and navigational instruments. It is speculated that the errors of instrument scales may be used to associate a dividing engine with its progeny. One means of finding relationships between instruments would be to look at the periodic errors and the Jurkevich-Swingler method would be ideal for such investigations. Error data for a dividing engine and scale errors for a circle divided on a second engine have been located in the literature and error data for two standard meters (Dutch) have been obtained from Prof. J. Koning (private communication). The similarity of the scale division errors and periodograms confirms that the standard meters were made on the same ruling engine and confirms that application of these methods would allow identification of dividing engines and their progeny.

6.7.1 Edward Troughton's Circular Dividing Engine (1793):

Troughton (1809, p.145; see §4.2.5.1) published a table of errors for his dividing engine along with his description of the dividing technique; the data has been plotted in Fig. 6.7.1 for the four quadrants. There is considerable scatter in the data, hence, to accentuate the periodic errors the points have been 'smoothed' by taking the mean of 5 successive points and then plotting the new data. The results appear in Fig. 6.7.2 where the periodicities begin to stand out. It is clear that an error in division occurred about the 250° division and this was transmitted to adjacent quadrants by the dividing technique. The standard deviation of the data (entire scale) is 6.74 divisions on his micrometer. Since 1 micrometer division equalled 0.00058mm on this machine the absolute error was 0.0039mm (a number to be noted later in this chapter). Troughton's data was then subjected to the Jurkevich-Swingler period search with the results illustrated in Fig. 6.7.3.

The source of some of the noted peaks is easy to determine from Troughton's description. The peak at 1.32° resulted from the fact that the rolling sector (with 16 segments) repeated at 1°20' intervals, i.e. 1.33° (Troughton: p.127). Thus we have found one of the primary periods. The peaks with '1' above them are aliases of this peak. One might expect multiples of this period to appear. However, reference to Troughton's description shows this will not be the case since after reaching the 1°20' division, he had to reset the rolling sector. This was the case for each run of 8 courses or runs of the rolling sector which brought him to the 11°15' divisions. Thus we expect and find a peak at 11.25° (actual 11.4°). Those peaks at 2.8, 5.6, 6.9 and 7.5 are close submultiples. It will be remembered that he used microscopes to find the divisions to 22.5° as a check for

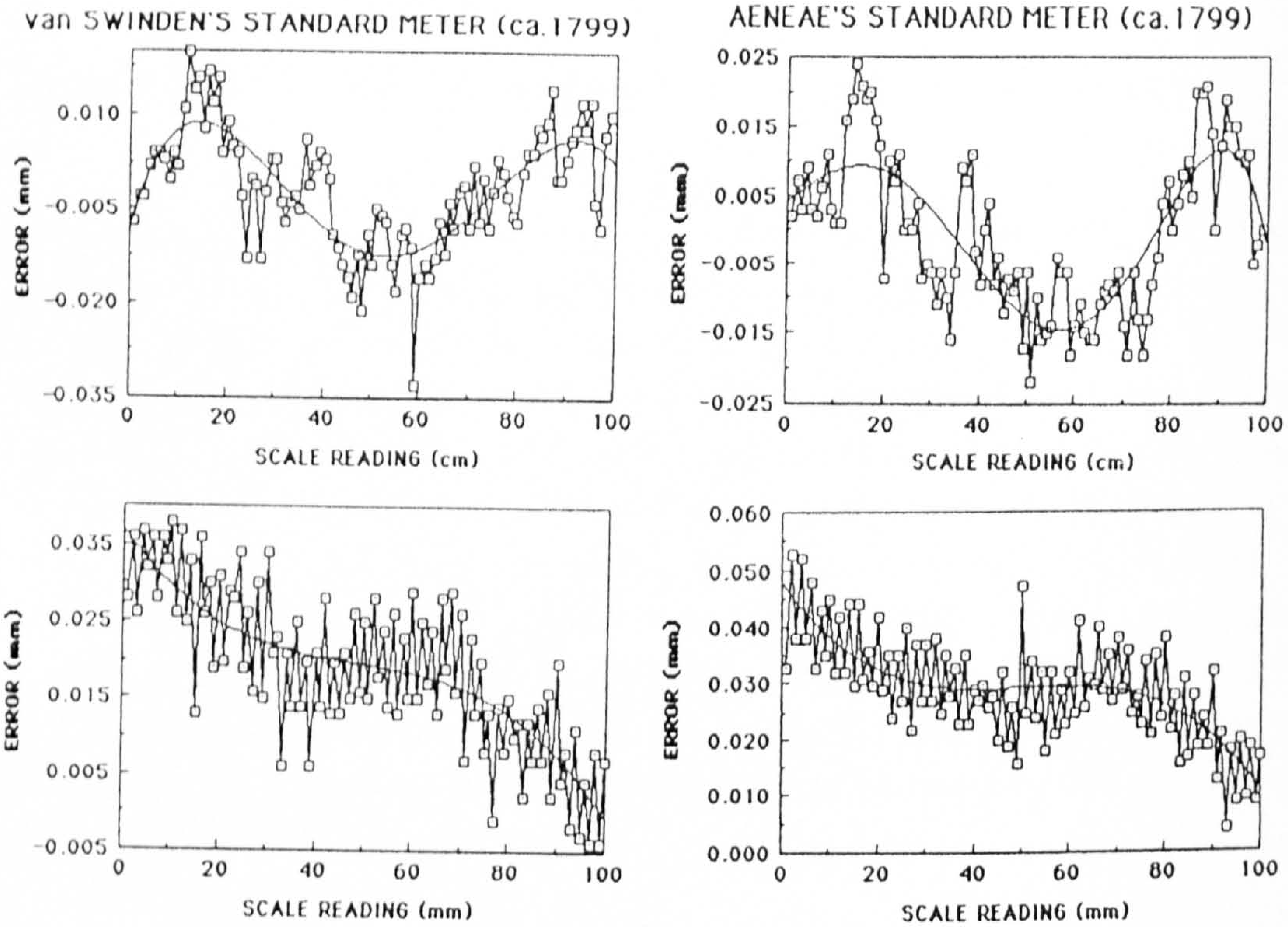
6.7 Periodograms as a Means of Studying Dividing Engine Ruling Techniques:

One avenue which was contemplated for study was the use of a precision rotary table to determine the errors of circular scales such as are found on surveying and navigational instruments. It is speculated that the errors of instrument scales may be used to associate a dividing engine with its progeny. One means of finding relationships between instruments would be to look at the periodic errors and the Jurkevich-Swingler method would be ideal for such investigations. Error data for a dividing engine and scale errors for a circle divided on a second engine have been located in the literature and error data for two standard meters (Dutch) have been obtained from Prof. J. Koning (private communication). The similarity of the scale division errors and periodograms confirms that the standard meters were made on the same ruling engine and confirms that application of these methods would allow identification of dividing engines and their progeny.

6.7.1 Edward Troughton's Circular Dividing Engine (1793):

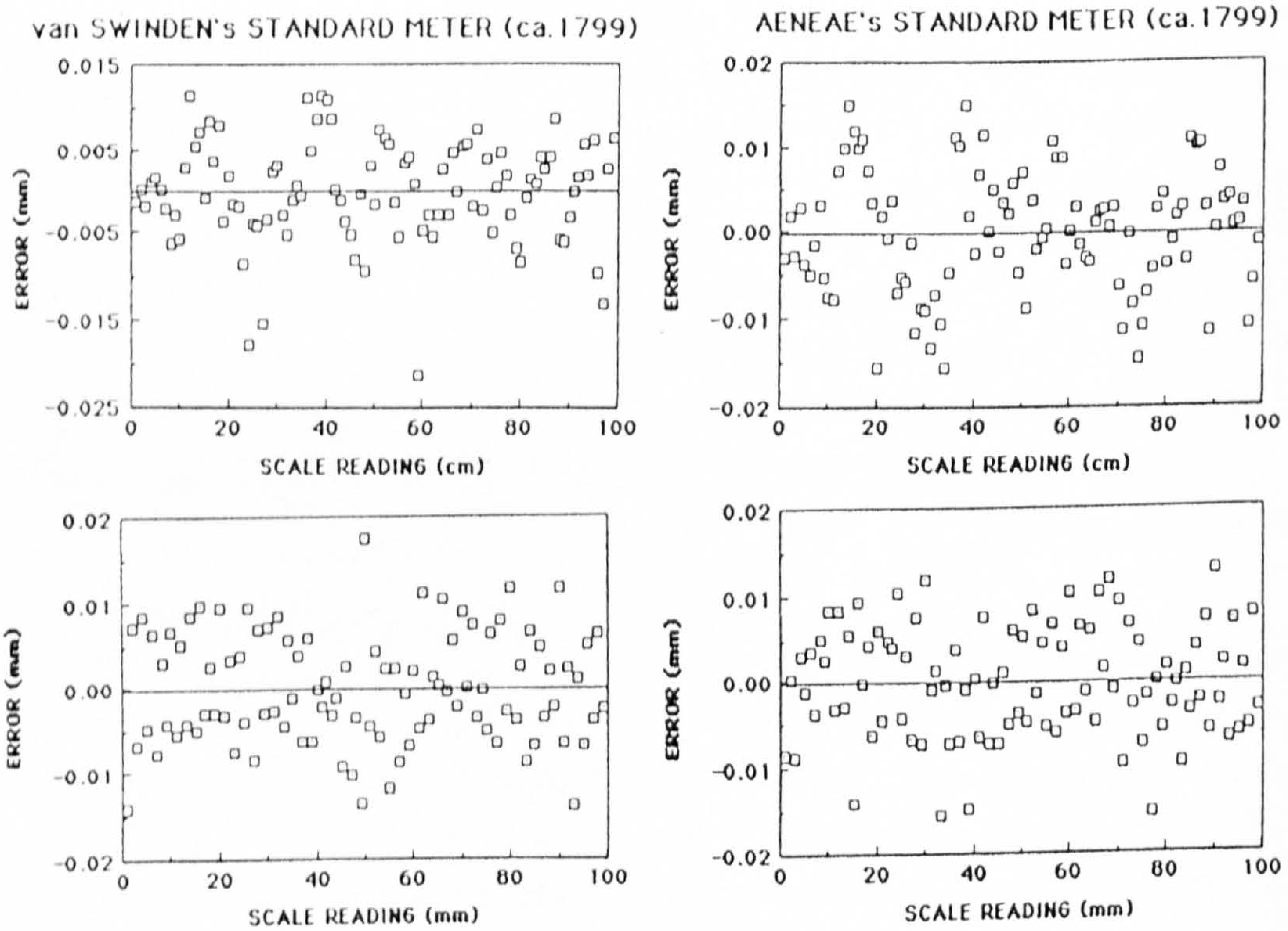
Troughton (1809, p.145; see §4.2.5.1) published a table of errors for his dividing engine along with his description of the dividing technique; the data has been plotted in Fig. 6.7.1 for the four quadrants. There is considerable scatter in the data, hence, to accentuate the periodic errors the points have been 'smoothed' by taking the mean of 5 successive points and then plotting the new data. The results appear in Fig. 6.7.2 where the periodicities begin to stand out. It is clear that an error in division occurred about the 250° division and this was transmitted to adjacent quadrants by the dividing technique. The standard deviation of the data (entire scale) is 6.74 divisions on his micrometer. Since 1 micrometer division equalled 0.00058mm on this machine the absolute error was 0.0039mm (a number to be noted later in this chapter). Troughton's data was then subjected to the Jurkevich-Swingler period search with the results illustrated in Fig. 6.7.3.

The source of some of the noted peaks is easy to determine from Troughton's description. The peak at 1.32° resulted from the fact that the rolling sector (with 16 segments) repeated at 1°20' intervals, i.e. 1.33° (Troughton: p.127). Thus we have found one of the primary periods. The peaks with '1' above them are aliases of this peak. One might expect multiples of this period to appear. However, reference to Troughton's description shows this will not be the case since after reaching the 1°20' division, he had to reset the rolling sector. This was the case for each run of 8 courses or runs of the rolling sector which brought him to the 11°15' divisions. Thus we expect and find a peak at 11.25° (actual 11.4°). Those peaks at 2.8, 5.6, 6.9 and 7.5 are close submultiples. It will be remembered that he used microscopes to find the divisions to 22.5° as a check for



6.7.4a Errors for the van Swinden and Aeneae standard meters.
Above 0-100cm by cm (5th degree polynomial fit);
below 0-10cm by mm (3rd degree polynomial fit).

6.7.4b Errors for the above standard meters after subtraction
of the polynomial fits.



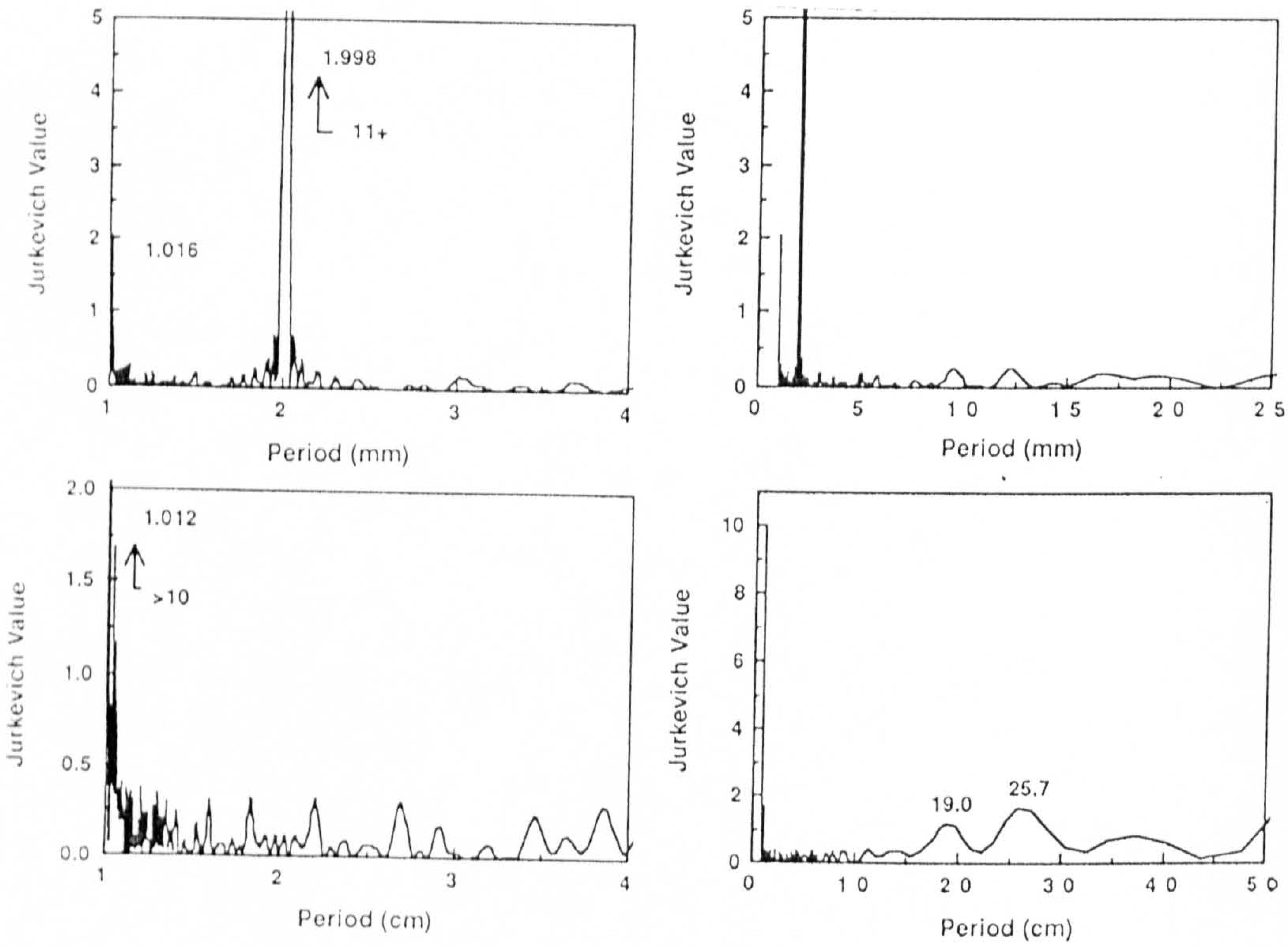
the runs of the sector; this peak too appears very strongly. The periods at 45.9, and 88.8 are understandable though further from the primary divisions than one might expect but those at 57.1 (≈5 revolutions of the sector) and 126.4 (11.25 revolutions) are not readily understood. What, however, is the source of the peak at 1.5°? Nothing in the dividing technique would suggest that we would expect this peak, so that we must conclude that it arose from the micrometer screw used to determine the errors. The peaks marked '2' are aliases of this peak. Below 1° quite a number of peaks appear as noted on the graph. The 0.154 peak is the spacing given by the unit segments on the rolling sector and the 0.139 and 0.173 peaks given by the 'adjustment' of ±1/8 revolution used by Troughton after each course of divisions (1°20'). The peaks noted at 0.278 (plus the one just to the left) and 0.285 are aliases of the three peaks just noted. The 0.100° period is an alias from the sampling frequency while the peak at 0.680 is a submultilple of the primary period 1.32. The broad base of this peak suggests it is not a real period. The source of the 0.358 peak is probably due to the micrometer, it being ≈1/4 of the 1.5 period while the 0.726 peak is ≈1/2. The periodic errors found thus confirm Troughton's description of his method of dividing the scale of his machine.

6.7.2 The Standard Meters of van Swinden and Aeneae:

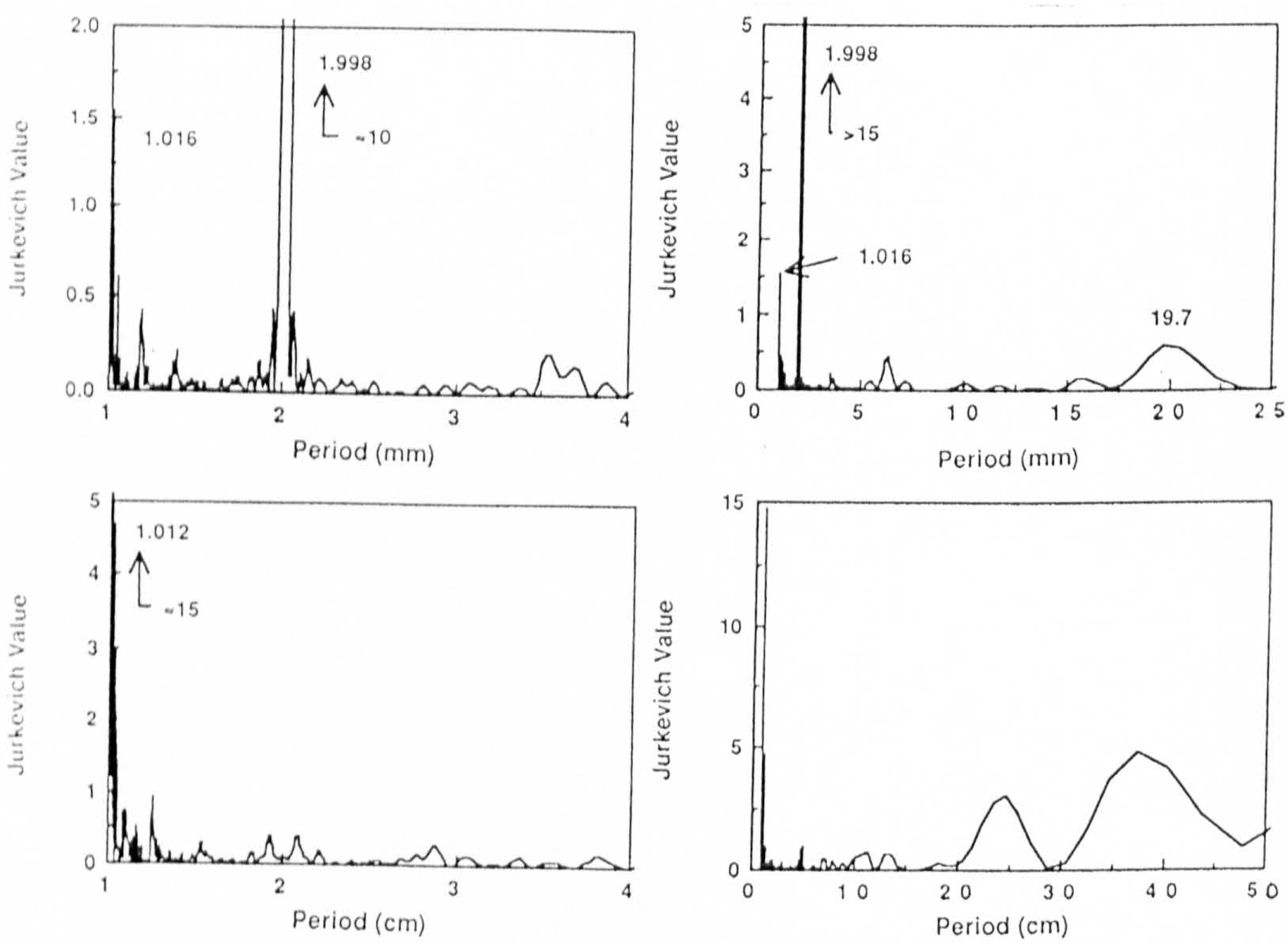
According to Koning (1988), the copies of the standard meters (brought back to the Netherlands after the 1798/9 conference in Paris to establish the metric system) had been made by Lenoir and were originally undivided. At the request of van Swinden and Aeneae, Lenoir subdivided the standards--probably in 1799. The method used has not been described as far is known. However, measurements made by Koning and his collaborator Mr. Sonnemans have proven useful in assessing Lenoir's technique and precision. The meters are preserved in the University Museum at Utrecht, but were removed to the Metrology Lab at Eindhoven where they were measured using a Zeiss (Jena) 3m universal comparitor. The precision of the measuring comparator was 2 microns, being limited by temperature effects and by the quality of the scale divisions to be measured. Both standard meters were measured from 0-10cm by 0.1mm and from 0-100cm by 1.0mm steps.

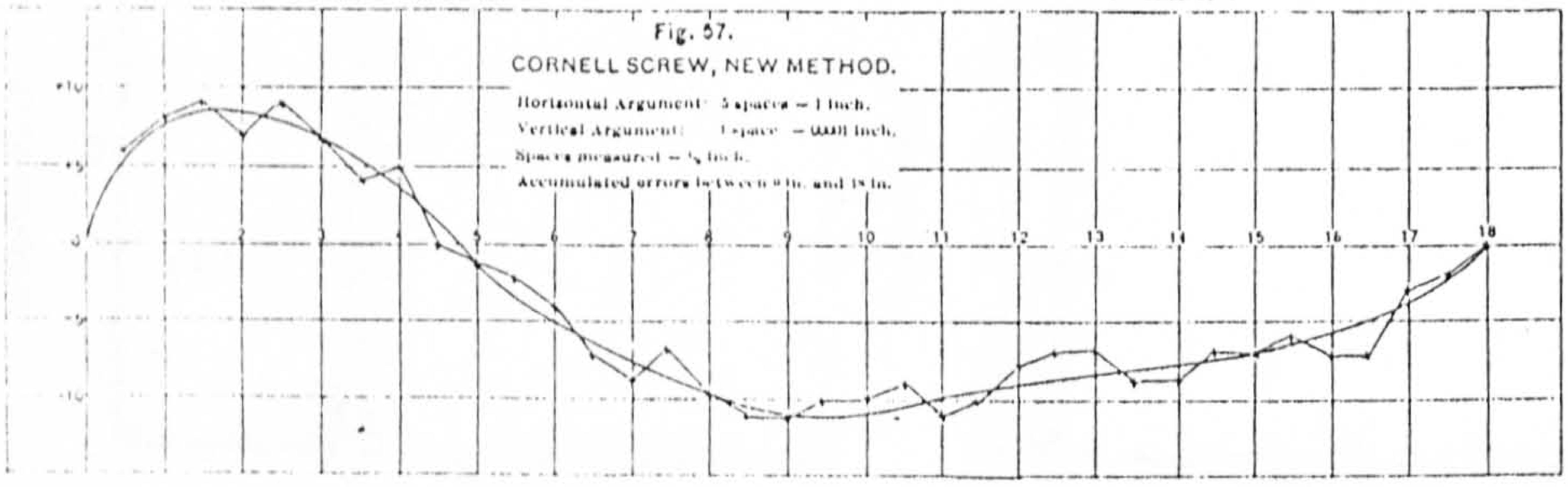
Fig. 6.7.4a shows the respective error curves for each range. For the 1-10cm range, a 5th degree polynomial fits both curves well, while for the 0-100cm range third degree polynomials fit well. The absolute errors are ≈±0.025mm but after subtracting the polynomial fits (Fig.6.7.4b), the standard errors are:

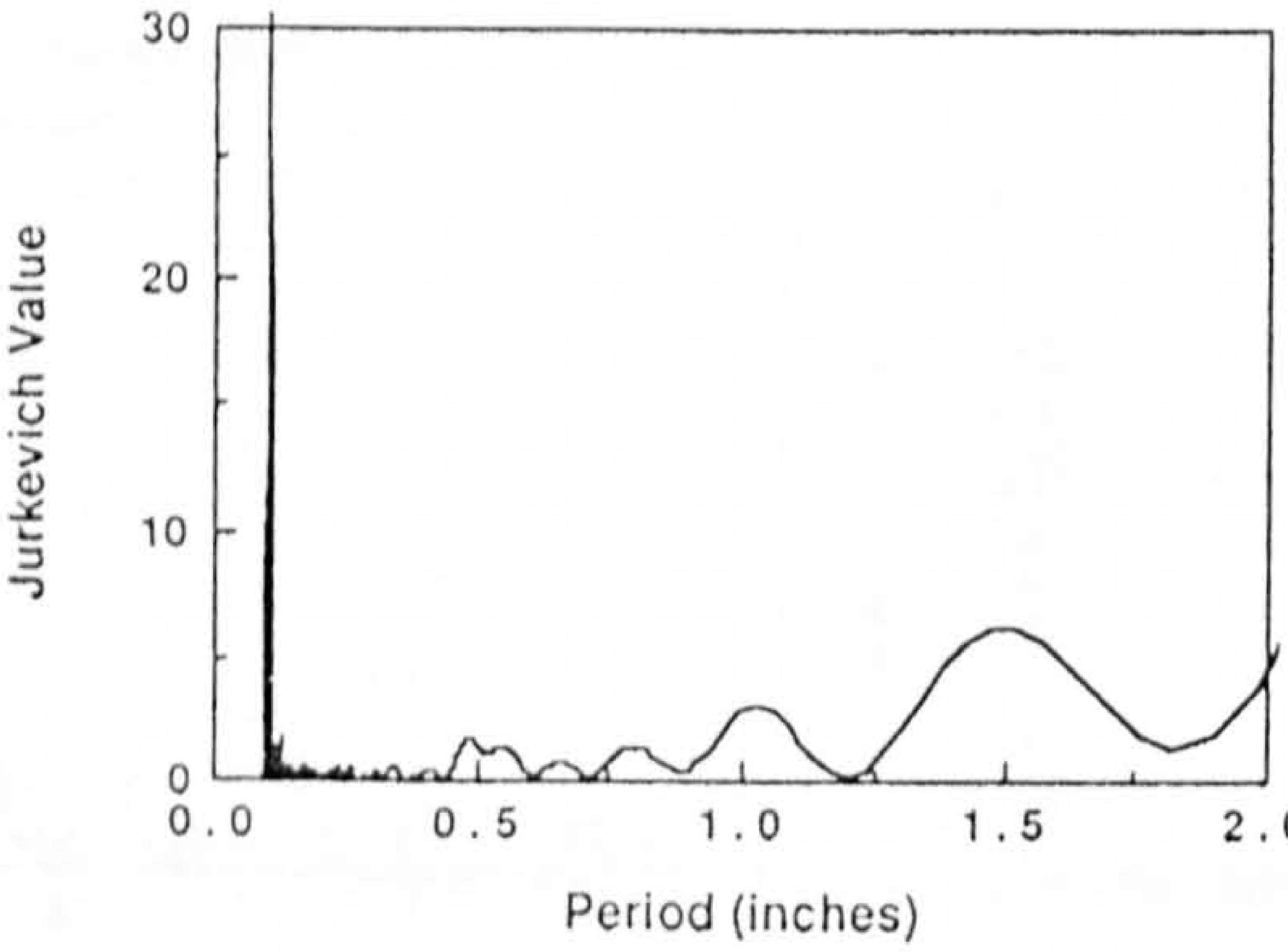
for van Swinden's meter:	0-10cm	0.0060mm
	0-100cm	0.0070mm
for Aeneae's meter:	0-10cm	0.0065mm
	0-100cm	0.0064mm



6.7.5a Periodograms for the van Swinden standard meter
5b Periodograms for the Aeneae standard meter (below).



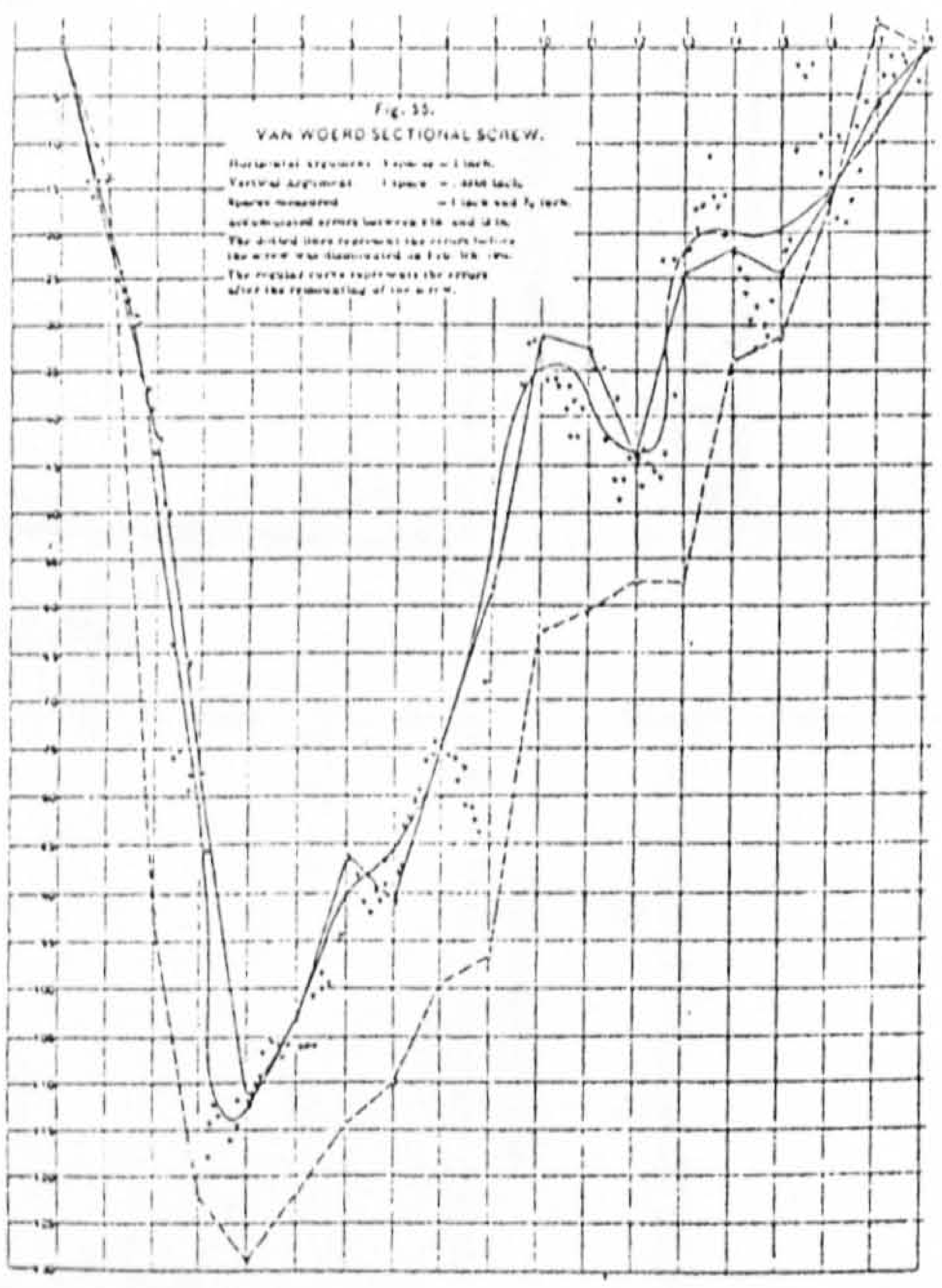




6.7.6a Errors determined by Rogers (1884) for the Cornell screw.

6.7.6b Periodogram of the errors of the Cornell screw.

6.7.6c Errors determined by Rogers for van Woerd's sectional or Waltham screw.



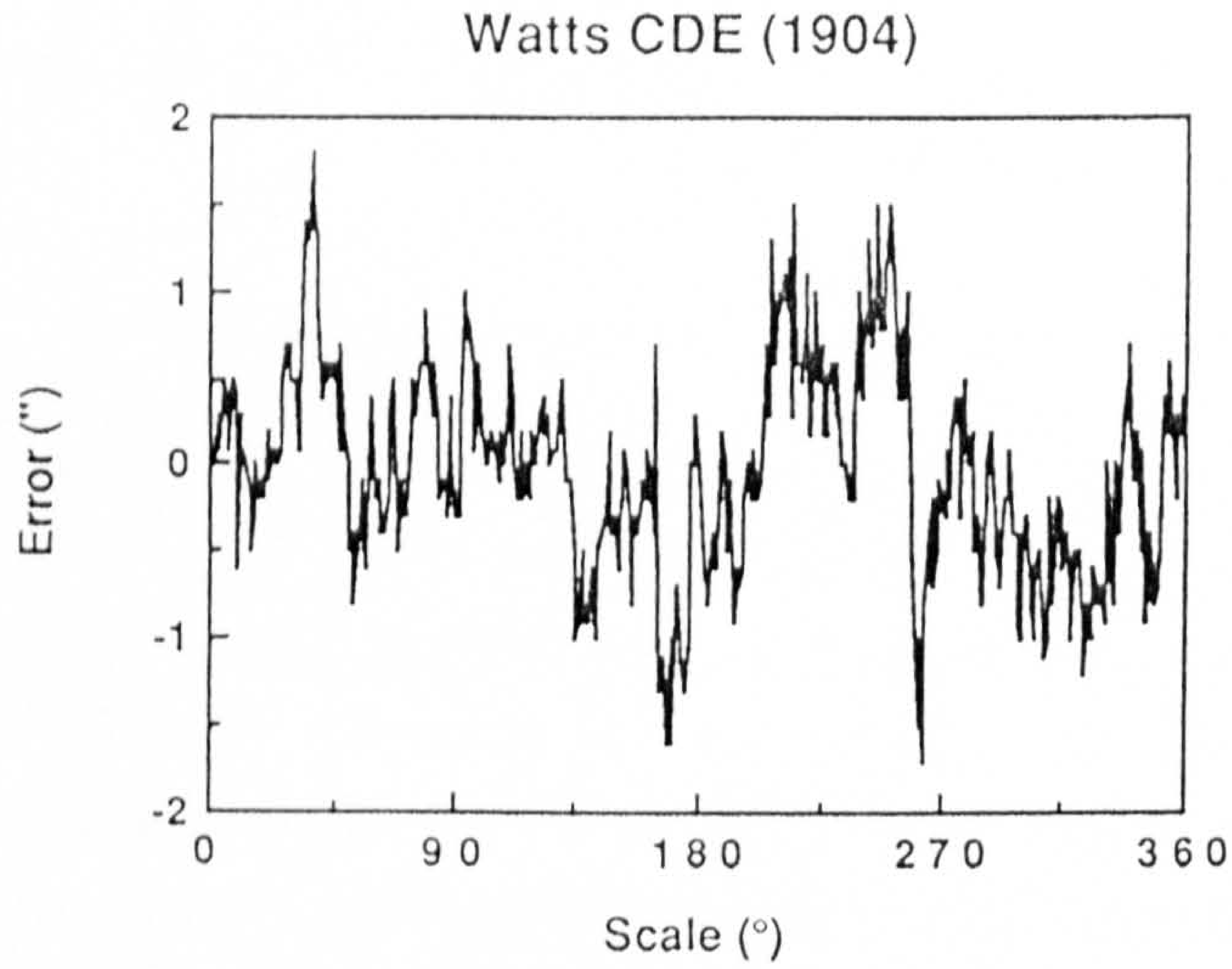
The similarities are also evident in the period search results shown in Fig. 6.7.5. We can deduce that the dividing engine had a screw of 2mm pitch. The peaks just over 1.01 are artifacts of the sampling frequency in all four cases. In the cm scales, the peak near 25cm is probably real and there is reason to believe the peak--weak as it is--near 37.5 is also real. Also in the cm scales of both meters one sees an interesting symmetric pattern centred on 2cm but the interpretation is not clear.

6.7.3 Rogers' Cornell Screw (1884):

Rogers (1884, fig.57) plotted the errors of the screw (Fig. 6.7.6a) he made at Cornell University. Although only 36 points are provided, these have been run through **Profil1** to determine the periodic errors (Fig. 6.7.6b). In this plot, the peaks at ≈0.1 are primarily due to the sample spacing. The pitch of this screw was 20 TPI (Rogers: p.237) and thus periods of a single revolution do not appear since the sample spacing was twice this value. Periods, though of low significance, appear at 0.5, 1.0 and 1.5in but this may well be related to the manner in which Rogers obtained the error values with a secondary micrometer. Without knowing the attributes of the testing micrometer, it is unwise to make firm statements on the validity of the periods found given the relatively few points being analyzed. A long period of 3.5in cannot be overlooked and, as Rogers suspected, is due to the grinding process. This screw had an absolute mean error of ≈0.0015-0.002mm (log -2.82 to -2.70) which represents an error of ≈0.03% of the pitch. This level of error places this screw off scale in Fig. 6.4.7a for dividing engines. The sectional screw made by van Woerd at the Waltham Watch Company (see §2.6.4.11) was tested by Rogers using the same means and found to have an maximum error (Fig. 6.7.6c) of 0.0013in (0.033mm) though he improved it to 0.00114in by remounting the screw. The average error was perhaps ≈0.0005in (0.013mm) which would place it in Fig. 6.4.6a/7a for dividing engines with a larger error than some of the earlier screws tested. Rogers, as Whitworth before him, was not impressed by the section screw approach to making a precision screw and this is again proven by the present comparisons.

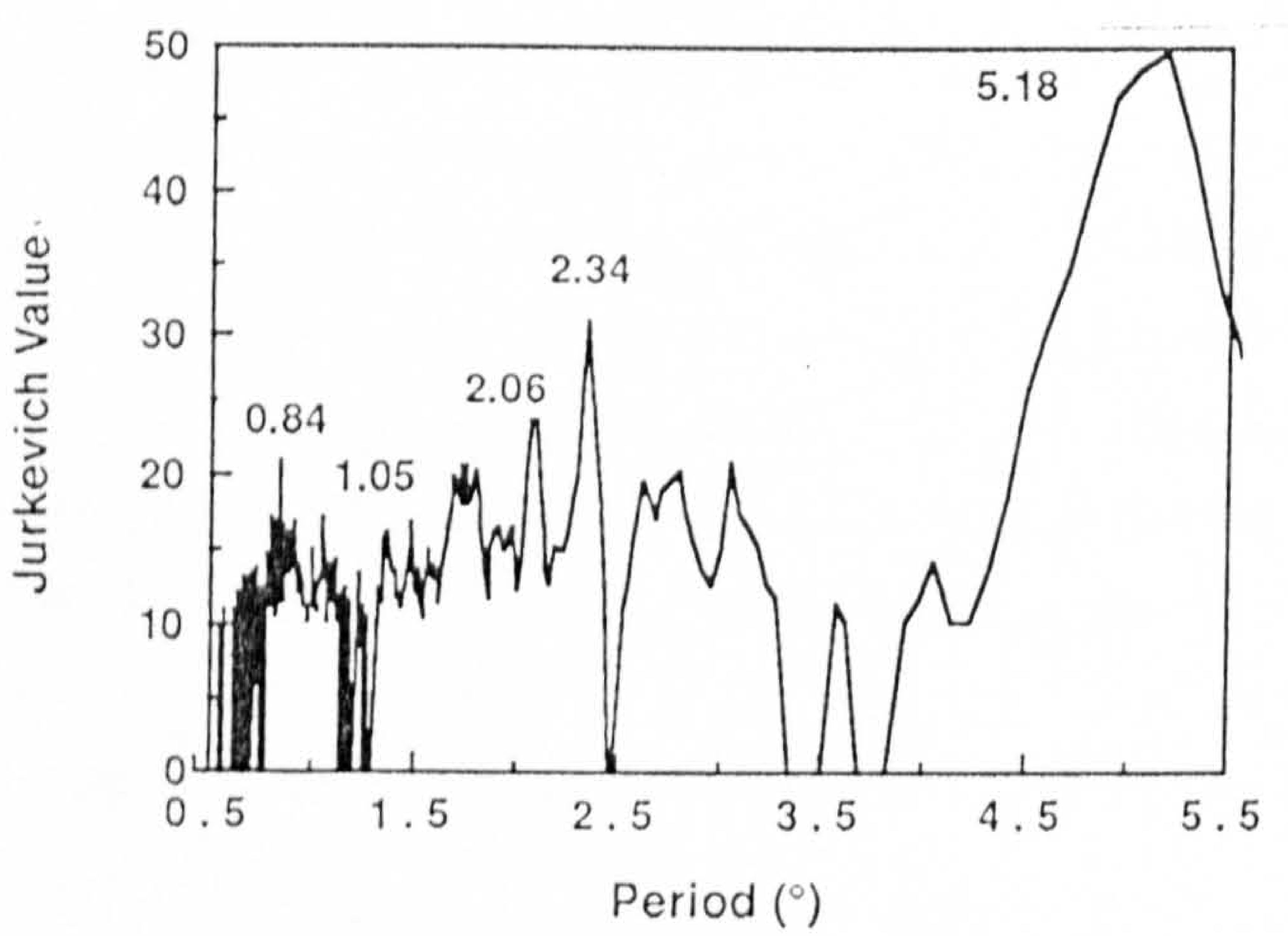
6.4.2 Watts Circular Dividing Engine (1904):

E.R. Watts & Son of London built a circular dividing engine of slightly over 4.5ft diameter in 1904 (McCaw: 1908, p.226). A 55cm diameter circle divided on it was submitted to careful scrutiny to determine the errors of the scale division; these were printed by McCaw and have been analysed by the Jurkevich-Swingler method. The divisions of the engine were first carried out by hand then checked with 7 micrometers and a second scale redivided, again checked and the final divisions cut with a mean accuracy of 0.6" according to the makers. The standard error of the 55cm scale (Fig. 6.7.7a) was 0.619" indicating that Watts came very close to, if not surpassing the



6.7.7a Errors observed in a 50cm diameter circular scale divided on the Watts circular dividing engine (1904).

6.7.7b Periodogram of the errors in the above circular scale.



objective since one would expect the copy to have suffered some deterioration in the graduation. The search for periodic effects indicates few significant periods (Fig. 6.7.7b). The search is hampered by the fact that the sampling spacing is precisely 1° and peaks below this are not significant; the 1.05 peak (if one can call it that) is caused by the sample spacing. Despite the strength of the 5.18 peak, its width suggests that it is less significant then the 2.06 and 2.34 peaks. Considering the small standard error of the divisions and the fact that it was close to Watts' objective for the accuracy of the dividing engine divisions, we may assume that the 55cm circle was a faithful copy and will reflect the periodic errors of the master. If true, then we can deduce that the Watts dividing engine was remarkably free of periodic errors.

6.8 Conclusions:

Several points should be reiterated about the methods adopted here and their application. First, the shadowgram method to create digitized profiles is preferable to direct or 'hand' measurement of shadowgraphs. The digitized method has wide application since it can be used on virtually any screw thread with reasonable results. For instruments which were intended for measurement (e.g. micrometers, etc.) application of the dial indicator technique is preferable. The accuracy was limited here by the dial indicator and relative motion between the indicator and instrument. Upgrading the measuring equipment to employ suitable digital encoders feeding into a data logger would allow considerable improvement in resolution and application to even the most precise 19th c dividing and ruling engines. The application of the periodogram method to search for 'finger prints' of dividing engines has been established. In conjunction with the proposed improvements for the dial indicator technique, the periodogram search for specific cases could be used to determine the origins and relationships of scaled instruments--though with the expenditure of considerable effort. None the less, every dividing engine will have a 'finger print' which will have been transferred to the scale made on it to a degree which is related to the care with which the copy was made. For major observatory (though not of course for originally divided instruments), nautical or surveying instruments the care used in their manufacture will ensure that the finger print has been passed on, and provides a means of identifying makers and dates.

Chapter 7

Significance of the Results

7.1 Some Problems Dependent on Precision Screws:

From the time of Hooke, astronomers and instrument makers were widely aware of the potential of screws to carry out tasks of a precision nature--an awareness that has been maintained for more than 300 years. The micrometer became but one component in the armoury of equipment used to make celestial observations for astronomical, nautical or surveying purposes. Though it was the key to the solution of the parallax problem for astronomers, the dividing engine, sextant and chronometer were also important components in the more practical problem of solving the longitude. Frequently overlooked is that these devices required a precision screw in their production and/or use; recalling this reiterates the practical and technical significance of the screw to the advancement of 17th-19th c science and technology. In solving the longitude problem, keeping time was but one aspect of a complex problem that also required observations using micrometric screws to provide the data for tables of stellar, lunar and planetary positions. Accurately determined geographical maps were also essential. Harrison's chronometer is given most of the credit, but without these secondary instruments and observations (and theories to reduce the data) the chronometer would have been a white elephant--and a very expensive one! As was suggested in the chapter on dividing engines, there is a correlation between the work on dividing engines and work on marine chronometers. This was not a chance occurrence but a deliberate attempt to prepare for the anticipated demand for accurate nautical and surveying instruments.

In addition to the main results of this research, five instruments were investigated in the last chapter on which information had been gleaned from other sources. In this final chapter we will compare the results of that chapter with observations made by scientists of the 17th to 19th centuries, and by investigators who have done comparative studies of scientific instruments. Although they will not be discussed in detail, a number of the astronomical problems became amenable to solution with the increasing perfection of the screw. Filar and scale micrometers, and scale dividing techniques, had impact on determination of the Sun's apparent diameter (and hence on eclipse prediction and shape of the Earth's orbit), solar parallax (and hence on the Sun's distance, physical diameter and comparison of the Sun's physical properties to those of stars), and, perhaps most importantly scientifically, stellar parallax. Hooke made his zenith sector in order to measure parallax in the 17th c, while Herschel attempted to use double stars to find the same elusive quantity. However, not until 1838, with the use of large proper motion stars did the search finally prove successful: this delay was directly related to the perfection of micrometer screws. Success in finding the parallax not only gave a direct confirmation of Copernican theory but also permitted meaningful comparison of stellar properties and, in conjunction with the spectrograph, began to revolutionize astronomy in the 19th c.

7.1.1 Consequences of Bradley's Search for Stellar Parallax:

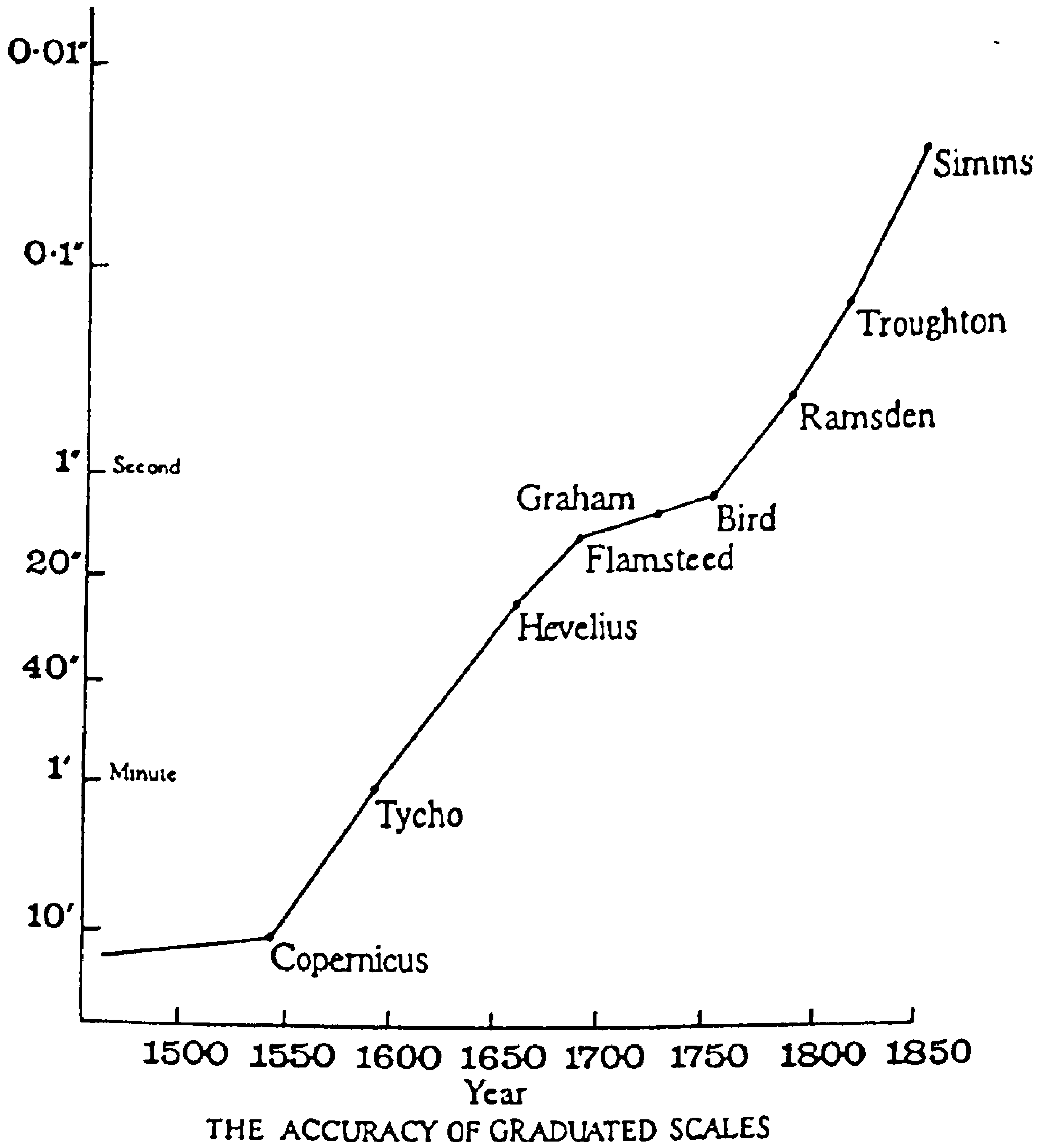
Though the search for stellar parallax was unsuccessful for a century and a half, there were some significant scientific off-shoots, e.g. the discovery of aberration (1728) and nutation (1748) both by James Bradley. The constant of aberration is ≈20.5" while nutation varies by ±9.2" over a 19 year period. These numbers indicate the state of astronomical mechanisms in the second quarter of the 18th c, with the discovery of nutation also indicating that Bradley had found methods to maintain or, at least, to determine the line of collimation of his quadrants over long periods. He also adopted an observing technique (1748, p.23) which allowed him to ignore the 5' divisions of his sector's scale. He states:

> I have expressed the Distance of each Star from the Point of the Arc, with which it was compared, in *Seconds* of a Degree and *tenth Parts* of a Second, exactly as it was collected from the Observations altho I am sensible, that the Observations themselves are liable to an Error of more than a *whole* Second, because I meet with some, that have been made with two or three Days of each other, that differ by 2", even when they are not marked as *defective* in any respect.

Reference to Chapman (1983) (Fig. 7.1.1) would lead to the conclusion that Bradley would have been able to measure to no better than 10", but in fact Bradley had found a method of using his scale micrometer that made him independent of the scale's divisions for this particular type of observation. Going by Bradley's admission, routine observations of 1" accuracy were not possible, though over a period of a few days an accuracy of 2" or better was achieved. As Sarton pointed out (1932, p.335) Bradley's success was partially due to the fact that he did not stop at attributing these tiny changes to errors of his instruments, but rather went on to consider their magnitude and to correct the errors thus allowing him to discover nutation. Bradley's sector, made by Graham in 1727, was of 12.5ft radius and 2" equaled 0.037mm (log=-1.43). Reference to Fig. 6.6.6a/7a shows that this 2" limit falls on the linear fit determined by the current measurements.

7.1.2 Bird's Micrometers:

Chapman's figure suggests that little improvement was made in instrumental accuracy in the first half of the 18th c by Graham and Bird. However, the bifilar micrometer (MHS-3) by Bird was measured by the shadowgraph technique to have an error of 0.012mm, which places it on the limit obtainable at the time (Fig. 6.6.6a/7a). Unfortunately, as with all filar micrometers, the accuracy obtainable in seconds of arc is dependent on the focal length and magnification of the telescope with which it was used. Thus we cannot make a direct comparison with Chapman's results since we do not know



7.1.1 Chapman's estimate of instrumental scale accuracy (1976) for some astronomical instrument makers.

with what telescope this instrument was combined. However, several scale micrometers by Bird have been studied and do allow a comparison. Seven instruments were studied by the shadowgraph (SG) and four were measured using the dial indicator (DI) method.

Table 7.1
Bird's Micrometers

Date	Code	Pitch	Diameter	Errors(mm) SG	DI	
ca.1767	MHS-8	0.473	0.188N	0.038		
ca.1767	SML-25a	0.5003	0.1676/92	0.018	0.0057	(=RS 63)
1770	MHS-4a	0.504	0.1288	0.012	0.0286	
	MHS-4d-n	0.499	0.128	0.022		
ca.1770	MHS-3a	0.640	7.14	0.012		(bifilar micrometer)
	MHS-3b-n	0.632	7.14N	0.026		
ca.1770	SML-24a	0.4704	0.1734	0.030	0.0204	
ca.1770	WMHS-8	0.5054	0.1602	0.016		
1773	MHS-7	0.487	0.188	0.032		(12ft zenith sector)
1773	MHS-6	0.530	0.281	0.023	0.0060	(8ft quadrant)

For the portable quadrant, SML-25a, the dial indicator method indicates an error of =4". But for the 8ft quadrant, MHS-6, the error indicated is ≈0.5"--considerably better than the ≈2" predicted by Chapman's figure. Unfortunately, the micrometer screw of the other high quality instrument in this sample, the zenith sector MHS-7, was rusted and the error estimate is not very reliable. We must conclude that the limiting factors in the Oxford mural quadrant were the scale division and maintenance of the line of collimation. Where differential measurements were made (and this was the technique most frequently used in parallax measurements at the time) the limiting factor would have been the micrometer itself. The errors for SML-25a and MHS-7 place these instruments on the lower limit anticipated from Figs. 6.6.6a and 7a.

7.1.3 Ramsden's Micrometers:

The Shuckburgh equatorial instrument (1791) preserved in the Science Museum (SML-6) also provides an opportunity to check the error graphs with that of Chapman. Shuckburgh (1793, p.109n) noted that the scale error of his instrument was 1" (≈0.005mm). The error found for the eyepiece filar micrometer of this instrument was 0.0056mm (dial indicator method) and suggests the error obtainable for a single differential observation was slightly more than 1". It is interesting to note that Shuckburgh recognized that errors were additive; he also determined all errors (except the measure of polar distance) to be constant and, therefore, by making many observations, the errors could be reduced to any desired level (p.117-119). Shuckburgh estimated the error of reading his microscope micrometers as 0.5" but this is unlikely to have been the case. The other Ramsden micrometers tested (SML-9a,13a) were of lower precision. Thus, although Ramsden may have been able to divide his scales to 0.5" as indicated by Chapman, the subdivision of those divisions could not be done with the same degree of exactness.

7.1.4 Herschel's Micrometers:

An unexpected finding in this research is the very low quality of the filar micrometer screws associated with William Herschel. As noted previously there is reason to believe that he or his brother, Alexander, made these and that the screws were formed with a screw plate or screw stocks. The diameters are the smallest encountered among the micrometers, and the threads the poorest. These instruments, unlike their user, were not at the leading edge of astronomical work. To understand how Herschel made progress in the area of double star studies--since it cannot be attributed to his instrumentation--one is referred to his paper of 1803 on "Account of the Changes...in the relative Situation of Double-stars", p.347 which relates his method of observing Castor in 1781. His novel observing technique permitted him to overcome the shortcomings of his micrometers. Given the results found in this work, it is little wonder Herschel turned to his lamp micrometer to measure double stars (Herschel: 1782).

7.1.5 Troughton Micrometers and the Impact of Glass-Making Technology:

The Groombridge transit circle was the first accurate instrument of its type made in Britain according to King (1979, p.234). As such, it may reasonably have been expected to detect the elusive parallax. The eyepiece micrometer (SML-40) was tested and found to have an error of 0.0034mm by the dial indicator method. The screw value of the 3.5in and 5ft focal length lens is (Roth: 1975, p.89) 59.00", i.e. 1 turn of the micrometer screw equals 59". Thus, from the 0.0034mm accuracy predicted by the dial indicator measurements, we could expect to measure to ≈0.46" with this instrument. However, the resolving power of a lens of 3.5in according to Dawes' rule is only 1.30". Thus the size of optical objectives was a contributing factor in the lack of parallax detection.

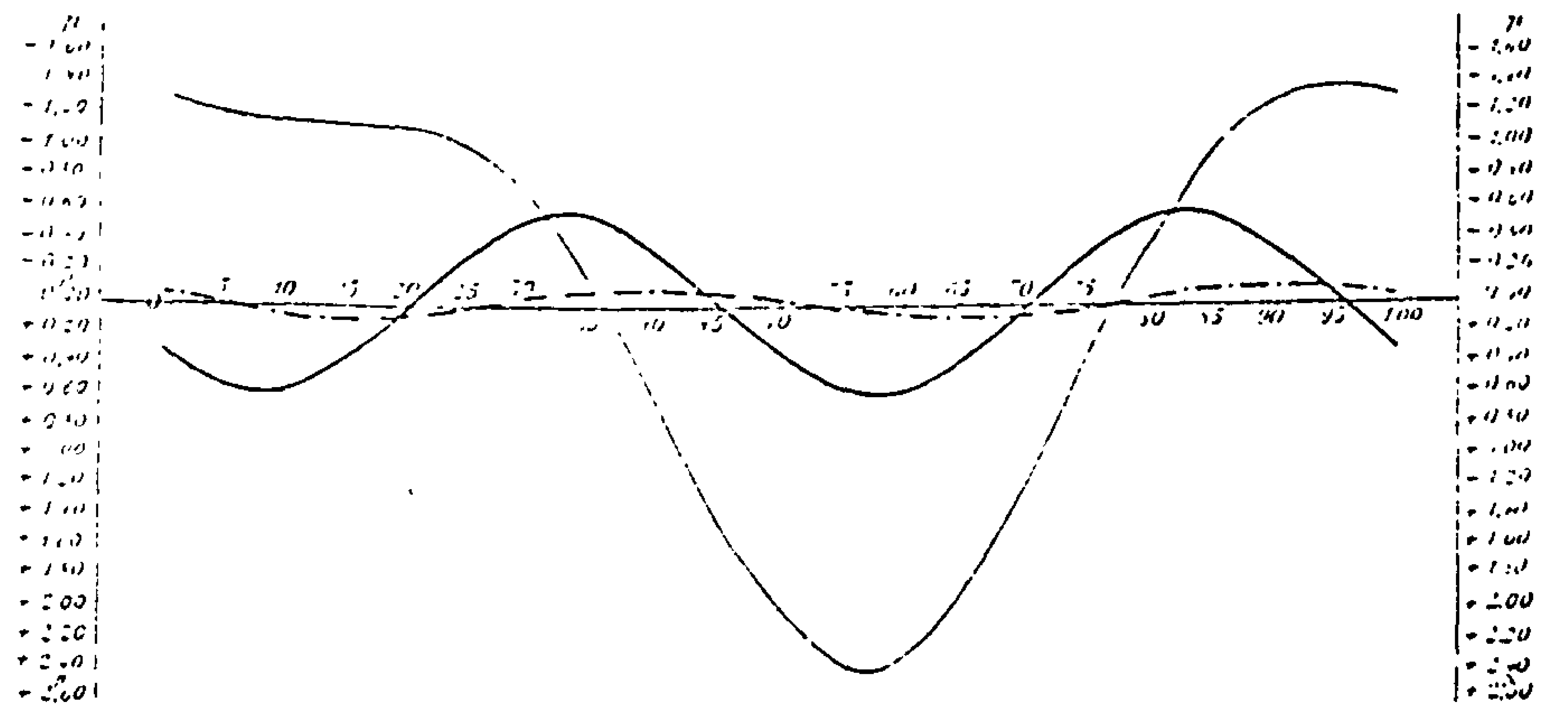
Without the quality glass required for larger telescopic objectives British astronomers were at a distinct disadvantage to their German counterparts, for Guinard's fine optical glass gave German makers a new superiority (King: 1979, p.176ff). This glass making technology was kept a close secret by Guinard, who was attracted to Germany from France by Utzschneider to work in conjunction with the Mathematical-Mechanical Institute in Munich. This occurred in 1805, just after Guinard had discovered the fireclay stirring rod which permitted homogeneous melts of glass. In 1809 Joseph Fraunhofer became the first person outside Guinard's family to be instructed in the secret process. After Guinard and his family returned to France, they maintained the secrecy so that the process resided only with them and Fraunhofer. Thus this crucial advantage was maintained. The Germans used all their glass while Guinard sold the best of his lens blanks to French makers; only second rate blanks made their way to Britain. The mechanical skill of French makers did not allow them to take advantage of the full potential of the high quality lenses, but Fraunhofer and the Munich Institute were undisputedly the finest makers of mechanism in the first quarter of the 19th c, and with the added advantage of having the best glass available it is not surprising that one of Fraunhofer's instruments was used in the eventual discovery of stellar parallax by Bessel.

The 2ft geodetic theodolite (SML-14) by Troughton & Simms used in the survey of the Lough Foyle base line was measured by the shadowgraph method. The error indicated for this instrument was ≈2-2.5". By comparison, the error of the bifilar micrometer at the Royal Observatory (ROG-4) has less than half the error (expressed in mm) of the geodetic theodolite. Although it is not certain with which telescope this micrometer was used, a slip of paper in the case for the micrometer indicates the screw value was 20.81".[1] The 0.0047mm error thus translates to an error of 0.39". Though perhaps not the best accuracy obtainable by a Troughton & Simms instrument, the fact that this filar micrometer was used in the mid-19th century when Airy was Director, means we can assume it was tested closely and satisfied that well known stickler for precise and carefully made mechanism. Such definition is, of course, only obtainable under moments of exceptionally steady seeing conditions. So although Troughton and his successor, William Simms, may have been capable of dividing scales to 0.2" or 0.03" respectively as claimed by Chapman, in reality this had little consequence since the atmospheric conditions never permitted resolution to these levels in single observations. Only after many repeated observations could the errors be beaten down by statistical means.

A later modification to the transit circle was the mural circle which became popular in the 1830's. Robinson reported on the 5ft diameter Armagh mural circle (1833-6, p.111). The telescope was of 63in focus and 3.8in aperture and had been erected in 1832. Though not directly related to the errors of the micrometer screws, the errors of the scale divisions are relevant to these discussions and comparisons. Fig. 4.3.5 shows the errors after some initial scale division errors and an error of eccentricity had been corrected 'in situ' by Thomas Jones, the instrument's maker. Jones' estimate of the errors was obtained simply by taking 269 diameter measures; this cannot be considered a rigorous test of the scale. 60% of the errors were below 0.5", but without the actual values only an estimate of the mean error can be provided, i.e.≈0.45". On a 5ft diameter circle 1" equals 0.0012mm; thus the average error was below 0.0006mm (log≈-3.22). Reference to Figs. 6.4.6a and 6.5.2 indicates this was well below any error measured for a dividing engine in this study. It is still much higher than the error one might anticipate by reference to Chapman's figure. However, Jones did not have the reputation of Troughton & Simms, and this is perhaps confirmation that his skill did not match that of his competitors.

---

[1] Using Roth's formula (1975, p.89), the focal length of the telescope was 8.20ft.



7.1.2

Errors of the Göttingen heliometer (from Anbronn: 1899).
- light solid line equals error of a single screw
- heavy solid line equals combined error of both screws
- dotted line equals error after subtraction of computed error.

Thomas Henderson observed at the new observatory at the Cape of Good Hope from April 1832 to May 1833, when he returned to his native Scotland to become Astronomer Royal for Scotland (Clerke: 1887, p.46). While at the Cape he used a mural circle with 'severe shortcomings', but by carefully examining the errors with the 6 scale microscopes he was able to quote a probable error for observations of 0.22". He also concluded that, from the laws of statistics, of the 720[1] sets of divisions read by the 6 microscopes, 328 sets would have errors below 0.2" and only one set would have an error exceeding 1" (Henderson: 1833-6, p.58). Among the stars Henderson observed was α Centauri. On being informed that it showed an annual proper motion of 3.6", he determined to make observations for evidence of stellar parallax. Unfortunately, he did not reduce the results for some years for it was January 1839 before his discovery of α Centauri's parallax was communicated. This was two months after Bessel had made his discovery; thus, like Adams soon to follow, Henderson lost priority to a Continental observer. What should be noted is that the instrument was judged to have faults, but by attention to the errors and their correction, the parallax was discovered in observations made 6 years prior to Bessel's. In the end, Bessel too had success only after discovering and correcting the instrumental errors.

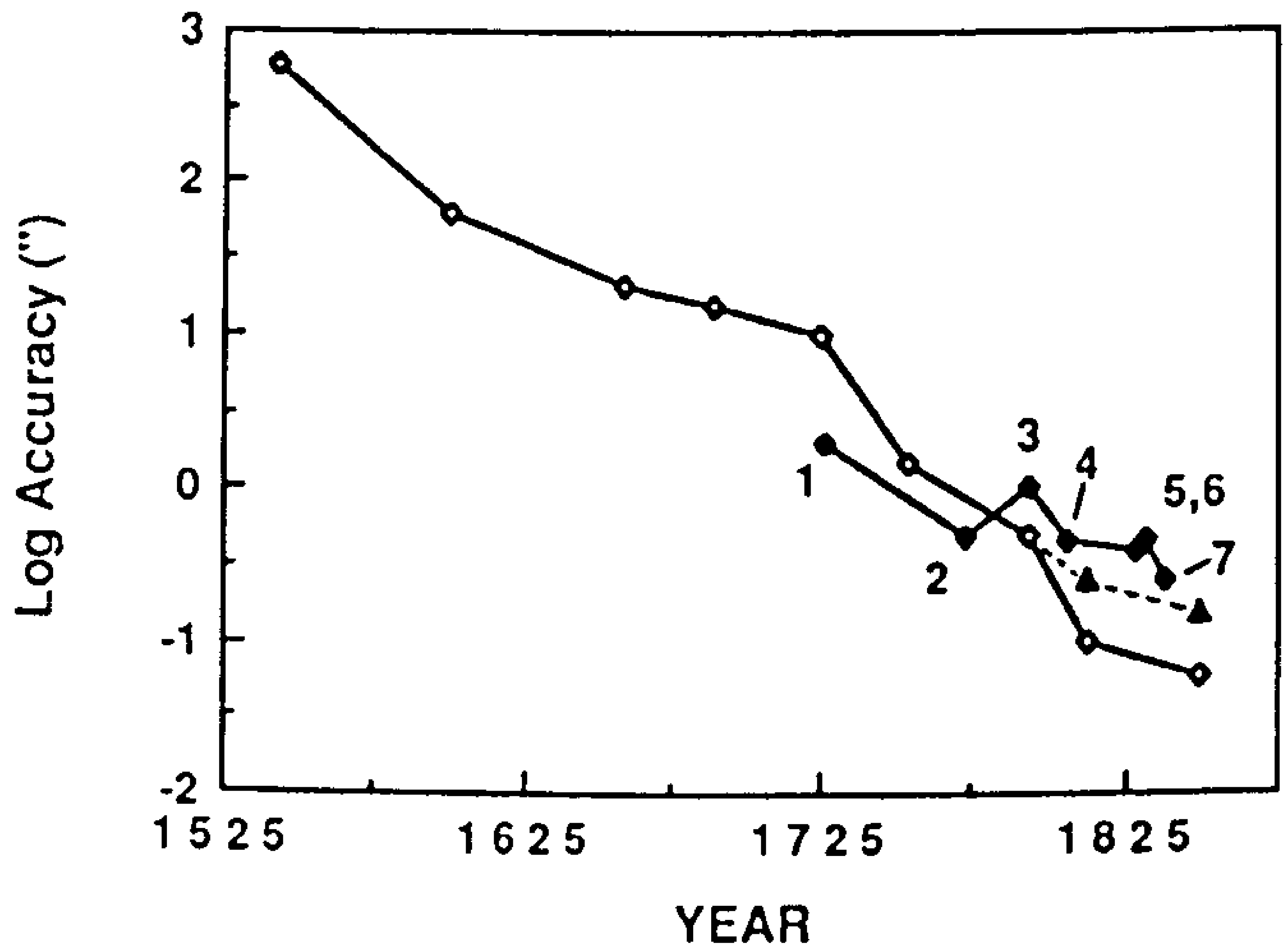
7.1.6 Fraunhofer's Göttingen Heliometer:

No micrometric type screws made by Fraunhofer were measured in this research, so no direct light can be shed on the discussion on parallax. However, Anbronn (1899) provides a figure (Fig. 7.1.2) and table (pp.42-43) of the errors of the Göttingen heliometer made by Fraunhofer, which was similar to the instrument made by Fraunhofer and Utzschneider and used by Bessel to determine the stellar parallax. The axes are both in hundredths of a turn of the screw. The light line is the error for one screw moving half of the lens; the heavier solid line is the combined error for both halves, while the dashed line is the error computed by Anbronn using correction formula (this line is not relevant to the current discussion). Unfortunately neither the pitch of the screw nor the focal length of the heliometer are known, and therefore the error in terms of the screw value cannot be provided. However, the solid curve gives an estimate of the mean error of the screw of ≈3% (max. error is 6%[2]). By reference to Fig. 6.4.4a we can see that, for ca.1825 when the heliometer was made, the 3% error places this instrument better than the average error for filar and scale micrometers--though not very much better.

---

[1] The scale was divided to 5' and thus had 4320 divisions. Using 6 micrometers permits 720 independent sets of data to be measured.

[2] It would perhaps be timely to reiterate that errors measured using the shadowgraph method are total errors while the errors quoted from the dial indicator measurements are mean errors. Thus, excluding other problems, we will anticipate and have observed that the dial indicator errors will be smaller.



7.1.3 Chapman's graph (replotted as year vs. log accuracy (")) with estimates of instrumental accuracy from this work. Point 1 = Graham's zenith sector (1727) made for Bradley (≥2"); 2 = Bird's 8ft quadrant made for the Radcliffe Observatory (MHS-6; ~0.5"); 3 = micrometer from Ramsden's Shuckburgh equatorial (≈1.0"); 4 = micrometer from Edward Troughton's Groombridge transit circle (≈0.46"); 5 = estimated errors of Thomas Jones' Armagh mural circle (≈0.45"); 6 = error of micrometer of Troughton & Simms geodetic theodolite (≈0.39"); and, 7 = estimated (i.e. not measured) error of Fraunhofer's Königsberg heliometer. Chapman's estimate of the accuracy for Troughton's and Simms' accuracy took into consideration that 6 micrometers were used to read the scales. The actual error of these scales was greater than he plotted by a factor of ≈2.45; the two triangles at 1812 and 1850 are the errors which Chapman should have plotted. As can be seen the new data corresponds quite well with Chapman's results though slightly larger suggesting, once again, that scientists were overly optimistic in the accuracy they assumed for their instruments.

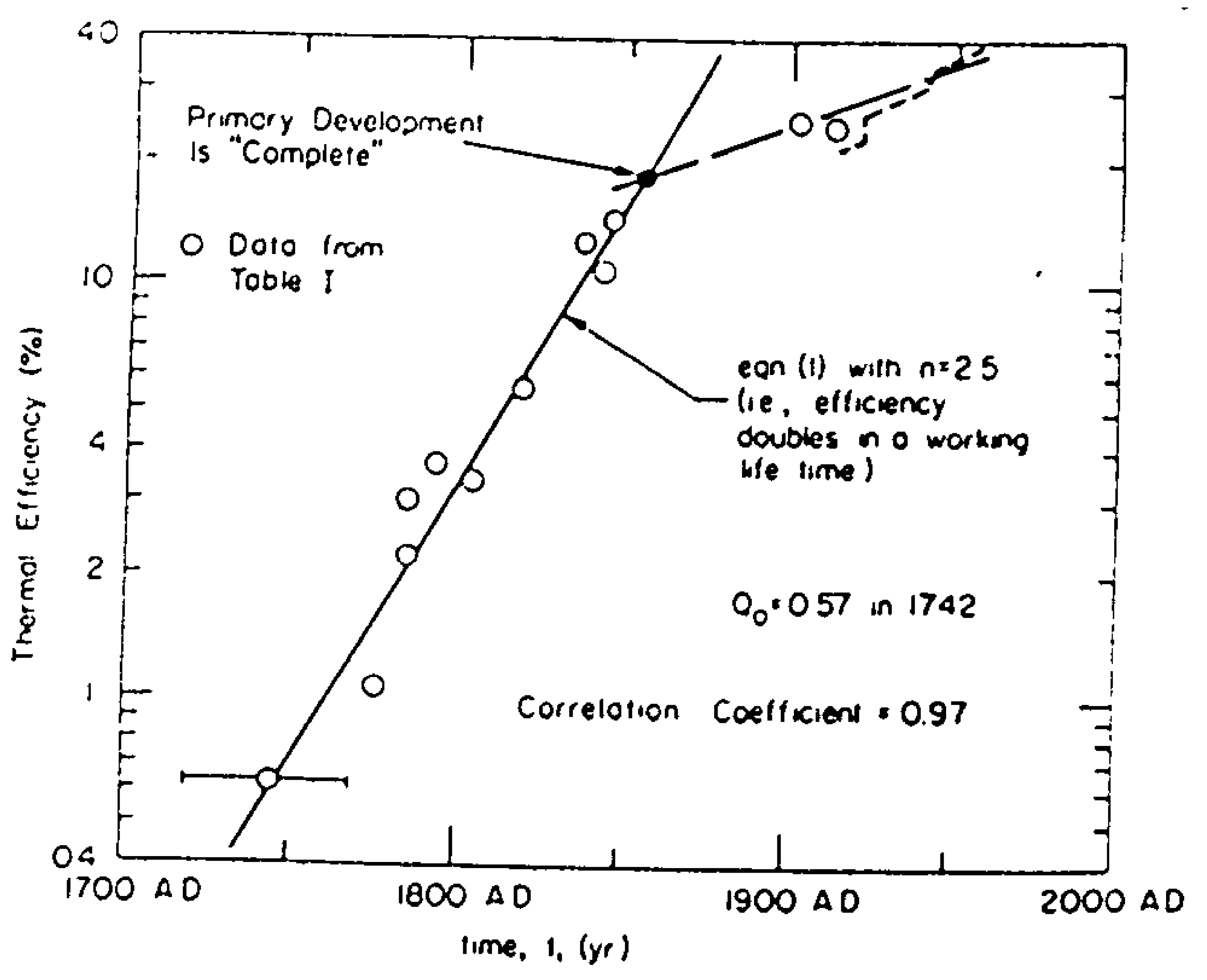
The Königsberg heliometer may have had superior screws, but Bessel's success had more to do with choosing a suitable object and understanding the need to correct for the screw errors and errors due to temperature fluctuations (Bessel: 1838/9, p.163). To successfully determine stellar parallax of 61 Cyg required instruments capable of measuring to ≈0.25" after correction for the errors. Bessel first determined its value as 0.3136" revised in 1840 to 0.3485" (Clerke: 1887, p.45). The modern value is 0.475". Even if the heliometer could measure to 0.25" without corrections, this would place the Königsberg heliometer below the precision predicted by Chapman for Troughton's scale division at that period (≈0.1"). It is more probable that the Göttingen and Königsberg heliometers were capable of measuring to ≈0.5" without error correction and to ≈0.25" with correction. Testing this would make an interesting follow-up to the current work though the current disposition of the Königsberg heliometer is not known. The Göttingen and Oxford heliometers have survived and would provide confirmatory evidence.

7.1.7 Observations on Instrumental Errors and Finding the Parallax and Longitude:

It is apparent that the uncorrected errors of the instruments of the first third of the 19th century did not much exceed 0.5". Improvements beyond this precision were made primarily by the application of statistics; first by incorporating several micrometers to average out errors, and, secondly, by averaging large numbers of observations. The method of reducing the errors used by Henderson paled in comparison with the rigorous mathematical analysis employed by Anbronn (1899, p.463ff) and Gill (1913, p.59ff) but, none the less, proved successful.[1] It appears that astronomers and instrument makers were aware of the limitations of optical quality and atmospheric seeing and that an absolutely precise micrometer screw--even if obtainable--would not by itself allow the detection of the tiny quantity being sought. The data obtained and illustrated in Fig. 6.4.6a/7a and Fig. 7.1.3 suggest this is correct since filar and scale micrometer screws improved very little beyond 0.007mm. Improvements in the overall construction of the astronomical, nautical and surveying instruments were required for improved results. New techniques were promoted by Airy, beginning with the zenith sector of his design and made by Troughton & Simms (Airy: 1839-43, p.188ff); his preference for one-piece castings helped solve the problem of maintaining the line of collimation which had always proved difficult from the earliest instruments used for celestial observations (e.g. Regiomonantanus, Walther, Copernicus, Hooke, etc.). Every astronomer looking for parallax from the 15th c on had this problem to cope with and, from the time of Hooke, had pitch errors of the micrometer screws to contend with as well.

---

[1] For a discussion of the application of statistical analysis in early astronomy and geodesy refer to Stigler: 1986, Chapter 1.



7.2.1

Rate of improvement of thermal efficiency of stationary steam power plants (from Lienhard: 1979). The declining rate after 1860 reflects a mature technology.

7.2 Placing These Research Results In Perspective:

The final task is to comment on how the current results fit with those made by others. We have already made several comparisons with the results of Chapman's 1976 Ph.D. thesis, "Dividing the Circle". His subsequent papers (1983(2), 1986, 1987) have been based on that research but add little new insight into the precision of instruments, although his models have brought to light some problems which would have been encountered during construction and use. In this chapter, we have thus far restricted discussion to the errors of screws used in precision mechanisms, but it is appropriate to expand discussion to comment on other investigations of scientific instrument accuracy.

Gerard L'E. Turner (1967) discussed the improvement of optics for microscopes, providing figures for the increase in resolution and numerical aperture as a function of time. He showed that the claimed characteristics were often exaggerated--a trait not reserved for microscopists as it has been pointed out here as well! Unfortunately a similar curve has not been developed for telescope optics, though of course a rough approximation is given by the objective diameters. Turner also replotted the graph of accuracy of mass measurement vs. date first published by F.G Skinner in **Science since 1500**. F.A.B. Ward's (1961) graph of time measurement vs. date is also reproduced by Turner and by Derek Howse (**Greenwich Time**). Victor Thoren (1973) carried out a study of the observations of Tycho Brahe to determine the accuracy of that indomitable observer: the results have been quoted on numerous occasions and agree with Chapman's curve. Less frequently quoted is Bernard Goldstein's (1977) discussion of the transversal scale of Levi ben Gerson, which provides an error estimate of a precursor to the micrometer subdivision of scales. Daumas (1963, 1972) made frequent comments on instrumental precision, as has Bennett (1987), but these were based on the limit to which the scale could be read rather than on any direct measurements.

Lienhard (1979) investigated fourteen technologies to determine the rate of improvement and found relationships of logarithmic form; he determined that there was a limit in the rate at which any technology could improve. Lienhard did not measure the rates of improvement himself but used secondary sources to find the required information. The data points in the case studies have remarkably little scatter to the logarithmic fit, e.g. increase of thermal efficiency vs. date for stationary steam power plants (Fig. 7.2.1). The success of his fits is perhaps a result of being able to locate values such as the 'highest', the 'fastest', the 'coldest', etc. The figures sometimes show declines in the rate of improvement due to the attainment of what Lienhard termed 'mature development' or other technical constraints[1]. However, the rate of improvement

[1] An example in Britain was the lack of access to high quality flint glass which slowed progress of the optical industry.

of micrometers found in this work also shows a decline in the rate after ca.1825. This may be due to the fact that micrometer design had reached a 'mature' status, or be partially due to stagnation within British instrument making. The vast majority of instruments studied here were of British manufacture. Although the British industry may have reached its peak German makers were now beginning to move ahead--a parallel would be comparison of the British clock making industry compared to the Swiss industry, ca.1840-50. However, the fact that mathematical means had been found to overcome errors of screws was in all likelihood also a contributing factor. The number of micrometers produced after ca.1840 and preserved in museums drops dramatically. This is reflected in the decline of study samples after this date, and thus affects our ability to draw firm conclusions as to why the rate of improvement decreased after ca.1825.

It is appropriate to comment on what the derived results imply about the techniques used to make screws. We followed the development of precision screw making techniques from the crude methods used by Hooke to the precise grinding used to finish Rogers' and Rowland's screws for ruling engines. As previously noted, the errors of screws finished by hand with single or multi-pointed chasers show different patterns of periodic errors and study of these provides a means of identifying forgeries. We have been able to draw some conclusions about the filar micrometers of Herschel (made with a screw plate or stocks) and can demonstrate the correspondence of pitch and diameter changes of micrometer screws with Ramsden's use of a screw lathe. For micrometer screws made on screw lathes, we should expect a nearly one-to-one correspondence between the accuracy of the lead screw, change gears and ways of the lathe with that of the screw produced. It has been demonstrated that the lead screw and gears of lathes do impart a signature on micrometer screws, while screws of later dividing and ruling engines bear little resemblance to the lead screws used to cut the rough thread, for the grinding process employed to finish them has made these errors very small.

In plots where we would expect standardization to have an impact (e.g. flank angles and truncations) we have found general trends towards the parameters defined in the Whitworth and British Association standards. Surprisingly, and not by deliberate choice, no instruments with Sellers form threads were tested; it was anticipated that a few would appear in French or German instruments of the late 19th c but none were among the test samples. This suggests the impact had not been as great as was suggested during the period when a new metric standard screw thread was being discussed by several nations in the 1890's. If one compares the digitized profiles of Appendix B with the overlays of the various standards it is amazing how little impact even the Whitworth standard had on instrument screws, since few of the samples can be considered faithful reproductions of that standard.

On the perfection of the screw, Wright's comments (1982, p.456) sum up a few points nicely:

> I suggest that the state of mechanical advancement is better indicated by the perfection of form and freedom from errors of a screw than by its fineness of pitch. Screws often bear evidence of the means used to produce them, whether by cutting with a single-point tool or with a chaser in a lathe or 'screwing engine' or whether by threading with screwing tackle that cut or that forced up the thread. Threads are sometimes polished after being formed. The thread form produced depends partly on the method used and partly on the deliberate choice of the designer or workman.

The current work provides a starting point for comparison of thread forms in Appendix E. Though a few museum curators, like Michael Wright or J.R. Varrell, have had considerable experience with screw threads on artifacts, the average curator has had no reference to consult for even rudimentary information. The fact that at least two other projects to identify instruments by screw threads have been dropped due to negative results proves the difficulty of the task. But as has been demonstrated, a degree of success can be achieved by the adoption of appropriate techniques. To identify a specific screw with a specific maker for binding screws is indeed a hopeless task, but when the screw has been made for a precision application ones chance of making a positive identification increases. Several characteristics can be combined and cross checked with the graphic material presented here to make an informed guess of the origins.

Screws made by three men stand out from the rest; those by the Duc de Chaulnes, Ramsden and Maudslay. Chaulnes has not been given his due credit because he failed to reach the level of scale division soon attained by Ramsden. But on reflection of his methods and the quality of his dividing engine screws, he must regain some of the credit due to him. The concepts of his dividing engines were innovative and demonstrated uncommon mechanical sense; the fact that he was able to make screws to better than 1% accuracy reiterates his mechanical skill for this was limited to but 4 or 5 other people for almost 50 years--Ramsden, John and Edward Troughton, Henry Maudslay and perhaps Samuel Rhee. Any other worker who reached this lofty attainment did so by copying the methods of one of these. Ramsden's name remains in the annals of the history of technology because of his success with the screw lathe and dividing engines. His innovative approach to mechanical problems is reflected in these two pieces of apparatus. Maudslay's workshop practice revolutionized precision mechanism, and the screws of Maudslay far surpassed any others of his day. In his tests on screw threads we must recognize the foundations of the standard screw systems that were to follow.

Chapman's assessment of scale division accuracy (Fig. 7.1.3) is not far off the truth--though perhaps optimistic after 1800--even though the technique employed to copy the scale divisions was very crude. Thirteen years after its completion, it remains one of the few 'hands-on' attempts at assessing instrumental accuracy. Too few historians of science and technology have applied modern technology to their ends; this is regrettable since the sources of empirical knowledge of scientific instrument accuracy are so scarce.

Contemporary results cannot be relied upon--as was demonstrated in the case of the Sun's diameter in the late 17th c (§3.2.6.1 and Brooks: 1988 II). This research has attempted to indicate some useful avenues of approach for the application of modern instruments to study the old. Even the technology employed here could be substantially improved; fortunately, using the power of the computer has permitted some of the shortcomings of the equipment to be overcome. The author will be the first to point out the limitations that the methodology placed on the study of dividing engines, but the results have been positive enough to demonstrate directions for useful future study. As for the discussion of micrometers, the results for filar and bench micrometers will benefit discussions of a variety of topics beyond those touched on in this and the previous chapter. The quality of the results for the filar and scale micrometers, as determined by the dial indicator, is particularly gratifying.

BIBLIOGRAPHY

BIBLIOGRAPHIES and ABSTRACTS

ABELL, Sydney George; LEGGAT, John and OGDEN, Warren Greene. **Bibliography of the Art of Turning and Lathe and Machine Tool History.** Isleworth, Middlesex: Published for the Soc. of Ornamental Turners by S.G. Abell, 1956.

Abstracts of the Papers Printed in the *Philosophical Transactions*, Vol.1 1800-14 (1832); Vol.2 1815-30 (1833); Vol.3 1830-5 (1837).

BOSTON, Orlan W. **A Bibliography on Cutting of Metals.** New York: American Soc. of Mechanical Engineers, 1945.

FERGUSON. **Bibliography of the History of Technology.** Cambridge, Mass.: MIT Press, 1968.

HOUZEAU, J.C. and LANCASTER, A. **Bibliographie Générale de l'Astronomie Jusqu'en 1880,** 3 vols. New Edition and Introduction by D.W. Dewhurst. London: The Holland Press, 1964.

ISIS. Critical Bibliographies, Vols. 53-78 (1962-1987).

KEYNES, Geoffrey. **A Bibliography of Robert Hooke.** Oxford: Clarendon Press, 1960.

LALANDE, J(oseph) J(erome) Le Francois de. **Bibliographie Astronomique avec L'Histoire de Astronomie Depuis 1781 Jusqua 1802.** Amsterdam: J.C. Gieben, 1803, 1970 (reprint).

MADDISON, F. Early Astronomical and Mathematical Instruments. *History of Science,* **2** (1963), 2, 17-50.

TURNER, Gerard L'E. The History of Optical Instruments: A Brief Survey of Sources and Modern Studies. *History of Science,* 8 (1969), 53-93.

WATT, Robert. **Bibliotheca Britannica.** 1824.

BOOKS AND JOURNAL PAPERS

ABRAHAM, R.M. **Surveying Instruments--Their Design, Construction, Testing and Adjustment.** London: C.F. Casella and Co. Ltd., 1926.

Accurate Screw Cutting. *American Machinist,* 28 (16 Feb. and 4 Mar., 1905), 231.

ADAMS, George. **Micrographia Illustrata.** London: Printed for the author, 4th ed., 1771. XLIX. (1st ed. 1746)

AGASSI, Joseph. How Technology Aids and Impedes the Growth of Science. *Proc. of the Biennial Meeting of the Philosophy of Science Ass'n.,* 2 (1982), 585-97.

AGRICOLA, Georgius. **De re Metallica.** Basel: Frohem, 1st ed., 1556. Reprinted, New York: Dover, 1950. (Dover edition translated by H.C. Hoover and L.H. Hoover).

AIRY, Sir George. On a New Construction of the Divided Eye-Glass Double Image Micrometer. *Memoires of the Royal Astronomical Soc.,* 15 (1846), 199-209 = *Monthly Notices of the Royal Astronomical Soc.,* 6 (1845), 229-231.

_____ An Account of Some Experiments with the Torsion-rod, for determining the Mean Density of the Earth. *Monthly Notices of the Roy. Ast. Soc.*, **5** (1839-43), 188-196.

ALLAN, James. Communications from Mr. Allan and Mr. Stancliffe on Mr. Allan's Dividing Instrument. *Philosophical Magazine*, **39** (1812), 119-21.

_____ Letters from James Allan Re His Theodolite and Screw-Cutting and Dividing Machines. *Trans. Soc. of Arts*, **34** (1816), 211-16.

_____ The Silver Isis Medal...to Mr. James Allan...for His Method of Making Screws for Mathematical Purposes... *Transactions of the Society of Arts*, **34** (1816), 207-12.

AMBRONN, L. **Handbuch der Astronomischen Instrumentenkunde**, Vol.1. Berlin: J. Springer, 1899.

American Standard Screw Threads. New York: Soc. of Automotive Engineers and Am. Soc. of Mechanical Engineers, May, 1924.

AMICI, G.B. Descrizione d'un Nuovo Micrometro. *Memorie di Mathematica e di fisica della Società Italiana* (Modena), **17** (1815), 344-59.

ASCLEPI, Giuseppe Maria. **De Objectivi Micrometri Usu in Planetarum Diametris Metiendis.** Exercitatio Optico-Astronomica Habita in Collegio Romano a Partibus Societatis Iesu, (1765).

_____ Letter Containing a Way for Taking the Diameter of the Planets. *Philosophical Transactions*, **2** (1667), 373-5.

_____ **Traite du Micrometre, Ou Manière Exacte pour Pendre le Diamèter de Planètes et la Distance Entre les Petites Étoiles.** Paris and Amsterdam: 1667. Also in **Divers Ouvrages de Mathematiques** and in *Memoires de L'Acadamie Royale des Sciences*, **7** (1729), 115-8.

Astronomical Almanac for the Year 1988. Washington: U.S. Government Printing Office and London: HMSO, 1987.

BABBAGE, Charles. On a New Zenith Micrometer. *Memoires of the Astronomical Soc.*, **2** (1826), 101-3.

BABCOCK, Horace W. Diffraction Gratings at the Mount Wilson Observatory. *Vistas in Astronomy*, **29** (1986), 153-74.

BAILY, Francis. **An Account of the Rev. John Flamsteed, the First Astronomer Royal.** London: Printed by order of the Lords Commissioners of the Admiralty, 1835.

_____ On the Circular Micrometer. *Philosophical Magazine* (London), **63** (1824), 177-81.

BALTHASAR, Theodor. **Micrometria, Hoc est, de Micrometrorum Tubis Opticis, Seu Telescopiis et Microscopiis Applicandorum Varia Structura....** Christian-Erlangae, Sumpt. J.A. Lorberi, Typis D.M. Schmatz, 1710, 457.

BARNES, Ken and PUGH, Francis. **The Art of the Engineer.** Cambridge: Lutterworth Press, 1981.

BARTY-KING, Hugh. **Eyes Right, The Story of Dollond and Aitchinson.** London: Quiller Press, 1986.

BATTISON, Edwin A. Screw-Thread Cutting By the Master-Screw Method Since 1480. *U.S. National Museum Bulletin* (Washington: U.S. National Museum, Smithsonian Institution), No.240 (1964), 105-20.

BAXANDALL, David. The Circular Dividing Engine of Edward Troughton, 1793. *Transactions of the Optical Soc.(U.K.),* **25** (1923/4), 135-40. (Baxandall 1923/4 I)

_____ Early Telescopes in the Science Museum from an Historical Standpoint. *Transactions of the Optical Soc.,* **24** (1922/3), 304-20.

_____ Replica of Two Galileo Telescopes. *Transactions of the Optical Soc. (U.K.),* **25** (1923/4), 141-4. (Baxandall 1923/4 II)

BECK, Conrad. **The Microscope, Theory and Practice.** London: R. and J. Beck, 1938.

BEDINI, Silvio A. Early American Scientific Instruments and Their Makers. *U.S. National Museum Bulletin* (Washington: U.S. National Museum, Smithsonian Institution), No.231 (1964).

_____ and PRICE, D(erek) J. de Solla. Instrumentation. In **Technology in Western Civilization**, edited by M(elvin) Kranzberg and C(arroll) W. Pursell, 2 vols. London: Oxford University Press,1967, Vol. 1, 168-87.

BEESON, C.F.C. **English Church Clocks.** London, Chichester: Phillimore, 1971.

BELL, Louis. **The Telescope.** London, New York: McGraw-Hill, 1922.

BENNETT, James A. **Dividing the Circle.** London: Phaidon-Christies, 1987.

_____ **The Mathematical Science of Christopher Wren.** Cambridge: Cambridge University Press, 1982, 38-42, 52.

_____ A Study of Parentalia with Two Unpublished Letters of Sir Christopher Wren. *Annals of Science,* **30** (1973), 129-47.

_____ "On the Power of Penetrating into Space": The telescopes of William Herschel. *Journal for the History of Astronomy,* **7** (1976), 75-108.

BENSON, W.A.S. The Early Machine Tools of Henry Maudslay. *Engineering,* **71** (1901), 65-8,80,134-8.

BERGERON, L.-E. **Manuel de Tourneur,** Vol.1. Paris: P. Hamelin-Bergeron, 1816.

BERRIMAN, A.E. **Historical Metrology.** London: Dent, 1953.

BERRY, Arthur. **A Short History of Astronomy.** New York: Dover, 1961. (1st pub. 1898).

BERTHOUD, Ferdinand. **Essai sur L'Horlogerie,** 2 vols. Paris: J. Cl. Jombert, 2nd ed., 1763.

BESSEL, Wilhelm. Extract of a letter from M. Bessel to Professor Henderson dated November 14, 1842. *Monthly Notices of the Roy. Ast. Soc.,* **5** (1843), 265.

_____ Extract of a letter from Professor Bessel to Sir John Herschel, Bart. dated Königsberg, November 4,1838. *Monthly Notices of the Roy. Ast. Soc.,* **4** (1838), 163-4.

BESSON, Jacques. **The Artum Instrumetorum et Machinarum.** Lugduni: A Pud Barth Vincent, 1582.

_____ **Theatre des Instrumens Mathematiques et Mechaniques de Jacques Besson...** Orleans: 1569.

BEVIS, John. The Description and Method of Using Mr. Dollond's New Catadioptric Micrometer as Executed under the Direction of James Short. *Gentleman's Magazine,* 29 (1759), 72-4.

_____ Re Gascoigne's Micrometer. *Philosophical Transactions,* 48 (1753), 190.

BICKNELL, W. Obituary for John Coventry. *Gentleman's Magazine,* 83 (1813), 180-1.

BIGGS, Robert. A Uniform System of Screw Threads. *Journal of the Franklin Inst.,* 79 (Feb. 1865), 111-24.

BION, Nicholas and STONE, Edmund (trs.). **The Construction and Principal Uses of Mathematical Instruments...of N. Bion.** London: Holland Press, 1972. (1st French ed. 1709, 1st English ed. 1723. The 1972 ed. is a reprint of the 1758 ed. It was also published in German.)

BIRCH, Thomas. **The History of the Royal Society of London for Improving of Natural Knowledge,** Vol.3. London: A. Millar, 1757.

BIRD, John. **The Method of Dividing Astronomical Instruments.** London: Published by order of the Commissioners of Longitude, 1767.

BOAS, Franz. 6th Annual Report, Bureau of Ethnology, Washington, 1888.

BOGUSLOWSKI, G. von. On the Use of a New Micrometer and Its Application to the Determination of the Parallax of Mars at His Opposition. *Memoires of the Royal Astronomical Soc.,* 15 (1846), 193-7.

BOND, G.P. The Metric System and Standard Screw Threads. *Engineering,* 61 (1896), 325. (A letter to the editor)

BOND, George M. A Standard Gauge System. *American Soc. of Engineers Transactions,* 3 (1882), 132-41.

BOSCOVICH, Roger Joseph. Account of a New Micrometer. *Philosophical Transactions,* 67 (1777), 789.

BOSSERT, Helmuth and STORCK, Willy F. (eds.). **Das Mittlelalterliche Hausbuch.** Leipzig: Seeman, 1912.

BOUGUER, Pierre. Mesure des Diametres des Plus Grandes Planets: Desc. d'Un Nouvel Instrument Qian Peut Nommer Heliometre... *Memoires des Academie des Sciences,* (1748), 11-34.

BOWDITCH, Nathaniel. **The New American Practical Navigator.** New York: E. & G.W. Blunt, 27th ed., 1857.

BRACHNER, Alto. **G.F. Brander, 1713-1783.** Munich: Deutches Museum, 1983.

BRADBURY, S(avile). **The Evolution of the Microscope.** Oxford: Pergamon, 1967.

_____ **The Microscope Past & Present.** Oxford: Pergamon, 1968.

BRADBURY, S. and TURNER, G. L'E. (eds.). **Historical Aspects of Microscopy.** Cambridge: Heffer for the Royal Microscopical Society, 1967.

BRADLEY, James. Apparent Motion of the Fixed Stars. *Philosophical Transactions* , **45** (1748), 1-43.

BRAHÉ, Tycho. **Astronomica Instaurate Mechanica.** Translation by Raeder, et al. (1946).

BRASHEAR, John A. The Evolution of Standards of Measurement. *Cassier's Mag.*, **20** (May-Oct. 1901), 410-19.

BREGUET, L(ouis). Account of a New Species of Chronometer Adapted to the Eye-pieces of Telescopes. *Edinburgh Philosophical Journal*, **1** (1819), 323-5.

______ Sur le nouveau Compteur... *Annales des Chemie et Physique*, **10** (1818), 431-2.

BREWSTER, David. Description of the Circular Segment Micrometer. *Edinburgh Journal of Science*, (1824), 104-5. Brewster also authored articles under the pseudonym "O".

______ **Treatise on New Philosophical Instruments.** Edinburgh: John Murray and William Blackwood, 1813.

A Brief Guide to the Museum of the History of Science, Oxford. Oxford: Printed at the University Press, 1949.

BRIERLEY, P.R. Small Screw Threads. *Horological Journal*, (Sept. 1954), 586-7.

_____ Small Screw Threads. *Machinery*, **91** (16 May 1957), 374-7.

_____ Small Screw Threads. *Horological Journal*, (Oct. 1957), 606-8, (Nov. 1957), 700-3.

British Standard Specification for British Association (B.A.) Screw Threads, B.S. 93-1951. London: British Standards Institution, 1951.

British Standard Specification for ISO Metric Screw Threads, B.S. 3643: Part 1: 1981

British Standard Specification for ISO Miniature Screw Threads, Metric Series, B.S. 4827: 1972. London: British Standards Institution, 1972.

British Standard Specification for Microscope Objective and Nosepiece Threads--B.S. 3569: 1962.London: British Standards Institution, 1962.

British Standard Specification for Parallel Screw Threads of Whitworth Form, B.S. 84: 1956. London: British Standards Institution, 1956.

British Standard Specification for Unified Screw Threads, Part 3. Diameters below 1/4in. B.S. 1580: Part 3: 1965. London: British Standards Institution, 1965.

BRITKIN, A.S. and VIDONOV, S.S. **A.K. Nartov, an Outstanding Machine Builder of the 18th Century.** Jerusalem: Israel Program for Scientific Translations, 1964. Translated from Russian by E. Tal and J. Baruch.

BROOKS, G.P. and BROOKS, R.C. The Improbable Progenitor. *J.Roy. Ast. Soc. of Canada*, **73** (1979), 1-23.

BROOKS, Randall C. Errors in Measurement of the Solar Diameter in the 17th-18th Centuries. *Journal for the History of Astronomy*, **19** (1988), 239-255. (Brooks: 1988, II)

_____ M. de Chabert and the 1750 Louisbourg Observatory. *J. Roy. Ast. Soc. of Canada*, **73** (1979), 333-348.

_____ Magnetic Influence on Chronometers, 1798-1834: A Case Study. *Annals of Science*, **44** (1987), 245-264.

_____ Standard Screw Threads for Scientific Instruments Part 1: Production Techniques And The Filière Suisse. *History and Technology*, **5** (1988), 59-76. (Brooks: 1988 I, pt.1)

_____ Standard Screw Threads for Scientific Instruments Part 2: The British Association Screw Gauge. *History and Technology*, **6** (1988), 45-59. (Brooks: 1988 I, pt.2)

BROWN, Joyce. Guild Organization in the Instrument Making Trade 1550-1830: The Grocers' and Clockmakers' Guilds. *Annals of Science*, **36** (1979), 1-39.

BROWNING, J. On the Bright Cross Micrometer for Measuring the Position of Lines in Faint Spectra. *Monthly Notices of the Roy. Ast. Soc.*, **30** (1869/70), 71-2.

BRYDEN, D.J. Note on a Further Portrait of James Short, FRS. *Notes and Records of the Royal Soc. of London*, **24** (1969/70), 109-12.

_____ **Scottish Scientific Instrument Makers, 1600-1900.** Information series: technology 1. Edinburgh: Royal Scottish Museum, 1972.

BUCHANAN, Robertson. **Practical Essays on Mill Work and Other Machinery.** London: John Weale, 1841. With an appendix by James Nasmyth on "Remarks on the Introduction of the Slide Principle", 393-418.

BURNHAM, S.W. The Position Micrometer of the Washburn Observatory. *English Mechanic*, **34** (1881), 39-40.

BURSTALL, A(ubrey) F(rederic). **A History of Mechanical Engineering.** London: Faber and Faber, 1963.

_____ **Simple Working Models of Historic Machines.** Cambridge, Mass.: MIT Press, 1968.

BURTON, Charles E. and GRUBB, Howard. On a New Form of "Ghost" Micrometer. *Monthly Notices of the Roy. Ast. Soc.*, **41** (1880/1), 59-63.

M.C. The Metric System and Standard Screw Threads (letter). *Engineering*, **61** (1896), 163.

CAMM, F(rederick) J(ames) **Screw Thread Manual.** London: G. Newnes, 1942.

CARDWELL, D.S.L. The Academic Study of the History of Technology. *History of Science*, **7** (1968), 112-24.

CARL, PH. Die Scraube in Ihren Anwendung auf Physikalishe, Mathematische und Astronomische Instrumente. *Repertorium fur Physik Technik fur Math und Ast. Instrumentatkund*, **11** (1867), 37-55.

CARPENTER, William B. **The Microscope and Its Revelations.** London: J. & A. Churchill, 7th ed., 1891.

Catalogue of the Whitworth Exhibition Held at the Invitation of Mechanical Engineers. London: 18/07-26/08/1966.

CATTERMOLE, M.J.G. and WOLFE, A.F. **Horace Darwin's Shop: The History of the Cambridge Scientific Instrument Company 1878-1968.** Bristol, Boston: Adam Hilger, 1987.

CAVALLO, Tiberius. **Description & Use of the Telescopical Mother of Pearl Micrometer.** London: Printed for the author and sold by C. Dilly, 1793.

_____ Description of a Simple Micrometer for Use with a Telescope, Pt. 2. *Philosophical Transactions*, **81** (1791), 283.

CAVENDISH, Henry. On an Improvement in the Manner of Dividing Astronomical Instruments. *Philosophical Transactions*, **99** (1809), 221-32.

CENTORE, F.F. **Robert Hooke's Contributions to Mechanics.** The Hague: Martinus Nijhoff, 1970.

CHABERT DE COGOLIN, Joseph-Bernard. **Voyage Fait par Ordre du Roi en 1750 et 1751, dans l'Amerique Septentrionale.** Paris: 1753. Reprinted New York: Johnson Reprint Corp., 1966.

CHANEY, H(enry) J(ames). **Our Weights and Measures. A Practical Treatise on the Standard Weights and Measures in Use in the British Empire. With Some Account of the Metric System.** London: Eyre and Spottiswoode, 1897.

CHAPMAN, Alan. The Accuracy of Angular Measuring Instruments Used in Astronomy Between 1500 & 1850. *Journal for the History of Astronomy*, **14** (1983), 133-7. (Chapman: 1983 I)

_____ The Astronomical Art--the Reconstruction and Use of Some Renaissance Instruments. *Journal of the British Astronomical Association*, 96 (1988), 353-357.

_____ Astronomical Instrumentation from the 17th Century. *Vistas in Astronomy*, **20** (1976), 141-56. (Chapman: 1976 II)

_____ The Design and Accuracy of Some Observatory Instruments of the 17th Century. *Annals of Science*, **40** (1983), 457-71. (Chapman: 1983 II)

_____ Dividing the Circle. Unpublished Ph.D. Dissertation, Oxford University, 1976 (British Thesis No. D26897/79). (Chapman: 1976 I)

_____ Gauging Angles in the 17th Century. *Sky & Telescope*, **73** (1987), 362-4.

_____ **The Preface to John Flamsteed's Historia Coelestis Britannica** (translated by Alison D. Johnson). London: National Maritime Museum, Maritime Monographs and Reports No.52, 1982. (Chapman: 1982 I)

_____ A Study of the Accuracy of Scale Graduations on a Group of European Astrolabes. *Annals of Science*, **40** (1983), 473-88. (Chapman: 1983 III)

_____ **Three North Country Astronomers.** Manchester: Neil Richardson, 1982. (Chapman: 1982 II)

_____ **Tycho Brahé in China...** *Annals of Science*, **41** (1984), 417-43.

CHAPMAN, W.A.J. **Workshop Techniques**, Pt. 3. London: Arnold, 1961, 414-8.

CHAULNES, DUC DE. **Description d'Un Microscope et de Differens Micrometre Distines a Measure des Partes Circulaires ou Droites avec la Plus Grande Precision.** Paris: L.F. DeLaTour, 1768. (Chaulnes 1768 I)

_____ Mémoire sur Quelques Expériences Relatives à la Dioptrique. *Hist. de l'Acad. des Sciences* (Paris), (1767), 423-70.

_____ Mémoire sur Quelques Moyens de Perfectionner les Instruments d'Astronomie. *Mémoires de l'Académie Royale des Sciences* (Paris), (1765), 411.

_____ **Nouvelle Methode pour Diviser les Instruments de Mathématique et d'Astronomie.** Paris: L.F. DeLaTour, 1768. (Chaulnes 1768 II)

CHENAKAL, Valentin L. The Astronomical Instruments of John Rowley in 18^{th} Century Russia. *Journal for the History of Astronomy,* 3 (1972), 119-35.

CHÉRUBIN D'ORLEANS, Pére. **La Dioptrique Oculaire ou la Theorique la Positive et la Mechanique de l'Oculaire Dioptrique.** Paris: Thomas Jolly, Simon Benard, 1671.

CHEVALIER, C. Description of a Dioptric Telescope and of a Micrometrical Lunette. *Monthly Notices of the Royal Astronomical Soc,* 5 (1843), 111-2.

Mr. Alvan Clark's New Micrometer for Measuring Large Distances. *Monthly Notices of the Roy. Ast. Soc.,* 19 (1858/9), 324.

CLAY, R.S. and COURT, T.H. **The History of the Microscope.** London: Charles Griffin & Co. Ltd., 1932.

CLERCQ, P.R. de. **Nineteenth-Century Scientific Instruments and Their Makers.** Comm. 221, National Museum for the History of Science and Medicine, Museum Boerhaave, Leiden, 1985.

CLERKE, Agnes M. **A Popular History of Astronomy During the Nineteenth Century.** Edinburgh: Adam & Charles Black, 1887.

CROM, Theodore R. **Horological Wheel Cutting Engines 1700-1900.** Gainesville: 1970.

CROMBIE, A.C. **Augustine to Galileo,** Vol. 2. London: Heinemann, 1961.

CROWTHER, J.G. **Scientists of the Industrial Revolution.** London: Cresset, 1962.

CULLEN, R.T. Diameters of the Solar Observation at Greenwich 1915-25. *Monthly Notices of the Roy. Ast. Soc.,* 86 (1925/6), 344-9.

DARIUS, Jon. A Sharper Focus. *Bulletin of the Scientific Instrument Society,* No.12 (1987), 1.

DAUMAS, Maurice. Precision of Measurement & Physical & Chemical Research in the 18^{th} Century. In **Scientific Change,** A.C. Crombie (ed.). London: Heinemann, 1963.

_____ **Scientific Instruments of the 17^{th} and 18^{th} Centuries.** London: Batsford and New York: Praeger, 1972. Translated from the 1953 French edition by Mary Holbrook.

DAWES, W.R. On the Measurement of the Position Angles of Double Stars, with the Divided Glass Double Image Micrometer. *Monthly Notices of the Royal Astronomical Soc.,* 18 (1858), 58.

DELAMBRE, Jean Baptiste Joseph. **Histoire de l'Astronomie Moderne.** New York, London: Johnson Reprint Corp., 1969.

DERHAM, William. Extracts from Gascoigne's and Crabtree's Letters, Proving Mr. Gascoigne to Have Been the Inventor of the Telescopic Sights of Mathematical Instruments and Not the French. *Philosophical Transactions*, 30 (1717), 603-610.

DERRY, T(homas) K(ingston) & WILLIAMS, Trevor I. **A Short History of Technology from the Earliest Times to A.D. 1900.** New York: Oxford University Press, 1960, 346-55.

DEWHURST, David W. Meridian Astronomy in Private and University Observatories of the UK: Rise and Fall. *Vistas in Astronomy*, **28** (1985), 147-58.

DICKINSON, H.W. Origin and Manufacture of Wood Screws. *Transactions of the Newcomen Soc.*, **22** (1941/2), 79-89.

_____ Richard Roberts; His Life and Inventions. *Transactions of the Newcomen Soc.*, **25** (1945/7), 123-37.

DIDEROT, Denis and ALEMBERT, Jean le Rond d'col. **Encyclopedie ou Dictionaire Raisonne des Sciences des Arts et Metiers** (1762-72) and **Recueil de Planches sur les Sciences** (1765-70), **les Arts Libereaux et les Arts Mechaniques,** Vol.3--entry "Astronomie", Vol.5--entry "Micrometres", 11 vols. Paris: Au Circle du Livre Precieux and Neuchatel: Samuel Faulche & Co., 1762-72.

DISNEY, A(lfred) N(orman); HILL, C(yril) F. and BAKER, W(ilfred) E. Watson (eds.). **Origin & Development of the Microscope.** London: The Royal Microscopical Society, 1928.

"Dividing". **London Encyclopedia or Universal Dictionary of Arts, Science and Literature.** 9th ed., 1832-6.

DOLLOND, George. An Account of a Micrometer Made of Rock Crystal. *Philosophical Transactions*, **110** (1821), 101-3.

DOLLOND, John. A Description of a Contrivance for Measuring Small Angles. *Philosophical Transactions*, **47** (1753/54), 178-181.

_____ An Explanation of an Instrument for Measuring Small Angles. *Philosophical Transactions*, 48 (1754/55), 551-564.

DONKIN, Bryan. Letter Re Metric Screws. *Engineering*, **61** (1896), 324-5.

DOOLITTLE, W.M.H. **Inventions in the Century,** Vol.16 of **The 19th Century** series. London, Edinburgh: W. & R. Chambers, 1903, 240-7.

DRACHMANN, A.G. **Ancient Oil Mills and Presses.** Copenhagen: Levin and Munksgaard, 1932.

_____ Heron's Dioptra and Leveling Instruments. In **A History of Technology,** Singer, et al. (eds.), Vol.3. Oxford: Clarendon Press, 1957, 609-12.

_____ Heron's Screwcutter. *J. Hellenic Studies*, **56** (1936), 72-77.

_____ **Mechanical Techniques of Greek & Roman Antiquity.** Copenhagen: Munksgaard, 1963.

_____ The Screw of Archimedes. *Actes du VIIIe Congres Inter d'Hist. des Sciences Florence-Milan*, 1956 (Paris/Firenze), **3** (1958), 940-3.

DREYER, J.L.E. **Tycho Brahe, A Picture of Scientific Life and Work in the Sixteenth Century.** London: 1890.

DURFEE, W.F. Engineering 300 Years Ago. *Cassier's Magazine*, **8** (1895), 97-106.

EARLE, John G. **On Standard Screw Threads**. New York: Soc. of American Engineers, 1928, 7-13.

Early Screw Thread System. *Machinery*, **60** (12 Mar. 1942), 181.

Early Uses of Diamond Tools for Cutting Metals: Ramsden's Screw-Cutting Machine and Barton's Differential Screw. *Industrial Diamond Review*, **4** (1944), 227-30.

EDWARDES, Ernest L. Translation of Christiaan Huygen's **Horologium**. (1658). Churchill, Ramsgate: Thanet Printing Works, (1970). Reprinted from *Antiquarian Horology*, (Dec. 1970).

ELLIOTT, A. and DICKSON, J. Home. **Laboratory Instruments: Their Design and Application**. London: Chapman & Hall, 1959.

ENGELMANN, Max. Schraubenmikrometer-Erstlinge. *Archiv für Geschichte der Mathematik der Natur Wissenschaften und der Technik*, **10** (1927), 294-302.

The Screw and Screwcutting. *The English Mechanic*, **1** (1865), 91,104, 115/6.

'ESPENASSE, Margaret. **Robert Hooke**. London: William Heinemann Ltd., 1956.

EVEREST, Sir George. On the Astronomical Circles of the Grand Survey of India with a Description of the Methods Employed to Remedy Their Defects. *Memoires of the Royal Astronomical Soc.*, **12** (1840), 141-52. A shortened version was printed in the *Abstracts of the Monthly Notices of the Roy. Ast. Soc.*, **5** (1839-43), 66-67.

FAUQUE, Danielle. Alexis-Marie Rochon 1741-1817. *Revue d'Histoire des Sciences*, **38** (1985), 3-36.

_____ **Naissance et Évolutions de l'Heliomètre 1748-1824**. Unpublished doctoral thesis (3e cycle), Ecole des Hautes Etudes en Sciences Sociales, Paris, 1983.

FELDHAUS, F.M. **Technik der Vorzeit der Geschichtlichen Zeit und der Naturvöker**. Leipzig, Berlin: Engleman, 1914; Munchen: Heinz Moos Verlag, 2nd ed., 1965.

_____ (ed.). **Early Engineering Reminiscences (1815-40) of George Escol Sellers**. Washington, D.C.: Smithsonian Institution, 1965.

_____ **The Various and Ingenious Machines of Agostino Romelli**. Baltimore: John Hopkins University Press and Ilkley, Yorkshire: The Scholar Press, 1976.

FIELD, J.V. and WRIGHT, M.T. The Early History of Mathematical Gearing. *Endeavour*, **9** (1985), 198-203.

FIENGO, Robert. Re Roman Nuts and Bolts. *Scientific American*, **251** (1984), 5.

FLAMSTEED, Rev. John. Observations of Jupiter and Its Satellites in Which He Discusses the Excellence of the Micrometer. *Philosophical Transactions*, **8** (1673), 6094-6000.

_____ **Historia Coelestis Britannica**, 3 vols. London: 1725.

FLINT, Albert S. The Repsold Transit Micrometer of the Washburn Observatory and Slot-Screen Apparatus. *Astronomical Journal*, **20** (1899-1900), 110-1.

FOLEY, Vernard, et al. Using the Early Slide Rest. *History of Technology*, **11** (1986), 25-63.

FONTANA, Felice. **Saggio del Real Gabinetto di Fisica E di Storia Naturale di Firenza**. Florence: (Gaetano Cambiagi), 1775.

FORBES, E.G. **Greenwich Observatory**--the story of Britain's oldest scientific institution, the Royal Observatory at Greenwich and Herstmonceaux, 1675-1975, Vol.1: Origins and Early History (1675-1835). London: Taylor & Francis, 1975.

_____ Robert Townely's Micrometer--17th c. *Journal for the History of Astronomy*, 7 (1976), 124.

FORBES, R.J. **Studies in Ancient Technology**, Leiden: E.J. Brill, Vol.3, 1965, Vol.7, 1966.

FORWARD, E.A. Early History of the Cylinder Boring Machine. *Transactions of the Newcomen Soc.*, **5** (1924/5), 24-38.

FOUCHY, Duc Grandjean de. Machines pour Caler et Mouvoir Commodement un Quart de Circle. *Machines et Inventions Approuvees par l'Academie des Sciences*, **7**, No.433 (1735), 47.

_____ Nouveau Micrometer Invented by Him. *Machines et Inventions Approuvees par l'Academie des Sciences*, **6** (1735), 45-7.

_____ Tour pour Faire sans Arbre Toutes Sortes de Vis. *Machines et Inventions Approuvees par l'Academie des Sciences*, **5** (1735), 91-2.

FRAUNHOFER, Joseph. Description of a New Micrometer. *Philosophical Magazine* (London), **63** (1824), 210-8.

_____ A Short Account of the Results of Recent Experiments upon the Laws of Light and Its Theory. *Edinburgh Journal of Science*, **7** (1827), 101-116.

French Standard Screw Threads. *Engineering*, **59** (1895), 546.

GARDNER, Martin. **The Ambidextrous Universe**. New York: Basic Books, 1964.

Gauging & Measuring Screw Threads. NPL Notes on Applied Science No.1. London: HMSO, 1955.

GAYTHORPE, S.B. On a Galilean Telescope Made About 1640 by William Gascoigne, Inventor of the Filar Micrometer. *Journal of the British Astronomical Association*, **39** (1929), 238-41.

GENTRY, G. **Standard Screw Threads & Twist Drills**. London: Percival Marshall, 1940.

GILBERT, K(eith) R(eginald). **Early Machine Tools**. London: Science Museum Booklet, HMSO, 1975.

_____ **Henry Maudslay, Machine Builder**. London: Science Museum Booklet, HMSO, 1971.

_____ Machine-Tools. In **History of Technology**, Singer, et. al. (eds.), Vol.4. Oxford: Oxford University Press, 1958, 417-441.

_____ **The Machine Tool Collection: Catalogue of Exhibits With Historical Introduction** (London, Science Museum). London: HMSO, 1966.

GILL, David. **A History and Description of the Royal Observatory, Cape of Good Hope**. Edinburgh: Neill & Co., 1913.

_____ Entry "Micrometers". In **Encyclopedia Britannica**, 9th ed., Vol.16, 1878. (Revised and reprinted in the 11th ed., Vol. 18, 1910-11.)

GILL, Thomas. On Screw-stocks, Dies, Taps and Screw Plates. *Gill's Technical Repository*, 8 (1835), 33-7,64-70,182-5,192-5.

GILLE, B. "Machines". In **History of Technology**, Singer, et al. (eds.), Vol. 2. Oxford: Clarendon Press, (1957), 629-58.

_____ **The Renaissance Engineers**. London: Lund Humphries, 1966.

GILLE, Bertrand. **Les Mechaniciens Grecs: La Naissance de la Technologie**. Paris: Editions du Seuil, 1980.

GLAZEBROOK, Sir R. "Measuring Apparatus". In **Dictionary of Applied Physics**, Vol.3. London: MacMillan, 1923.

_____ Standardization in Its Various Aspects. *Engineering*, 85 (1908), 409.

GOLDSTEIN, Bernard R. Levi Ben Gerson: On Instrumental Errors and the Transversal Scale. *Journal for the History of Astronomy*, 8 (1977), 102-12.

GOMPERTZ, Benjamin. On the Theory of Astronomical Instruments. *Memoires of the Ast. Soc.* (London), 1 (1822), 348-54.

GORDON, G.F.C. **Clockmaking Past and Present**. London: The Technical Press, 1949. (1st ed. 1925.)

GORDON, R.B. 16th Century Metal Working Technology Used in Two German Astrolabes. *Annals of Science*, 44 (1987), 71-84.

GOVI, G. Della Invenzione del Micrometro par QL Instrumenti Astronomici. *Bullettino di Bibliografi di Storia Della Scienze Mathematiche e Fisiche* (Rome), 20 (1887), 614.

P. Gr. The Early Use of Polished Diamond Tools. *Industrial Diamond Review*, 3 (1943), 19-20.

"Graduation". **London Encyclopedia or Universal Dictionary of Arts, Science and Literature**. 9th ed. 1832-6.

"Graduation". **Penny Cyclopedia**. 20 vols. + Supp. London: 1830-40s. Entry "Graduation" was published in 1838.

GRANT, Robert. **History of Physical Astronomy from the Earliest Ages to the Middle of the 19th Century**. London: Baldwin, 1852.

GRAVES, Frederick E. Nuts and Bolts. *Scientific American*, 250 (1984), 136-44.

GRAY, Stephen. Part of a Letter from Mr. Stephen Gray, about a Way of Measuring the Height of the Mercury in the Barometer More Exactly. *Philosophical Transactions*, 20 (1698), 176-178.

GREENER, C.E. Gun-Making Handicrafts. *Transactions of the Newcomen Soc.*, 5 (1924/5), 57-71.

GREGORY, Olinthus. **A Treatise of Mechanics**, 2 vols. London: Geo. Kearsley, 1806.

GRODZINSKI, P. A Ruling Engine Used by Sir John Barton and Its Products. *Transactions of the Newcomen Soc.*, 26 (1947-9), 79-88.

GUNTER, R.T. **Early Science at Oxford**, Vol. 2 (1923), 15 vols. Oxford: University Press, 1920-67.

GUYE, Samuel and MICHAEL, Henri. **Time & Space: Measuring Instruments from the 15th-19th Century**. London: Pall Mall Press, 1971.

HABAKKUK, H.J. **American and British Technology in the 19th Century.** Cambridge, Eng.: University Press, 1962, 196.

HABELL, K(enneth) J(oseph) and COX, Arthur. **Engineering Optics.** London: I. Pitman, 1948.

HACKMANN, Willem D. Instrumentation in the Theory and Practice of Science: Scientific Instruments as Evidence and as an Aid to Discovery. *Annalli Dell 'Istituto e Museo di Storia della Scienza*, 10 (1985), 87-115.

_____ The Relationship Between Concept and Instrument Design in 18th c Experimental Science. *Annals of Science*, 36 (1979), 205-224.

HALL, A.R. **A Guide to the Historic Scientific Instruments in the Whipple Museum of the History of Science.** Cambridge: 1949.

HALL, J.J. Iron Work Fastenings of the 14th Century and the Method of Their Conversion in Modern Times. *Transactions of the Newcomen Society*, 16 (1935/36), 129-139.

HAMILTON, J.A. Further Considerations on the Comparative Observations of the Differences.... *Transactions of the Irish Acad.*, 11 (1810), 25.

_____ On Comparitive Micrometer Measures. *Transactions of the Irish Acad.*, 10 (1806), 69-117.

HARRIS, John. **Lexicon Technicum.** London: Printed for D. Brown, T. Goodwin (etc.), 1704.

HARRISON, William and ATHERTON, Peter. UK Patent 1179 : Making Screws and for Division of Mathematical Instruments, 1778.

"Harry". Cutting Screws. *English Mechanic*, 5 (1867), 270.

HARTLEY, Sir Harold. Britain's Heritage of Scientific & Technological Instruments. *Notes & Records of the Royal Soc. of London*, 22 (1967), 37-9.

HASLUCK, Paul N. **Screw Threads and Methods of Producing Them.** London: Hasluck, 6th ed., 1904.

HAWKINS, A.H. Woodscrew Machinery. Paper read before the Newcomen Soc., 10/12/1941.

HAYWARD, A.T.J. **Repeatability & Accuracy.** London: Mechanical Engineering Publications Ltd., 1977.

HEALY, Robert. On Cutting Screws by Means of the Common Turning Lathe. *Tulloch's Philosophical Magazine*, 19 (1804), 172-5.

HEATHER, J.F. **Mathematical Instruments.** London: Crosby, Lockwood & Son, 1924. (1st ed. ca.1870.)

HELLMAN, C.D. John Bird (1709-1776), Mathematical Instrument Maker in the Strand. *ISIS*, **17** (1932), 127-51.

HEMSLEY, Sydney H. **Optical Instruments in Engineering.** London: P. Elek Ltd., 1945.

HENRION, P. **Usage du Micrometre.** Paris: 1630.

HENRY. On the Annual Oscillations of the Level and Azimuthal Errors of the Greenwich and Cambridge Transit Instruments. *Abst. Monthly Notices of the Royal Astronomical Society*, **8** (1847/8), 134-5.

HERRMANN, Dieter B. **The History of Astronomy from Herschel to Hertzsprung.** Cambridge: University Press, 1984.

HERSCHEL, John. Entry "Light". In **Encyclopaedia Metropolitana**, 2nd ed., 1849, Vol. 4, 488-491. The first edition of this encyclopedia appeared between 1819-45. The article quoted was revised by Herschel in 1849.

HERSCHEL, William. Account of a Comet. *Philosophical Transactions*, **71** (1781), 492-501.

_____ Account of the Changes that Have Happened...in the Relative Situation of Double Stars. *Philosophical Transactions*, **93** (1803), 339.

_____ Catalogue of Double Stars. *Philosophical Transactions*, **75** (1785), 40-126.

_____ Description of a Lamp Micrometer and the Method of Using It. *Philosophical Transactions*, **72** (1782), 163-72.

_____ On the Diameter and Magnitude of Uranus with a Micrometer, Pt.1. *Philosophical Transactions*, **73** (1783), 4-14.

HERTEL, Christian Gottlieb. **Vollstandige Anweisung zum Glass-Schleiffen, Wol Auch zu Verfertigung Derer Optischen Machinen.** Magdeburgischen: Halle, 1716.

HEVELIUS, Johann. **Machinæ Coelestis.** Danzig: Simon Reiniger, 1673.

HEWITT, Charles J. Standard Screws for Watches. *Engineering*, **59** (1894), 621-2, 653-3.

HILGARD, J.E. Method of Deducing the Value of a Micrometer Screw from Observations of a Circumpolar Star Near Culmination or Elongation. *Astronomical Journal*, **2** (1852), 92-3.

HOKE, William E. Some Aspects of Progressive Improvement in the Screw Thread. *Review of Scientific Instruments*, **2** (1931), 554-70.

HOLLMAN, Samuel Christian. On the Application of the Micrometer to the Microscope. *Philosophical Transactions*, **43** (1744/45), 239.

HOLTZAPFFEL, Charles. **Turning & Mechanical Manipulation**, 4 Vols. London: Holtzapffel & Co., 2nd ed., Vol.1, 1852, Vol.2, 1854, Vol. 4. 1879.

HOOKE, Robert. **Animadversions on the First Part of the Machina Coelestis of Johannes Hevelius.** London: Printed by T.R. for J. Martyn, 1674.

_____ **An Attempt to Prove the Motion of the Earth from Observations.** London: Printed by T.R. for J. Martyn, 1674.

_____ A Description of an Instrument for Dividing a Foot into Many Thousands of Parts... *Philosophical Transactions*, **2** (1667), 541-4.

_____ **A Description of the Helioscopes and Some Other Instruments.** London: Printed by T.R. for J. Martyn, 1676.

HOOVER, Herbert C. and HOOVER, Loult H. (trs.). Agricola, **De Re Metallica.** New York: Dover, 1950. 1st published 1556.

HORNBLOWER, J.C. Method of Measuring Any Aliquot Part of an Inch by a Screw. *Nicholson's Magazine*, **6** (1803), 247-9.

"Horologer": Turning Small Screws. *English Mechanic*, **5** (1867), 108.

HORREBOW, Nicolas. **Dissertatio de Novo Micrometro.** Hafniæ: 1735.

HORWITZ, H.T. Beiträge Z. Aussereuropäischen und Vorgeschichtlichen Technik. *Beiträge zum Gesch. D. Technik und Industrie*, 7 (1916), 169.

HOWE, Herbert A. A New Travelling Wire Micrometer for an Equatorial. *Astronomical Journal*, **27** (1912/3), 160-2.

HOWGROVE-GRAHAM, R.P. New Light on Ancient Turret Clocks. *Transactions of the Newcomen Soc.*, **29** (1953-5), 137-49.

_____ Some Clocks and Jacks with Notes on the History of Horology. *Archaeolgia*, **77** (1926), 257-312.

HOWSE, Derek. **Francis Place and the Early History of the Greenwich Observatory.** New York: Science History Pub., 1975.

_____ **Greenwich Time and the Discovery of the Longitude.** Oxford, New York, Toronto, Melbourne: Oxford University Press, 1980.

_____ The Tompion Clocks at Greenwich and the Dead Beat Escapement. *Antiquarian Horology*, 7 (1970/1), 18-34, 114-133.

HUME, K(enneth) J(ohn). **Engineering Metrology.** London: MacDonald, 1950.

HUME, L. and SHARPE, K.J. **Practical Metrology.** London: MacDonald and Co., 1956.

HUNTER, William. Essay on a New Method of Applying the Screw. *Philosophical Transactions*, **71** (1781), 58-66.

HUNTING, Merrill M. Gauging Screw Threads with a Beam of Light. *Scientific American*, **127** (1920), 215-32.

HUTTON, Charles. **Hutton's Mathematical and Philosophical Dictionary....** London: Printed for the author, 1815.

HUYGENS, Christian. **Horologium.** Hague Comitum: A. Vlacq, 1658.

_____ Premiere Id ée du Micrometre (1666). *Histoire de l'Academie des Sciences*, **1** (1733), 10.

_____ **Systema Saturium.** The Hague: Adriani Vlacq, 1659.

HYMAN, Anthony. **Charles Babbage, Pioneer of the Computer.** Princeton, N.J.: Princeton University Press, 1983.

IKEDA, Tetsuro. On the Wearing of the Micrometer Screw of the Wanschaff Zenith Telescope. *Proceedings of the Imperial Academy of Tokyo,* 13 (1937), 305-10.

L'Indistrie Francaise, 1901-2--Instruments de Precision. Paris: Editions Alain Brieux, 1980.

INGALLS, Albert G. **Amateur Telescope Making,** Bk. 2. New York: Scientific American, 1965.

The Interchangeability of Large Screws. *Engineer,* 80 (1905), 141-2.

An International Standard for Metric Screw Threads. *Engineering,* 67 (1899), 154-5.

"Iron and Steel Manufacture: Nut and Wood Screws". **Lardner's Cyclopedia,** Vol.1 (1829), 200-9.

IVORY, James. On the Theory of Astronomical Refractions. *Philosophical Transactions,* **128** (1838), 169-229.

JENKINS, Rhys. Historical Notes on Some Derbyshire Industries. *Transactions of the Newcomen Soc.,* 14 (1933/4), 163-77.

JONES, R.V. Through Music to the Stars: William Herschel 1738-1822. *Notes and Records of the Royal Society,* 3 (1978), 37-56.

JONES, Thomas. U.K. Patent No.3446 for Sectograph or Instrument for Dividing Lines and Distances, 1811.

JOSTEN, C.H. **Catalogues of Scientific Instruments in the Collection of J.A. Billmeir Exhibited at the Museum of the History of Science, Oxford.** Oxford: 1955.

KAISER, F. Untersuchung des Airyschen Doppelbildmicrometers. *Annalen der Sternwarte* (Leiden), 3 (1872), 101-274.

KATER, Henry. An Improved Method of Dividing Astronomical Circles and Other Instruments. *Philosophical Transactions,* 104 (1814), 419-35.

KELLER, Alex. Has Science Created Technology? *Minerva,* 22 (1984), 160-82.

_____ The Missing Years of Jacques Besson, Inventor of Machines, Teacher of Mathematics, Distiller of Oils, and Huguenot Pastor. *Technology and Culture,* 14 (1973), 28-39.

_____ Engineering in the Renaissance. In **Great Engineers and Pioneers in Technology,** Roland Turner and Steven L. Goulder (eds.), New York: St. Martin's Press, 1981, 151-243.

KELLERMAN, R. and TREUGE, W. **Die Kulturgeschichte der Schraube.** Munich: Bruckmann, 1962.

KENWORTHY, J.T. Screw Threads. *Institute of Production Engineers Journal,* 18 (1940), 265-84.

KIELY, E(dmond) R(ichard). **Surveying Instruments: Their History & Classroom Use.** N.ew York: Bureau of Publications, Teachers College, Columbia University, 1947.

KING, Henry. **The History of the Telescope.** New York: Dover, 1979. (1st pub. 1955)

KIRBY, R.S., et al., (eds.). **Engineering in History.** New York: McGraw-Hill, 1956.

KLEMM, F(riedrich). **A History of Western Technology.** London: G. Allen & Unwin, 1959.

KÖNIG, Albert. **Die Fernrohre und Entfernungsmesser.** Berlin: Julius Springer, 1937.

KONING, Prof. J. De Meterstandaarden van V. Swinden en Aeneae. Unpublished manuscript. Nuenen, The Netherlands: 1988.

J.C.L. Cutting Screws. *English Mechanic,* **42** (1881), 126.

LA HIRE, Pierre de. Construction d'une Micrometre Universel pour Toutes Eclipses de Soleil et de Lune et par l'Observation des Angles. *Memoires de l'Academie des Sciences,* (1717), 57-67. (LaHire 1717 I)

_____ Construction et Usage d'un Nouveau Reticle pour les Observations des Eclipses du Soleil et de la Lune et pour Servir de Micrometre. *Histoire de l'Academie des Sciences et les Memoires de Math et Physique,* (1701), 117-31.

_____ De: Recherche des Dates de l'Invention du Micrometre. *Histoire de l'Academie des Sciences avec les Memoires des Math et Physique,* (1717), 78-87. (LaHire 1717 II)

LALANDE, J(oseph) Jerome Le Francois de. **Astronomie,** 3 vols. Paris: La Veave Desaint, 3rd ed., 1792.

_____ **Bibliographie Astronomique.** Paris: De l'Imprimerie de la Republique, 1803.

LAMBERT, J.H. **Anmerkungen, etc. C'est-a-dire, Remarques sur les Micrometre de Verre de M. Brander, et sur Leur Usage; avec des Additions Concernant l'Histoire et les Advantages de Cette Invention.** Augsburg: E. Kletts, 1769.

LANCHESTER, G.H. F.A. Lanchester, LL.D., F.R.S., His Life and Work. *Transactions of the Newcomen Soc.,* **30** (1955/7), 221-37.

LAUFER, Berthold. The Eskimo Screw as a Cultural-Historical Problem. *American Anthropologist,* **17** (1915), 396-409.

LAX, William. On a Method of Examining the Divisions of Astronomical Instruments. *Philosophical Transactions,* **99** (1809), 232-45.

LeFEVRE. Micrometre Invente par Lui. *Machines et Inventions Approuvees par l'Academie des Sci.,* **1** (1735), 103-5.

LeMAIRE, Jacques. Maniere d'Employer des Vis. *Machines et Inventions Approuves par l'Academie des Sciences,* **4** (1735), 179-80.

LeMONNIER, Pierre Charles. **Description et Usage des Principaux Instruments d' Astronomie.** (Paris): 1774.

LILLEY, S. **Men, Machines & History.** London: Lawrence & Wishart, 1965.

LLOYD, A. Alan. **Some Outstanding Clocks Over 700 Years, 1250-1950.** London: Leonard Hill, 1958.

LOOMIS, Elias. **An Introduction to Practical Astronomy.** New York: Harper & Bros., 1870.

LOUVILLE, J.E. d'Allonville de. Application du Micrometre a la Lunette du Quart de Cercle Astronomique... *Histoire de l'Academie des Sciences avec les Memoires des Math et Phys.*, (1714), 65-75.

LUBBOCK, Constance A. **The Herschel Chronicle.** Cambridge: University Press, 1933.

LUDLAM, William. An Introduction to Mr. Bird's Method of Dividing Astronomical Instruments. *Philosophical Transactions*, **75** (1785), 64-7.

LUER, Herman. Zur Geschichte der Schraube. *Zeitschift fur Architekur und Ingenieurwesen*, **46** (1900), 171-80.

M^c^CAW, G.T. A New Dividing Engine. *Monthly Notices of the Royal Astronomical Soc.*, **69** (1908), 226-8.

M^c^CRACKEN, Daniel D. and DORN, William S. **Numerical Methods and Fortran Programming.** New York, London and Sydney: John Wiley and Sons, 1964.

M^c^KEON, Robert M. Les Debuts de l'Astronomie de Precision 1: Histoire de la Realization du Micrometre Astronomique. *Physis*, **13** (1971), 225-88.

_____ 2: Histoire de l'Acquisition des Instruments d'Astronomie et de Geodesie Munis d'Appareils de Visee Optique. *Physis*, **14** (1972), 221-42.

"Machinery". In **Screw Thread Handbook.** London: Machinery Pub. Co., 1950.

MAIN, R. On the Present State of our Knowledge of the Parallax of the Stars. *Memoires of the Astronomical Society*, **12** (1842), 1 or *Monthly Notices of the Astronomical Society*, **5** (1843), 50.

MALLOCK, A. On a Machine for Ruling Large Diffraction Gratings. Reports of the 52nd Meeting of the British Association for the Advancement of Science (Southampton), (1882), 466-72.

MALVASIA, Cornelius Marquis de. **Ephemerides Novissimea Motuum Coelestium...Mutinæ.** Mutinae, Impensis authoris, ex typographia Andreae Cassiani, 1662.

MARINONI, Johann Jacobo. **De Astronomica Specula Domestica.** Vienna: L.J. Kaliwoda, 1745.

MARTIN, Benjamin. **The Description & Use of a New Invented Pocket Reflecting Microscope with a Micrometer.** Chichester, Eng.: Printed by W. Lee, n.d. (ca.1738).

MARTIN, L.C. Surveying & Navigational Instruments from the Historical Standpoint. *Transactions of the Optical Soc.* (UK), **24** (1922/3), 289-303.

MASKELYNE, Nevil. Description of a Method of Measuring the Difference of RA & Dec with Dollond's Micrometer Together with Other New Applications of the Same. *Philosophical Transactions*, **61** (1771), 536.

_____ Directions for Use of the Common Micrometer. *Philosophical Transactions*, **62** (1772), 46-53.

_____ A Prismatic Micrometer. *Philosophical Transactions*, **67** (1777), 799.

MATHEWS, Martin. **Engine Turning 1680-1980: The Tools and Technique.** Saint Charles, IL.: Sevenoaks, 1985.

MAUNDER, Walter (ed.). "Queries", *Journal of British Astronomical Association*, **10** (1899), 193.

MAYALL, John, Jr. Nobert's Ruling Engine. *J. of Society of Arts*, (8/05/1885), 707-15.

MERCER, Henry C. **Ancient Carpenter's Tools.** Daylestown, PA: Bucks Co. Historical Soc., 4th ed., 1975. (1st ed. 1929).

MERTON, Thomas. On the Reproduction and Ruling of Diffraction Gratings. *Proceedings of the Royal Society*, **201** (1950), 187-191.

The Metric System and Standard Screw Threads. *Engineering*, **61** (1896), 87-8, 291, 352.

MICHEL, Henri. **Scientific Instruments in Art & History.** London: Studio Vista, 1967.

Micrometer Measuring Machine by Pratt & Whitney. *Engineering*, **64** (1898), 595.

"Micrómetro". **Encylopedia Universal Ilustrada.** 70 vols. ca.1930-3.

MILLBURN, John R. **Benjamin Martin: Author, Instrument Maker & Country Showman.** Leiden: Noordhoff, 1976.

_____ **Retailer to the Sciences: Benjamin Martin's Scientific Instrument Catalogues 1756-82.** London: Vade-Mecum Press, 1986.

_____ **Supplement to Benjamin Martin.** London: Vade-Mecum Press, 1986.

MILLS, A.A. and TURVEY, P.J. Newton's Telescope--An Examination of the Reflecting Telescope Attributed to Sir Isaac Newton in the Possession of the Royal Society. *Notes and Records of the Royal Society*, **33** (1979), 133-55.

MOORE, A.D. Henry A. Rowland. *Scientific American*, **246** (1982), 118-26.

MORAN, Bruce T. German Prince Practitioners: Aspects in the Development of Courtly Science, Technology and Procedures in the Renaissance. *Technology & Culture*, **22** (1981), 253-74.

MORRIS, Stephen L. A Photoelectric Study of Three Southern Delta Scuti Stars. Unpublished M.Sc. Thesis, Saint Mary's University, Halifax, N.S., 1979.

MORRISON, Leslie V.; STEPHENSON, F. Richard and PARKINSON, John. Diameter of the Sun in AD 1715. *Nature*, **331** (1988), 421-423.

MORRISON-LOW, A.D. and CHRISTIE, J.R.R. **"Martyr of Science": Sir David Brewster 1771-1868.** Edinburgh: Royal Scottish Museum, 1984.

MOSKOWITZ, Saul. The Method of Lunar Distances and Technological Advance. *Navigation*, **17** (1970), 101-21.

_____ Surveyor's Theodolite with Micrometer Readout. *Bulletin of the Scientific Instrument Soc.*, No.11 (1986), 2-3.

MÖTEFINDT, Don Hugo. Zur Gesschichte der Schraube. In **Studien zur Vorgeschichtlichen Archaologie** by Alfred Goetze. Leipzig: 1925, 199-206.

MOXON, Joseph. **Mechanic Exercises**, 2 vols. London: Printed for Joseph Moxon, 1703. (1st ed. 1677-83.)

MUDD, Thomas. An International Standard of Screw Threads. *Cassier's Magazine*, 9 (1895/6), 563-8.

MUDGE, William. An Account of the Measurement of an Arc of the Meridian. *Philosophical Transactions*, 93 (1803), 383-412.

MUIRHEAD, James Patrick. **The Life of James Watt.** London: John Murray, 1858.

_____ **The Origin and Progress of the Mechanical Inventions of James Watt**, 3 vols. London: James Murray, 1854.

MUMFORD, Lewis. **Technics & Civilization.** London: Routledge, 1934.

MUSSON, A.E. Joseph Whitworth--Toolmaker & Manufacturer. *Engineering Heritage*, 1 (1964), 124.

I.B.N.: A Draught and Description of an Engine to Turn Screws. *Gentleman's Magazine*, 23 (1753), 77.

NASMYTH, James. "Remarks on the Introduction of the Slide Principle". In Buchanan, **Practical Essays on Mill Work and Other Machinery.** London: John Weale, 1841, 393-418.

NEEDHAM, Joseph and WANG LING. **Science and Civilization in China, Introductory Orientations**, Vol.1. Cambridge: University Press, 1954.

_____ with collaboration of Wang Ling. **Science and Civilization in China**, Vol.4. Cambridge: The University Press, 1965. Pt. 2 in Mechanical Engineering.

NEEDHAM, Joseph; WANG LING, LU GWEI-DJEN and HO PING-YU. **Clerks and Craftsmen in China and the West.** Cambridge: University Press, 1970.

NOBERT, F.A. Ueber Kreistheilung im Ullgemeinem und... *Verhandlungen des Vereizs zur Befordering des Gewerbfleisses in Preussen*, (1845), 202-13.

NOLLET, L'Abbe Jean Antoine. **L'Art des Experiences, ou Avis aux Amateurs de la Physique sur le Choix, la Construction et l'Usage des Instruments.** Paris: P.E.G. Durand, 1770-4.

"O" [David Brewster]. Account of Mr. Barton's Method of Making Iris Metal Ornaments... with the Prismatic Colours. *Edinburgh Philosophical Journal*, 8 (1822/3), 128-32.

O'Dell, C.A. and Van Helden, A. How Accurate were Seventeenth-century Measurements of Solar Diameter? *Nature*, 330 (1987), 629-631.

OLMSTED, John W. The "Application" of Telescopes to Astronomical Instruments: 1667-1669. *ISIS*, 40 (1949), 213-25.

PARKINSON, A(lbert) C(harles). **Screw Thread Cutting & Measurement, Including Thread Forms.** London: Sir I. Pitman & Sons Ltd., 1943.

PARKINSON, A(lbert) C(harles) and DAWNEY, W.H. **Thread Grinding & Measurement.** London: I. Pitman, 1949.

PARKINSON, John H.; MORRISON, Leslie V. and STEPHENSON, F. Ruhand. The Constancy of the Solar Diameter Over the Past 250 Years. *Nature*, 288 (1980), 548-51.

PARSONS, William Barclay. **Engineers & Engineering in the Renaissance.** Cambridge, Mass., London: MIT Press, 1939, reprinted 1967.

PAYEN, J. La Construction des Instruments Scientifique en France au XIX^{e} Siècle. In de Clercq, **19th Century Scientific Instruments and Their Makers.** Leiden, 1985, 159-182.

PEARSON, Rev. William. On the Construction of a Micrometrical Eye-Piece of a Telescope. *Memoires of the Astronomical Soc.,* 1 (1822), 82-95. (Pearson 1822 I)

_____ On the Construction of a New Position Micrometer, Depending on the Doubly-Refractive Power of Rock Crystal. *Memoires of the Astronomical Soc.,* 1 (1822), 103-8. (Pearson 1822 II)

_____ On the Doubly-Refracting Property of Rock Crystal, Considered as a Principle of Micrometrical Measurements, When Applied to a Telescope. *Memoires of the Astronomical Soc.* (London), 1(1822), 67-81. (Pearson 1822 III)

_____ **An Introduction to Practical Astronomy**, Vol.1, 1824, Vol. 2, 1829. London: Printed for the author, 1824-29.

PETERS, Th. Metric System and Standard Screw Threads. *Engineering,* 61 (1896), 163.

PETERSON, H.L. **How Do You Know It Is Old?** New York: Scribners, 1975.

PETIT, Father P. Nouvelle Machine pour Measurer Exactement les Diamètres des Astres. *Journal des Savants,* 66 (16 Mars 1667), 102-104.

PETREE, J. Foster. Henry Maudslay--Pioneer of Precision. *Engineering Heritage,* 1 (1964), 100-105.

_____ **Henry Maudslay, 1771-1831 & Maudslay & Sons & Field Ltd.** London: The Maudslay Soc., 1945, 1949.

_____ Maudslay, Sons & Field as General Engineers. *Transactions of the Newcomen Soc.,* 15 (1935/6), 39.

PIAZZI, G. Account of the Life and Labours of the Late Mr. Ramsden. *Tilloch's Magazine,* 16 (1803), 253-62.

PIKE, Benjamin. **Pike's Illustrated Descriptive Catalogue of Optical, Mathematical and Philosophical Instruments...,** 2 vols. New York: the author, 2nd ed., 1856. (1st ed. 1848).

PLUMIER, Charles. **L'Art de Tourneur ou de Faire en Perfection Toutes Sortes d'Ouvrages au Tour.** Lyon: Jean Certe, 1701. Reprinted Paris: 1749.

POGSON, Norman. On the Ocular. Reports of the 28th Meeting of the British Association for the Advancement of Science (Leeds), 1858, 20-1.

POLLARD, Alan F.C. The Mechanical Amplification of Small Displacements. *Journal of Scientific Instrumentation,* 15 (1938), 1-55.

POND, John. Description of Stars with a Description of the Astronomical Circle and Remarks on Its Construction. *Philosophical Transactions,* 96 (1806), 420-67.

PORRITT, A. Jesse Ramsden (An 18th c Halifax Inventor). *Transactions of the Halifax Antiquarian Soc.,* (3 Feb. 1970), 15-27.

PORSILD, Marten P. Principle of the Screw in the Technique of the Eskimo. *American Anthropologist*, 17 (1915), 1-16.

POULSON, Ernst. **"Let's Try It", the Life of Sir Joseph Whitworth.** Derbyshire: 1984.

POWELL, Baden. On a New Double-image Micrometer. *Monthly Notices of the Royal Astronomical Soc.*, 7 (1847), 24. Concept had been previously published in *l'institut, journal des académies et sociétés scientifiques*, 1re section, 8 (1845), 180.

PREECE, W.H. On the BA Standard Gauge for Small Screws. *Reports of the 57th Meeting of the British Association for the Advancement of Science (Manchester), (1887)*, 884.

_____ Screw Gauge--2nd Report of a Committee Appointed to Consider Means By Which Practical Effect Can Be Given to the Introduction of the Screw Gauge Proposed by the Association in 1884. *Reports of the 54th Meeting of the British Association for the Advancement of Science (Toronto), (1897)*, 426.

_____ Screw Gauge--3rd Report. *Reports of the 68th Meeting of the British Association for the Advancement of Science (Bristol),* (1898), 627.

PRICE, D(erek) J. de Solla. The Early Observatory Instruments of Trinity College Cambridge. *Annals of Science*, 8 (1952), 11-12.

_____ Fake Antique Scientific Instruments. *Actes du VIIIe Congress International d'Histoire des Sciences* (Florence), 6 (1956), 380-94.

_____ The Manufacture of Scientific Instruments from ca.1500-ca.1700. In **History of Technology**, Singer, et al. (eds.), Vol. 3. Oxford: Oxford University Press, 1957, 620-47.

_____ Precision Instruments to 1500. In **History of Technology**, Singer, et al. (eds.), Vol. 3. Oxford: Oxford University Press, 1957, 582-619.

_____ **Science Since Babylon**. New Haven, CT.: Yale University Press, 1961.

_____ Some Early English Instrument Makers. *Endeavour*, 14, No.54 (Apr. 1955), 90-4.

PRITCHARD, C. On the Moon's Photographic Diameter and On the Applicability of Celestial Photography to Accurate Measurement. *Memoires of the Roy. Ast. Soc.*, 47 (1882/3), 1-30.

Quekett, J.T. **A Practical Treatise on the Use of the Microscope**. London: 1848.

RAEDER, H.; STROMGREN, E. and RAEDER, B. **Tycho Brahe: Description of His Instruments & Scientific Work**. Copenhagen: Ejnor Munksgaard, 1946. (Trs. of Tycho Brahe's **Astronomiae Instauratae Mechanica**, 1598.)

RAMSDEN, Jesse. Description of a New Construction of an Eyepiece, Pt. 1. *Philosophical Transactions*, 73 (1783), 94-99.

_____ **Description of An Engine for Dividing Mathematical Instruments.** London: Published by order of the Commissioners of Longitude, 1777.

_____ Two New Micrometers. *Philosophical Transactions*, 69 (1779), 419.

RAMSDEN, John. **Machinery for Cutting Screws**. U.K. Patent 14213, 6/07/1852.

RAPER, Richard. **A History of Technology--Consolidated Indexes, Vol.5.** Oxford: Oxford University Press, 1984. See Singer. et al.

RAYLEIGH, Lord J.W. On the Manufacture and Theory of Diffraction-gratings. *Philosophical Magazine*, 4th series, **47** (1874), 81-93.

REED, Laureen G. A Search for Multiple Periodicies in Three Delta Scuti Stars. Unpublished M.Sc. Thesis, Saint Mary's University, Halifax, N.S., 1986.

REED, L. G. and WELCH, Gary A. A Search for Multiple Periods in three Delta Scuti Stars. *Astronomical Journal*, 95 (1988), 1510-1527.

REES, Abraham. **Cyclopedia or Universal Dictionary of the Arts, Sciences and Literature.** London: Longman, Hurst, Rees, Omre & Brown, 1819.

Report on British Standard Whitworth (B.S.W.) Screw Threads and Their Tolerances. London: British Standards Institution, No.92-1919, June 1919.

Report of the British Association Committee Recommending the Adoption of a New Thread Form for All Screws from No. 0 to 11 Inclusive. *Engineering*, **72** (1901), 563.

Report on the British Standard Screw Threads. London: The Engineering Standards Committee, No.20, February, 1913.

Reports to the BAAS from the Committee to Study the BA Thread. *Reports of the 52nd Meeting of the British Association for the Advancement of Science (Southampton), (1882)*, 311-314..

Reports to the BAAS from the Committee to Study the BA Thread. *Reports of the 69nd Meeting of the British Association for the Advancement of Science (Dover)*, (1899), 464-469.

REPSOLD, J.A. Neuer Vorschlogzur Vermeidung des Persolichen Zeit-Fehlers Bei Durchgangs--Beobachtungen. *Astronomische Nachrichten*, **123** (1890), 177-82.

_____ **Zur Geschichte der Astronomische Messwerkzeuge von Purbach bis Reichenbach, 1450 bis 1830.** Leipzig: Wilhelm Engelmann, 1908.

RIBES, E.; RIBES, J.C. and BARTHALOT, R. Evidence for a Large Sun with a Slower Rotation During the 17th century. *Nature*, **326** (1987), 52-6.

RIDDLE, Edward. On Mr. Troughton's Expedient for Correcting Errors Arising from the Eccentricity of the Point Round Which the Indexes Revolve in Reflecting Circles. *Philosophical Magazine*, 54 (1819), 161-3.

RIGAUD, Stephen Peter. **Miscellaneous Works & Correspondence of the Rev. James Bradley.** Oxford: University Press, 1832.

_____ **Correspondence of Scientific Men**, 2 vols. Oxford: 1841. (Reprint, Hildesheim: Georg Olms, 1965.)

ROBINSON, Eric and MCKIE, Douglas (eds.). **Partners in Science, Letters of James Watt and Joseph Black.** Cambridge, Mass.: Harvard University Press, 1970.

ROBINSON, Henry W. and ADAMS, Walter (eds.). **The Diary of Robert Hooke (1672-1680).** London: Taylor & Francis, 1935.

ROBINSON, T.R. Description of the Armagh Mural Circle, and Examination of its Divisions. *Abstracts of the Memoires of the Roy. Astro. Soc.*, **3** (1833-6), 111-3.

ROE, Joseph Wickham (Wichler). **English and American Tool Builders.** New Haven, CT: Yale University Press and London: Humphrey Milford, Oxford University Press, 1914.

_____ **English and American Tool Builders.** New York: McGraw-Hill, 1926, 99, 247.

ROGERS, W(illiam) A(ugustus). Additional Contribution to the Perfect Screw Problem. *Transactions of the American Soc. of Mechanical Engineers,* 12 (1891), 725-8.

_____ On a Practical Solution of the Perfect Screw Problem. *Transactions of the American Soc. of Mechanical Engineers,* 5 (1884), 216-59.

ROLT, Frederick Henry. **Gauges & Fine Measurements,** 2 vols. London: MacMillan, 1929.

ROLT, L(ionel) T(homas) C(aswell). **Great Engineers.** London: Bell, 1962.

_____ **The Mechanicals: Progress of a Profession.** London: Heinemann, 1967.

_____ **Tools for the Job: A Short History of Machine Tools.** London: Batsford, 1965.

ROSS, Andrew. Dividing Engine. *Transactions of the Society of Arts,* 48 (1830), 302-32.

ROTH, G.D. (ed.), trs. by Arthur Beer. **Astronomy, A Handbook.** Cambridge, Mass.: Sky Publishing, 1975.

ROUTLEDGE, Robert **Discoveries and Inventions of the 19th Century.** London: 1876.

ROWLAND, H.A. Preliminary Notice of the Results Accomplished in the Manufacture and Theory of Gratings for Optical Purposes. *Philosophical Magazine,* 5th Series, 13 (1882), 469-74.

_____ Entry "Screw" in the **Encyclopedia Britannica,** 11th ed., Vol.24, 1910-11, 477-482.

ROY, Gen. William. An Account of a Trigonometrical Survey. *Philosophical Transactions,* 85 (1795), 415-460.

_____ An Account of the Measurement of a Base on Houndslow Heath. *Philosophical Transactions,* 75 (1785), 385-480.

_____ An Account of the Trigonometrical Operation Whereby the Distance Between the Meridians of Royal Observatory at Greenwich and Paris Has Been Determined. *Philosophical Transactions,* 80 (1790), 111-270.

SARTON, George. Discovering the Main Nutation of the Earth's Axis (1748). *ISIS,* 17 (1932), 333-53.

SAUVAGE, M. Ed. Metric Screw Threads. *Engineering,* 61 (1896), 360.

SAVERY, Servington. Invention of a New Micrometer. *Philosophical Transactions,* 48 (1753/54), 165.

SCHRODER, H. A Delicate Fine Adjustment. *Journal of the Royal Microscopical Soc.,* 6 (1886), 685-6.

SCHUCHARDT, Gerd. New Machine System for High Accuracy Circular Scale Dividing. *Jena Review*, No.2 (1986), 192-4.

SCHUCKBURGH, Sir George Evelyn. An Account of an Equatorial Instrument. *Philosophical Transactions*, 83 (1793), 67-128.

_____ An Account of Some Endeavours to Ascertain a Standard of Weight and Measure. *Philosophical Transactions*, 88 (1798), 133-82.

SCOBLE, W.A. The Blythswood Dividing Engine for Ruling Diffraction Gratings. *National Physical Lab, Collected Researches*, 8 (1912), 213-51.

SCOTT, John. **Henry Hindley: A Noted York Clockmaker.** Transcript of a Lecture Given Before the Yorkshire Philosophical Society 10/03/1919.

"Screw-cutter": The Metric System and Standard Screw Threads. *Engineering*, 61 (1896), 194, 324-5, 451.

Screws and Screw Making. Colchester, Eng.: Britannia Comp., n.d. (ca.1891).

Screw Thread Bibliography, 1942. Springfield, VT.: Janes & Lawson Machine Co., 1942.

SEGNER(I), Johannes Andreae von. **De Extendend Compo Micrometri Commentarii Societatis Scientiarum.** Gottingen: (1751), 1, 27-40.

SELLERS, William. A Uniform System for American Screw Treads. *J. of the Franklin Inst.*, 77 (1864), 344.

SHORT, James. Letter Concerning a Paper of the Late Servington Savery, Esq., Relating to His Invention of a New Micrometer. *Philosophical Transactions*, 48 (1753/4), 167.

SIMMS, William. On a Self-Acting Circular Dividing Engine. *Monthly Notices of the Roy. Ast. Soc.*, 5 (1843), 291-3.

_____ On a Self-Acting Circular Dividing Engine. *Memoires of the Royal Astronomical Soc.*, 15 (1846), 83-90.

SIMPSON, A.D.C. Richard Reeve--The "English Campani" and the Origin of the London Telescope-Making Tradition. *Vistas in Astronomy*, 28 (1985), 357-65.

SINCLAIR, Bruce. At the Turn of the Screw: William Sellers, the Franklin Institute, and the Standard American Thread. *Technology & Culture*, 10 (1969), 20-34.

SINGER, Charles Joseph; Holmyard, E.J.; Hall, A.R. and Williams, Trevor I. (eds.). **A History of Technology**, 4 vols., Vol. 2, 1956, Vol.3, 1957, Vol.4, 1958. Oxford: Clarendon Press, 1954-58.

SKEMPTON, A.W. (ed.). **John Smeaton FRS.** London: Thomas Telford Ltd., 1981.

SKEMPTON, A.W. and BROWN, Joyce. John & Edward Troughton, Mathematical Instrument Makers. *Notes and Records of the Royal Society*, 27 (1973), 233-62.

SMART, C(harles) E. **The Makers of Surveying Instruments in America Since 1700.** Troy, New York: Regal Art Press, 1962.

SMEATON, John. Account of an Observation of the Right Ascension and Declination of Mercury. *Philosophical Transactions*, 77 (1787), 318-42.

_____ Observation on the Graduation of Astronomical Instruments by Hindley's Method. *Philosophical Transactions*, 76 (1786), 1-47.

_____ Re His Pyrometer. *Philosophical Transactions*, 48 (1753/4), 598-609.

(SMEATON, John). Description of Mr. James Short's New Pyrometer. *Gentleman's Magazine*, 25 (1755), 400-1. An edited version of the *Philosophical Transactions* paper.

SMILES, Samuel. **Industrial Biography & Iron Workers.** London: Murray, 1863.

_____ **Industrial Biography: Iron Workers & Tool Makers**, Vol. 2. London: Murray, 1905.

_____ (ed.). **James Nasmyth Engineer: An Autobiography.** London: 1883. (Reprinted 1905.)

SMITH, D.W. Simple Machine for Micrometer Rulings. *Journal of the New York Microscopical Soc.*, 13 (1897), 53-55.

(_____) *Journal of the Royal Microscopical Soc.*, 17 (1897), 438-9. Abstracted from the above paper.

SMITH, Robert. **A Complete System of Optics**, 2 vols. Cambridge: Printed for the author, 1738.

SOUTH, James. On the Discordances Between the Sun's Observed and Computed RA...& Also a Description of the 7' Transit... *Philosophical Transactions*, 116 (1826), 423-83.

"Spectrum". In **American Cyclopedia**, Vol.15, 1881, 238-254.

SPENCER-JONES, Harold. **The Royal Observatory, Greenwich.** London, New York, Toronto: for the British Council by Longmans, Green & Co., revised ed., 1946.

SPON, Edward and BYRNE, Oliver (eds.). **Spon's Dictionary of Engineering, Civil, Mechanical, Military, and Naval.** London, New York: E. & F.N. Spon, 1874.

SPRAT, Thomas. **The History of the Royal Society of London, for the Improving of Natural Knowledge.** London: Printed by T.R. for J. Martyn, 1667.

STANCLIFFE, John. Letter to James Allan, Feb. 10, 1812. *Philosophical Magazine*, 39 (1812), 119-121.

Standard Screw Threads. *Engineer*, 74 (1902), 303-5.

Standard Screws for Watches. *Engineering*, 58 (1894), 568.

Standardization in Its Various Aspects. *Engineering*, 72 (1908), 409-10.

STEAVENSON, W.H. A Peep into Herschel's Workshop. *Transactions of the Optical Society* (London), 26 (1924/5), 210-220.

STEEDS, W. **A History of Machine Tools, 1700-1910.** Oxford: University Press, 1969.

STIGLER, Stephen M. **The History of Statistics.** Cambridge, Mass., London: Belknap Press of the Harvard University Press, 1986.

STIMSON, Alan. The Influence of the Royal Observatory at Greenwich upon the Design of 17th & 18th Century Angle-Measuring Instruments at Sea. *Vistas in Astronomy*, 20 (1976), 123-30.

_____ Some Board of Longitude Instruments in the Nineteenth Century. In de Clercq, **19th Century Scientific Instruments and Their Makers.** Leiden, 1985, 93-115.

STOTT, Carole. The Greenwich Meridional Instruments. *Vistas in Astronomy*, 28 (1985), 133-45.

STRADANUS (Jan Van Der Straet). **New Discoveries** (1580s). New York: Burndy Library, 1953.

STRANG, J. Martin. Optical Methods of Distance Measurement. In **Proceedings of the Optical Convention**, Pt. 2. London: 1926, 683-701.

STRONG, John. Rowland's Diffraction-Grating Art. *Vistas in Astronomy*, 29 (1986), 137-41.

STURGEON, Thomas William. **Micrometers.** U.K. Patent 3428, 1/04/1811.

SWEET, John E. The Measuring Machine in the Workshop. *Cassier's Magazine*, 20 (1901), 389-398.

SWINGLER, D.N. A Relationship Between the Jurkevich Periodogram and the Fourier Transform Spectral Estimator. *Astronomical Journal*, 90 (1985), 675-9.

SYMONDS, R.W. **Thomas Tompion: His Life & Work.** London: 1951.

_____ Funiture: Post Roman. In **History of Technology**, Singer, et al. (eds.), Vol.2. Oxford: Clarendon Press, 1956, 240-258.

TANN, Jennifer. Boulton and Watt's Organization of Steam Engine Production. *Transactions of the Newcomen Soc.*, 49 (1977/8), 41-56.

TAYLOR, C. **A Survey of Screw Cutting Machines.** 1972.

TAYLOR, E.W.; WILSON, J.S. and MAXWELL, P.D.S. **At the Sign of the Orrery: The Origins of the Firm of Cooke, Troughton & Simms Ltd.** (now Vickers Ltd.). York: 1960.

TAYLOR, E.G.R. **Math Practitioners of Hanovarian England 1714-1840.** Cambridge: University Press, 1966.

_____ **Math Practitioners of Tudor & Stuart England.** Cambridge: University Press, 1967.

TAYLOR, William. Reports of the BAAS, 1894, 58, 568.

_____ The Manufacture of Optical Elements. In **Proceedings of the Optical Convention.** 1926, 594-603.

THIOUT, Antoine. **Traite de l'Horlogerie, Mechanique et Pratique...** Paris: C. Moette, 1741.

THOREN, Victor E. New Light on Tycho's Instruments. *J. for the History of Astronomy*, 4 (1973), 25-45.

THURY. **Notice sur la Systeme des Vis de la Filiere Suisse.** Geneve: H. Georg, 1880.

_____ **Systematique des Vis Horologeres.** Geneve: L.-E. Privat, 1878.

TOPPING, J. **Errors of Observation and Their Treatment.** London: Chapman & Hall Ltd., 3rd ed., 1956.

TORLAIS, Jean. **An Physicien au Siecle des Lumierres l'Abbe Nollet.** Paris: Sipuco, 1954.

TOTH, Nicholas. Archaeological Evidence for Preferential Right-handedness in the Lower and Middle Pleistocene, and Its Possible Implications. *J. of Human Evolution,* **14** (1985), 607-614.

TOWNLEY, Richard. Of a Letter, Written by Mr. Richard Townley to Dr. Croon, Touching the Invention of Dividing a Foot into Many Thousand Parts, for Mathematical Purposes. *Philosophical Transactions,* **2** (1667), 457.

_____ **Neveu de Christophe Townley, a Perfectionne le Micrometer de Gascoigne...** 1670.

TROUGHTON, Edward. An Account of a Method of Dividing Astronomical & Other Instruments. *Philosophical Transactions,* **99** (1809), 105-45. Reprinted in *Philosophical Magazine,* **34** (1809), 81-95, 163-175.

_____ An Account of the Repeating Circle and of the Altitude and Azimuth Instruments. *Memoires of the Astronomical Soc.,* **1** (1822), 33-54.

_____ Entry "Graduation". **Edinburgh Cyclopedia, 10** (1830), 348-384.

TUCKER, R.H. Greenwich Meridian Astronomy. *Vistas in Astronomy,* **28** (1985), 159-67.

TURNER, A.J. Mathematical Instruments and the Education of Gentlemen. *Annals of Science,* **30** (1973), 51-88.

TURNER, G.L'E. The Contribution to Science of Friedrich Adolph Nobert. *Bull. Inst. of Physics & Physical Soc.,* **18** (1967), 338-48. (Turner, 1967, I)

_____ Descriptive Catalogue of Van Marum's Scientific Instruments. In **Martinus Van Marum, Life and Work,** E. Lefebre and J.G. De Bruyn (eds.), Vol. 4. Leyden: 1973.

_____ **Essays on the History of the Microscope.** Oxford: Seneca, 1980.

_____ The History of Optical Instruments: A Brief Survey of Sources and Modern Studies. *History of Science,* **8** (1969), 53-93. (Turner, 1969, I)

_____ James Short & His Contribution to the Construction of Reflecting Telescopes. *Notes and Records of the Royal Society,* **24** (1969), 91-108. (Turner, 1969, II)

_____ Micrographia Historica: The Study of the History of the Microscope. *Proceedings of the Royal Microscopical Soc.,* **7** (1972), 1220-49. (Quekett Lecture).

_____ The Microscope as a Technical Frontier in Science. In **Historical Aspects of Microscopy,** Bradbury and Turner (eds.) and *Proceedings of the Royal Microscopical Soc.,* **2** (1967), 175-99. (Turner, 1967, II)

_____ The Use of Scientific Collections for Research. *Museums Journal,* **64** (1967), 272-275. (Turner, 1967, III)

_____ Waterhouse Ruling Engine. Unpublished manuscript, 1988.

TURNER, Roland and GOULDEN, Steven L. (eds.). **Great Engineers and Pioneers in Technology,** Vol.1. New York: St. Martin's Press, 1981.

TURRELL, Edmund. On Splitting and Polishing Diamonds... *Gill's Technical Repository,* **1** (1827), 1-13, 62-73, 129-35, 193-7, 257-60, 321-30.

Two Historical Lathes. *Engineer,* **110** (1910), 430-1.

ULRICH, G.C.J. On the Formation and Application of Fine Metallic Wires to Optical Instruments. *Monthly Notices of the Royal Astronomical Society,* **7** (1846), 294-5.

UNWIN, W.C. The Standardization of the Screw Thread. *Engineering,* **69** (1900), 75, 110, 143, 176.

USHER, Abbott Payson. **A History of Mechanical Inventions.** New York: McGraw-Hill, 1929 and Cambridge, Mass.: Harvard University Press, 1954.

_____ Machines and Mechanisms. In **History of Technology**, Singer, et al. (eds.), Vol.3. Oxford: Clarendon Press, 1957, 324-46.

VAN HELDEN, Albert. Huygens and the Astronomers. In **Studies on Christian Huygens**, H.J.M. Box, et al. (eds.). Lisse: Swets and Zeitlinger, 1980, 147-65.

_____ **Measuring the Universe.** Chicago and London: University of Chicago Press, 1985.

VARLEY, Cornelius. Copying Screws By the Lathe. *Transactions of the Soc. of Arts,* **43** (1825), 90-3.

VARRALL, J.R. Preserving Screw Threads. *Mariner's Mirror,* **68** (1982), 439-41.

VILLE, Chevallier de. **Traite de Fortifications de l'attaque et de la defense des Places**. Lyon: Irenee Barlet, 1629.

VINCENT, Clare. A Beam Compass by Christoph Trechsler the Elder and the Origin of the Micrometer Screw. *Metropolitan Museum Journal,* (in press).

VULPES, Benedetto. **Reale Museo Borbonico**, 14, tab.36, f.1/2.

WALKER, Ezekiel. Description of an Improved Micrometer. *Philosophical Magazine,* **38** (1811), 127-30.

_____ On Bradley's Method of Observing Transits and Another Method By Which the Thickness of the Wires Is of No Importance. *Journal of Natural Philosophy, Chemistry and the Arts,* **2** (1802), 22-3.

_____ On Micrometer Telescopes. *Philosophical Magazine* (London), **47** (1816), 14-16.

WALSH, G. Original Screw. *Transactions of the Society of Arts,* **42** (1824), 127-129.

WARD, F.A.B. **Catalogue of European Scientific Instruments in the British Museum**. London: British Mus. Pub., 1981.

_____ **Time Measurement**. London: Science Museum, 1961.

WARNER, Brian and Nancy. **Maclear and Herschel; Letters and Diaries at the Cape of Good Hope, 1834-8.** Cape Town: A.A. Balkena, 1984.

WARNER, Deborah Jean. Lewis M. Rutherfurd, Pioneer Astronomical Photographer and Spectroscopist. *Technology and Culture,* **12** (1971), 180-216.

_____ Rowland's Gratings: Contemporary Technology. *Vistas in Astronomy,* **29** (1986), 125-30.

"S.W.". Request for Screw Cutting Apparatus Not Depending on Master Screw. *Gentleman's Magazine*, **39** (1769), 286.

WARNER, Worchester Reed and SWASEY, Ambrose. **A Few Astronomical Instruments From the Works of Warner and Swasey.** Cleveland: Warner, n.d. (ca.1900).

WATT, James. Account of a Micrometer for Measuring Distances. *Edinburgh Philosophical Journal*, **2** (1820), 121-5.

WATTS, C.B. Experiments in the Design of the Travelling Wire Micrometer. *Astronomical Journal*, **50** (1944), 179-82.

WELLMAN, V. Uber Eine Neue Form des Ring-Und Rauten Micrometer. *Astronomical Nachrichen*, **123** (1890), 265-70.

WESLEY, Walter G. The Accuracy of Tycho Brahe's Instruments. *J. for the History of Astronomy*, **9** (1978), 42-53.

WHIPPLE, Robert S. Some Scientific Instrument Makers of the 18th Century. *J. of Scientific Instruments*, **7** (1930), 241-53, 273-81. *Nature*, **126** (1930), 244-6, 283-6.

The Whipple Collection of Instruments and Books. *Engineering*, (10/11/1944, 2/03/1945, 23/03/1945).

WHITEHEAD, T.N. **The Design and Use of Instruments and Accurate Mechanisms.** New York: MacMillan Co., 1934.

WHITWORTH, Joseph. **Miscellaneous Papers on Mechanical Subjects.** London: Longman, Brown, Green, Longmans, and Roberts, 1858, 23-36.

_____ On a Uniform System of Screw Threads. *Proceedings of the Institution of Civil Engineers*, (1841) 157-60.

WICKMAN, Joseph. **English and American Tool Builders.** New York, London: 1926.

WILBUR, W.R. **History of the Bolt and Nut Industry in America.** Cleveland, Ohio: (Ward & Shaw), 1905.

"William Sellers". *Cassier's Magazine*, **10** (1896), 231-3.

WILLIAMS, Edward; MUDGE, William and DALBY, Isaac. An Account of the Trigonometrical Survey Carried Out in the Years 1791, 1792, 1793 and 1794. *Philosophical Transactions*, **85** (1795), 414-591.

WILLIS, Robert. **Principles of Mechanism.** London: John W. Parker and Cambridge: J. & J.J. Deighton, 1841, 152-67, 356-9, 428-9.

WILLIS, Robert and GLAISHER, James. **Lectures on the Results of the Great Exhibition of 1851**, 2nd series. London: (Royal Society for the Encouragement of Arts, Manufacture and Commerce), 1852.

WITTMANN, A. The Diameter of the Sun. *Astronomy and Astrophysics*, **61** (1977), 225-7.

_____ Evidence Against a Secular Decrease of the Solar Diameter. *Solar Physics*, **66** (1980), 223-31.

WOERD, Charles van. Machine for Threading Sectional Leading Screws. U.S. Patent No.293930 (19/02/1884).

WOLF, A(braham). **A History of Science, Technology and Philosophy in the 16th and 17th Centuries**, 2 Vols. London: Allen & Unwin, 2nd ed., 1950. (1st ed. 1935) (Wolf I)

_____ **A History of Science, Technology and Philosophy in the 18th Century**, 2 Vols. London: Allen & Unwin, 2nd ed., 1952. (1st ed. 1935) (Wolf II)

WOLF-BERRY, Sir John. Standardization in British Engineering Practice. *Reports of the 76th Meeting of the British Association for the Advancement of Science (York), (1906)*, 339-46.

WOLLASTON, Francis H. A Description of a New System of Wires in the Focus of a Telescope... *Philosophical Transactions*, **75** (1785), 346-52.

_____ Description of a Transit Instrument. *Philosophical Transactions*, **83** (1793), 133-53.

WOLLASTON, William Hyde. Description of a Single Lens Micrometer. *Philosophical Transactions*, **103** (1813), 119-22.

WOODBURY, Robert S. **History of the Lathe to 1850.** Cleveland: Soc. Hist. Tech., 1961.

_____ **Studies in the History of Machine Tools.** Cambridge, Mass.: MIT Press, 1972.

WOODCROFT, Bennett. **Alphabetical Index of Patentees of Inventions.** London: Evelyn, Adams & MacKay, 1969. 1st published 1854.

WREN, Christopher, Jr. **Parentalia: Or, Memoirs of the Family of the Wrens...** London: Printed for T. Osborn, 1750.

WRIGHT, M.T. More on Screw Threads. *Mariner's Mirror*, **68** (1982), 456-7.

WYNTER, Harriet and TURNER, Anthony. **Scientific Instruments.** London: Studio Vista, 1975.

ZAGORSKII, F.N. **An Outline of the History of Metal Cutting Machines to the Middle of the 19th c.** New Delhi: Amerind Pub. Co., 1982.

ZAHRTMANN, C.C. On London Instrument Makers. *Philosophical Magazine*, **63** (1824), 252.

ZETTER, M. Ch. La Vis et l'Ecrou dans l'Histoire des Peuples. *Bulletin de la Soc. d'Encouragement pour l'Industrie Nationale*, **125** (1927), 637-46.

ZINNER, Ernst. **Astronomische Instrumente des 11. bis 18. Jahrhunderts.** Munich: Beck, 1979. (1st ed. 1956).