A method for improving plasma temperature estimates from incoherent scatter analysis during artificial ionospheric modification experiments

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[1] Spectral features in incoherent scatter data, such as those caused by the purely growing mode (PGM), can often be strongly enhanced during the first few seconds of artificial ionospheric heating experiments, such as those carried out using the high-power European Incoherent Scatter HF heater at Tromsø. These features, often referred to as "overshoot" effects, are indicators of turbulent non-Maxwellian plasma, and the analysis of these spectra using standard incoherent scatter data analysis software leads to a poor estimation of the plasma parameters (particularly electron and ion temperature) during RF heating experiments. In this study, a procedure is developed to derive a more reliable estimate of plasma temperature during periods when the incoherent scatter spectrum is affected by contamination from the PGM. This is achieved by removing the PGM from the measured spectrum and then analyzing the modified spectrum using standard software. The results are compared to those obtained from the analysis of the original, contaminated spectra. It is found that the differences between the results obtained from the corrected and uncorrected spectra are strongly proportional to the magnitude of the PGM feature. We also show that the bulk temperatures during the remainder of the "heater on" period after the overshoot can generally be estimated reliably by the standard analysis software, though with some important exceptions. These results are important since the plasma temperatures play a crucial role in governing thermal conduction processes, and their correct estimation is thus very important to understanding the underlying physical processes which occur during ionospheric heating.

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1. Introduction

[2] The European Incoherent Scatter (EISCAT) heating facility in Tromsø has been used over the past several decades in experiments involving high-power, high-frequency (HF) radio waves, to artificially modify the high-latitude ionosphere. A comprehensive description of the facility and its experimental capabilities has been given by *Rietveld et al.* [1993]. Artificial heating experiments are known to give rise to a wide variety of phenomena, including the generation of artificial field-aligned irregularities (FAI) in the *F* region ionosphere, which have been studied extensively [e.g., *Robinson*, 1988, 1989; *Stubbe*, 1996], and are the result of strong localized heating which occurs when the transmitted electromagnetic heater wave is mode-converted into electrostatic plasma waves at the upper hybrid resonance (UHR) frequency. FAI are known to cause strong anomalous absorption of the high-power heater waves, which consequently leads to greater bulk heating of the electron gas than would be expected from purely collisional heating arising due to the influence of electromagnetic waves.

[3] The EISCAT UHF incoherent scatter radar, colocated with the Tromsø heater, and the CUTLASS coherent scatter radars in Finland and Iceland, are frequently operated in independent experiments to diagnose the state of the ionospheric plasma during heating events. Their different operation frequencies (931 MHz and 8–20 MHz) and their noncoincident locations allow for the study of contrasting scale sizes of physical phenomena, with the possibility to make complementary measurements parallel and perpendicular to the magnetic field within the heated volume above Tromsø. Simultaneous observations during artificial modification experiments using these radars have frequently been reported [e.g., *Robinson et al.*, 1997; *Honary et al.*, 1999; *Dhillon and Robinson*, 2005].

[4] The development of field-aligned irregularities is essentially nonlinear in nature, possessing characteristic growth and decay rates which, from theoretical work, have been

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shown to be strongly dependent on thermal conduction coefficients. The thermal conduction is itself determined by the background electron temperature [*Gurevich*, 1978; *Robinson*, 1989]. The action of the heater electric field leads to strong Langmuir turbulence just below the reflection height of the ordinary ("O") mode heater wave, often termed the "interaction height." This Langmuir turbulence arises due to the parametric decay instability (PDI), which enhances the ion acoustic lines in the EISCAT spectra during the first few milliseconds of artificial heating. Upper hybrid turbulence can excite the oscillating two-stream instability [*Kuo et al.*, 1997], sometimes abbreviated to OTSI or purely growing mode (PGM). This produces a central peak in the incoherent scatter spectrum, which is also termed the "overshoot" effect, due to its short-lived characteristics. Its amplitude can be variable, and is usually indicative of the competition between the growth rates of the PDI and OTSI. These growth rates have been detailed in literature [*Fejer*, 1979]. Modeling work based on numerical solutions to the Zakharov equations by *Guio and Forme* [2006] verified that the spectral feature at zero frequency arising from the PGM is linked to the existence of electron density structures, and can be explained by strong Langmuir turbulence theory (SLT).

[5] In the standard analysis of EISCAT data, the Grand Unified Incoherent Scatter Design and Analysis Package (GUISDAP) [*Lehtinen and Huuskonen*, 1996] is used to infer plasma parameters from the measured data. The theoretical model used by GUISDAP assumes that the backscattered signal arises from plasma characterized by Maxwellian distributions of ion thermal velocity, which would typically lead to the classic double-humped configuration in the ion acoustic spectrum at F region heights where the strong heating occurs. Clearly this condition does not apply under conditions of strong plasma turbulence, when a non-Maxwellian velocity distribution gives rise to a "distorted" ion acoustic spectrum. Non-Maxwellian plasmas can arise naturally, for example due to ion neutral collisions under the influence of strong electric fields or during auroral processes where beam-driven instabilities cause natural Langmuir turbulence that enhances the ion acoustic waves to which the radar is sensitive [see, e.g., *Kofman and St.-Maurice*, 1996; *Forme and Fontaine*, 1999].

[6] The plasma instabilities excited by artificial heating can also give rise to unreliable estimates of plasma parameters at the interaction height, when incoherent scatter data are processed using standard analysis software. *Honary et al.* [1993] highlighted that the incoherent scatter analysis could not be relied upon in their particular case of heating at a harmonic of the electron gyrofrequency. *Honary et al.* [1999] and *Ashrafi et al.* [2006] also commented on the invalidity of conventionally analyzed data during heating experiments, due to distortion of the spectra by enhancements in the ion acoustic lines. *Stocker et al.* [1992] and *Bond* [1997], among others, have drawn attention to the problems caused by the contamination of the ion acoustic spectrum caused by the presence of the PGM.

[7] *Gurevich et al.* [1998] showed that if an ACF, measured in a scattering volume containing strong temperature inhomogeneities due to striations was fitted with a theoretical function, based on a homogeneous Maxwellian plasma, the electron temperature could be significantly underestimated. *Rietveld et al.* [2003] also addressed the effect of an invalid Maxwellian assumption on the apparent temperature, but did not provide a means of testing this. They did, however speculate that the electron temperatures within striations could be 10000 K or even higher, on the basis that the temperatures recovered from their data analysis were likely to be an average over the scattering volume, as pointed out by *Gurevich et al.* [1998]. *Ashrafi et al.* [2006] employed a theoretical model of electron temperature enhancements, based on stationary solutions to the linearized perturbation equations of *Gurevich* [1978]. These were applied to experimental data and shown to produce electron temperatures up to 5700 K, although this was emphasized to be an overestimate, since nonlinear effects were not accounted for. EISCAT measurements of the averaged electron temperature during typical heating events rarely reach this magnitude.

[8] The PGM is a short-lived feature. Its typical lifetime is only a few milliseconds, though its influence on the incoherent scatter spectrum persists until it is quenched by the thermal parametric instability (TPI), which can take a few seconds to develop. Since EISCAT data are typically pre-integated for periods of between 1 and 5 s, the PGM feature often only appears in the first one or two data dumps taken after the heater is switched on, and during this period the spectra from the interaction height can be very distorted, sometimes exhibiting a strong central peak or a triple-humped appearance. Previous workers have, however, tended to assume that once this initial overshoot feature has apparently disappeared, the standard analysis of data obtained thereafter can be taken as correct.

[9] While the average incoherent scatter spectrum during the remainder of the "heater on" period following the disappearance of the PGM often appears Maxwellian in character, the possibility of ongoing plasma turbulence should be not be ruled out, because of the continuing interaction of the plasma with the strong heater wave. During more recent heating experiments using the SPEAR facility on Svalbard, the incoherent scatter spectra measured using the EISCAT Svalbard Radar (ESR) were reported to have exhibited a PGM-like feature that persisted for several minutes of heating, even though SPEAR has considerably lower power than the Tromsø heater [*Robinson et al.*, 2006]. This evidence suggests that the overshoot feature may not always be fully quenched, but that some remnant of it can continue to contaminate the measured spectra.

2. Rationale of the Present Study

[10] In this paper, we consider data from a number of past heating experiments carried out at Tromsø in which an apparent reduction in the electron temperature occurred after the heater began transmitting, and sometimes lasted for longer than the initial few seconds of heating. Figure 1 shows plasma parameters derived from conventional GUISDAP analysis of data from a heating experiment on 7 October 1997, when the heater was transmitting in a "power seeding" cycle between 1246 UT and 1304 UT. This heater cycle consisted of transmissions in 1 min on, 2 min off cycles at increasing power levels of 2.5, 5, 10, 25 and 50% of full power, each followed by a "seed pulse" of 20 s duration at 100% power. For full experimental details and objectives of the experiment, the reader is referred to *Wright et al.* [2006]. During this experiment, the EISCAT UHF radar was pointed field-aligned, and was operated in the standard CP1K mode.

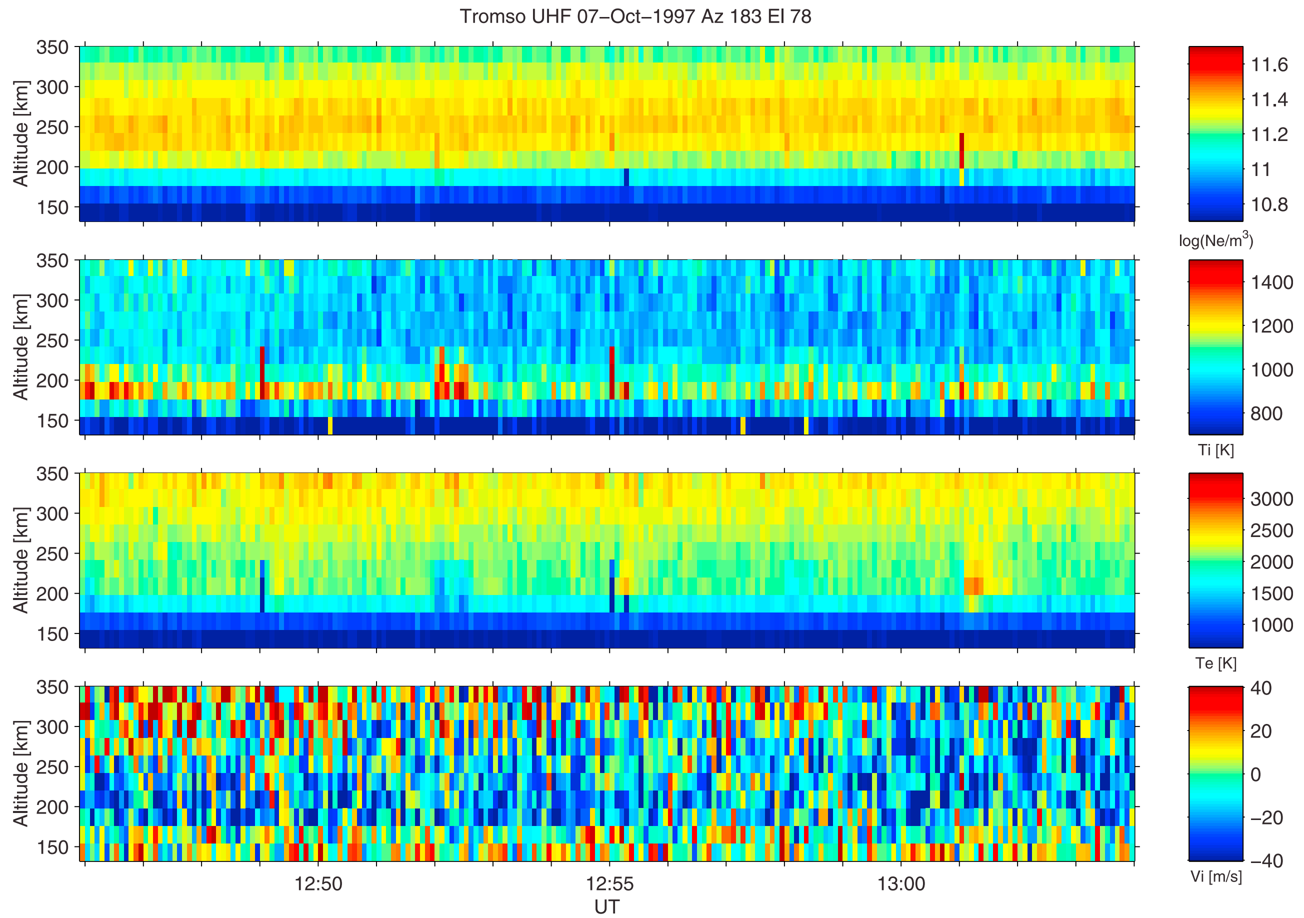

Figure 1. Plasma parameters from GUISDAP analysis of EISCAT UHF data, for the heating experiment between 1246 and 1304 UT on 7 October 1997. The first panel shows the electron density (log scale), the second panel shows the ion temperature, the third panel shows electron temperature, and the fourth panel shows the ion velocity. The red colored tabs indicate intervals when the heater was transmitting at low power, with the dark red tabs indicating the 20 s "seed" pulses which were used in this particular experiment.

[11] At 1246 UT, 1249 UT, 1252 UT, 1255 UT and 1258 UT, when the heater was pumping at 2.5%, 100%, 5%, 100% and 10%, respectively, periods of distinctly lower electron temperatures occurred over the altitude range from approximately 190 to 230 km. These can be seen in the third panel of Figure 1, and appear to persist for the entire duration of the heating interval during the lower-power transmissions, but for only one or two integration periods during the high-power "seed pulses." At the same time as the electron temperature was apparently reduced, the ion temperature (second panel in Figure 1) was apparently quite appreciably enhanced, while neither the electron densities (first panel in Figure 1) nor the ion velocities (fourth panel in Figure 1) showed any significant change.

[12] Usually during heating experiments, it is only the electron gas which should be heated greatly [e.g., *Gurevich*, 1978; *Robinson*, 1989], while the ion temperatures would not be expected to increase in such a dramatic manner, since the ions are much less mobile. Furthermore, the concept of a decrease in the electron temperature under the action of a strong, modifying EM wave field is physically unrealistic. These facts suggest that for these events, the apparent temperature reductions are artifacts of the data analysis, occurring because of a reduction in the ratio between the spectral power in the ion acoustic peaks and the power at the center of the spectrum. A strong PGM feature would account for such behavior, and would also explain why the effects are usually, but not always, limited in altitude extent to a single (22.5 km) range gate, since the plasma turbulence responsible for creating the PGM occurs only within a narrow height region, of the order of 10 km or less.

[13] To our knowledge, there has been an absence of literature to date that documents how the effect of the PGM on the incoherent scatter data analysis could be parameterized or even removed. Therefore, our initial goal in this study was to quantify the effect of the PGM on the analyzed electron temperature derived from the standard GUISDAP analysis, as well as the effect on its associated uncertainty. In order to do this, we have developed a method to remove the PGM feature from the "overshoot" spectra, and have used this technique to correct the spectra in order to produce more realistic temperature estimates.

[14] As well as removing PGM effects from clearly contaminated spectra, we have also attempted to test the reliability of the standard analysis results for spectra obtained during the later stages of "heater on" periods, after the most

obvious PGM effects have disappeared. As mentioned above, previous authors have often assumed that these spectra can be fitted by conventional analysis techniques and in order to have confidence in their results, it would be desirable to demonstrate that this was indeed the case. The technique which we present is useful therefore, not only for those experiments where the PGM effect clearly persists for the duration of the heater transmission period, but also for the reanalysis of cases where more subtle effects, such as apparent decreases or unexpectedly small enhancements in the electron temperature, might suggest that results derived from standard analysis could be questionable. In addition to these applications of the technique, important parameters relating to the characteristics of heater-induced turbulence and instabilities may be retrieved which are contained within the properties of the PGM feature. An outline of our technique is given in section 3. In section 4, a selection of results from investigations of both overshoot-contaminated spectra and apparently uncontaminated "heater on" spectra are presented and discussed.

3. Method of Ion Acoustic Spectrum Correction: Removal of the PGM

[15] In order to evaluate the effect of the PGM on the parameters recovered from incoherent scatter analysis, it was necessary to develop a technique to remove the contamination arising from this instability from the incoherent scatter spectrum, so that data analysis could be compared with the PGM effects included and excluded from the spectrum. This section describes the technique which we have used for removing PGM effects from the incoherent scatter spectra measured at the heater wave interaction height.

[16] The EISCAT UHF data used in this study were obtained from the CP1K long-pulse experiment. This is a standard observing mode in which the radar observed in a fixed field-aligned direction, using a transmission based on plain (uncoded) long pulses for the investigation of the ionospheric *F* region. In this experiment, autocorrelation functions (ACFs) were obtained from the radar data at range gates separated by 22.5 km, and the height of the heater interaction region was found by locating the range gate in which the zero lag of the ACF (equivalent to backscattered spectral power) reached a maximum value during the initial overshoot. The observed incoherent scatter spectra were recovered from the measured ACF by the application of a Fast Fourier Transform. In the "overshoot" spectra, we typically observed a double-humped incoherent scatter spectrum, contaminated with a strong Gaussian feature at the center of the spectrum, corresponding to the effect of the PGM. In reality the center of the spectrum is actually offset from the radar frequency by a Doppler shift which is due to the bulk motion of the plasma. However, since the spectrum is obtained from the Fourier Transform of the ACF with spectral resolution of the order of 1 kHz, the typical ion velocity may often be smaller than the associated velocity resolution and thus we cannot distinguish whether the PGM is truly at zero frequency or at the Doppler-shifted frequency. It would be possible to verify that the PGM was located at the Doppler-shifted frequency if the field-aligned velocity was greater, or if the spectral resolution of the experiment was greater, as is the case in some more recent EISCAT experiments.

[17] The procedure that we have adopted to remove the PGM contamination is a combination of the standard analysis procedure usually carried out by GUISDAP, together with the subtraction from the measured spectrum of a Gaussian function that represented the PGM contamination. In the standard analysis, the GUISDAP fitting routines are initiated by taking a priori plasma parameter estimates of the ion temperature, line-of-sight drift velocity, neutral particle concentration, electron temperature and electron density, which are supplied from an ionospheric model. These are used as a starting point from which to compute an ensemble of theoretical spectra, which are based on Maxwellian assumptions using GUISDAP. The plasma parameters are then varied iteratively over a number of steps until an acceptable convergence between the measured and theoretical spectra is achieved, and a fit residual, R_1 of the fitted theoretical spectrum with the measured, unmodified spectrum is calculated. This parameter is essentially a measure of how well the theoretical spectrum, defined by the final set of analysis parameters, fits to the measured spectrum. It is the ratio of the measured error to the error expected for a purely Maxwellian incoherent scatter spectrum.

[18] In our modified algorithm, an additional procedure follows this usual GUISDAP fitting. This involves subtracting Gaussian functions defined by different amplitude and width from the measured spectrum to produce a "corrected" spectrum. A theoretical spectrum is fitted to each corrected spectrum using the GUISDAP routines, corresponding to a different set of plasma parameters and fit residual. The corrected spectrum which was associated with the smallest fit residual, R_2, was taken as the best result which could be achieved by modifying the spectrum.

[19] In order to determine the significance of the Gaussian peak (PGM) in the incoherent scatter spectra, the fit residuals of the measured and corrected spectra were compared against each other. That is to say, if R_2 was less than R_1, then the plasma parameters estimated from the fitted corrected spectrum were stored as the best result. Where R_1 was not improved by modifying the spectrum, this was taken as an indication that a correction to the spectrum was not necessary. Our procedure is summarized in the form of a flowchart in Figure 2.

[20] This approach, realized by modifying the standard GUISDAP analysis code, is equivalent to regarding the contaminated spectrum as the superposition of a normal symmetric double-humped incoherent scatter spectrum and a Gaussian function centered at zero frequency, corresponding to the effect of the PGM, which occur from different sized scattering volumes. The technique is then equivalent to removing this PGM feature, and analyzing the remainder of the spectrum with conventional incoherent scatter analysis techniques.

[21] It should be pointed out that, as well as being useful for the analysis of spectra which are clearly contaminated by PGM effects, the technique can equally be applied to spectra measured at the interaction height after the initial overshoot has subsided. These spectra have been frequently interpreted in previous literature as if they arose from purely Maxwellian plasma (see the discussion in section 1). Applying our new fitting method to all of the spectra measured during HF heating allows us to explore the possibility that small PGM effects, not necessarily detectable by eye, might nonetheless

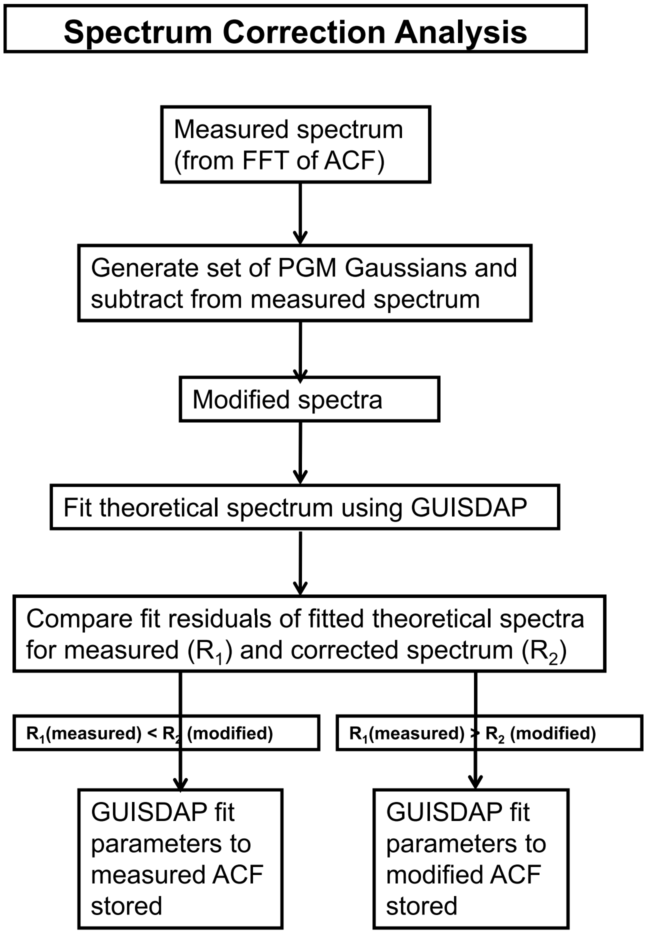

Figure 2. Flowchart to illustrate the spectrum correction procedure used to remove the purely growing mode (PGM) feature from the incoherent scatter spectrum.

be continuing to contaminate the central region of such spectra after the more obvious PGM contamination has ended. In our technique, such effects would manifest themselves as low-amplitude Gaussians which could then be removed before the next stage of fitting. By applying the modified analysis technique, even where no obvious PGM effects are visible, we can estimate whether there is any systematic bias in the temperatures previously recovered from standard analysis in the later stages of each "heater on" interval.

[22] In section 4, we compare the results produced by the above technique to the parameters recovered from standard GUISDAP analysis. We will concentrate particularly on the differences in the derived electron temperature, since this parameter tends to display the most striking differences. A variety of cases are examined, ranging from spectra obtained immediately after "heater on" and strongly contaminated by overshoot features, to spectra measured in the later phases of "heater on" periods, where no overshoot effects are apparent. In particular, we examine the difference in electron temperature between the standard and modified analyses as a function of the ratio between the amplitude of the PGM "spike" and the amplitude of the (symmetric) ion acoustic lines. This kind of empirical parameterization is convenient, since the PGM contamination in measured spectra can vary greatly due to different instability growth rates or the distance between the interaction height and the range gate centers of the CP1K experiment.

4. Results

4.1. Example 1: 1358 UT, 7 October 1997

[23] During the interval 1358–1400 UT on 7 October 1997, the Tromsø heater was transmitting at full power at 4.544 MHz as part of a cycle of 2 min on, followed by 2 min off. The EISCAT ion acoustic spectrum was most enhanced in the range gate centered at 209 km. At this range gate, a significant PGM was measured at the center of the spectrum, whose amplitude was greater than the ion lines, although the three spectral lines were clearly distinguishable.

[24] Figures 3a–3d display the data from this interval, ordered as follows: Figure 3a displays the measured spectrum (in blue), and the theoretical spectrum computed from a priori values which provides the basis for the first iterative step in GUISDAP (shown in green). Figure 3b shows the measured spectrum (in blue) together with the Gaussian peak which was subtracted to produce the best fit with a theoretical spectrum (in green). The green spectrum therefore corresponds to the effect of the PGM. The blue spectrum in Figure 3c is the modified spectrum obtained by subtracting the PGM effects from the measured spectrum, and it is compared to the best fitted incoherent scatter spectrum obtained from the fitting procedure (shown in green). The spectra shown in Figures 3a–3c have been normalized according to spectral power.

[25] In this example, the modified analysis technique was successful in fitting a Gaussian function to the PGM, and in removing it from the overshoot spectrum. This is found to result in a difference of almost 700 K between the electron temperatures derived from the standard GUISDAP estimate (1171 K) and the corrected spectrum estimate (1858 K). In other words, failure to remove the PGM effect would have resulted in an underestimate of nearly 700 K in the electron temperature at the time of the overshoot.

[26] Figure 4 shows the result of applying this technique to an averaged spectrum obtained from the heater interaction height during the same 2 min interval, but excluding from the averaging the spectra obtained immediately after the heater switch on, which were obviously strongly contaminated by PGM effects. In this case, the best fitted Gaussian function is identically zero; in other words, the technique has detected no PGM contamination during this part of the heating interval, so that the measured and modified spectra are identical, and very close to the shape of the best fitted theoretical spectrum. The suggestion is, therefore, that no correction of the spectrum is required, and that the straightforward application of GUISDAP would have given a correct temperature estimate.

4.2. Example 2: 1255 UT, 7 October 1997

[27] Earlier on the same day as the preceding example, the Tromsø heater was pumping in the "LE2" special mode, full details of which are given by *Wright et al.* [2006]. Figure 5 shows incoherent scatter spectra measured between altitudes of 150 km and 300 km in the interval 1255:00–1255:20 UT, when the heater was operating at full power. The GUISDAP analysis from this period is shown in the color plot of Figure 1, and it is clear that this short interval is associated with an apparent reduction in electron temperature at the

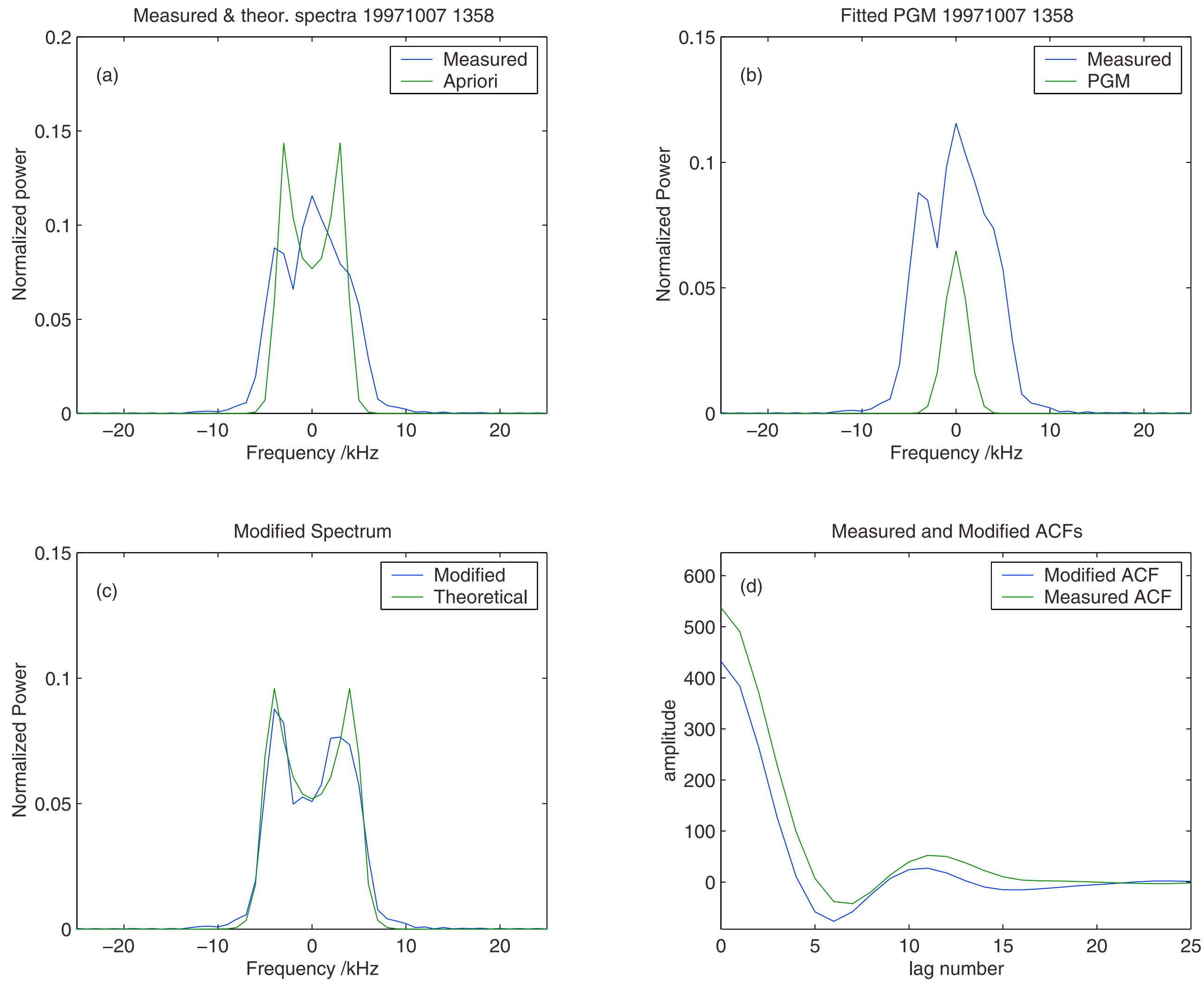

Figure 3. (a) The measured ion acoustic spectrum (blue) and the a priori theoretical spectrum (green). (b) The measured spectrum (blue) and best fitted Gaussian peak subtracted to produce the "corrected" spectrum which corresponded to a lower fit residual when compared with the fit to the measured spectrum. (c) The fitted theoretical spectrum (green) and the best fit corrected spectrum (blue). (d) The measured ACF (green) and the ACF that results from the inverse Fourier Transform of the best fit corrected spectrum.

range gate centered on 209 km, where power profile measurements would suggest that the heater interaction altitude was located. This appears as the dark colored region in the third panel of Figure 1, which is in fact spread over several range gates in altitude between approximately 170 km and 230 km during the first 5 s of heating. However, the strongest reduction effects occur at the interaction altitude range gate. Figure 5 suggests that PGM effects can be seen in the spectra from these adjacent range gates also. In this case, therefore, all three of the affected spectra were reanalyzed using the modified fitting routines described in section 3.

[28] Figure 6 displays the same sequence of plots as shown in Figure 3, for the overshoot spectrum at 1255 UT, from the most severely contaminated range gate at 209 km. It is clear that, in the measured spectrum, shown in blue in Figures 6a and 6b, the amplitude of the PGM feature substantially exceeds the amplitude of the ion lines; however the correction routines nonetheless succeeded in removing the central peak (see Figure 6c) and in obtaining a convergent fit to the remainder of the spectrum. The corresponding ACF of the corrected spectrum is noticeably lower in amplitude when compared with the originally measured ACF (Figure 6d), as expected from the fact that the subtraction of the PGM contamination has led to a considerable reduction in spectral power. The original GUISDAP analysis estimate of the electron temperature from the uncorrected overshoot spectrum, which is the spectrum measured during the first 5 s of the heating, at this altitude was 638 K, whereas the subsequent analysis estimate based on the "corrected" spectrum was 1525 K, indicating an error of about 900 K. It will be noted from Figure 1 that temperatures of this order are much more consistent with the majority of the data obtained from this altitude following the overshoot, during the remainder of the heating interval in question.

4.3. Statistical Effects of PGM Removal

[29] Based on the promising results obtained above, we next carried out a statistical study into the effectiveness of our

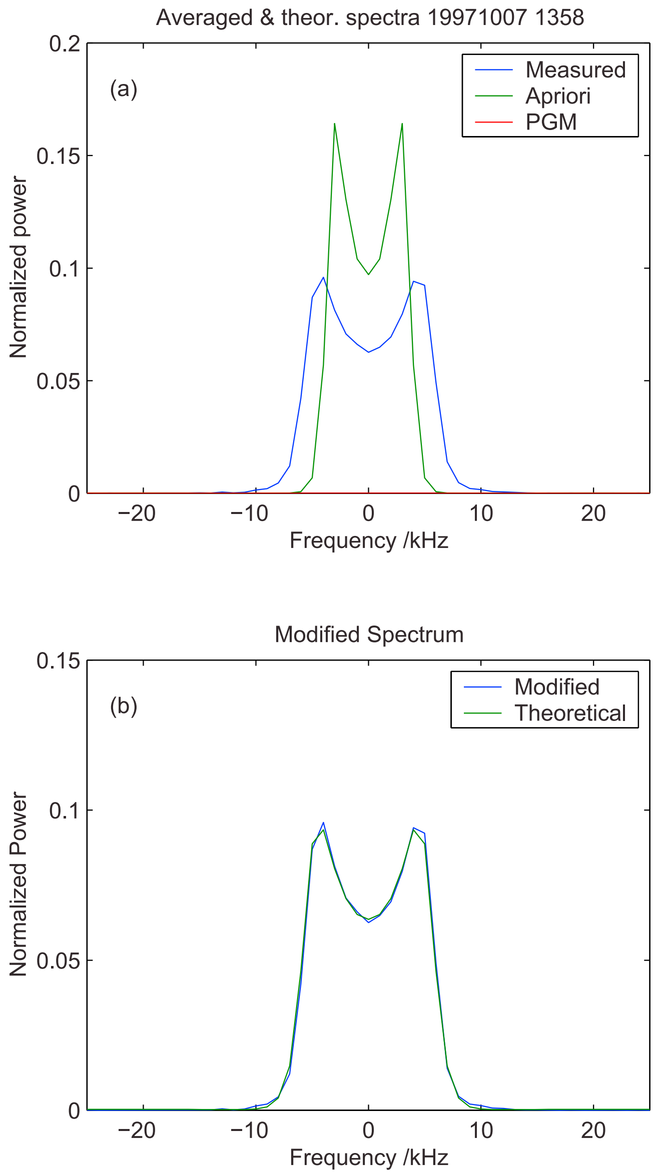

Figure 4. (a) The averaged EISCAT ion acoustic spectrum and (b) best fit theoretical spectrum for the heating from 1358 to 1400 UT on 7 October 1997 indicating that no subtraction of a Gaussian peak is required to improve the variance.

spectral correction technique. For this purpose, we selected a set of almost 100 overshoot spectra, which were contaminated by a PGM. These spectra originated from a range of interaction altitudes during heating experiments carried out between 1996 and 1999. Each of the contaminated spectra was reanalyzed using our spectrum correction software to obtain the difference between the electron temperature arising from the modified analysis and the original temperature estimate, obtained by using GUISDAP on the uncorrected spectra.

[30] In Figure 7a, the difference in electron temperature between the two types of analyses is plotted as a function of the ratio of PGM-to-ion acoustic line amplitude. Since the amplitudes of the upshifted and downshifted ion acoustic lines were not always equal, the ratio was taken as the amplitude at zero frequency (PGM amplitude) divided by an average of the two ion line amplitudes. Figure 7a shows a convincing trend relating the difference in temperature estimates to the amplitude of the PGM, relative to the amplitude of the ion acoustic lines. In most cases this parameter is positive; this implies that the presence of a PGM almost invariably tends to cause an underestimation in the fitted electron temperature by the uncorrected GUISDAP analysis. The strong correlation and positive gradient of the linear function fitted to the data points also imply that the difference tends to be in proportion to the relative amplitude of the PGM, and that the differences between the electron temperatures from the two types of analysis can be in excess of 1500 K when the PGM is particularly strong.

[31] As well as checking the dependence of the analysis results on the magnitude of the PGM effects, it is also important to examine the difference in the reported fit residuals arising from our modified analysis method. If we are correct in inferring that the removal of the PGM feature leads to a better fit between the modified spectra and the synthesized theoretical spectra, we should expect to see that the fit residual is consistently smaller and always reduced when the spectral correction method is applied to remove the PGM feature, because the corrected spectrum analysis results are only accepted if the fit residual is lower than that of the uncorrected spectrum. For a measured spectrum well described by a theoretical Maxwellian spectrum, the fit residual should therefore have a value close to unity.

[32] Figure 7b, which shows the percentage change in the fit residual as a function of the amplitude ratio of the PGM to the ion lines, confirms that this is indeed the case. In all of the instances where the PGM removal has been applied, the change in the fit residual is less than zero, meaning that the magnitude of the fit residual has been improved. It can also be noted that, in around 15% of the spectra which were corrected, the reduction can be very close to 100% of the standard analysis result which implies a very significant improvement in the fit quality. It is notable that there is no strong trend relating the reduction in the fit residual to the size of the PGM relative to the ion lines as implied by the low correlation coefficient of around −0.236, although Figure 7b does suggest that the greatest reductions in the fit residual occur when the largest PGM features are removed.

[33] Figure 7c shows the distribution of these changes in fit residual as a histogram, and illustrates that a high proportion, of greater than 80% of the total number corrected spectra, resulted in the fit residual being reduced by greater than 50% of the uncorrected spectrum value. These results show that the fit can be substantially better by simply removing the PGM feature from the overshoot spectra. However, the effectiveness of the method cannot be determined from examination of the absolute values of the residuals alone. The distribution of the absolute values of the fit residual (rather than the change in the fit residual) after the spectrum correction, are presented in Figure 7d. This shows that for around 10% of the total sample, the corrected spectrum fit residual may still be well in excess of 10, even though they are lower than those of the uncorrected spectrum and the majority of the values lie between 0 and 10. This result may suggest that the overshoot spectrum may still be contaminated by other “non-Maxwellian” effects such as asymmetry in the ion lines, or enhancement of one or both of the lines due to Langmuir turbulence which the

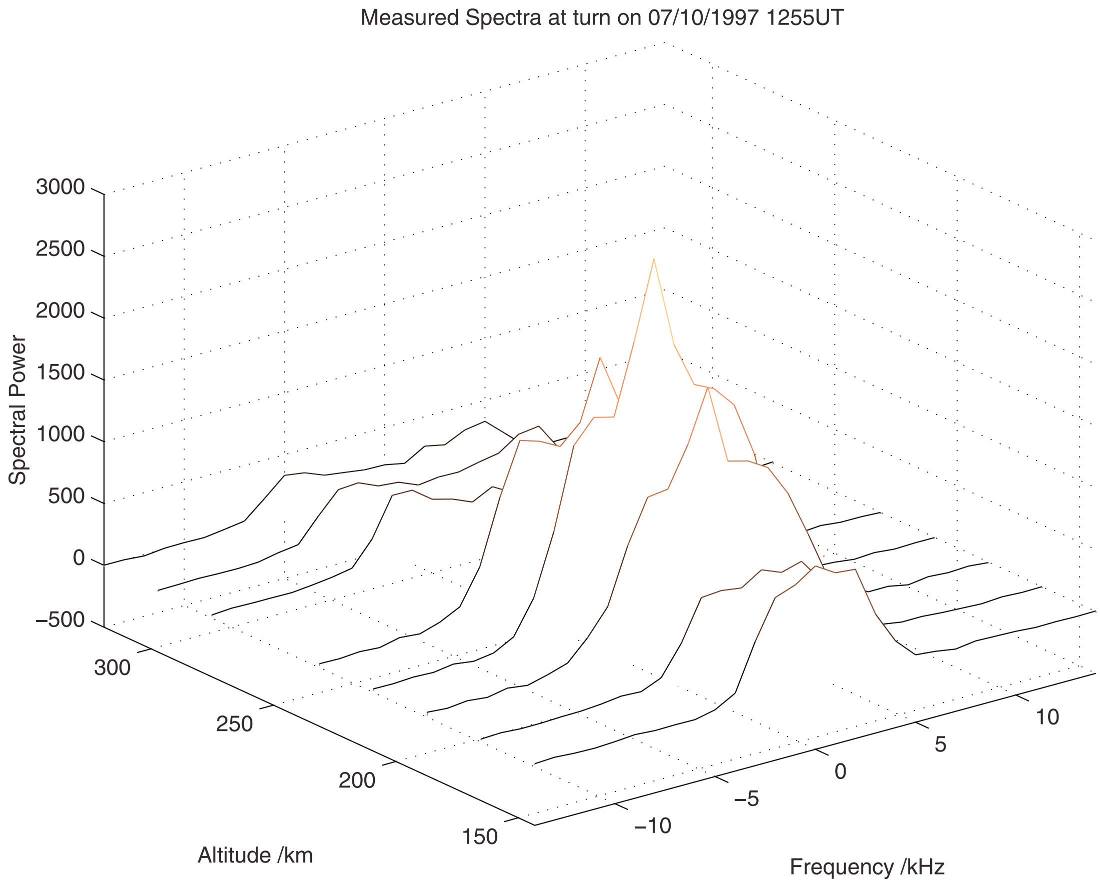

Figure 5. Waterfall plot of the measured EISCAT radar spectra during the initial overshoot for the heating at 1255 UT on 7 October 1997.

technique would not be capable of correcting. Hence the "corrected" spectrum resulting from this technique may not represent a pure incoherent scatter spectrum, which would be identified by a fit residual close to unity.

4.4. Application to Intervals Without Obvious PGM Contamination

[34] In section 1, emphasis was placed on the importance of obtaining an estimate of the electron temperature during the later parts of "heater on" periods, after the initial clear overshoot has disappeared. The spectra obtained at these times reflect the bulk changes in electron temperature caused by the heating, whose determination is important to understand thermal conduction effects in the modified ionosphere. To investigate whether the modified fitting procedure could improve the estimation of plasma temperatures during these intervals, the fitting procedure was applied only to spectra that had been averaged during times from 30 s after the "heater on" until the end of the heating period.

[35] As outlined in section 3, the fitting procedure was carried out in such a way that if the fit residual of the measured spectrum at the interaction height was smallest when no Gaussian peak was subtracted, this was taken as an indication that no correction to the spectrum was required. Such a case has already been mentioned in section 4.1, and is shown in Figure 4.

[36] In the cases where a Gaussian peak could be subtracted to lower the fit residual, the remainder of the spectrum was then analyzed, and a new estimate of the temperature was obtained as before. An example is shown in Figure 8, for the averaged spectrum obtained between 1506 UT and 1509 UT on 25 April 1996. Figure 8a illustrates the average of the measured spectrum (in blue), the initial fit spectrum derived from the GUISDAP a priori parameters (in green) and the PGM corresponding to the best fit Gaussian spectrum (in red). Figure 8b shows the modified spectrum after the removal of the PGM, together with the best fit theoretical spectrum. Even though the measured spectrum appeared to be close to double humped, the subtraction of a Gaussian PGM-type feature is nevertheless found to produce a theoretical spectrum whose fit residual is lower when compared to the fit to the uncorrected spectrum.

[37] In a statistical study analogous to that reported in section 4.3, averaged spectra from approximately 50 "heater on" intervals were analyzed in this way, omitting the first 30 s of the heating interval in each case. The results are displayed in Figure 9. In this plot, the concept of the "PGM ratio" has been dropped, since a PGM peak was not always apparent in the averaged spectra, and the *x* axis now shows the ratio between the amplitude of the spectrum at zero frequency and the amplitude of the ion lines. Higher values of this ratio should generally correspond to larger electron temperatures, or at least higher ratios of electron to ion temperature. The

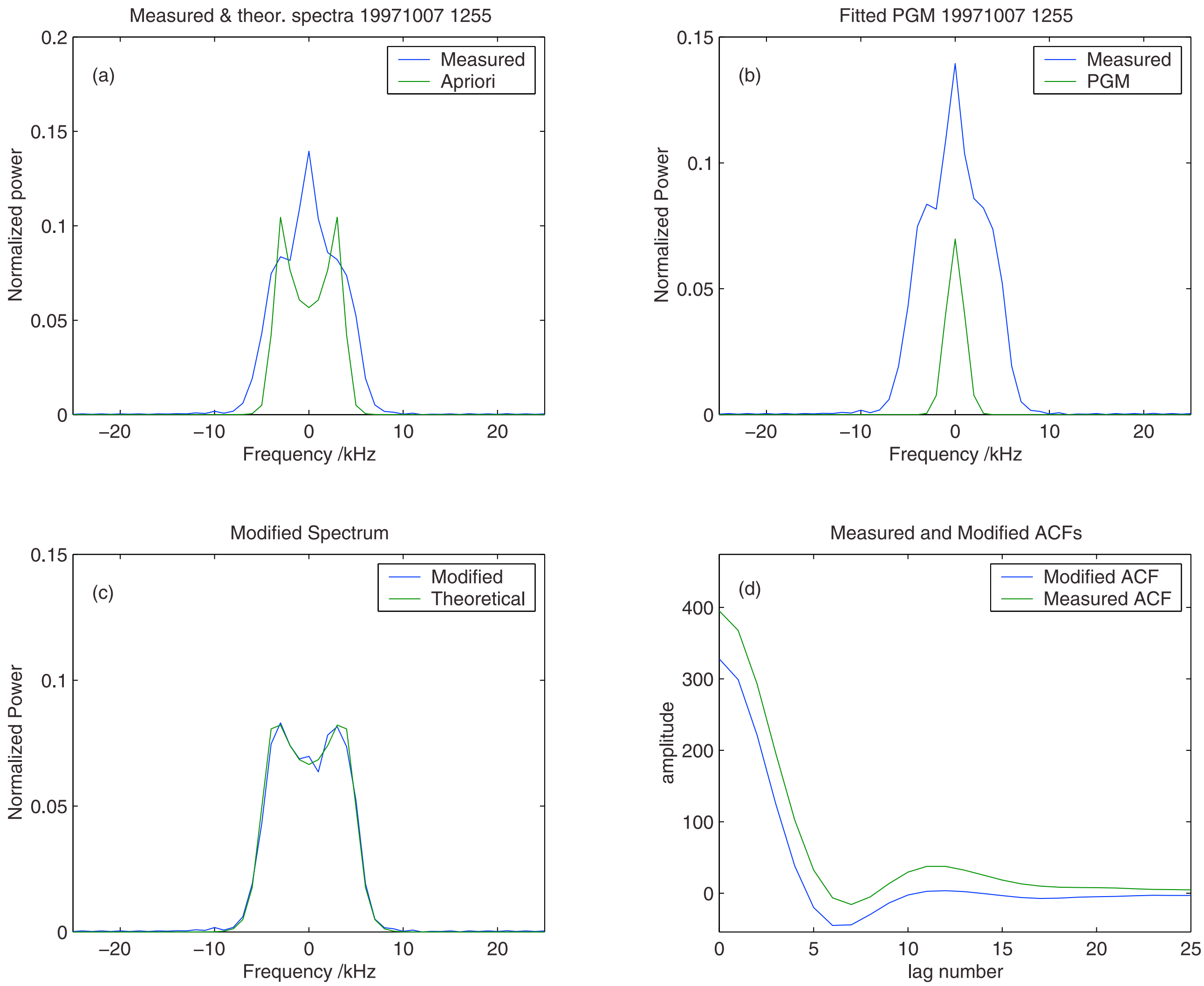

Figure 6. Spectrum correction results for the spectrum at 209 km, at 1255 UT on 7 October 1997. (a) The measured ion acoustic spectrum (blue) and the a priori theoretical spectrum (green). (b) The measured spectrum (blue) and best fitted Gaussian peak. (c) The fitted theoretical spectrum (green) and the best fit corrected spectrum (blue). (d) The measured ACF (green) and the ACF that results from the Fourier Transform of the best fit corrected spectrum.

y axis of Figure 9 shows the difference between the electron temperatures obtained from the analysis of the corrected spectra (if required) and those obtained from a standard GUISDAP analysis of the uncorrected spectra.

[38] There is a striking dissimilarity between Figures 9 and 7a, where the initial overshoot period was not excluded from the averaged spectra. It is notable that many of the points in Figure 9 show an electron temperature difference of zero, or close to zero, implying that, in many cases, the removal of a PGM from the averaged spectra was either unnecessary or had no significant effect. It thus appears that in most cases, the standard GUISDAP analysis of these averaged spectra would have given a true estimate of the bulk electron temperature change. Nonetheless, a few cases were found where a correction of the spectrum was possible, and some of these had the effect of increasing the electron temperature by up to 90 K.

[39] As mentioned in section 1 it is known that, when the heater is pumping around an electron gyrofrequency, both the ion line enhancement and sometimes the PGM have been known to persist throughout the heating interval. Since we have shown that the standard analysis, without correcting for the presence of the PGM, grossly underestimates the electron temperature, we would expect that such intervals might appear to be characterized by only modest electron temperature enhancements or even decreases in electron temperature, instead of the usual much larger temperature enhancement that evolves as a result of the TPI. In carrying out this study, our data set included an experiment where the heater was pumping at (or close to) the third gyroharmonic (4.05 MHz) between 1222 UT and 1240 UT on 23 April 1997. During this interval, the electron temperatures derived from GUISDAP analysis of the spectra from the interaction region exhibited an apparent decrease during heating in a similar manner as in the example given in Figure 1.

[40] Simultaneous apparent enhancements in the ion temperature and minor increases in the electron density occurred along with these apparent electron temperature reductions, while the ion velocity did not exhibit any changes correlated

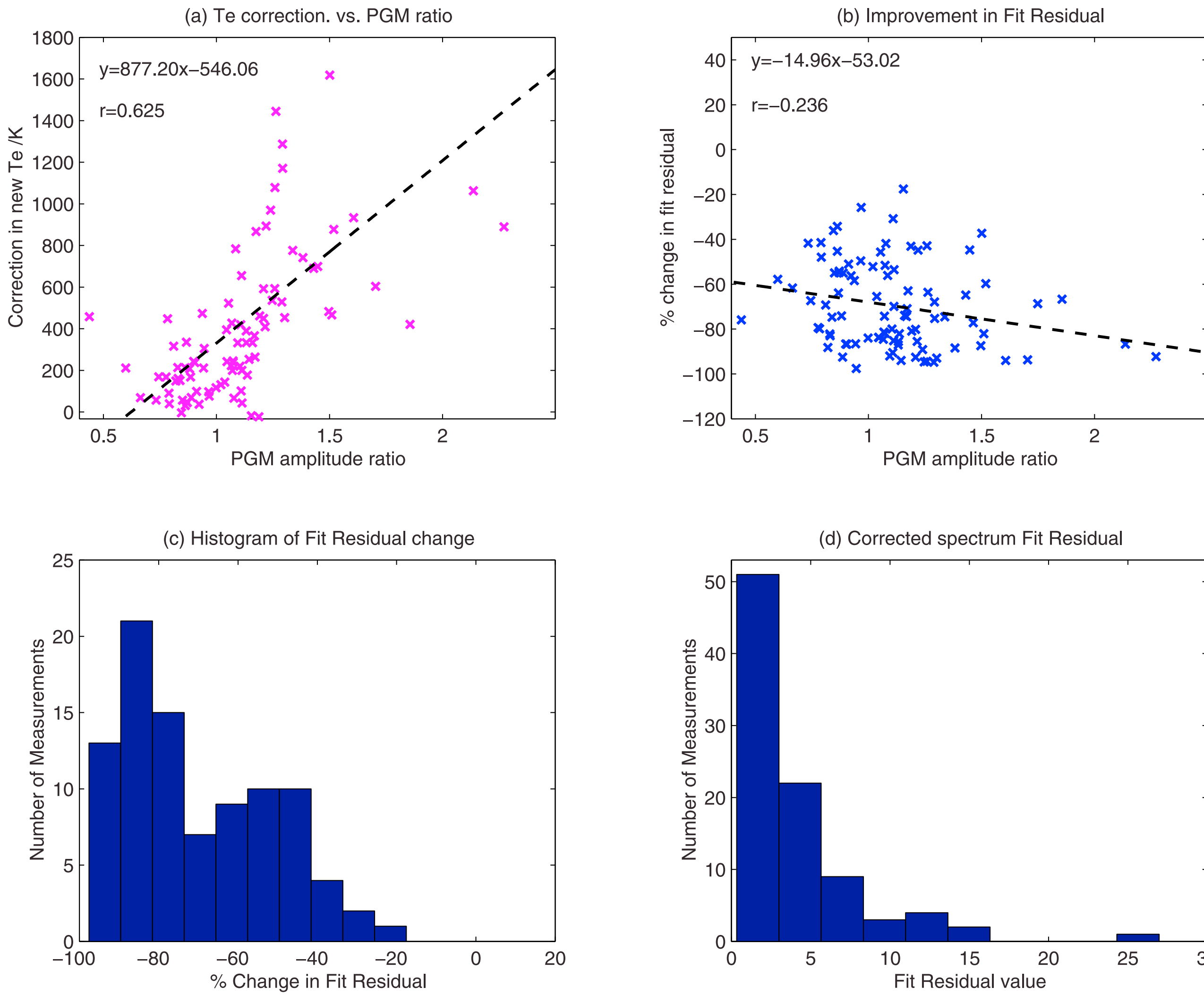

Figure 7. (a) Relationship between the PGM amplitude ratio and the difference between the electron temperature estimates ("correction") from the analysis of the corrected and uncorrected ACF, for spectra at heater turn-on time, i.e., during the initial overshoot; (b) the relationship between the PGM amplitude ratio and the percentage change in the GUISDAP fit residual due to the removal of a Gaussian purely growing mode from the spectrum; (c) distribution of the percentage change in the GUISDAP fit residual; and (d) the distribution of the absolute values of the fit residual after the removal of the PGM.

with the heating intervals over the altitude range of interest. In an attempt to investigate these apparent temperature variations, the averaged spectrum during the heating interval from 1238 UT to 1240 UT on this date was subjected to our method for removing the PGM contamination. Figure 10, in the same format as Figures 4 and 8, reproduces the averages of the measured and modified spectra for this period excluding, as before, the spectra obtained in the first 30 s after "heater on." Also shown in Figure 10 is the Gaussian contribution which has been removed in order to create the modified spectrum. This suggested that, although the effect is small, this period does indeed show contamination by a long-lasting PGM feature.

5. Conclusions

[41] During HF heating events, the presence of plasma turbulence and the excitation of instabilities cause strong departures in the shape of the incoherent scatter spectrum from the "double-humped" configuration which characterizes unperturbed Maxwellian plasma. Specifically, the presence of a central peak or purely growing mode is often observed, and we have show that this invariably leads to an underestimation in the electron temperatures derived by using standard analysis software. In this study we have shown a novel method, allowing improved estimates of ionospheric plasma parameters to be recovered from incoherent scatter spectra contaminated by the PGM. This technique has been used in two ways: first to estimate plasma parameters during the period at the beginning of a "heater on" when the spectrum is strongly affected by PGM contamination, and second to analyze the averaged incoherent scatter spectra measured during the latter part of HF heating periods, defined as starting 30 s after the time of "heater on." Both kinds of result are of interest, because while the later averages, after the overshoot, provide a more valid measurement of the bulk temperature

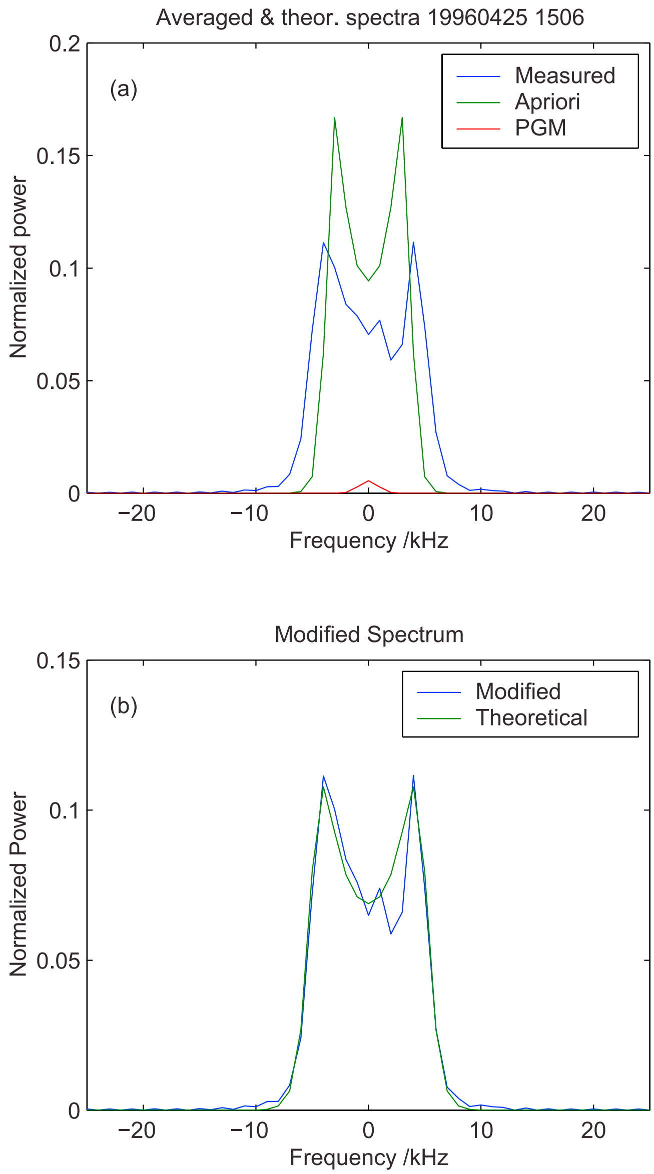

Figure 8. (a) The measured spectrum (blue), theoretical spectrum fitted using a priori values of the plasma parameters (green), and best fit Gaussian peak (red) and (b) the corrected averaged spectrum for 1506 UT, 25 April 1996 (averaged 1506:30–1509:00 UT), after removal of the Gaussian peak at the heater interaction altitude of 209 km.

changes which control thermal conduction and FAI generation, an improved interpretation of the initial spectra can provide information about the risetime of the irregularities and yield insights into the energy deposition and anomalous absorption processes involving the pump wave [*Mantas et al.*, 1981].

[42] As well as demonstrating the application of our technique on specific example spectra, we have performed a statistical study on heating experiments carried out over the three year period from 1996 to 1999. The results suggest that, in the majority of cases, the analysis of most of the longer averages from each heating interval (excluding the first 30 s) produces the same answer as would be obtained using the standard GUISDAP incoherent scatter analysis. This suggests that the standard analysis is largely accurate when dealing with spectra measured after the initial overshoot has disappeared. The probable explanation for this is that, after the first few seconds of each "heater on" period, the PGM tends to be quenched by the Thermal Parametric Instability (TPI).

[43] Regarding the initial intervals that are strongly contaminated by PGM effects, we have demonstrated that the naive application of standard analysis techniques can result in serious underestimates of the electron temperature, with corresponding overestimates of the ion temperature. The electron density can also be overestimated. We have shown that the magnitude of the electron temperature underestimate is strongly proportional to the relative amplitudes of the PGM and ion acoustic lines. The ability to parameterize the underestimate in this way is significant because, in the data we have considered, a large degree of variability was encountered in the observed PGM amplitudes, most likely caused by varying ionospheric conditions and differences in the heater transmission parameters.

[44] However, some caution must nevertheless be exercised in the interpretation of the corrected overshoot spectra and the electron temperatures inferred from them, since it is possible that other spectral effects, such as enhancement of the ion acoustic lines due to Langmuir turbulence which can also occur on the same time scales and thus bias the analysis results. These effects would not be accounted or corrected for through the technique described in this study. Nevertheless, the technique removes the major source of systematic error in the electron temperatures during this initial phase of heating which is brought about by the PGM.

[45] Although we have not made an in-depth study of the amplitudes and widths of the PGM which were recovered from the fitting technique, these parameters can in principle provide important information on the nature of the plasma instabilities induced by the action of the heater wave before large-scale modifications of the plasma take place. The width of the PGM is essentially a measure of the lifetime of the OTSI, and the amplitude of the PGM indicates the strength of the interaction between the heater wave and plasma. As was

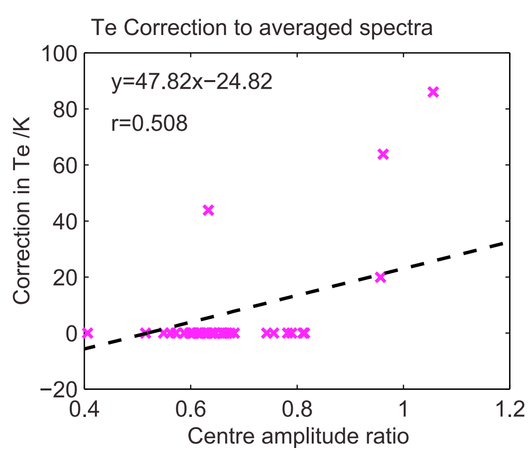

Figure 9. The relationship between the amplitude ratio at the center of averaged spectra and the corrected ACF analyzed electron temperature estimates, after the initial overshoot period, for approximately 50 averaged spectra corrected and analyzed by using our fitting routines.

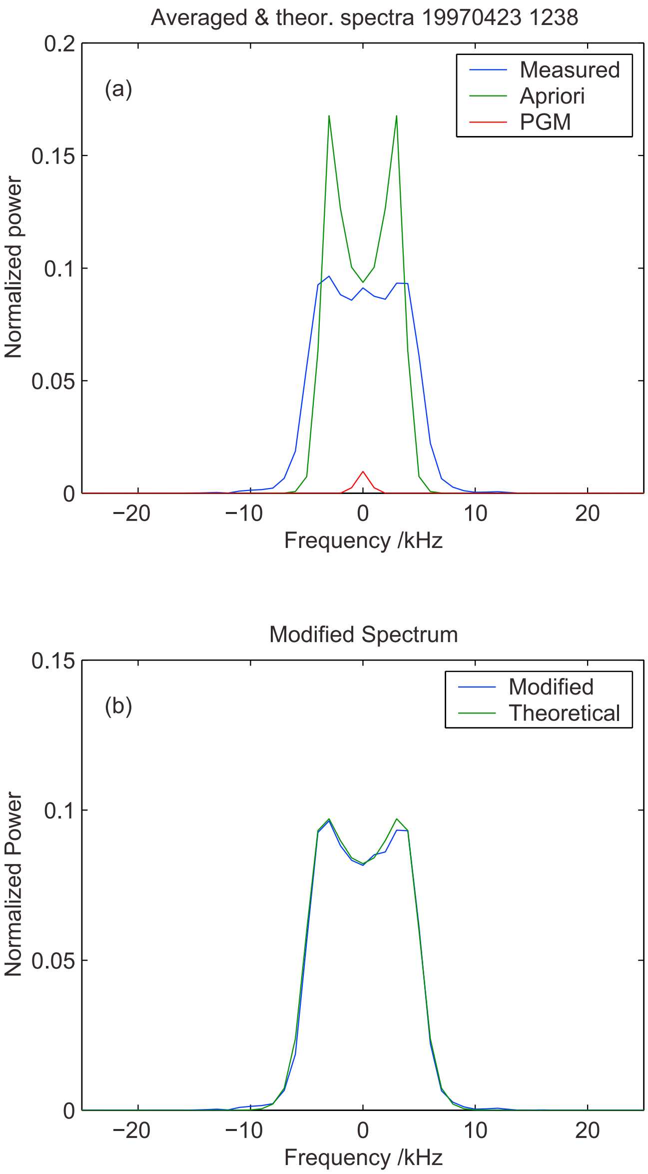

Figure 10. (a) The averaged ion acoustic spectrum at 209 km during heating around the third electron gyroharmonic, 1238–1240 UT on 23 April 1997, and (b) the modified spectrum (blue) after a Gaussian peak (shown in red at the center of Figure 10a) has been subtracted to obtain a minimum variance with a theoretical spectrum.

pointed out earlier, these parameters may vary according to a number of controllable and noncontrollable factors related to the heater operation and the ionosphere. Also, we note that although the PGM was observed to sometimes appear over several consecutive (22.5 km) range gates, the altitudinal spread over which the PGM occurs is much smaller than the scattering volume associated with the long-pulse experiment data. The long-pulse experiment allows for a measured spectrum with good signal-to-noise ratio at the present time resolution of 5 s, but experiments with higher spatial resolution which are comparable to the height interval over which the instabilities take place would be more desirable to make a more detailed study of the turbulence characteristics. However, with the higher spatial resolution data, where there is lower signal-to-noise ratio, the effect of greater measurement uncertainties on the technique may be worse than the lower spatial resolution, long-pulse data used here. Nevertheless, it is anticipated that these considerations could be made in a further study to extend this work.

[46] While the present study has been carried out using EISCAT UHF radar data obtained at Tromsø, its applications should also be applicable to other radar facilities where HF heating experiments are carried out. It is worth noting, however, that there are important exceptions to the general findings summarized above. For example, when the heater is pumping at frequencies close to a gyroharmonic, PGM contamination has been observed to be long lasting and may even affect the entire heating period, meaning that the spectral correction method proposed here should be applied to all measurements made while the heater is turned on. It should also be noted that, in experiments carried out using the SPEAR heating facility on Svalbard in conjunction with the EISCAT Svalbard Radar, long-lasting PGM contamination has been observed, even during periods when the pump frequency is not close to a gyroharmonic, possibly due to the more dynamic nature of the polar cap ionosphere. We suggest that this may partially explain why previous studies have reported only mild increases, if any, in the electron temperatures measured during HF heating by SPEAR and that it might be worthwhile to apply some of the reanalysis techniques discussed here to the data from such experiments, in order to validate the accuracy of previous estimates.

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