

EISCAT Svalbard radar observations of SPEAR-induced E- and F-region spectral enhancements in the polar cap ionosphere

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Abstract. The Space Plasma Exploration by Active Radar (SPEAR) facility has successfully operated in the high-power heater and low-power radar modes and has returned its first results. The high-power results include observations of SPEAR-induced ion and plasma line spectral enhancements recorded by the EISCAT Svalbard UHF incoherent scatter radar system (ESR), which is collocated with SPEAR. These SPEAR-enhanced spectra possess features that are consistent with excitation of both the purely growing mode and the parametric decay instability. In this paper, we present observations of upper and lower E-region SPEAR-induced ion and plasma line enhancements, together with F-region spectral enhancements, which indicate excitation of both instabilities and which are consistent with previous theoretical treatments of instability excitation in sporadic E-layers. In agreement with previous observations, spectra from the lower E-region have the single-peaked form characteristic of collisional plasma. Our observations of the SPEAR-enhanced E-region spectra suggest the presence of variable drifting regions of patchy overdense plasma, which is a finding also consistent with previous results.

Keywords. Ionosphere (active experiments; plasma waves and instabilities; polar ionosphere)

1 Introduction

Among the most important phenomena associated with overdense RF heating are the stimulation of non-propagating plasma density irregularities at the upper-hybrid height and the excitation of Langmuir and ion-acoustic waves at the O-mode reflection height (e.g. Robinson, 1989; Rietveld et al., 1993; Kohl et al., 1993; Mishin et al., 2004). These ion-acoustic and Langmuir waves can be detected in the inter-

action region by radars pointing in a wide range of directions, including those close to the geomagnetic field direction (e.g. Stubbe et al., 1992; Kohl et al., 1993; Djuth et al., 1994; Isham et al., 1999; Honary et al., 1999; Rietveld et al., 2000; Dhillon and Robinson, 2005). These wave modes give rise to enhancements in both the E- and F-region ion and plasma line incoherent scatter spectra. These spectral enhancements are thought to be caused by excitation of instabilities (Perkins and Kaw, 1971) that include the purely growing mode (Fejer and Leer, 1972), also called the oscillating two-stream instability or modulational instability (Rietveld et al., 2002), and the parametric decay instability (Fejer, 1979). These two instabilities were first observed using the HF heating facility at Arecibo (Carlson et al., 1972; Gordon and Carlson, 1974) as summarized in the review by Carlson and Duncan (1977). Among other results, many observations of these phenomena have been obtained using the EISCAT incoherent scatter radar systems (e.g. Stubbe et al., 1992; Kohl et al., 1993; Stubbe, 1996) during RF heating experiments at Tromsø.

The SPEAR system (a recent addition to the global array of HF high-power facilities) began experimental operations in April 2004, when the first results using the high-power beam were obtained (Robinson et al., 2006). Since then, further successful experimental campaigns have been undertaken, during which RF-induced enhancements in both field-perpendicular and field-parallel scatter have been detected by coherent and incoherent scatter radars, respectively. Field-parallel SPEAR-induced spectral modifications whose characteristics are consistent with excitation of the purely growing mode and the parametric decay instability have been observed in the F-region by the EISCAT Svalbard UHF incoherent scatter radar system (Robinson et al., 2006). In this paper, we add to these results by concentrating mainly upon enhancements in sporadic E-layers and restrict our attention to E- and F-region SPEAR-enhanced spectral data accumulated by the EISCAT Svalbard Radar (ESR) during experimental SPEAR/ESR/CUTLASS campaigns conducted

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in December 2004 and November/December 2005. Heating of sporadic E-layers was first reported by Gordon and Carlson (1976) using the Arecibo 430 MHz incoherent scatter radar. Further observations were obtained by Djuth (1984), during typical daytime conditions as well as during intervals where sporadic E-layers were present, and Djuth and Gonzales (1988), who studied the temporal evolution of enhanced plasma lines during heating of sporadic E-layers and found enhancements upshifted and downshifted from the transmitter frequency by the heater frequency. Also, Schlegel et al. (1987) noted significant increases in the E-region ion line spectral power recorded by the EISCAT 933 MHz mainland UHF radar. More recently, Rietveld et al. (2002) presented RF-induced E- and F-region spectral enhancements that were detected by both the UHF (operating at 931 MHz after renovation) and 224 MHz VHF EISCAT mainland radars. They concluded that there was evidence consistent with E-region excitation of the parametric decay instability and purely growing mode.

In Sect. 2 of this paper, the experimental configuration and certain technical aspects of the SPEAR system are described, together with the ESR. Section 3 will provide an overview of the experiments conducted in the SPEAR campaigns and a discussion of the results will be presented in Sect. 4. Throughout this paper, repeated references will be made to the paper by Robinson et al. (2006), where initial observations of simultaneous SPEAR-enhanced coherent and incoherent scatter data are presented, and henceforth this publication will be referred to as R2006.

2 Instrumentation

SPEAR is a new combined HF high-power heater and coherent scatter radar system (R2006; Wright et al., 2000) located in the vicinity of Longyearbyen (Spitzbergen in the Svalbard archipelago with a magnetic dip angle of approximately 8.5 degrees) and is designed to carry out a range of space plasma investigations of the polar ionosphere and magnetosphere. The first results obtained using SPEAR have been presented in R2006. Full details of the SPEAR system, including technical specifications and operating constraints, can be found in R2006. During the intervals covered here, SPEAR operated using the full 6×4 array, transmitting O-mode-polarized radio waves in the field-aligned direction with a frequency of 4.45 MHz and an effective radiated power (ERP) of approximately 15 MW. The half-power beam width is approximately 21 degrees.

The CUTLASS coherent scatter radars (Milan et al., 1997) were also in operation during the experimental intervals presented below. Both the Iceland and Finland radars ran an experimental mode that used 15 km range gates on channel A and 45 km range gates on channel B, with beam 6 of Iceland and beam 9 of Finland overlooking the SPEAR site. Because of a combination of the frequency sweeps (11–13 MHz), in-

tegration time (1 s) and beam sweeps (beams 3–5) that were used, the temporal resolution of the data from any specific range-beam cell varied from 9–15 s. Further details of the CUTLASS operating modes utilized during the experiments are given in R2006.

The incoherent scatter radar data presented below were recorded using the ESR (Wannberg et al., 1997), which is collocated with SPEAR. The ESR, which operates at frequencies close to 500 MHz, was used to detect the Langmuir and ion-acoustic waves generated during the excitation of instabilities near the O-mode reflection height. During the December 2004 campaign, the ESR ran an experimental mode that used the fixed (field-aligned) 42 m dish to collect ion line data and the steerable 32 m dish (also pointed field-aligned) to collect plasma line data. The ion line spectra were obtained on a channel with a transmitter frequency of 499.9 MHz. The height discriminated ion line spectral data were obtained in two altitude ranges of 105–210 km and 129–757 km with range resolutions of 4.750 km and 14.250 km, respectively. The frequency resolutions of data from the two altitude ranges were 0.992 kHz and 0.880 kHz, respectively, with the frequency ranges of both being ± 31 kHz. The temporal resolution of the ion line data was 6.4 s. Although plasma line data were also recorded on a separate transmitter channel at a frequency of 500.3 MHz, no E-region plasma line spectral enhancements were detected because the excited E-region lay below the lowest altitude from which plasma line data were collected (150 km).

During the December 2005 campaign, the ESR ran an experimental mode that used the steerable 32 m dish (pointed field-aligned) to collect both ion and plasma line data using long pulses. The ion line spectra were obtained on two channels with transmitter frequencies of 499.9 and 500.3 MHz. The height-discriminated ion line spectral data for both channels were obtained for an altitude range of 86–481 km with a range resolution of 28.226 km. The frequency resolutions of data from the two channels were 2.0 kHz with the frequency ranges of both being ± 50 kHz. Only data from the 499.9 MHz channel have been presented in this paper. The plasma line data were recorded on a separate channel with a transmitter frequency of 500.1 MHz. Plasma line spectra were obtained in two overlapping frequency bands of 3.2–4.8 and 4.5–6.1 MHz both upshifted and downshifted from the transmitter frequency. The plasma line data were obtained for altitude ranges of 90–315 and 240–465 km, although in this paper data are only shown from the 90–315 km altitude range, which includes the E-region. Because of the long pulses used, together with a lack of data regarding the echo strength versus range across the long pulse, the plasma line data are not discriminated in altitude. The temporal resolution of both the ion and the plasma line data was 5.0 s.

3 E- and F-region spear-enhanced incoherent scatter data

This section covers observations of SPEAR-enhanced ion and plasma line spectra measured by the ESR and data from three intervals have been shown below. During 13:10–13:42 UT on 10 December 2004 (interval 1), SPEAR transmitted an O-mode 4-min-on/4-min-off cycle at 4.45 MHz and E- and F-region data from this interval are shown. Upper E-region data from 12:46–12:52 UT on 3 December 2005 (interval 2) and lower E-region data from 15:14–15:20 UT on 4 December 2005 (interval 3) are also shown. During intervals 2 and 3, SPEAR transmitted an O-mode 2-min-on/2-min-off cycle at 4.45 MHz. These data illustrate succinctly the effects on the SPEAR-enhanced spectra of an ionosphere with a well developed E-layer (interval 1), a relatively structured ionosphere (interval 2) and an ionosphere with an irregular E-layer (interval 3). These ionospheric conditions were deduced using ionograms, recorded using the Svalbard ionosonde (R2006), which were taken during each of these data intervals. Each of the ionograms, which are shown in Fig. 1, was obtained when SPEAR was not transmitting. Panel (a) shows an ionogram taken at 13:26 UT on 10 December 2004 (interval 1). This shows clearly a blanketing sporadic E-layer that affects O-mode waves with frequencies from 2–10 MHz. There is also evidence of second-hop scatter from approximately 4–9 MHz. Panel (b) shows an ionogram recorded at 12:50 UT on 3 December 2005 (interval 2). This ionogram shows evidence of structure in the ionosphere and has features consistent with the presence of E- and F-layers. Panel (c) shows an ionogram obtained at 15:18 UT on 4 December 2005 (interval 3). This ionogram is suggestive of an irregular E-layer that interacts with radio waves that have frequencies in the range of about 2–7 MHz. The sporadic E-layer echoes exhibit an altitude extension of about 20 km at frequencies between 3 and 6 MHz. Although the altitude resolution in the ionograms is 6 km, the extended altitude range may be caused by the oblique nature of some of the echoes detected by the ionosonde receiver/processing system.

The CUTLASS Finland and Iceland radars were operating during the three data intervals and they collected data, which are shown in Fig. 2, using the scanning mode that was described in Sect. 2. The three labelled rows of panels correspond to intervals 1, 2 and 3, respectively. The columns of panels, from left to right, correspond to data from Finland Channel A, Finland Channel B, Iceland Channel A and Iceland Channel B. The Finland data were taken using beam 9 and the Iceland data with beam 6 (see Sect. 2). The horizontal black bars in each of the panels indicate when SPEAR was transmitting, with the vertical dashed lines denoting the SPEAR switch-on and switch-off times. Finland channel B data for interval 1 are missing and therefore no data are shown in this panel. Clearly, definite SPEAR-enhanced CUTLASS backscatter was only observed during 12:48–12:50 UT on 3 December 2005 (within interval 2) by

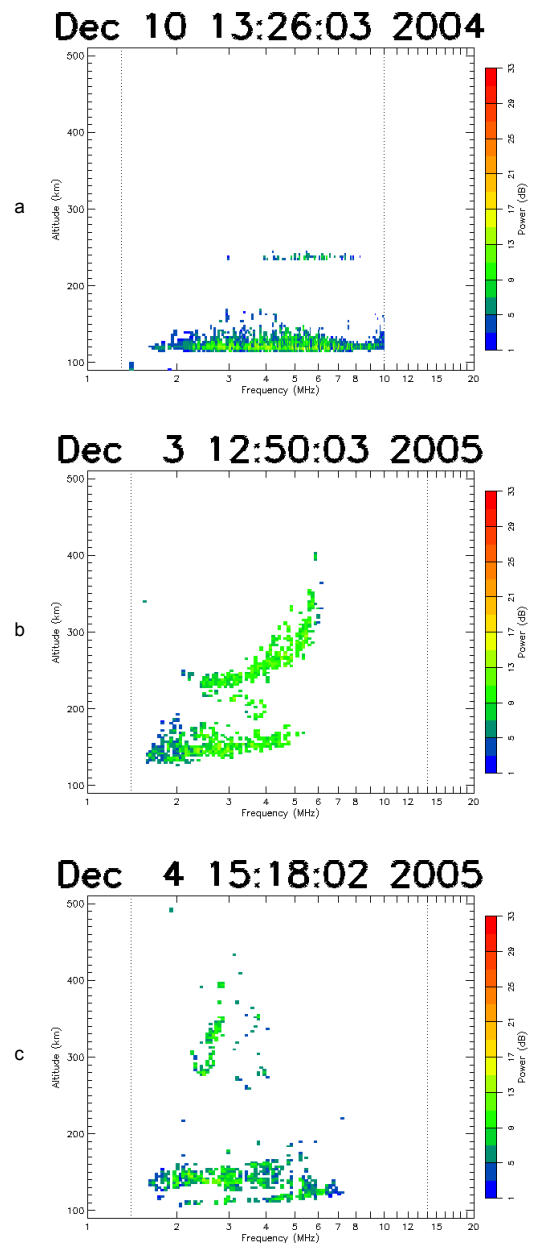


Fig. 1. Ionograms, recorded during SPEAR-off using the Svalbard ionosonde (R2006) from the three data intervals that have been discussed in this paper. Panel (a) shows an ionogram taken at 13:26 UT on 10 December 2004 (interval 1) in an ionosphere with a well developed blanketing sporadic E-layer that affects O-mode waves with frequencies from 2–10 MHz. There is also evidence of second-hop scatter from approximately 4–9 MHz. Panel (b) shows an ionogram recorded at 12:50 UT on 3 December 2005 (interval 2) in a relatively structured ionosphere that has features consistent with an F-region layer. Panel (c) shows an ionogram obtained at 15:18 UT on 4 December 2005 (interval 3) in an ionosphere with an irregular E-layer that affects O-mode waves with frequencies from about 2–7 MHz.

CUTLASS BACKSCATTER POWER FOR 3 INTERVALS

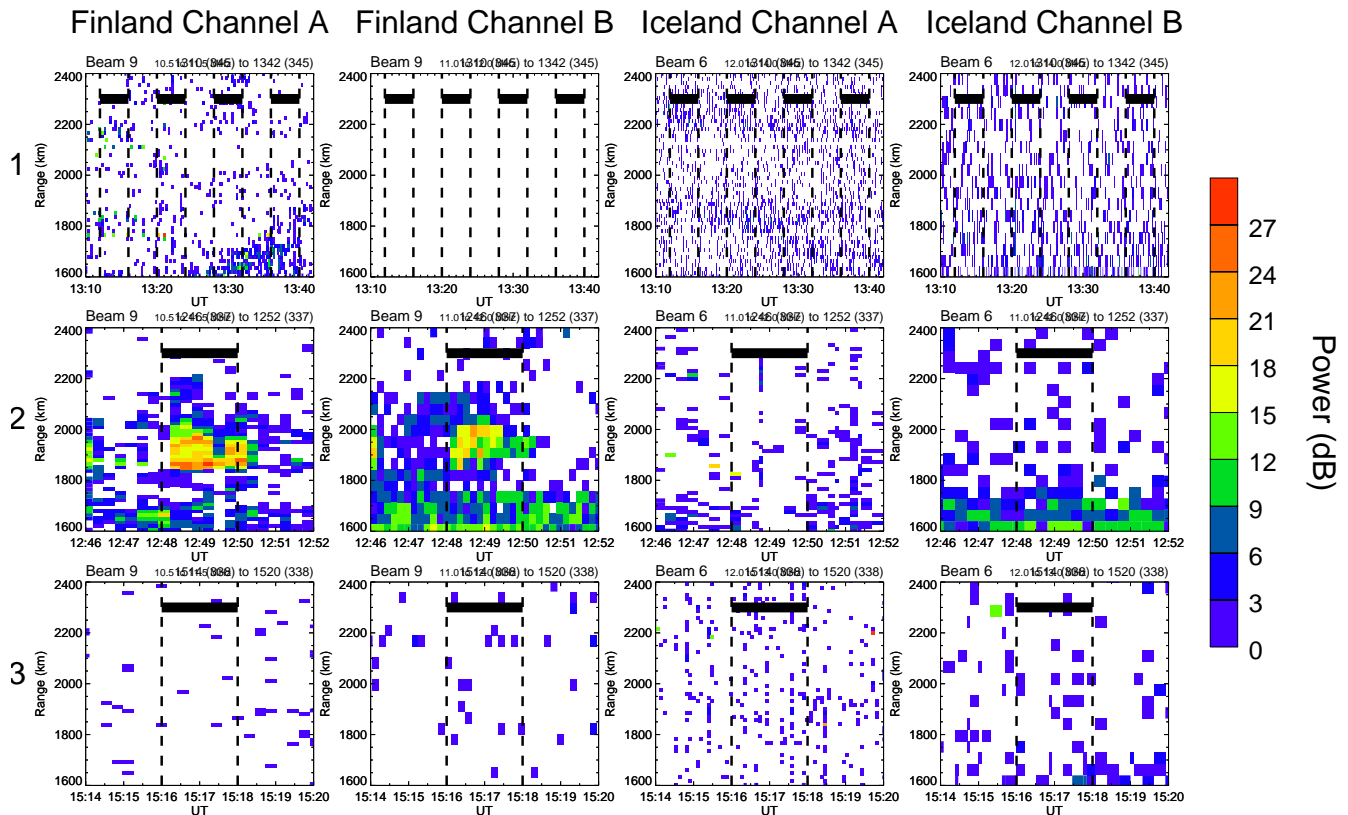


Fig. 2. Range-time-intensity plots of the CUTLASS backscatter power from the Finland (beam 9) and Iceland (beam 6) radars. The data from intervals 1, 2 and 3 are shown in rows 1, 2 and 3, respectively. The columns of panels, from left to right, correspond to data from Finland Channel A, Finland Channel B, Iceland Channel A and Iceland Channel B. Finland channel B data for interval 1 were missing and have not been shown. Definite SPEAR-enhanced CUTLASS backscatter was only observed during 12:48–12:50 UT on 3 December 2005 (within interval 2) by the Finland radar.

the Finland radar. We shall return to these results later in the discussion given in Sect. 4.

We turn now to ESR incoherent scatter radar data, shown in Figs. 3, 4 and 5, which correspond to intervals 1, 2 and 3, respectively. Figures 3, 4 and 5 all contain panels that show time series of ion and plasma line amplitudes. In all such panels horizontal black bars denote the period or periods during which SPEAR was transmitting. Also, the dashed horizontal lines give the mean ion or plasma line amplitude during the particular SPEAR-on or SPEAR-off interval in which they occur. Figure 3 shows ion line data from interval 1 (10 December 2004, 13:10–13:42 UT), during which SPEAR was switched on at 13:12, 13:20, 13:28 and 13:36 UT. Panels (a) and (b) show E-region data. Panel (a) shows averaged spectra from an altitude range of 110–120 km. The solid and dashed lines correspond to SPEAR-on (13:28–13:32 UT) and SPEAR-off (13:32–13:36 UT) intervals, respectively. The single central peak in the spectrum is indicative of collisional plasma and there is a clear increase

in its amplitude during the SPEAR-on period. This is consistent with previous observations of HF-enhanced E-region ion line spectra (e.g. Rietveld et al., 2002). Panel (b) shows the amplitude of the central (0 kHz) ion line (110–120 km) for 13:10–13:42 UT. The SPEAR-induced spectral enhancement is generally present throughout the SPEAR-on periods, with its amplitude, although variable, typically being an order of magnitude larger during SPEAR-on than SPEAR-off. Ionograms taken at around 13:40 UT (not shown), in which the signature of the E-layer is not as pronounced, indicate that the sporadic E-layer has weakened and this is consistent with the lower (SPEAR-induced and natural) ion line amplitudes seen at this time.

Panels (c–f) of Fig. 3 show F-region (160–220 km) ion line enhancements corresponding to the E-region enhancements shown in panels (a) and (b). SPEAR-induced spectral enhancements were found to occur within the altitude range of 160–220 km. Panel (c) shows averaged ion line spectra for SPEAR-on and SPEAR-off. For the case of SPEAR-off,

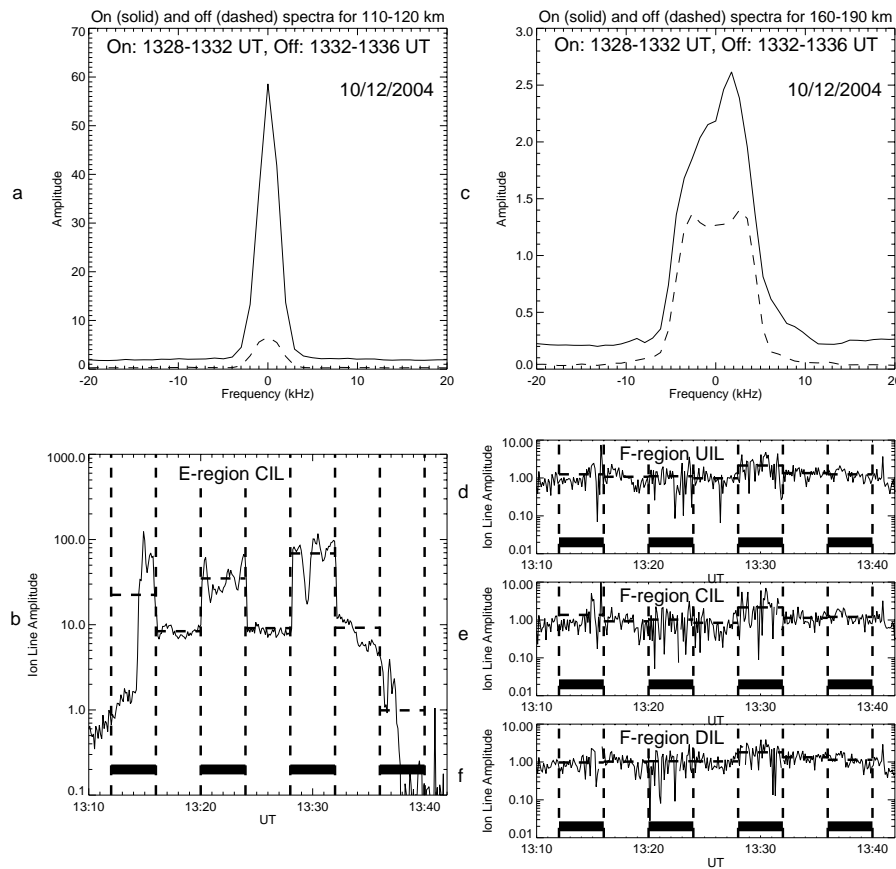


Fig. 3. Ion line spectra and amplitudes from the E- (110–120 km) and F-regions (160–220 km) for 13:10–13:42 UT on 10 December 2004 (interval 1). Panels (a) and (b) show E-region data, with averaged ion line spectra for SPEAR-on and SPEAR-off shown in panel (a) and the central (0 kHz) ion line amplitude shown in panel (b). Panels (c–f) show F-region data with averaged ion line spectra for SPEAR-on and SPEAR-off shown in panel (c), while panels (d–f) show the upshifted (d), central (e) and downshifted (f) ion line amplitudes. The E-region spectral enhancement, characterized by a clear increase in the ion line amplitude for SPEAR-on compared to SPEAR-off, is consistent with excitation of collisional plasma. The spectral enhancements in the F-region are not as distinct as those for the E-region and are consistent with a high proportion of the pump wave energy being deposited in the sporadic E-layer.

denoted by the dashed line, the spectrum has the usual form of an F-region ion line spectrum, with two ion-acoustic peaks whose separation is related to the plasma temperature. The spectrum for SPEAR-on (solid line) has enhancements in the central peak, corresponding to the purely growing mode, and the ion-acoustic peaks, corresponding to the parametric decay instability. The asymmetry of the spectrum contrasts with the high degree of symmetry seen in previous SPEAR-enhanced F-region ion line spectra (R2006), which were obtained when no significant E-region was present. Unsurprisingly, this asymmetry does not have the form of previous asymmetries that have been attributed to the parametric decay instability (Stubbe et al., 1992). We shall return to and further discuss these F-region ion line spectral asymmetries later in this section.

Panels (d–f) show the amplitudes of the upshifted ion line peak (UIL) (d), the central part of the spectrum (CIL) (e), and the downshifted ion line peak (DIL) (f). The ion line data

have been presented in this format because the variability in the amplitudes, and hence the action of the purely growing mode or the parametric decay instability, can be monitored. Clearly, changes in the CIL amplitude generally occur simultaneously with changes in the DIL and UIL amplitudes. The separation of the ion-acoustic peaks during the SPEAR-on periods remains unchanged, which implies no change in the electron temperature during SPEAR-on. Clearly, the E-region CIL amplitude varied appreciably during the SPEAR-on periods, as shown in panel (b), and this is accompanied by considerable variability in the F-region ion line amplitude. There is not a clear demarcation in amplitude between the times when SPEAR was transmitting and those times when it was not, with the possible exception of 13:28–13:32 UT where the amplitude of all three spectral components is increased by approximately a factor of two compared to the amplitude for SPEAR-off.

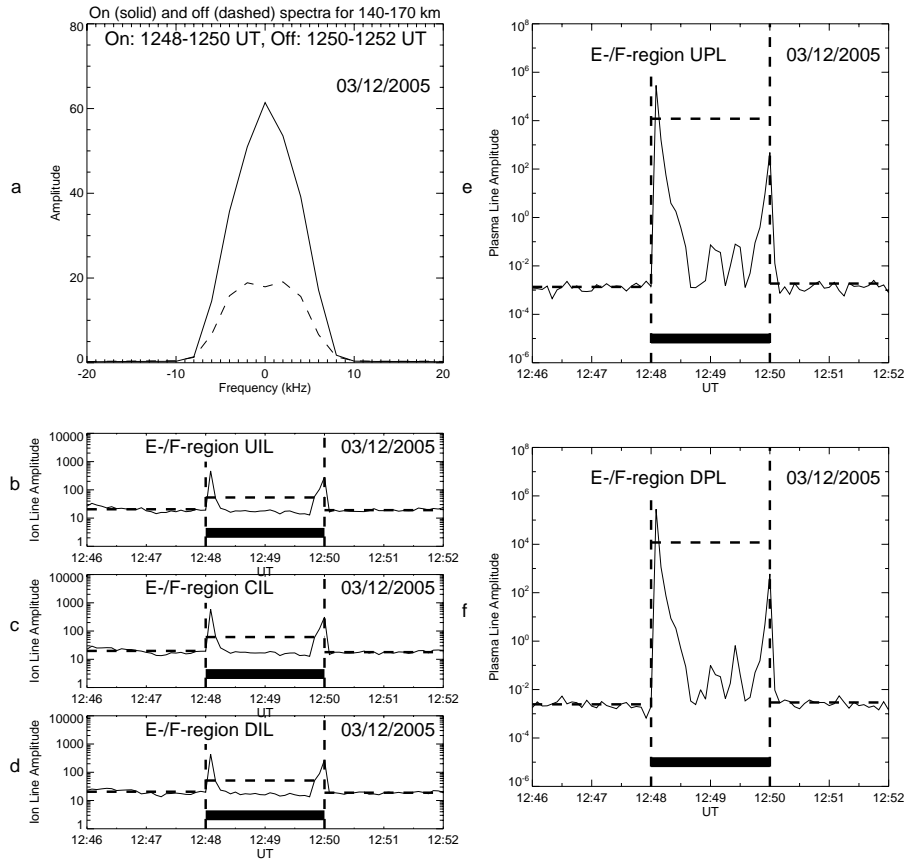


Fig. 4. Ion and plasma line spectra and amplitudes, for the upper E-region, from 3 December 2005. Panels (a–f) show upper E-/lower F-region (140–170 km) spectral data for 12:46–12:52 UT on 3 December 2005 (interval 2). Averaged ion line spectra for SPEAR-on and SPEAR-off are shown in panel (a), while panels (b–d) show upshifted (b), central (c) and downshifted (d) ion line amplitudes. Panels (e) and (f) show upshifted (e) and downshifted (f) plasma line amplitudes. SPEAR was transmitting from 12:48–12:50 UT and well correlated ion and plasma line enhancements are present at the beginning and the end of the SPEAR-on interval. Noticeable enhancements are also present in the plasma line data at approximately 12:49:00 and 12:49:30 UT. However, these enhancements do not have obvious ion line counterparts.

Figure 4 shows ion and plasma line data from interval 2 (3 December 2005, 12:46–12:52 UT). The data originate from an altitude range of 140–170 km, which corresponds to the upper E- and lower F-regions. Panel (a) shows averaged ion line spectra for SPEAR-on (12:48–12:50 UT, given by the solid line) and SPEAR-off (12:50–12:52 UT, given by the dashed line). As above, the SPEAR-off spectrum has the usual form of an F-region ion line spectrum with two ion-acoustic peaks. The enhancements in the central part and ion-acoustic peaks of the SPEAR-on spectrum are consistent with SPEAR-induced instabilities and are similar to the SPEAR-induced F-region enhancements reported in R2006. Panels (b)–(d) show the amplitudes of the UIL (b), the CIL (c), and the DIL (d) for 12:46–12:52 UT, with SPEAR transmitting from 12:48–12:50 UT. As stated above, the ion line data allow us to monitor the action of the purely growing mode and the parametric decay instability. Changes in the CIL amplitude are generally well correlated with changes in the UIL and DIL amplitudes. Also, the amplitudes of all

three spectral components towards the beginning and the end of the SPEAR-on interval are at least an order of magnitude higher than during the rest of the SPEAR-on interval. The amplitude increases at the beginning of the SPEAR-on interval are characteristic of the commonly seen ion line overshoot, which has generally been absent from previous observations of SPEAR-enhanced data (R2006). Increases similar to those at the end of the SPEAR-on interval have been seen previously and will be discussed further in Sect. 4. The ion line amplitudes during the rest of the SPEAR-on interval are comparable to those during the SPEAR-off periods. Panels (e) and (f) show the amplitudes of the upshifted (UPL) (e) and downshifted (DPL) (f) plasma lines (at ± 4.45 MHz) for 12:46–12:52 UT. The SPEAR-induced UPL and DPL enhancements are clearly well correlated, both with each other and with the ion line enhancements. Also, the UPL and DPL amplitude increases at the beginning of the SPEAR-on interval are consistent with the plasma line overshoot. As for ion line data, increases at the end of the SPEAR-on interval

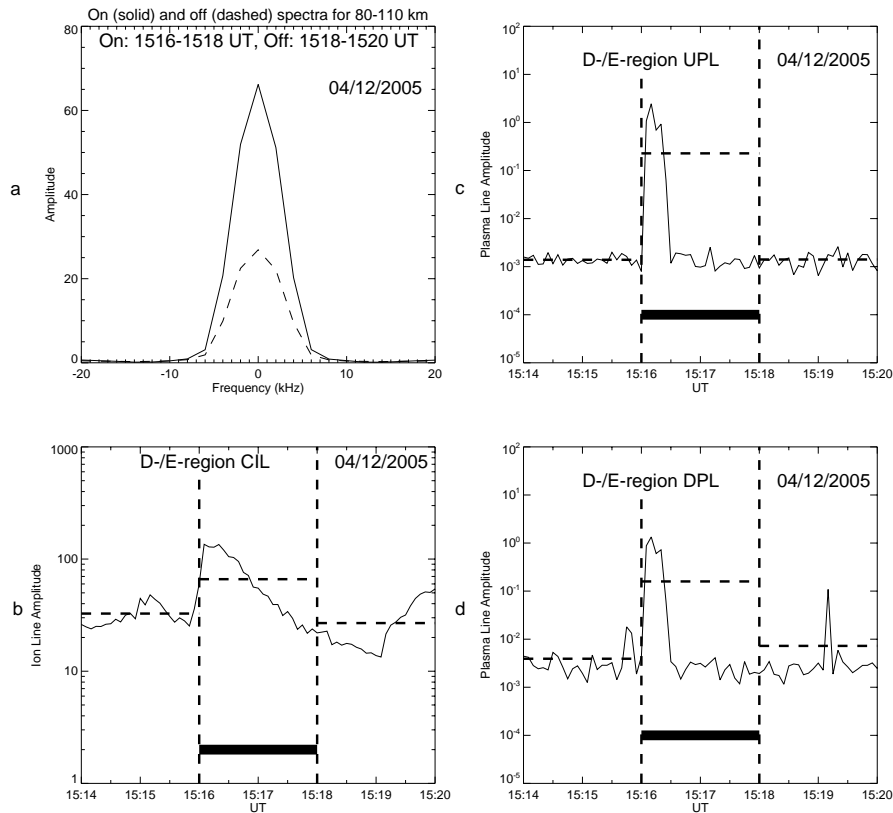


Fig. 5. Ion and plasma line spectra and amplitudes, for the lower E-region, from 4 December 2005. Panels (a–d) show upper D-/lower E-region (80–110 km) spectral data for 15:14–15:20 UT on 4 December 2005 (interval 3). Averaged ion line spectra for SPEAR-on and SPEAR-off are shown in panel (a). Panel (b) shows the central ion line amplitude, while panels (c) and (d) show the upshifted (c) and downshifted (d) plasma line amplitudes. SPEAR was transmitting from 15:16–15:18 UT and there is an increase in the ion and plasma line amplitudes at the beginning of the SPEAR-on interval. As for the E-region data from 10 December 2004, these lower E-region spectral enhancements are consistent with excitation of collisional plasma.

have been seen previously (see Sect. 4). Incidentally, the plasma line enhancements just after 12:48 UT are among the strongest yet seen during all periods that SPEAR has been operating. There are also intermittent plasma line enhancements at around 12:49:00 UT and 12:49:30 UT.

Figure 5 shows ion and plasma line data from interval 3 (4 December 2005, 15:14–15:20 UT). The data originate from an altitude range of 80–110 km, which corresponds to the upper D- and lower E-regions. Panel (a) shows averaged ion line spectra for SPEAR-on (15:16–15:18 UT, given by the solid line) and SPEAR-off (15:18–15:20 UT, given by the dashed line). As for SPEAR-off data from interval 1, there is a single central peak in the ion line spectrum, which identifies collisional plasma. As mentioned above, increases in its amplitude have been observed previously (e.g. Rietveld et al., 2002). Panel (b) shows the CIL amplitude for 15:14–15:20 UT. Clearly, the amplitude is highly variable during the SPEAR-on times, with the spectral enhancement being greatest from about 15:16–15:17 UT. Panels (c) and (d) show the UPL (c) and DPL (d) amplitudes (at ± 4.45 MHz) for

15:14–15:20 UT. The SPEAR-induced UPL and DPL enhancements, which appear at just after switch-on (at 15:16 UT) and last for about 30 s, are clearly well correlated with each other. Unlike previously seen RF-induced signatures of the overshoot, where the spectral enhancement disappears after switch-on of the high-power beam (usually after one data dump), the SPEAR-induced enhancements here (and also incidentally in the apparent overshoot data in interval 2) persist for longer. Also, insufficient plasma line resolution made it impossible to differentiate between the actions of the parametric decay instability and the purely growing mode during SPEAR-on. There are no identifiable SPEAR-induced ion or plasma line enhancements during the rest of the SPEAR-on interval.

We return now to the E- and F-region spectra from interval 1 (13:10–13:42 UT on 10 December 2004). In order to highlight the variability in these spectra, we now concentrate on data taken during the 4-min-on period from 13:28–13:32 UT. E-region data are shown in Fig. 6 and we consider these first. The figure shows ion line spectra taken during

both SPEAR-on and SPEAR-off. Each panel in the figure shows an ion line spectrum with the x-, y- and z-axes showing frequency, altitude and amplitude, respectively. The panels in Fig. 6 are presented in chronological order with the time above each panel corresponding to the end of the particular 6.4 s integration period (with the fractional second being discarded) during which the ion line data were recorded. The black circles above a number of the panels denote complete integration periods during which SPEAR was transmitting. Although the amplitudes of these E-region spectra vary during the 4-min-on period, with a notable reduction present around 13:29:30 UT, the form of the spectral enhancements, characterized by an increase in the central peak amplitude, is a consistent feature of all the SPEAR-on spectra. Figure 7 shows F-region spectra corresponding to the E-region spectra displayed in Fig. 6. Each panel in Fig. 7, as for Fig. 6, shows the frequency, altitude and amplitude plotted using the x-, y- and z-axes. The times of the F-region spectra, shown above the panels, correspond to the times of the E-region spectra. Clearly, these F-region spectra have a considerable degree of variability, with the forms of the SPEAR-enhanced spectra (which are present at altitudes between 160 and 220 km) changing throughout the SPEAR-on interval. Furthermore, the spectra are all generally asymmetric, with the number and positions of identifiable peaks changing over time. Some of these peaks occur in the central part of the ion line spectrum and at the ion-acoustic frequencies and such SPEAR-induced spectral enhancements have been identified with the actions of the purely growing mode and the parametric decay instability, respectively (R2006). Also, an interesting feature is that the most significant F-region spectral enhancements occur concurrently with the highest increases in the E-region spectral amplitude.

4 Discussion

In this study, we have provided ESR observations of the temporal evolution of E- and F-region ion and plasma line spectral enhancements caused by the interaction of the SPEAR high-power pump wave with sporadic E-layers. We have presented evidence of corresponding E- and F-region SPEAR-induced ESR ion line spectral enhancements during the presence of a non-blanketing porous sporadic E-layer. These results constitute the first observations of SPEAR-enhanced E-region ion line spectra and were obtained during the December 2004 experimental campaign. However, no accompanying E-region plasma line enhancements were observed, although the absence of such observations can be explained by recalling that the enhancements occurred at altitudes too low for plasma line data to be collected. However, the lack of F-region plasma line data is more difficult to explain as previous F-region SPEAR-induced ion line enhancements have been accompanied by corresponding plasma line enhancements. Generally simultaneous SPEAR-induced E-region

ion and plasma line spectral enhancements were first seen in ion and plasma line data collected during the December 2005 campaign. Simultaneous E-region ion and plasma line enhancements were seen in data from two intervals, the first of which contained upper E-region enhancements, with the other containing lower E-region enhancements while a sporadic E-layer was present. Upper F-region spectral enhancements were not seen during these two intervals from December 2005. The lower E-region data were obtained when a sporadic E-layer was present and have the same characteristics as those of the E-region data from the December 2004 campaign.

Ion line data from interval 1 (10 December 2004) include E-region amplitude enhancements in the central (0 kHz) spectral component and F-region amplitude enhancements in both the ion-acoustic peaks and the central part of the ion line spectrum. Unlike previous SPEAR-enhanced F-region ion line data where plasma line enhancements were also observed (R2006) no F-region plasma line enhancements were seen in data from interval 1. Also, any enhancements in the E-region plasma line spectrum were not recorded as they would have occurred below the lowest altitude from which plasma line data were collected (150 km). For the well developed porous sporadic E-layers in this interval, the strong E-region enhancements indicate that a high proportion of the transmitted pump wave energy excited instabilities in the E-region. Also, the porous nature of the sporadic E-layer probably led to intermittent excitation of the F-region, thereby causing highly variable F-region ion line amplitudes. For example, the presence of the F-region spectrum for 13:28–13:32 UT (shown in panel (d) of Fig. 2), which in this case happens to be asymmetric (because of variable spectral forms in the 4-min SPEAR-on interval), is consistent with patchy E-region plasma that is in frequent motion during SPEAR-on. The variability of the E- and F-region spectra collected during this 4-min interval may be seen clearly in the data presented in Figs. 6 and 7. As mentioned above, the F-region spectra, shown in Fig. 7, are generally irregular and asymmetric and their form varies from data dump to data dump over the period that SPEAR is transmitting. This is indicative of highly variable density-dependent absorption within and penetration through the sporadic E-layer during the SPEAR-on period. As mentioned in R2006, the variability in the plasma density leads to strong local fluctuations in the electric field strength of the high-power wave. Therefore, the threshold electric fields necessary for instability excitation will only be exceeded intermittently and for short periods during the SPEAR-on interval.

It is clear from Figs. 6 and 7 that the most significant E- and F-region spectral enhancements tend to occur simultaneously. This concurrence of high E- and F-region SPEAR-enhanced spectra is surprising as there is not thought to be a correlation between the presence of sporadic E-layers, for which the density enhancements are localized in altitude, and high densities in the F-region. If the plasma density of the

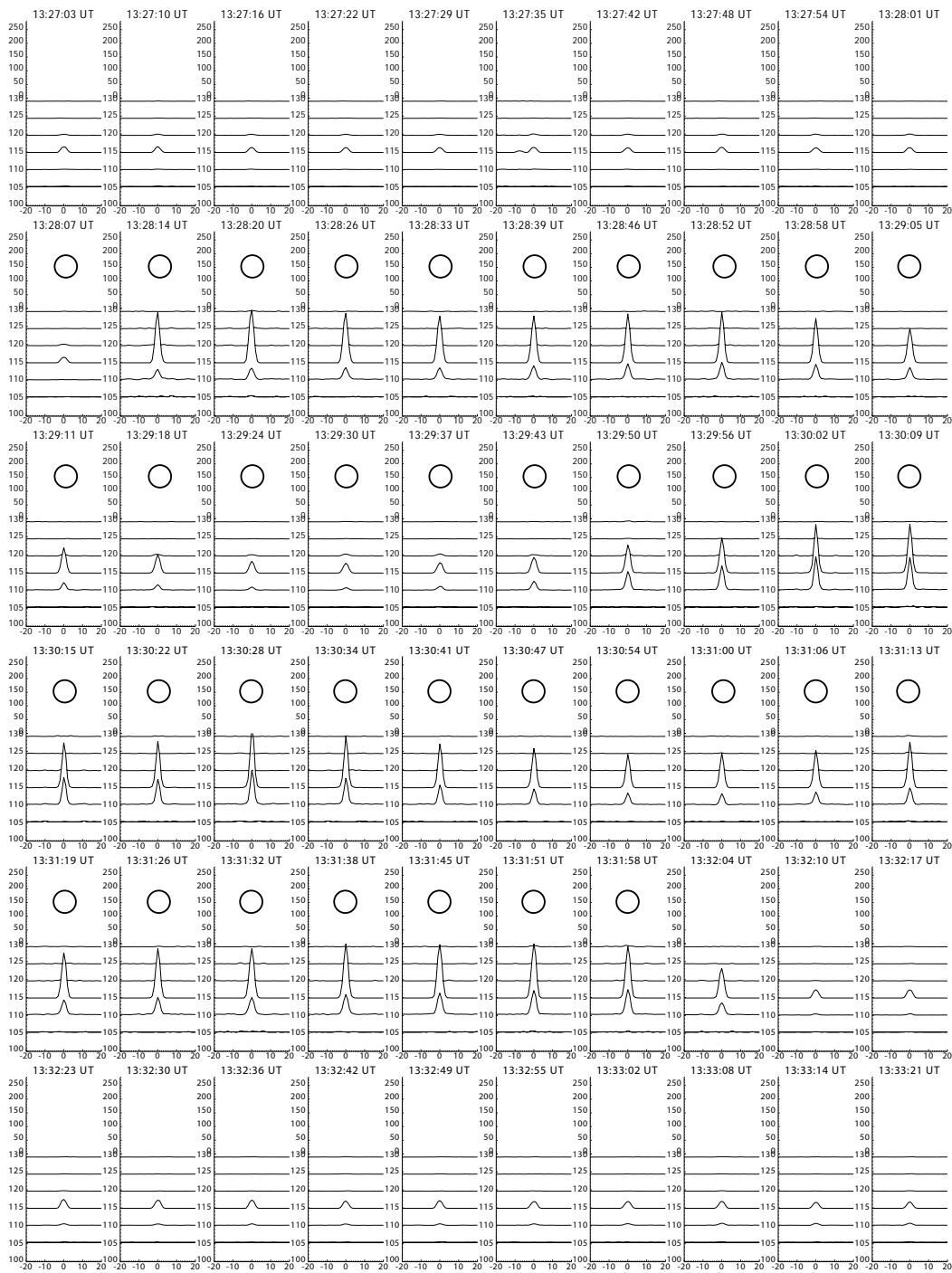


Fig. 6. Successive E-region ion line spectra from approximately 13:27–13:33 UT on 10 December 2004 (within interval 1). Each panel shows an ion line spectrum with the x-, y- and z-axes showing frequency, altitude and amplitude, respectively. The panels are presented in chronological order and cover two time periods during which SPEAR was switched off, separated by the 4-min interval during which SPEAR was switched on (13:28–13:32 UT). The time above each panel corresponds to the end of the particular 6.4-s integration period during which the ion line data were recorded. These times have been shown with the fractional second being discarded. The black circles above a number of the panels denote complete integration periods during which SPEAR was transmitting. Clearly, the amplitudes of these E-region spectra vary during the 4-min-on period, with a notable reduction present around 13:29:30 UT. However, the form of the spectral enhancements is characterized by an increase in the central peak amplitude during SPEAR-on. This is a consistent feature of all the SPEAR-on spectra and may be used to differentiate these spectra from those for SPEAR-off.

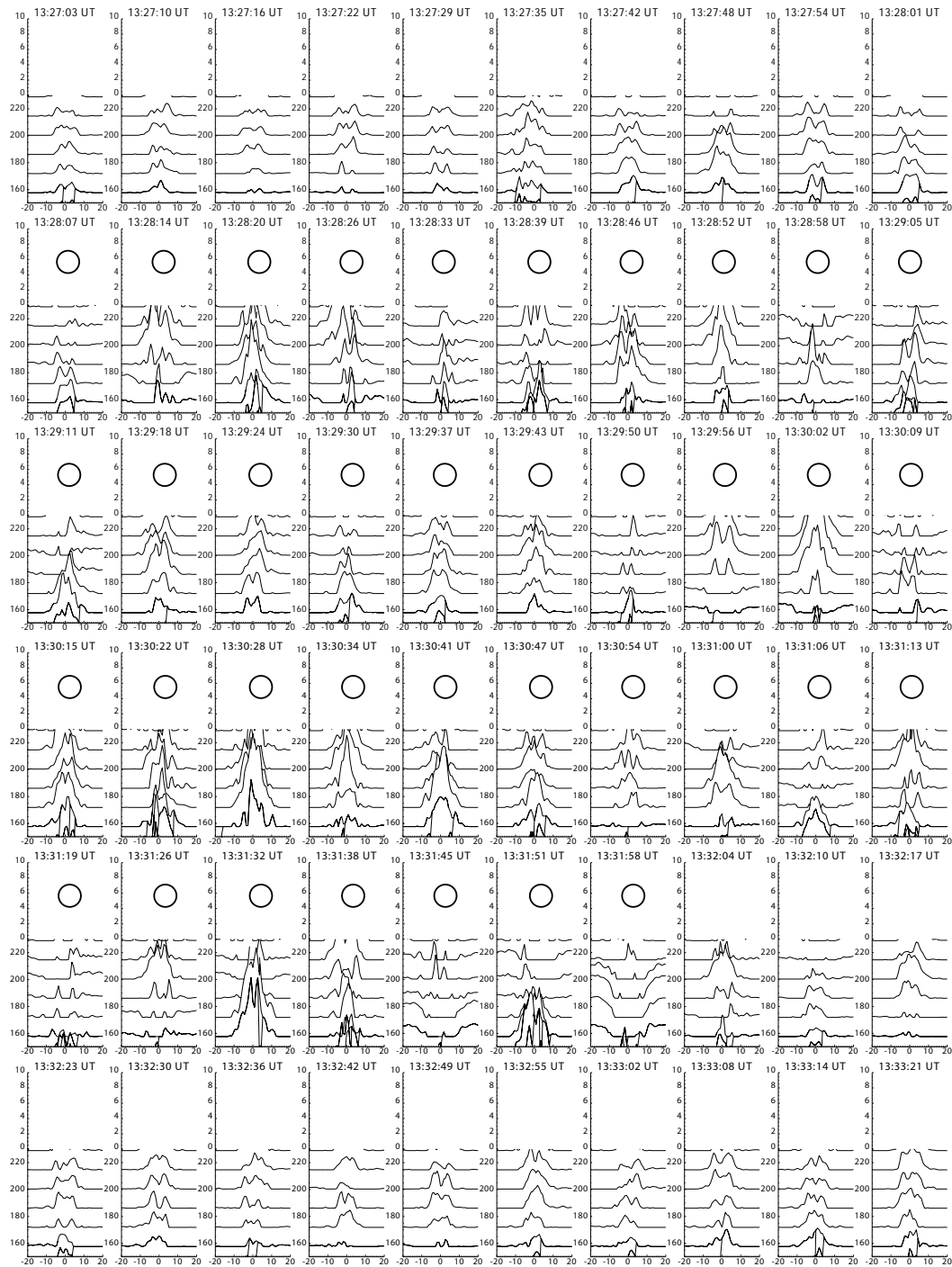


Fig. 7. F-region spectra corresponding to the E-region spectra displayed in Fig. 6, i.e. for approximately 13:27–13:33 UT on 10 December 2004. As for Fig. 6, each panel shows the frequency, altitude and amplitude plotted using the x-, y- and z-axes. The times shown above the panels of F-region spectra correspond exactly to the times of the E-region spectra. Once again, the black circles above a number of the panels label complete integration periods during which SPEAR was switched on. Clearly, these F-region spectra have a considerable degree of variability, with the forms of the SPEAR-enhanced spectra (which are present at altitudes between 160 and 220 km) changing throughout the SPEAR-on interval. Furthermore, the spectra are all generally asymmetric, with the number and positions of identifiable peaks changing over time. Some of these peaks occur in the central part of the ion line spectrum and at the ion-acoustic frequencies. Also, the most significant F-region spectral enhancements occur concurrently with the highest increases in the E-region spectral amplitude.

sporadic E-layer is high, then this implies that the majority of the high-power wave energy ought to be absorbed or reflected in the E-region, with little to progress to the F-region. However, any RF energy that does manage to penetrate the patchy sporadic E-layer is free to propagate to the F-region, where, for sufficiently high F-region plasma density, it can excite the instabilities that enhance the F-region spectra. This hypothesis is consistent with our data as the presence of F-region spectral enhancements indicates that a significant proportion of the RF energy penetrated the sporadic E-region and propagated through to the F-region, in which, presumably, the plasma density was sufficiently high throughout the interval.

The data from interval 2 (3 December 2005) contain upper E-/lower F-region enhancements in the amplitudes of both the central part of the ion line spectrum and of the ion-acoustic peaks, the separation of which is related to the plasma temperature. In F-region collisionless plasma located well away from the collisional E-region, the ion-acoustic peaks in ESR ion line spectra, which are recorded using transmission frequencies of 500 MHz, usually appear at about ± 5 kHz (R2006). However, for these data (upper E-/lower F-region) the peaks are at approximately ± 2 kHz. This reduced peak separation is a consequence of the increasing ion-neutral collision frequency, for decreasing altitude, from the collisionless conditions that obtain in the upper F-region, to the lower E-region collisional regime. The ion line enhancements, which were accompanied by simultaneous enhancements in both the upshifted and downshifted plasma lines, imply that both the parametric decay instability and purely growing mode were operating. This is consistent with previous SPEAR-enhanced F-region data where simultaneous ion and plasma line enhancements were also observed (R2006).

There is evidence of overshoot phenomena in the ion and plasma line data from interval 2 at SPEAR switch-on. Features that could be characterized as overshoots have only been observed occasionally in SPEAR-enhanced data, and this lack of observation has been attributed to the lower power (15 MW) transmitted by SPEAR (R2006). On the other hand, the overshoot is seen frequently in heater-enhanced Tromsø incoherent scatter data, where much higher powers (several hundred MW) are available with the Tromsø heater (Rietveld et al., 1993). In addition to clear amplitude increases at SPEAR switch-on, there are also increases towards the end of the SPEAR-on interval. Although such ion and plasma line amplitude increases have been observed previously in SPEAR-enhanced ESR data (e.g. Fig. 17 in R2006), there have usually been additional amplitude enhancements during the rest of the SPEAR-on interval. However, our observations do not contain significant ion line enhancements during the rest of this SPEAR-on interval, although plasma line enhancements are present. Substantial ion line enhancements only occur at around the time when SPEAR is switched off. While initial inspection of the data suggests that these signatures may provide evidence of en-

hancements associated with SPEAR switch-off, closer examination reveals that these increases appear to be purely coincidental, as they actually occur before and die away at SPEAR-off.

As for the E-region data from interval 1, the upper D-/lower E-region ion line spectra from interval 3 (4 December 2005) have a single central (0 kHz) peak, indicating collisional plasma, rather than a pair of ion-acoustic peaks. The effect of SPEAR was identified by an increase in the amplitude of this central peak and this is consistent with the action of the purely growing mode and/or the parametric decay instability (Rietveld et al., 2002). However, in contrast to the interval 1 data, these ion line enhancements were accompanied by plasma line enhancements (upshifted and downshifted by the SPEAR transmission frequency of 4.45 MHz), which lasted for about 30 s after SPEAR switch-on, and these also indicate excitation of either or both instabilities. Previous SPEAR-induced ion and plasma line enhancements have tended to occur simultaneously (R2006), and this may also be the case here, although there is a degree of variability in the ion line amplitude during the SPEAR-on interval which makes it difficult to associate unambiguously any ion line amplitude increases with the action of SPEAR.

The data from all three intervals are consistent with the SPEAR-affected region of ionosphere being traversed by patches of overdense plasma, giving rise to varying ion and plasma line amplitudes in both the E- and F-regions (R2006). This patchiness results in intermittent blanketing of the F-region, during which the transmitted pump wave interacts with the sporadic E-layer. When the pump wave does not encounter E-region plasma, it is free to propagate to and excite instabilities within the F-region, thereby further increasing the variability of the F-region ion and plasma line signatures. This variability is clear in data from interval 1, which indicate patches present during most SPEAR-on intervals. For interval 2 data, ion and plasma line enhancements indicate that patches were present at the beginning and near the end of the SPEAR-on interval. Such enhancements indicating propagating patches were also present at the beginning of the SPEAR-on period in interval 3, but generally absent during the rest of period.

Our observations, which as stated above were obtained while SPEAR operated with an ERP of approximately 15 MW, are consistent with a negligible SPEAR-induced change in the plasma temperature. As suggested in R2006, this relatively low SPEAR pump power may result in limited heating of the plasma when compared to the temperature enhancements that are routinely seen using the Tromsø heater, which has an ERP of several hundred MW (Rietveld et al., 1993). This variability in the temperature enhancements provides motivation for a study, involving variable heater powers, into the dependence of temperature increases and associated RF-induced spectral enhancements on the transmitted pump wave power. Similar motivation exists to study further the infrequent occurrence of the overshoot in our

observations, again using an experiment with variable heater powers to investigate how the presence and frequency of the overshoot are affected by the heater power.

Turning now to the CUTLASS coherent scatter data shown in Fig. 2, only data from interval 2 (3 December 2005) displayed detectable SPEAR-induced backscatter enhancements observed by CUTLASS, and then only in data recorded by the Finland radar. The SPEAR-enhanced backscatter was present for the entire 2-min SPEAR-on interval in both channels. Combining these observations with the well accepted result that irregularities are generated at altitudes below those at which the O-mode pump wave is reflected, the ESR observations indicate that the artificial irregularities detected by CUTLASS were generated at the upper E-/lower F-region. These altitudes are lower than those from where SPEAR-enhanced CUTLASS backscatter has been seen previously. These observations are unusual as modelled propagation paths obtained using ray tracing indicate that interaction altitudes in excess of 200 km are usually required in order for SPEAR-induced artificial backscatter to be seen in CUTLASS data (Yeoman, private communication, 2007). Since the irregularities are elongated and extend along the field lines, it is instructive to see whether, although the irregularities may be generated in the upper E-/lower F-region, the backscatter from them may originate from higher altitudes. Senior et al. (2004), who followed on from studies undertaken previously (Jones et al. 1984; Robinson et al. 1989), investigated the altitudinal extent of RF-induced artificial field-aligned irregularities and determined that they had e-folding scale lengths of approximately 20 km. Previous studies by Jones et al. (1984) and Robinson (1989) found e-folding scale lengths of 20 and 52 km, respectively. Although the results of Robinson et al. (1989) do not necessarily support our findings, the figure of 20 km, obtained by both Senior et al. (2004) and Jones et al. (1984), provides evidence that the upper E-/lower F-region field-aligned density irregularities do not extend high enough to reach the region from where CUTLASS backscatter is usually observed. This supports the hypothesis that the SPEAR-enhanced backscatter does not originate from those F-region altitudes consistent with ray-tracing studies and from where previous SPEAR-enhanced CUTLASS backscatter has been observed. This result may indicate interesting propagation characteristics and results from future campaigns will be examined in order to study this further. There were no SPEAR-induced CUTLASS backscatter enhancements for the data from intervals 1 (10 December 2004) and 3 (4 December 2005). This is consistent with the ESR enhancements originating within the lower E-region, as CUTLASS backscatter is expected to be absent from such low altitudes because of unfavourable propagation.

The theory of RF-induced enhancements in sporadic E-layers has evolved over time. Both Gordon and Carlson (1976) and Djuth (1984) observed sporadic E-layer plasma line enhancements exactly at the radar frequency \pm the pump

frequency. Djuth (1984) concluded that the modulational instability was probably below threshold during these observations, and therefore direct conversion may play a role in explaining the sporadic E-layer data. Djuth and Gonzales (1988) subsequently examined the temporal development of the RF-enhanced sporadic E-layer plasma line in great detail and concluded that, although direct conversion of the pump wave into Langmuir waves by in situ small-scale irregularities can explain rapid (less than 20 μ s) RF-enhanced plasma line growth, slower (greater than 100 μ s) observed growth times are difficult to explain with this process. Instead, it was proposed that mode conversion along sporadic E-layer vertical gradients near the critical layer provides a better overall description of the observations, and that the formation of density cavities (cavitons) near the reflection height may play an essential role in the production of Langmuir waves. These cavitons (e.g. Morales and Lee, 1977) could give rise to the sporadic E-layer ion line enhancements reported in this paper. These cavitons and the spatial extent of associated density inhomogeneities are consistent with the study by Robinson (2002) who applied a multiple scatter theory to the propagation of electromagnetic test waves during RF-induced heating and found a broadening of the interaction region.

It is noteworthy that the observed plasma line growth times in the range $<4 \mu$ s to 20 μ s are much shorter than those anticipated for a convective parametric decay instability. Newman et al. (1998) suggested that an absolute (i.e., non-convective) parametric decay instability could develop in the sporadic E-layer plasma. This was used to explain the large sporadic E-layer airglow enhancements observed by Djuth et al. (1999) at altitudes of approximately 120 km. Bernhardt et al. (2003) indicated that linear mode conversion may also be important in explaining the sporadic E-layer airglow. Also, Gondarenko et al. (2003) performed simulations that indicate that linear mode conversion in sporadic E-layer plasma above Arecibo gives rise to localized regions containing amplified electric fields. These enhanced electric fields could accelerate electrons and lead to the production of the intense airglow.

Rietveld et al. (2002) presented plasma line/ion line observations in an auroral E-layer having a scale height of 5–10 km. This is significantly different from sporadic E-layer plasma, where the scale height is 0.2–1 km or less (Djuth, 1984). The underlying plasma physics are greatly affected by the vertical scale length. One expects the (propagational or convective) parametric decay instability and the oscillating two-stream instability (modulational instability) to be excited in plasma with a scale height of 5–10 km, but not in sporadic E-layer plasma where the electron density gradients are much steeper. The reason for this is that in a steep sporadic E-layer electron density gradient, the Langmuir wave vector quickly rotates away from the direction of the pump field thereby decoupling from the pump. In addition, the wave rapidly propagates outside of the narrowly confined

altitude region of instability preventing significant Langmuir wave amplification from occurring (e.g. Perkins and Flick, 1971; Fejer and Leer, 1972; Muldrew, 1978). Thus, the thresholds of the oscillating two stream instability and the standard propagational/convective parametric decay instability become extremely large and therefore do not represent viable processes with which to explain the observations. In summary, although the results of Rietveld et al. (2002) certainly complement previous studies, they do not apply to the production of Langmuir waves in sporadic E-layers.

Modelling conducted by Goldman et al. (1995, 1997) was consistent with the findings of Djuth (1984) and Djuth and Gonzalez (1998) regarding the inhibition of the parametric decay instability in sporadic E-layers. In agreement with the findings of Djuth (1984), we have also observed steep vertical gradients in the plasma density of sporadic E-layers, together with plasma density peaks at multiple altitudes. However, our results from the lower F-/upper E-region may be explained by invoking both the purely growing mode and the parametric decay instability. This is consistent with the study by Djuth (1984), who found that, unlike in sporadic E-layers, F-region conditions supported excitation of the parametric decay instability. Our data therefore provide supporting evidence for previous results obtained by Djuth (1984), Djuth and Gonzalez (1988) and Rietveld et al. (2002), and are not inconsistent with previous modelling and observations.

5 Conclusions

In this paper, we have presented SPEAR-induced spectral enhancements in ESR incoherent scatter data from the E- and F-regions of the polar ionosphere. We have seen sporadic E-layer enhancements consistent with the formation of cavitons (e.g. Morales and Lee, 1977) and upper E- and F-region enhancements consistent with the actions of both the purely growing mode and the parametric decay instability. The conditions for excitation of these instabilities in various ionospheric layers, together with other mechanisms for RF-enhanced ion and plasma lines, have been given previously (Djuth, 1984; Djuth and Gonzales, 1988; Rietveld et al., 2002) and our observations agree with earlier findings.

Former observations of RF-enhanced spectra in sporadic E-layers have been made at low, mid and high latitudes, using high-power facilities such as those located at Arecibo and Tromsø. Our observations of SPEAR-enhanced spectra in sporadic E-layers were made in the polar ionosphere and constitute the first such results that have been obtained. In addition to the importance of these results in their own right, our measurements satisfactorily complement low-, mid- and high-latitude studies that have been performed previously.

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