Pc 1 ionospheric electric field oscillations

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ABSTRACT. During an extended ionospheric heating experiment near Tromsø, Norway on 20 September 1985, ELF waves of 1425 Hz were generated in the ionospheric *D*-region and the horizontal wave-field was recorded on the ground with high temporal resolution. A half hour interval near noon shows amplitude and phase oscillations of ~ 3 s period which are associated with a Pc 1 geomagnetic pulsation recorded simultaneously on the ground at several Scandinavian stations. We interpret these data as representing ionospheric electric field pulsations in a region ~ 16 km diameter with amplitudes in the range ~ 4-12 mV/m. The electric pulsation polarization ellipse was found to be predominantly left-hand polarized ranging from circular to linear with rare intervals of right-hand polarization. These observations show the potential of using heating-induced ELF waves for examining ionospheric electric fields from dc upto at least Pc 1 frequencies which cannot be readily measured by other ground-based techniques.

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INTRODUCTION

Geomagnetic pulsations in the Pc 1 frequency range (0.2-5 s period) detected with ground-based magnetometers have been extensively studied (Jacobs, 1970 ; Perraut *et al.*, 1984) in the last 25 years. The naturally occurring structured Pc 1 emissions are generally accepted to originate from hydromagnetic waves of left-hand (or slow) mode in the outer magnetosphere and are generated near the geomagnetic equator through a cyclotron resonant interaction between the hydromagnetic waves and nonthermal protons (Gendrin, 1975 ; Roux *et al.*, 1982). When the left-hand polarized wave packet enters the ionosphere, mode coupling with the right-hand polarized (fast) mode can occur through the Hall current and this wave can propagate isotropically in a horizontal ionospheric duct centred on the *F*2-region and bounded by the Alfvén velocity maximum at 2000-3000 km and the *E*-region. Leakage from this ionospheric duct allows the waves to be observed on the ground far from the ionospheric source. Near the source the wave is expected to be left-hand polarized, but further away right-hand and linear polarization can be expected (Greifinger, 1972). In recent years this picture has become more complicated through extensive theoretical and experimental studies of the effects of multi-component plasmas on the propagation of Pc 1 waves (Rauch and Roux, 1982). When He^+ ions are present in the source region, Perraut *et al.* (1984) showed that higher frequency left-hand waves may have their polarization changed to right-hand as they move along the field line and could, under certain conditions, reach the ground. They were able to reconcile high latitude ground-based observations with geostationary satellite observations of Pc 1 waves.

We present here a novel way of examining the electric field in the lower ionosphere (*D*-region) associated with a Pc 1 geomagnetic pulsation of ~ 3.3 s period seen simultaneously on the ground. The electric field of the pulsation was detected by its effect in modulating the strength and direction of extra low frequency (ELF) waves of 1425 Hz which were being generated in the *D*-region of the ionosphere by ELF amplitude modulated powerful HF waves from the heating facility near Tromsø, Norway. We believe that these observations, representative of the electric field averaged over about a 16 km diameter circle in the *D*-region, are the first detailed observations of such high frequency electric field oscillations using a ground-based technique. Lower frequency oscillations in the Pc 5 range have previously been reported using the same technique (Rietveld *et al.*, 1983, 1987).

Incoherent scatter radars can measure ionospheric electric fields with about 10 s time resolution and have been used to study Pc 3-5 pulsations (Glangeaud *et al.*, 1985). Coherent auroral radars also have not had adequate time resolution although they have the potential to examine short period waves as Keys (1965) showed. His figure 2 shows the intensity of 55 MHz auroral radar backscatter from ~ 110 km altitude ionospheric irregularities ~ 700 km south of

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New Zealand being modulated in patches with a line-of-sight dimension of ~ 28 km with a periodicity of 7-8 s (Pc 2 pulsations). Those observations can be interpreted as the electric field oscillating around the threshold of ~ 25 mV/m required to excite the plasma irregularities which give rise to the backscatter. No radar technique has, however, looked at waves with periods as short as 3 s.

In the next section we describe the method used to obtain our results and the geophysical conditions during the experiment. Accompanying magnetometer observations are then presented and compared with the ELF data. An interpretation of the ELF data is given and the results are then discussed within the context of other measurements and theory.

ELF DATA

The generation of monochromatic ELF waves by ELF/VLF modulated heating of the lower ionosphere has been described by Stubbe *et al.* (1982) and Rietveld *et al.* (1987). Essentially the amplitude modulated powerful HF wave periodically heats the electron gas through Ohmic heating, and thereby modulates the horizontal conductivity tensor through the electron-neutral collision frequency. This conductivity modulation in the presence of an ambient horizontal electric field leads to an oscillating ionospheric current which radiates ELF waves which are received on the ground by two orthogonal (NS and EW) magnetic loop antennas 17 km south of the HF heating transmitter. The signals from each of the two antennas were synchronously detected within a ~ 3 Hz bandwidth centred on the modulation frequency of 1425 Hz in our case. The in-phase and quadrature signals from each antenna were then sampled, averaged and stored on floppy disk at 0.12 s intervals. Subsequent analysis involved calculating the ELF polarization ellipse parameters, a (amplitude) and β (ellipse orientation), from the stored data (see fig. 1).

On 20 September 1985 the Max-Planck-Institut für Aeronomie's HF heating facility at Ramfjordmoen near Tromsø, Norway was operated at 2.759 MHz, x-mode with 270 MW effective radiated power, almost continuously from 0703 to 1611 UT with square wave amplitude modulation at 1425 Hz. The antenna beam was pointed vertically with a half-beam width of 7.5°. The 20th of September was geomagnetically disturbed with $\sum Kp = 32$ and was the fourth most disturbed day of the month. During the heater's operation Kp was 4^- from 06-09 UT, 5^- from 09-12 UT, 3^+ from 12-15 UT and 3 from 15-18 UT. Neither STARE nor EISCAT data were available on this day so no independent estimate of the ambient ionospheric electric field could be made.

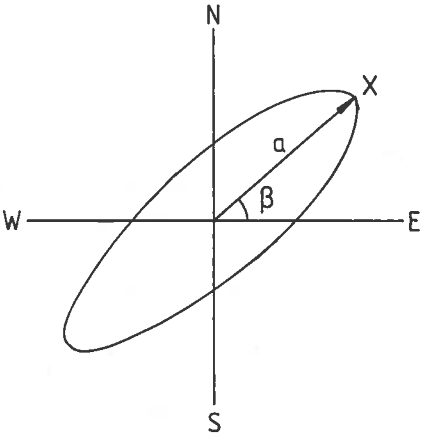

Figure 1
ELF *polarization ellipse parameters calculated from the voltages induced in two orthogonal loop antennas.*

A HF radar provided digital ionogrammes every 15 min. From 0800 until 1245 UT the minimum frequency at which echoes appeared was usually above 3.0 MHz, indicating high ionospheric absorption. At 1130 UT the minimum frequency decreased to 1.8 MHz and at 1330 UT to ~ 1.6 MHz, revealing a poorly defined spread *F*-layer.

Reasonably strong ELF signals at 1425 Hz were received throughout most of the heater's operation, with amplitudes peaking at ~ 1.1 pT between 1055-1100 UT and again at ~ 1353 UT. At other times the amplitude varied sometimes irregularly and sometimes periodically between ~ 0.1 to 1.0 pT. The amplitude fluctuations were often accompanied by changes in the ELF magnetic field ellipse orientation, β, of upto about ± 90° from a mean value of about 145° anticlockwise from east. We shall not discuss the long period fluctuations, other examples of which were analysed by Rietveld *et al.* (1983, 1987), but instead we examine the short period Pc 1 fluctuations which the high time resolution of this data allowed.

Figure 2 shows a half hour interval of unfiltered 1425 Hz ELF data in the form of amplitude, a (ellipse half major axis) in pT and orientation, β, of the major axis (degrees anticlockwise from east) (see fig. 1). This interval showed particularly clear coherent oscillations of about 3.3 s period in both amplitude and direction with a slowly varying envelope. The other, longer timescale variations were also typical of the rest of the 9 h experiment. The maximum amplitude variation of the 3.3 s period pulsations was ~ 0.09 pT p-p at 1241:10 UT. Frequency spectra made during the half hour time interval indicated that the pulsation frequency varied slowly in the range 0.26-0.36 Hz (3.8 s-2.8 s period) but no obvious structure, such as the characteristic rising frequency elements in Pc 1 pearl magnetic pulsations, was discernable in the spectra.

MAGNETOMETER

At the same time a magnetometer from the University of Göttingen was operating about 20 km south-east of the heater site. The horizontal (H and D) and vertical (Z) geomagnetic field fluctuations were recorded digitally at a sample rate of one per second. This sampling rate was chosen to record the longer period Pc 2-5 pulsations and was barely sufficient to record Pc 1 pulsations of ~ 3.3 s period. Nevertheless clear magnetic pulsations of about the same period as the ELF pulsations were recorded with similar amplitudes in all three magnetic components. In figure 3 we show both ELF data (in the same form as fig. 2) and the *H* and *D* components of the magnetometer data for the 3 min interval 1240-1243 UT where the pulsations were strongest. The magnetometer data have been high-pass filtered (3 dB at 0.05 Hz) and a 4-point Lagrangian interpolation applied. The maximum amplitude in the magnetic *H* component reaches about 0.4 nT p-p at ~ 1241 UT at the same time as the maximum in the ELF pulsations (~ 0.09 pT p-p). Soon afterwards a minimum is observed at 1241 : 30 UT in both ELF and the *H* component data. It appears that the same variations are present in both the ELF and magnetometer pulsations.

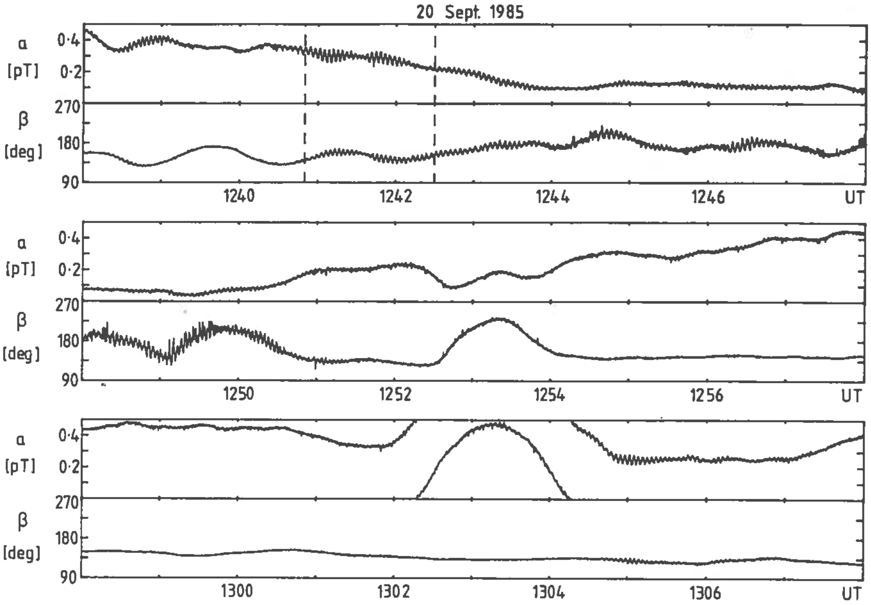

Figure 2
The temporal variation of the amplitude (a) *and orientation* (β) *of the* 1425 Hz ELF *ellipse in figure* 1 *for a half hour interval (without filtering) showing the* 3 s *period oscillations. In the third panel the amplitude between* 1302 *and* 1304 UT *represents* 0.5 *to* 1.0 pT.

To examine these variations in more detail, the interval between the dashed lines in figure 3 is presented in the form of hodograms in figure 4. The upper block in figure 4 shows, for successive 10 s intervals, the horizontal variations of the ELF polarization ellipse between 0.1 and 0.5 Hz. Figure 5 illustrates how the ELF pulsation ellipses are obtained from the oscillations in *a* and *β* for three different examples labelled *a*, *b* and *c* in figures 3, 4 and 5. One can clearly see how the 3.3 s ELF pulsation varies from almost linear polarization at the beginning and end of this interval to almost circular polarization near the middle. The sense of rotation is always left-handed (looking along the magnetic field or downwards).

The lower block in figure 4 shows the horizontal magnetic pulsation ellipse derived from the *H* and *D* components in figure 3. It is clear that the 4-point Lagrangian interpolation between the 1 s samples does not reproduce the original data fully. Nevertheless what is clearly shown is the exclusively left-handed polarization of the magnetic pulsations, and to some extent amplitude changes that coincide with the ELF pulsation amplitude changes. The variation from linear to circular polarization is also observable although not so convincingly in the magnetometer data.

The major axes of the magnetic pulsation ellipses, in as far as they can be determined from the data, appear to be aligned about 70° to 90° anticlockwise from those of the ELF pulsation ellipses. This is best seen in the first and last ellipses in the first row of each block. Such a large angle between ELF and magnetometer pulsation ellipses was previously observed during a daytime Pc 5 event reported by Rietveld *et al.* (1987) and will be further discussed below. Hodograms of the ELF pulsations made for the complete half hour interval in figure 2 showed the polarization of the ~ 3 s period pulsation to be nearly linear at ~ 1239, 1246 : 40, and 1250 : 20 UT. For the rest of the time when the pulsations were strong the polarization was left-hand elliptical and even approached left-hand circular at 1305 UT. For only a few oscillations at 1246 : 10-1246 : 40 and 1306 : 10 UT was the ellipse right-hand polarized and highly elliptical but with low amplitude. In general one can say that the electric field pulsations varied from linear to left-hand elliptical polarization and approached circular polarization when the amplitudes were largest such as at 1241 : 50 and 1305 : 00 UT.

The Pc 1 event is strong and was also detected by a Finnish chain of four induction magnetometers extending from 69.8° N ($L = 6.0$) to 60.5° N ($L = 3.3$) at about 26° E. Sonograms (frequency-time displays with power density as degree of greyness) of *H* and *D* components from the four stations are displayed in figure 6. A fairly constant frequency pulsation of ~ 0.3 Hz is seen at all stations in both components up to 1300 UT, after which there is a gradual increase and broadening in frequency as well as an increase in

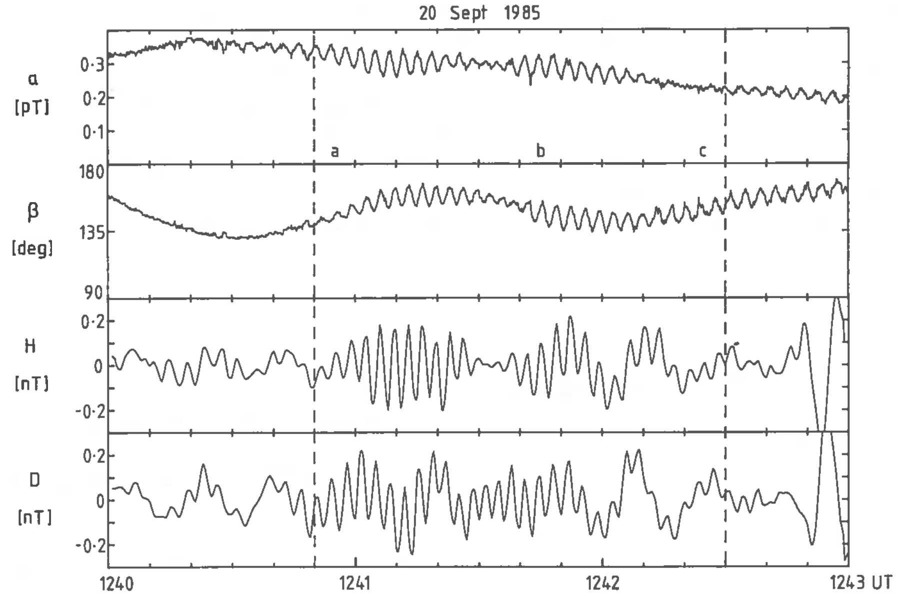

Figure 3
ELF ellipse parameters (top two panels) for a selected interval shown together with the H and D magnetometer components (bottom two panels) which were high-pass filtered with a corner frequency of 0.05 Hz. *The same periodicity and similar amplitude variation between* ELF *pulsations and especially the H component magnetic pulsations are evident.*

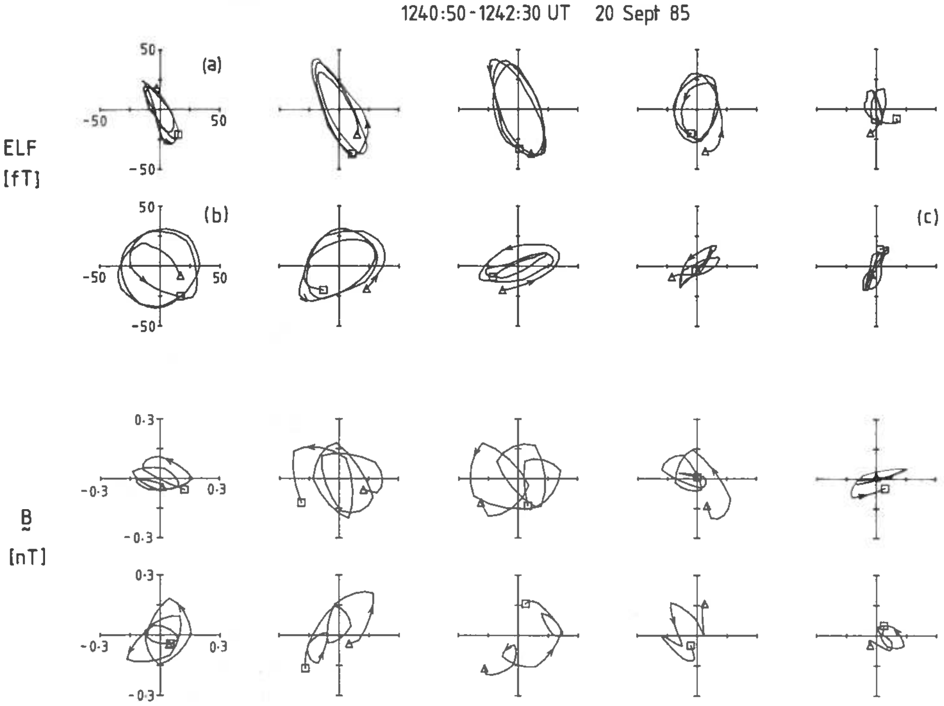

Figure 4
Hodograms of the ELF *ellipse variations (upper two rows) or the trace of point X in figure* 1 *for successive* 10 s *intervals between the dashed lines in figures* 2 *and* 3. *The first and last points are marked with a triangle and square respectively. The hodograms were constructed by filtering* a *and* β *between* 0.1 *and* 0.5 Hz. *The bottom two rows show the corresponding magnetic hodograms with a* 4-*point Lagrangian interpolation. Note the left-hand polarization in both data sets.*

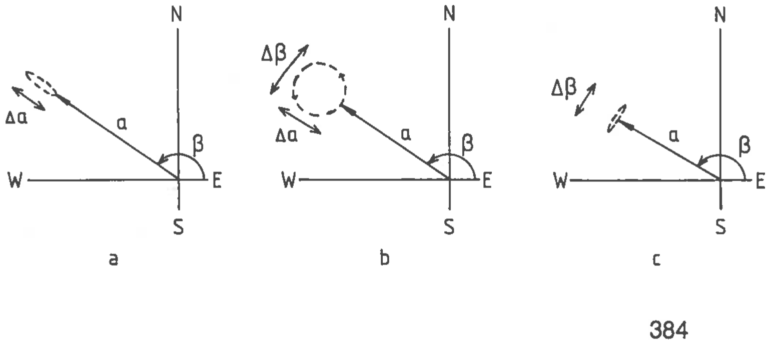

Figure 5
Schematic illustration showing how the three ELF *pulsation hodograms labelled a, b, and c in figure* 4 *are obtained from the amplitude,* a, *and orientation,* β, *pulsations in figure* 3 : *pulsations largely in amplitude* (a) *giving almost linear polarization, pulsations in both amplitude and direction* (b) *resulting in nearly circular polarization, and pulsations in direction only* (c) *resulting in linear polarization.*

amplitude. The data in figure 6 do not allow us to deduce absolute amplitudes or polarization but it is clear that the maximum pulsation amplitudes observed near Tromsø, (1240-1251 UT) both ELF and magnetometer, do not coincide with the maximum amplitudes in the Finnish data.

INTERPRETATION OF ELF DATA

The ELF primary source current, $\Delta \mathbf{j}$, in the ionosphere is given by

$$\Delta \mathbf{j} = \left(\frac{\partial \underline{\sigma}}{\partial T_e} \cdot \Delta T_e \right) \mathbf{E}_0 \qquad (1)$$

where T_e is the electron temperature, $\underline{\sigma}$ the horizontal conductivity tensor and $\mathbf{E}_0$ the driving electric field. This equation neglects electron density modulation by the heater wave which is too slow to affect the conductivity at 1425 Hz.

We have assumed that the variations in the ELF polarization ellipse can be interpreted as variations in the pulsation electric field which, superimposed on a larger background field, drives the currents radiating the waves. This assumption implies that the measured wavefield is directly related to $\Delta \mathbf{j}$ and that the term in brackets in the above equation remains constant which is probably correct on the timescale of at least a Pc 1 wave period of ~ 3 s. We discuss this assumption further at the end of this section. The term in brackets is determined essentially by the electron density and collision frequency profiles. We have developed a model which, for given electron density and neutral density and temperature profiles, calculates the ELF wave amplitudes and phases on the ground 17 km away from the heater for a given ELF modulation frequency and background electric field. The model, described in Rietveld *et al.* (1987), takes into account the localized extent of the ionospheric antenna and multiple reflections of the ELF waves between earth and ionosphere and was able to explain the amplitudes

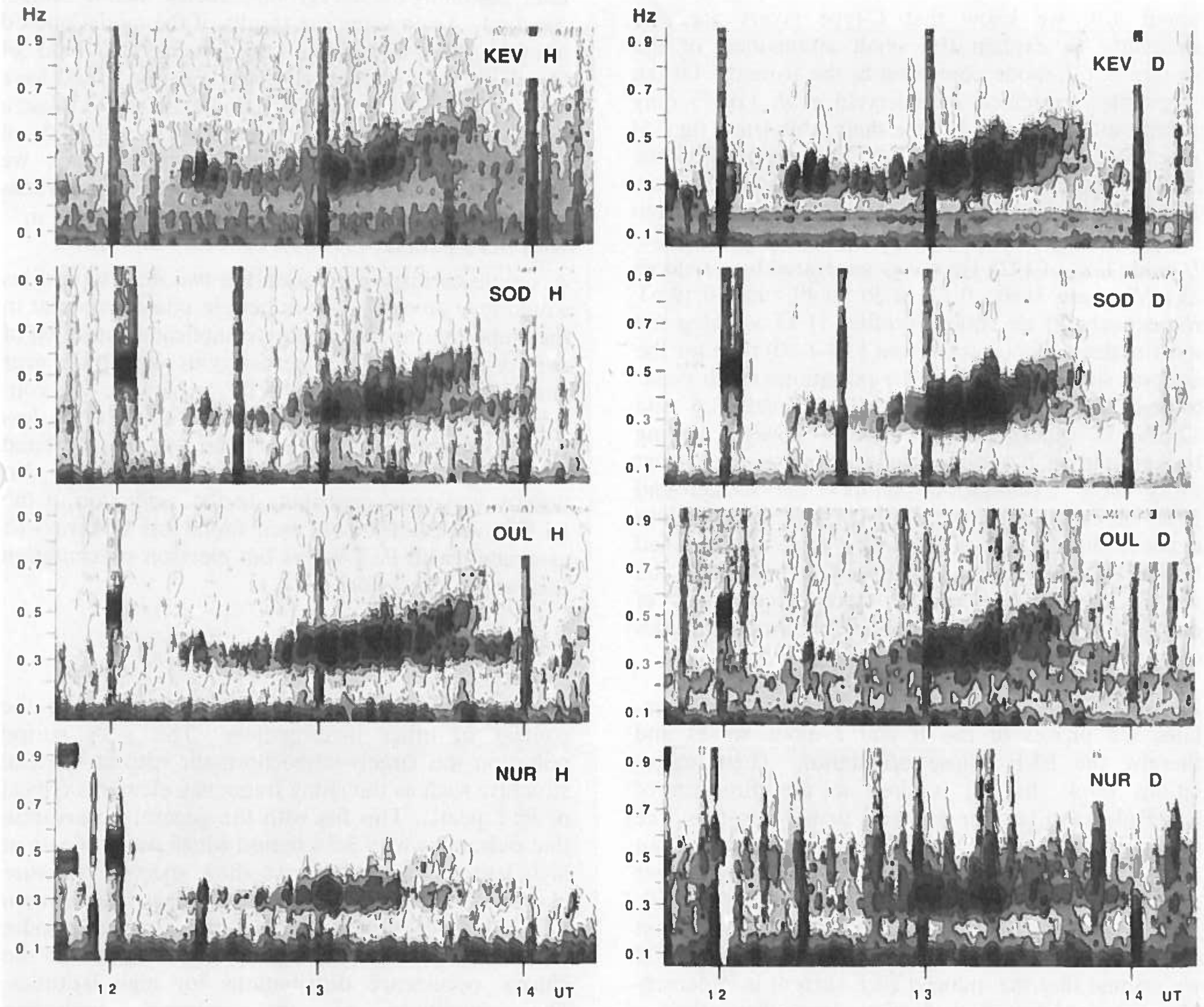

Figure 6
Sonograms of magnetic H and D components of the Pc 1 *event recorded by four Finnish induction magnetometer stations : Kevo* (69.8° N, 27.0° E), *Sodankylä* (67.4° N, 26.6° E), *Oulu* (65.1° N, 25.5° E) *and Nurmijärvi* (60.5° N, 24.7° E).

received on the ground quantitatively quite well. In order to estimate the amplitude of the Pc 1 electric field oscillations, an independent measurement of the background average electric field above the heated ionosphere by the EISCAT incoherent scatter radar or alternatively by the STARE coherent radar would have been ideal to calibrate the ELF amplitude measurements. In the absence of such data, however, we must rely on the model calculations. For this we need the ionospheric electron density profile mainly in the *D*- and *E*-regions, which also was not measured. We must therefore use a likely profile based on previous experience. The measurements were made with a sunlit ionosphere under disturbed auroral conditions. Absorption was high as shown by the ionosonde data. In a previous study by Rietveld *et al.* (1987) under similar geophysical conditions and heating parameters, high electron densities at low altitude were found necessary to explain the ELF data. A so-called *C*-layer was needed to explain the low apparent source heights of ~ 55 km during the day, deduced from multifrequency ELF phase measurements. Our data, from one ELF frequency, do not allow a source height to be estimated. From the ratio of the *R*-mode to *L*-mode ELF amplitude, (not shown) which was about 1.0, we know that *C*-type layers are also necessary to explain the small attenuation of the evanescent *L*-mode compared to the *R*-mode. Of the 14 profiles examined by Rietveld *et al.* (1987) only profiles 6, 11, 12, 13, 14 (see their table 1 and fig. 14) give R/L ratios near 1. For these 5 profiles the R/L ratios are 1.20, 1.07, 1.08, 1.10 and 1.04 respectively whereas for the other profiles they range from 1.35 to 1.79. The total amplitude (*R*-mode + *L*-mode), *a*, of 1425 Hz waves generated by a field of 25 mV/m are 0.66, 0.22, 0.30, 0.49, and 0.19 pT respectively. If we choose profiles 11-14 as being the most realistic (R/L ratios from 1.04-1.10) then for the interval shown in figure 3 the pulsations reach peak-to-peak amplitudes at 1241 UT between 4.6 and 12 mV/m superimposed on a slowly varying background of between 15 and 40 mV/m. Note that using these « calibration factors » the background field increases briefly at 1303 UT (fig. 2) to values between 50 and 130 mV/m which were also reached but rarely and only barely exceeded throughout the rest of the 9 h experiment. Such large values of electric field are not unreasonable for auroral latitudes during disturbed conditions.

Besides calculating amplitudes, our model also calculates the phases of the *R* and *L*-mode waves and thereby the ELF ellipse orientation. These calculations show that $\Delta \mathbf{j}$ is close to the direction of $\mathbf{E}_0$ (Pedersen-like) for electron density profiles like the *C*-layers used above, and is nearer (within about 30°) perpendicular to $\mathbf{E}_0$ (Hall-like) for the higher nighttime profiles (see fig. 20 of Rietveld *et al.*, 1987). The data presented in that paper verify the trend but do not agree very well with the absolute directions. If we assume that the induced ELF current is Pedersen-like for our disturbed daytime ionosphere then a largely N-S oriented oscillation of the ELF magnetic polarization ellipse, such as the first ellipse in the upper part of figure 4, is caused by a largely E-W oriented in $\Delta \mathbf{j}$ and $\mathbf{E}_0$. This same E-W oscillation in $\mathbf{E}_0$ causes a largely E-W magnetic perturbation on the ground through the Hall current in the *E*-region, thus explaining the mainly E-W oriented first magnetic field hodogram in the lower part of figure 4. In the absence of better quality magnetic data or other independent data we shall not try to deduce the absolute orientation of the pulsation electric field any more accurately although relative changes are probably well given.

The assumption that our ELF pulsations were caused purely by the electric field need not be correct. The term in brackets in equation 1 is determined mainly by the electron density profile near the height of ELF wave generation (60-80 km). One could imagine that electron precipitation pulsations which may be associated with Pc 1 pulsations could modulate the term in brackets through the conductivity. Although precipitation pulsations of ~ 3 s period do occur the electron recombination time constant in the lower *D*-region is probably longer so that a significant modulation of the density with this period seems unlikely. Nevertheless we can estimate what density changes would be required to explain the pulsations in our data, assuming the background electric field to remain constant. Again using the results of the model quoted above, and assuming a constant electric field of 25 mV/m, we find that the density profile would have to oscillate between profiles number 12 and 14 to get a peak to peak oscillation in the 1425 Hz amplitude of 0.11 pT which is about the largest amplitude we observed. This means that the density at 55 km would have to oscillate between ~ 1×10^9 and ~ 4×10^9 m^{-3} with 3.3 s period.

A simple oscillation between the two density profiles would give an oscillation in beta in phase with that in the amplitude, so that a more complicated variation of density profile would be necessary to explain the near circular polarization of the ELF pulsations. We consider such a complicated density variation to be less likely than the electric field interpretation outlined here, although we cannot rule out the possibility that density variations contribute to the oscillation of the ELF wave. Electric field oscillations should always be associated with Pc 1 waves but electron precipitation oscillations need not.

DISCUSSION

We shall now try to put our observations in the context of other investigations. The ~ 3 s period pulsation was largely monochromatic with no spectral structure such as the rising frequency elements typical of Pc 1 pearls. This fits with the general observation that pulsations with 3-8 s period which predominate at high latitudes do not always show spectral structure (Jacobs, 1970). The occurrence near local noon (LT = UT + 1 h) also fits with the broad maximum around midday and in the afternoon found in the diurnal occurrence distributions for high latitudes. The amplitude of the magnetic pulsation (~ 0.4 nT p-p) is not unusually large for Pc 1 pulsations. The sense of polarization of Pc 1 pulsations at high latitudes has been found to include both right and left-handed senses in about equal ratios even though it was originally thought that only the left-hand mode propagates through the magnetosphere (Fraser, 1975 and references therein). Theoretical investigations of the incidence of spatially localized sources of left-hand mode Alfvén waves on the ionosphere by Greifinger (1972) showed that at small lateral distances within the source extent the ground signal has dominantly left-handed polarization but is reversed to right-handed outside the lateral extent. At large distances from the source the signal is ionospherically ducted and the polarization is linear. Our observation of mainly left-hand polarized waves with occasional occurrences of linear and right-hand polarized waves can thus be interpreted as a localized source region of the Pc 1 waves moving around but being generally close to Tromsø. Some of the differences in the times of occurrence of maximum amplitudes between the Tromsø and Finnish magnetometer data may also be explainable by a moving source region. A general eastward drift of the source region seems to be necessary to explain the increasing amplitude at later times at the more eastward stations. A separate study of the absolute amplitudes and polarization of the pulsations detected by the Finnish chain is necessary, however, to determine more about the extent and location of the source region. The spatial extent of such Pc 1 source regions has been estimated as less than ~ 300 km in radius by Hayashi *et al.* (1981) from an array of 13 magnetometer stations.

One advantage of our electric field polarization measurements over ground magnetic field polarization measurements is that our results are independent of ground conductivity effects whereas magnetic measurements, especially in the Pc 1 frequency range may be affected by conductivity inhomogeneities from 1-10 km in depth. In other respects, however, our measurements do not discriminate between the field from the source region and that from ionospherically ducted waves since we are looking at the very bottom of the ionosphere. Another advantage of our technique over the ground magnetometer is that our measurements reflect the changes in electric field only in the heated region which is determined by the heating antenna pattern which has a 7.5° half-angle to the 3 dB point in our case. This defines a disk of 16 km diameter at 60 km altitude whereas a magnetometer has signal contributions from a much larger region which could lead to increased noise or perhaps phase mixing and interference. Comparisons of these ELF pulsations with better data from a magnetometer designed to record high frequency pulsations need to be made to see what differences and advantages may exist in such ELF pulsation data. It is also clear that our method of detecting such electric field pulsations works best when a large quasi-static background field exists to raise the background ELF signal level well above the noise which is determined mainly by atmospherics normally and occasionally by magnetospheric hiss or chorus. At much lower latitudes, away from the auroral region, Pc 1 pulsations of similar or weaker amplitudes are also observed. In fact the preferred region of generation seems to be near the plasmapause. If there were no significant background dc electric field present to enhance the ELF signal level, a narrower bandwidth would be necessary to detect the pulsating signal, but not so narrow that the seconds-scale time variations would become unresolved.

The limitations in our method of deducing the pulsation electric field quantitatively include the need for an ionospheric electron density and temperature profile to calibrate the measured ELF field strength in terms of ionospheric electric field.

CONCLUSIONS

We have presented measurements of ionospheric electric field oscillations of ~ 3 s period associated with a Pc 1 geomagnetic pulsation near Tromsø, Norway. The pulsation was also detected by magnetometers over a large part of Scandinavia. The technique involves high time resolution measurements of the 1425 Hz ELF wave field on the ground generated in the lower ionosphere by an amplitude modulated ionospheric RF heating experiment. An ionospheric model was used to estimate a maximum peak-to-peak electric field oscillation in the range ~ 4-12 mV/m.

The temporal variation of the Pc 1 electric field polarization ellipse over a half-hour period could be deduced, showing polarization ranging from right-handed elliptical to left-handed circular with left-handed polarization being dominant. Independent ground magnetometer observations confirmed the sense of polarization and temporal variation but were not good enough for a detailed comparison. These observations show that heating-induced ELF waves may be used to study electric field variations in a localized region of the ionosphere from dc upto at least Pc 1 (0.3 Hz) frequencies. Further simultaneous comparisons with other ionospheric techniques would be useful.

Acknowledgements

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