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Observations of the spatial structure of electron precipitation pulsations using an imaging riometer

A. Senior and F. Honary

Department of Communication Systems, Lancaster University, Lancaster, LA1 4YR, UK

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Abstract. Electron precipitation can be modulated by geomagnetic pulsation activity. This can be observed as pulsation of cosmic noise absorption as measured by riometers. Observations of such pulsations exhibiting field-line resonance and particle-driven characteristics using an imaging riometer are presented and the capability of the instrument to map their spatial structure is demonstrated. It is shown that for the events studied, the spatial variation of pulsation phase as measured by the riometer agrees with that inferred from ground-based magnetometers, whereas the spatial variation of pulsation amplitude may show a different structure. It is suggested that this is consistent with the mechanism proposed by Coroniti and Kennel (1970) where one would expect a fixed phase relationship between magnetic and absorption pulsations, but where the amplitude of the absorption pulsation can depend on several factors other than the amplitude of the magnetic pulsation.

Key words. Ionosphere (ionosphere–magnetosphere interactions; particle precipitation) – Magnetospheric physics (MHD waves and instabilities)

1 Introduction

Geomagnetic pulsations have been studied extensively through the use of ground-based magnetometer data and satellite data (e.g. Campbell, 1973; McPherron et al., 1972). Ground-based magnetometers have a wide field-of-view, the diameter of which is often taken to be equal to the height of the ionospheric E-layer, that is, around 120 km, but their observations are constrained by the "screening" effect of the ionosphere which serves to modify the structure of the wave field from that actually present in the magnetosphere (Hughes and Southwood, 1976). One consequence of this is that waves with small spatial scale sizes can have ground amplitudes greatly reduced from their magnetospheric values, approximately in proportion to the factor $\exp(-k)$, where k is the horizontal wave number. Satellites, on the other hand, are able to make in situ observations of the magnetospheric wave field, but are limited by their orbits to observing one part of the magnetosphere for a short period.

As observed on the ground, the spatial structure of magnetospheric ultra-low frequency (ULF) waves may be described in terms of their amplitude and phase variations with latitude and longitude. These variations have different characters for different types of wave activity. Orr (1984) describes the variation of amplitude and phase exhibited by field-line resonance events — forced oscillations of the magnetosphere. In a field-line resonance, the amplitude distribution is peaked at a particular latitude, corresponding to field lines whose natural frequencies are the same as that of the forcing wave. At the same time, the phase shows a 180° shift with latitude, centred on the resonant latitude. Generally, the phase equatorwards of the resonant latitude leads that poleward of it, but it is possible for the reverse to be the case when the resonance occurs near the plasmapause. Other types of waves exhibit significant phase variations with longitude (azimuthal phase variations). These waves may be excited by drift- or drift-bounce resonant interactions with particles (Southwood et al., 1969). A parameter of significance for these waves is their azimuthal wave number, m, defined as the number of complete wavelengths in one azimuthal circuit of the Earth or equivalently, the number of degrees phase change per degree of longitude.

There have been a number of observations using wide-beam riometers and balloon-borne X-ray detectors of electron precipitation pulsations associated with magnetospheric ULF wave activity with the same periodicity (Ziauddin, 1960; Anger et al., 1963; Heacock and Hunsucker, 1977; Olson et al., 1980; Higuchi et al., 1988). One interpretation of these observations is that the electron precipitation is in some way modulated by the ULF wave. If this is the case, then there exists the possibility of using the spatial structure of this precipitation as a proxy for the spatial structure of the wave. The large-scale spatial structure of these events has been studied previously, for example, by Barcus and Rosenberg

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Correspondence to: A. Senior (a.senior@lancaster.ac.uk)

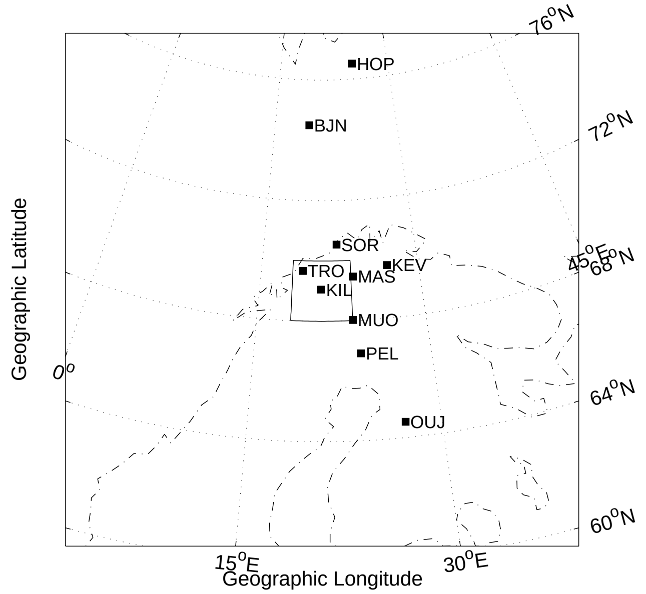

Fig. 1. The locations of the instruments used in this study. IMAGE magnetometers are indicated by the squares. The box centred on station KIL represents the IRIS field-of-view as used for the images in this paper.

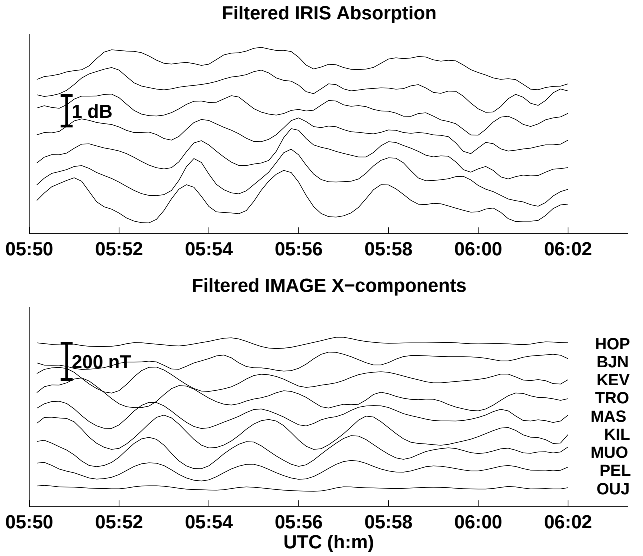

Fig. 2. Time series of Event 1 seen in absorption and magnetic X-components. North is at the top of each plot.

(1965). They used balloon observations of bremsstrahlung X-rays and cosmic noise absorption from wide-beam riometers to investigate the electron precipitation. They observed that the precipitation activity occurred in belt-like regions over 1000 km long and 100–400 km across. Kikuchi et al. (1988) made use of a scanning narrow-beam riometer to investigate the spatial structure in one dimension with a high resolution. This led to the discovery of a type of absorption pulsation having a high m-number and eastward propagation. The development of the imaging riometer (Detrick and Rosenberg, 1990) has made possible the observation of a two-dimensional small-scale spatial structure of electron precipitation pulsations. Imaging riometer observations of precipitation pulsations have been reported by Rosenberg et al. (1991) and Weatherwax et al. (1997). This paper demonstrates a new technique for analysing the data based on mapping the amplitude and phase variations of the pulsation and compares the results to theory.

2 Instrumentation

The Imaging Riometer for Ionospheric Studies (IRIS) at Kilpisjärvi, Finland (69.05° N, 20.79° E, $L = 5.95$) (Browne et al., 1995) provides continuous measurements of the ionospheric absorption of cosmic noise at 38.2 MHz. Riometric absorption is generally attributed to precipitation of energetic electrons which cause enhanced ionisation in the D-region of the ionosphere where the electron-neutral collision frequency is large. The riometer uses an 8×8 phased array of crossed-dipole antennas to produce a 7×7 array of beams. When mapped onto the ionosphere at a fixed height, this beam projection gives 49 point measurements of the absorption. For the data presented in this paper, the usual mapping height of 90 km has been used, giving a field-of-view of approximately 200×200 km with a spatial resolution of 20–40 km. The antenna array is aligned so that the central "row" and "column" of beams are aligned geographically west-east and north-south, respectively. Absorption images are created by interpolating the point measurements from the beams onto a regular grid. Absorption measurements with riometers are sometimes affected by ionospheric scintillation in the presence of a strong point source of radio waves at the frequency of operation, such as a "radio star". Scintillation causes random large-amplitude short-period variations of cosmic noise power and hence, of measured absorption. Usually only a small number of imaging riometer beams are affected in this way at any one time. In this paper, all data from beams affected by scintillation have been excluded from the analysis, with the exception of the time-series plots in Fig. 5.

Magnetic data were provided by the International Monitor for Auroral Geomagnetic Effects (IMAGE) (Lühr et al., 1998), a magnetometer network with stations distributed across Fenno-Scandia. Figure 1 shows the locations of the instruments used in this study and also the field-of-view of IRIS at a height of 90 km. This field-of-view corresponds to that used for the images presented in this paper.

3 Observations

We present observations of two pulsation events having different characteristics occuring in late April and early May 1995 and observed with IRIS and the IMAGE magnetometer array.

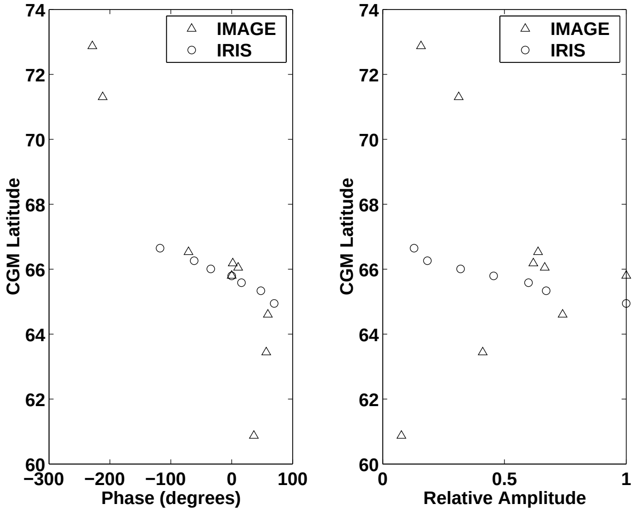

Fig. 3. Amplitudes and phases of absorption and magnetic X-components for Event 1.

3.1 Event 1

Between 05:50 and 06:00 UT on 3 May 1995, a pulsation with a period of approximately 150 s and, therefore, on the boundary between the Pc4 and Pc5 bands was observed in the IRIS absorption. Simultaneously, a pulsation with the same period was also observed in the IMAGE array. Figure 2 shows the time series of absorption from the central north-south column of the IRIS beams and the X-components of the IMAGE stations. The time series have been band-pass-filtered to the period range 40–600 s, covering the Pc4 and Pc5 bands. The plots show that there is a clear north-south phase shift in the pulsation observed in the absorption, with the south leading the north in phase. The same pattern can be observed in the magnetometer X-components, although there is some confusion in the traces around KEV (Kevo) and TRO (Tromsø), which is probably due to the wide separation in longitude of these stations.

Figure 3 shows plots of the amplitude and phase of the peak Fourier component of the spectra of the absorption and X-component time series. The phase has been referenced to zero at Kilpisjärvi, which is where the amplitude peak in the X-component occurs. The phases of the X-components show a 180° swing through the amplitude peak and this observation suggests that the pulsation takes the form of a field-line resonance, that is, a forced oscillation of the magnetosphere. The phases of the pulsation in the IRIS beams match well with this pattern; however, the amplitudes do not correspond with the X-component amplitudes but instead show a monotonic decrease with increasing latitude.

We may use the two-dimensional capability of the imaging riometer to construct a map of the amplitude and phase variations of the pulsation. Given a time series of absorption for each beam over the period of interest, we can produce a time series of images of absorption in the manner described in Sect. 2. We then perform a Discrete Fourier Transform on the time series of each pixel, resulting in a spectrum for each pixel covering the time interval of interest. Images or maps of the amplitude and phase of any Fourier component of interest can then be produced. Figure 4 shows such maps for this event. Note that the colour scale for the phase map has been chosen so that it “wraps around” where the phase angle naturally jumps from +180° to −180°, thus providing continuity in the colouration. The principal characteristics already referred to (Figs. 2 and 3) can easily be seen. The phase map shows that there is little or no azimuthal phase shift.

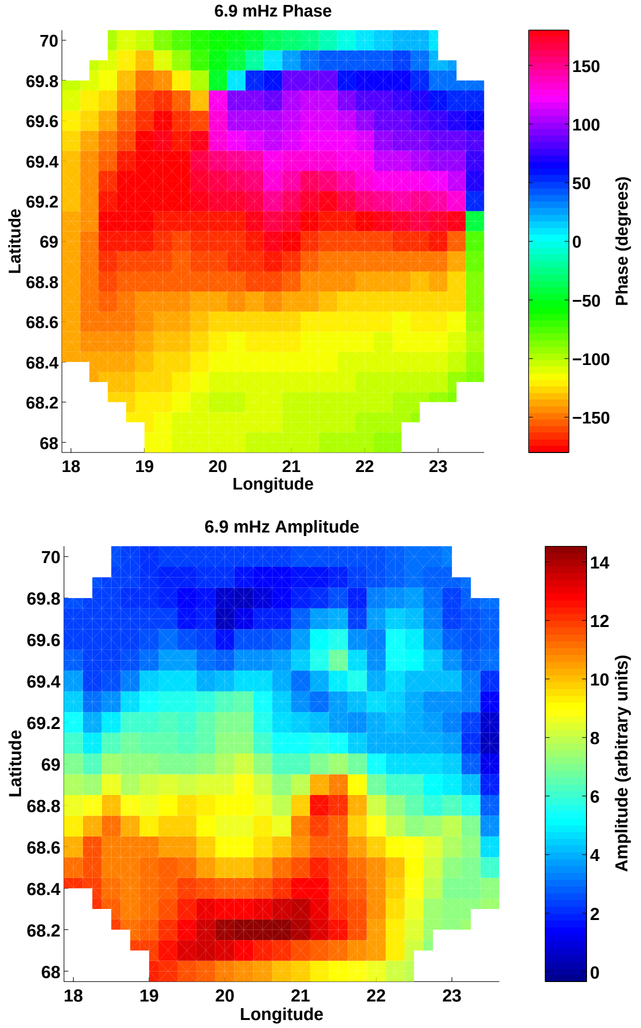

Fig. 4. Maps of the amplitude and phase of Event 1 in IRIS absorption.

3.2 Event 2

On 26 April 1995, between 03:00 and 03:30 UT, a pulsation with a period of around 100 s was present in the IRIS absorption. This pulsation, falling in the Pc4 band, was also observed weakly in the IMAGE array. Figure 5 shows time series plots of the pulsation in the central west-east row of IRIS beams and the Y-components of the IMAGE array. A west-east section was taken for this event, in order to demonstrate

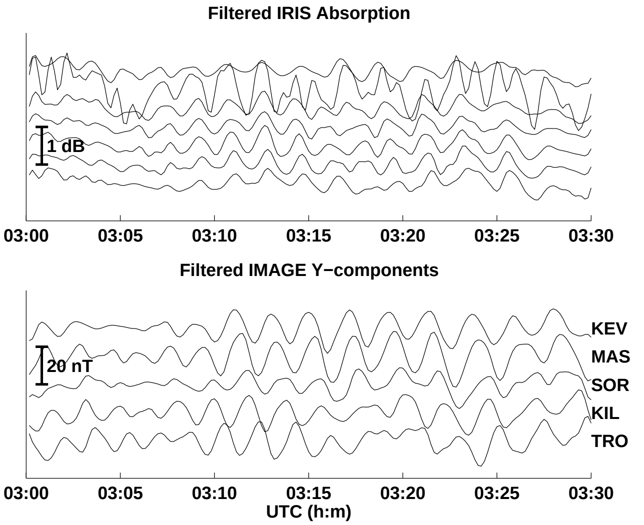

Fig. 5. Time series of Event 2 in absorption and magnetic Y-component. East is at the top of each plot.

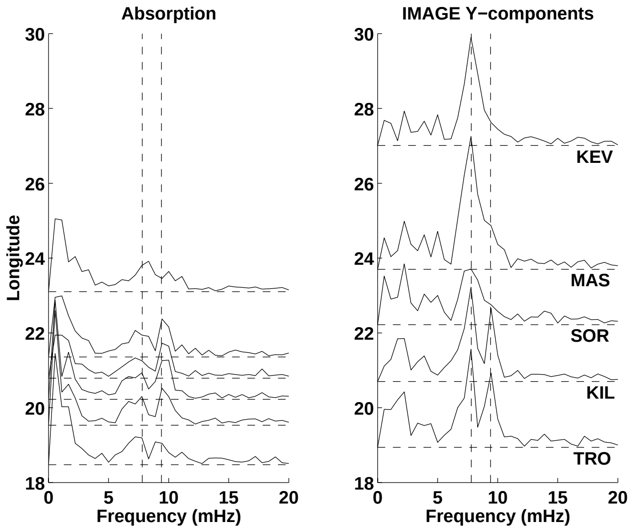

Fig. 6. Spectra of Event 2 in absorption and Y-component. The vertical dashed lines indicate frequencies of 7.8 and 9.4 mHz. The horizontal dashed lines indicate the baselines of each spectrum. These have been placed at the longitude of the corresponding IRIS beam or magnetometer. The spectrum of the IRIS beam affected by scintillation has been omitted.

that the pulsation exhibits an azimuthal phase shift. The time series have been filtered as for those in Event 1. One of the IRIS beams is affected by scintillation which explains the irregular time series for this beam.

A spectral analysis of the time series of absorption and magnetic Y-component reveals that this pulsation is bichromatic, with spectral peaks at 7.8 and 9.4 mHz. Figure 6 shows the spectra for this event. The 9.4 mHz component is dominant in the absorption. Magnetometers TRO and KIL under the IRIS field-of-view show the biggest response at 9.4 mHz, but the 7.8 mHz component always dominates the 9.4 mHz component in the magnetometers. Note that the spectrum of the IRIS beam affected by scintillation shown in Fig. 5 has been omitted, since the scintillation renders its spectrum difficult to interpret. In order to investigate the structure of this dual pulsation, we may carry out the same mapping procedure used for Event 1, but applying it this time to both spectral components. The results can be seen in Fig. 7. The amplitude maps show that the two pulsations maximise in different parts of the field-of-view, and that both regions are somewhat elongated and approximately L-shell aligned. The phase map for the 9.4 mHz component — dominant in the absorption — exhibits a clear azimuthal phase shift of about 120° across the field-of-view, corresponding to an azimuthal wave number $m \approx 22$.

The 7.8 mHz component, on the other hand, shows a north-east/south-west phase shift, with phases in the north-east leading those in the southwest. The azimuthal component of this phase shift, corresponding to $m \approx 18$, is in the same direction as the 9.4 mHz component. The presence of the additional north-south phase shift is in marked contrast to the 9.4 mHz component, however.

This event occurs in the morning sector (approximately 05:45 MLT) and both frequency components show a westward phase propagation. This suggests that these pulsations might be excited by drift- or drift-bounce resonance with ring current ions (Southwood et al., 1969). The north-south phase shift of the 7.8 mHz component with the north leading the south in phase suggests that this component could be exhibiting field-line resonance characteristics across the plasmapause (Orr, 1984), though this seems unlikely since geomagnetic activity was moderate to high over the 24 hours preceeding the event ($2^- \leq K_p \leq 5^-$), meaning that the plasmasphere was probably quite depleted and the plasmapause was at much lower L-values than those in the field-of-view at the time of the event.

4 Discussion

Riometric absorption is generally attributed to precipitation of energetic electrons which cause enhanced ionisation in the D-region of the ionosphere where the electron-neutral collision frequency is large. It seems natural, therefore, to attribute pulsations in the absorption to pulsations in the electron precipitation. Precipitation pulsations events have been observed previously using imaging riometers. Rosenberg et al. (1991) showed an example of a quasi-periodic Pc5-like pulsation. They did not carry out any detailed analysis of the structure of the event, except to state that it was uniform across the field-of-view. Also, they did not compare the riometer observations with magnetometer data. Later, Weatherwax et al. (1997) showed an example of Pc5-modulated precipitation. They compared the observations with magnetometer data and found similar spectral features. They also noted that the pulsation was confined to a narrow (∼ 1°) latitude band embedded in a background of steady precipita-

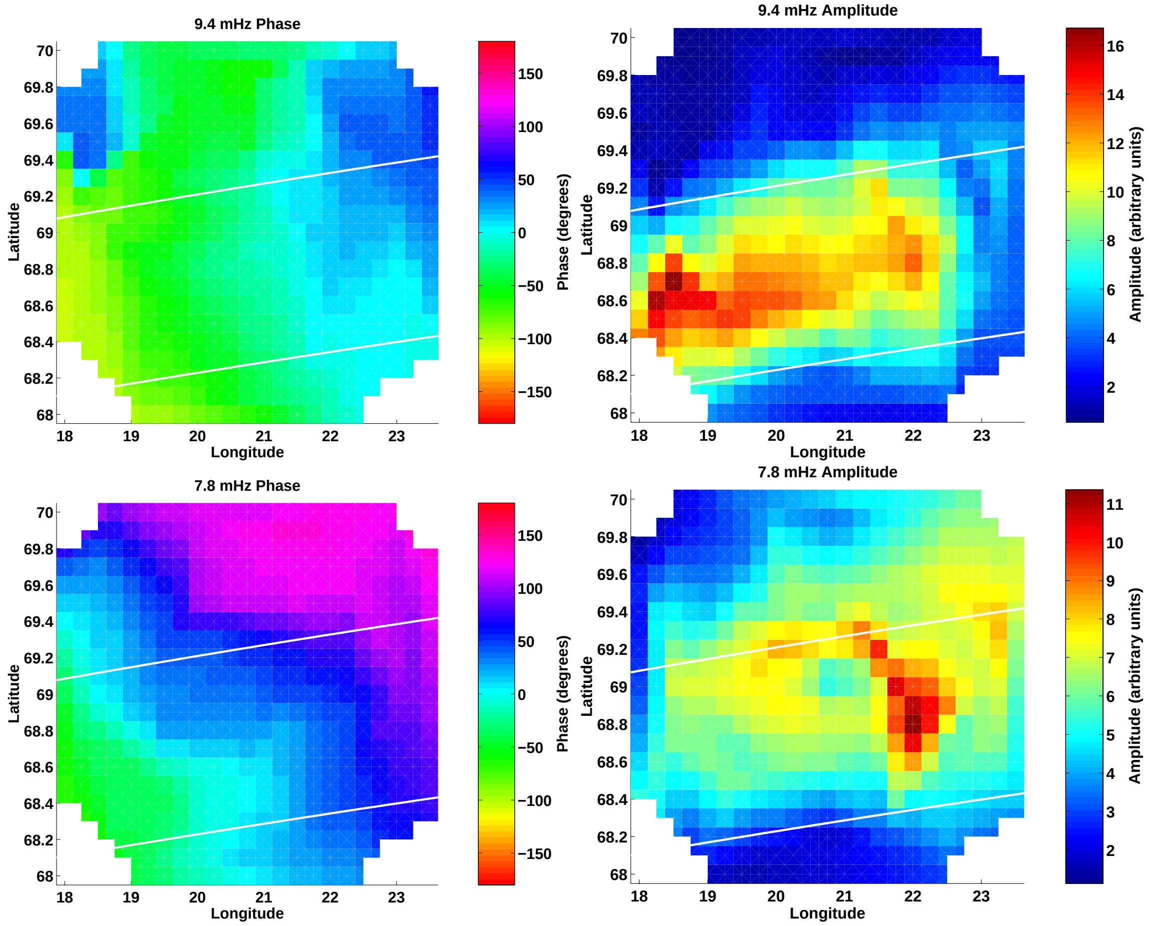

Fig. 7. Maps of the amplitude and phase of the two spectral components of the Pc4 pulsation. The white lines are lines of constant geomagnetic latitude (CGM, 1995 at 90 km). The maps cover the time interval 03:00–03:30 UT.

tion. This is similar to our observations in Event 2. Weatherwax et al. (1997) did not, however, make use of the analysis technique demonstrated here to map the amplitude and phase variations of the pulsation.

Coroniti and Kennel (1970) developed a theory of how electron precipitation could be modulated by a magnetic pulsation. The principle is that precipitation is induced by an electron pitch-angle diffusion process driven by the Doppler-shifted cyclotron resonance interaction with whistler-mode waves. An equilibrium, corresponding to a steady precipitation state, exists which is then disturbed by the magnetic pulsation that modulates the growth-rate of the whistler-mode turbulence and hence, modulates the precipitation. Haugstad (1975) discussed some objections to this theory and proposed modifications to it to correct them. Under this Coroniti-Kennel-Haugstad (CKH) theory, one would expect a fixed phase relationship between the magnetic pulsation and the resulting precipitation pulsation, so that the spatial variations of the two would be the same. It is not possible to compare exactly the phase variations observed by the magnetometer and the riometer due to their differing spatial resolutions, but they appear to be similar for the events reported here.

There is evidence, however, that the amplitudes of the absorption and magnetic pulsations do not agree. In Event 1, the phase variations observed both by the magnetometers and by the riometer put the resonant L-shell close to the centre of the IRIS field-of-view, since this is the centre of the 180° phase swing. The peak amplitude in the absorption, however, occurs towards the equatorward edge of the field-of-view. In general, we might not expect the amplitudes of absorption and magnetic pulsations to correspond in terms of their spatial distribution, since, under the CKH theory, the amplitude of the absorption pulsation depends on several factors, including the amplitude of the magnetic pulsation and the nature (strong or weak) of the pitch-angle diffusion process. The energy of the precipitated electrons would also affect the level of absorption produced.

It is interesting to compare the background levels of absorption with the amplitudes of the absorption pulsation. The CKH theory suggests that the effect of the pulsation modulation is only to raise the precipitation rate (and hence absorption) above the level which would exist in the absence of the pulsation. Therefore, in this study, the "background" has been estimated from the minima of the absorption time series

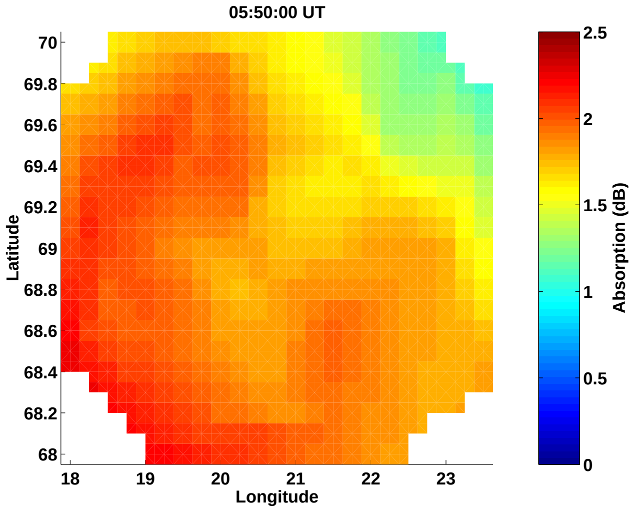

Fig. 8. The background level of absorption during Event 1. This is the mean background absorption over the 10-min interval from 05:50 to 06:00 UT.

during the pulsation. Figure 8 shows the background absorption for Event 1. Here we see that the absorption maximizes to the south and west. The pulsation maximizes to the south. Figure 9 shows the background absorption for Event 2. In this case, the absorption maximizes to the north. The 9.4 mHz component of the pulsation maximizes in a very well-defined L-shell-aligned band equatorward of the peak background absorption. The 7.8 mHz component is more evenly distributed across the field-of-view but also peaks equatorward of the peak background absorption. These observations demonstrate that maximum absorption and maximum absorption pulsation amplitude do not necessarily coincide and that a significant amplitude of absorption pulsation can exist on a relatively low background absorption. This is consistent with the CKH theory which indicates an exponential dependence of precipitation rate on the magnetic pulsation amplitude.

We should add that Weatherwax et al. (1997) believed that their observations were not consistent with the CKH theory and suggested several alternative theories. However, their observations were made on much higher L-shells on closed field-lines which mapped deep into the tail and it is possible that a different mechanism might indeed be responsible for the precipitation pulsation in this case.

5 Conclusions

In summary, imaging riometers have been employed to map the spatial structure of pulsation events which show an absorption signature in terms of their distribution of amplitude and phase. Maps of the phase of the absorption pulsation appear to be in agreement with phase measurements from ground-based magnetometers, whereas maps of the amplitude appear not to show such good agreement. This is probably because the absorption pulsation amplitude does not depend on the amplitude of the magnetic pulsation alone. The high spatial resolution of imaging riometers may make it possible for these instruments to resolve the spatial structure of pulsations which are strongly screened from magnetometers on account of their small horizontal scale size.

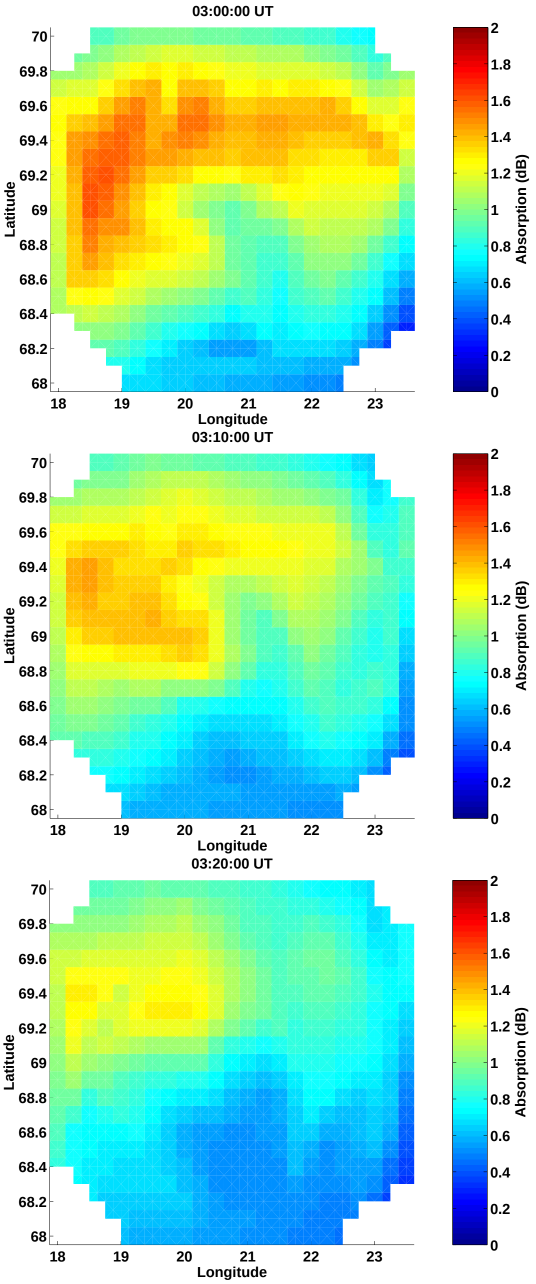

Fig. 9. The background level of absorption during Event 2. These are a series of 10-min means starting at the times shown on each plot.

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