GEOPHYSICAL RESEARCH LETTERS, VOL. 26, NO.6, PAGES 659-662, MARCH 15, 1999

Discrete field line resonances and the Alfvén continuum in the outer magnetosphere

R. A. Mathie
Department of Physics, University of York, York, England

F. W. Menk
Department of Physics, University of Newcastle, Newcastle, New South Wales, Australia

I. R. Mann, D. Orr
Department of Physics, University of York, York, England

Abstract. Using Pc5 pulsation events observed with the IMAGE magnetometer array, we demonstrate that mHz frequency field line resonances (FLRs) represent local enhancements in the background Alfvén continuum of field line eigenfrequencies. By comparing resonance profiles for a typical event with the continuum frequency profile determined using cross-phase techniques, we show that pulsation frequencies as low as 1-2 mHz can couple to FLRs on high latitude closed field lines. We also suggest that the transition to open field lines on days of higher geomagnetic activity may lead to a breakdown in pulsation characteristics at the highest latitudes of the IMAGE array. In addition, we show evidence of the U-shaped diurnal variation in field line eigenfrequency and suggest that this is primarily due to field line stretching, especially on the magnetosphere flanks.

1. Introduction

Compressional ULF (~1-100 mHz) waves in the outer magnetosphere can couple to shear Alfvén waves, driving field line resonances (FLRs) where the frequency of the driving oscillation matches the local field line eigenfrequency. When observing a pulsation event of a particular frequency on a ground array of magnetometer stations, a driven FLR is characterized by constant frequency across a range in latitudes with a local peak in amplitude and a phase reversal across the resonant latitude [e.g., *Samson and Rostoker*, 1972]. Possible source mechanisms for the generation of FLRs in the outer magnetosphere include the Kelvin-Helmholtz instability (KHI) at the magnetopause or recently studied cavity and waveguide modes, invoked to explain the observation of discrete, quantized frequencies of oscillation [e.g., *Ruohoniemi et al.*, 1991]. However, it is not clear whether FLRs in the outer magnetosphere can reach the low frequencies claimed by some authors [e.g., *Walker et al.*, 1992], or how frequently these low frequency FLRs occur in the magnetosphere.

The resonant frequency of a field line is determined by its length, magnetic field strength and the local plasma density, and is therefore expected to change smoothly with latitude. An input of broadband ULF power to the magnetosphere can therefore lead to the excitation of a continuum of shear Alfvén wave frequencies. Evidence for this has been shown in spacecraft observations [e.g., *Takahashi and McPherron*, 1982]. This field line eigenfrequency continuum can be detected in ground-based observations using cross-phase and related techniques [e.g., *Menk et al.*, 1994]. The temporal variation in eigenfrequency at a particular latitude can provide information on changes in plasma density threading the field line [*Waters et al.*, 1995] or changes in field line length.

Previous high latitude studies of Pc5 (1-10 mHz) pulsations have identified an inverted U-shaped diurnal variation in the frequency at a particular latitude [*Saito*, 1969]. This feature was called the "arch" and discussed as a cusp signature by *McHarg et al.* [1995]. However, it is likely that the "arch" is at least partly generated by the diurnal variation in field line length in the outer magnetosphere [*Waters et al.*, 1995; *Ables et al.*, 1998]. What has not yet been done is to observationally prove that the very low frequency discrete FLRs in the outer magnetosphere represent localised enhancements in the Alfvén continuum. In this paper we examine Pc5 pulsations in the outer magnetosphere with three main objectives: (1) to observe discrete frequency FLRs and examine their relationship to the Alfvén continuum, (2) to obtain an estimate of the low frequency limit for sustainable resonances on high latitude field lines and (3) to examine the diurnal variation of field line eigenfrequencies in the outer magnetosphere.

2. Data and Analysis

Observations presented in this paper were recorded with the IMAGE magnetometer network [*Lühr*, 1994]. The IMAGE data are sampled every 10 s in geographic (X,Y,Z) coordinates and are rotated into geomagnetic (H,D,Z) coordinates before analysis. All coordinates quoted in this study are corrected geomagnetic for 1996. We examined in detail 137 discrete, monochromatic Pc5 pulsation events recorded in March 1994, 1995, and 1996 [*Mathie et al.*, 1999], and present here the analysis of a typical pulsation event from 22 March, 1996. For all events, power spectral analysis was first used to find the dominant frequency, then a more accurate estimate of this frequency was obtained by using complex demodulation [e.g., *Beamish et al.*, 1979] to perform a phase-time analysis. The complex demodulation analysis gives instantaneous demodulate values of amplitude and phase for an event from which profiles were generated by plotting the average of the central three amplitude and phase demodulate values against the latitude of the observing station (see *Mathie et al.* [1999] for further details).

For selected events, the field line eigenfrequency continuum was also examined using a cross-phase analysis between adjacent IMAGE stations across the entire latitudinal extent

Paper number 1999GL900104.
0094-8276/99/1999GL900104$05.00

of the array. The cross-phase technique compares the phase at a pair of nearby meridionally spaced stations to give an estimate of the eigenfrequency of the field line above the station mid-point [e.g., *Waters et al.*, 1995]. Whole-day dynamic cross-phase spectra were produced using a 256 point FFT stepped in 450 second intervals to illustrate the diurnal variation in field line eigenfrequency. However, the resonant frequency for each station pair was then measured from static cross-phase plots. These give a more reliable estimate of the local natural eigenfrequencies as they also include parameters of the cross-phase such as power difference and power ratio between adjacent stations and the interstation coherence, each of which provides an indication of the local natural eigenfrequency [e.g., *Waters et al.*, 1995; *Menk et al.*, 1999]. The typical interval duration for these plots was 90 minutes and the plots were examined each hour for the days of interest.

3. Results

Figure 1 shows the stacked IMAGE time series over 0430-0830 UT on 22 March, 1996, filtered between 1 and 5 mHz. A Pc5 pulsation event is apparent in the interval 0540-0740 UT, with a coherent wave packet from 0545 UT followed by an enhancement in the wave amplitude at 0650 UT. Figure 2 shows normalised stacked power spectra for the interval 0540-0740 UT. Spectral peaks are apparent at all stations at 1.8 mHz and 3.0 mHz with further significant peaks at higher frequencies, including 6.3 mHz. The existence of multiple spectral peaks within a particular interval is typical of events observed with IMAGE [e.g., *Mathie et al.*, 1999].

Figure 3 shows the H and D component amplitude and phase profiles for the interval 0540-0740 UT for the 1.8, 3.0 and 6.3 mHz signals. The peak amplitude of the 1.8 mHz signal was observed at 0710 UT and this frequency component is clearly associated with the amplitude enhancement at 0650 UT seen in Figure 1. The 3.0 mHz signal peaks at 0605 UT and the 6.3 mHz signal at 0635 UT. Conventional FFT or pure state analysis [e.g., *Ziesolleck and McDiarmid*, 1995] yields similar plots but with lower frequency resolution. Each of the three spectral components displays FLR characteristics, with a well defined H component amplitude maximum and corresponding phase reversal. Note that the D component amplitude also shows a significant peak for the 1.8 mHz event (Figure 3a). This may indicate weaker coupling between the fast and Alfvén waves at this frequency, resulting in a sizeable radial oscillation of the high latitude field lines. For each of the frequency components, the D component phase also displays some changes at the resonant field line, though not as large a change as in the H component. Similar phase changes have been reported in other ground-based observations of FLRs [e.g., *Ziesolleck and McDiarmid*, 1995]. From these profiles, we estimate resonant latitudes of 74.3° ± 0.2 for the 1.8 mHz signal, 71.5° ± 1.0 for the 3.0 mHz signal and 66.1° ± 0.4 for the 6.3 mHz signal, the errors being estimates made from a consideration of shape of each of the amplitude peaks.

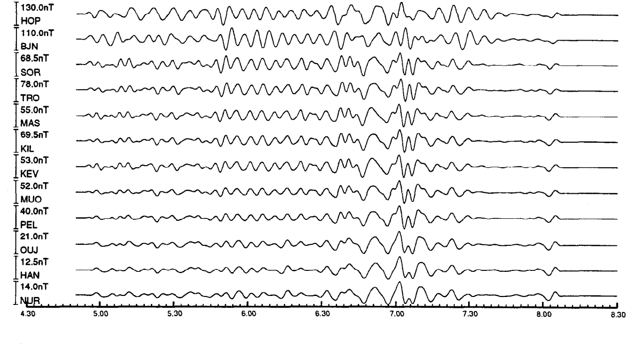

Figure 1. H component IMAGE magnetogram stackplot for the interval 0430-0830 UT, 22 March, 1996, filtered between 1 and 5 mHz.

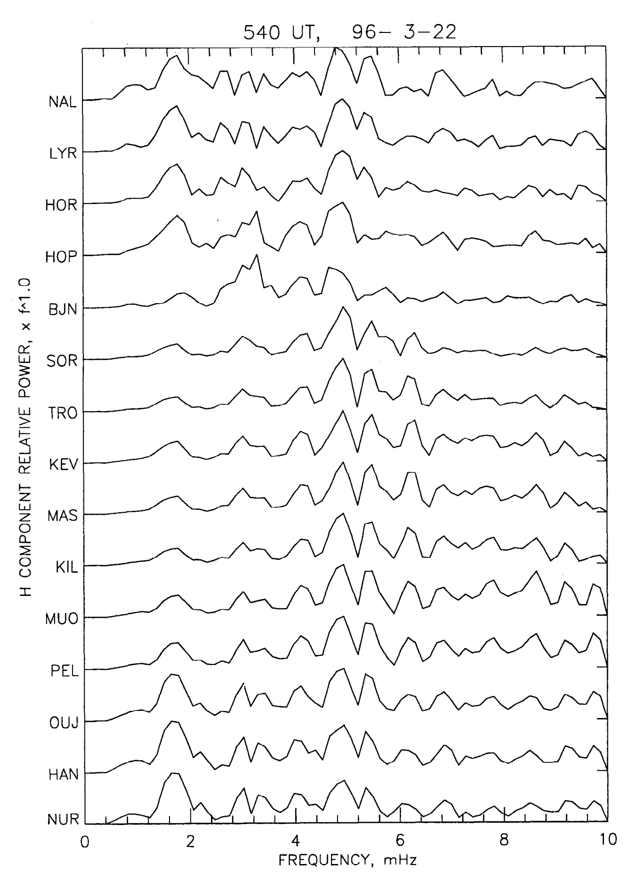

Figure 2. H component stacked power spectra for the interval 0540-0740 UT, 22 March, 1996.

Figure 4 shows the cross-phase continuum profile for the interval 0630-0800 UT, centered on the time of maximum amplitude of the 1.8 mHz signal. The error bars arise from the uncertainty in determining an exact eigenfrequency estimate from the cross-phase peak, the zero crossing of the interstation power subtraction spectrum and the dip in the coherence in the static cross-phase plots. The dotted lines on this plot indicate the frequencies of the three spectral components identified from the complex demodulation analysis presented above, and which give the latitudes at which these frequencies would be expected to resonate according to the cross-phase continuum. These latitudes are 74° ± 1.0 (1.8 mHz), 72.3° ±0.5 (3.0 mHz) and 67.8° ±0.5 (6.3 mHz), with errors estimated from the possible shape of the continuum curve indicated by the error bars in figure 4. Within the error bars of each analysis, there is good agreement between the estimated resonant latitudes for both the 1.8 and 3.0 mHz signals. The slight mismatch in the 6.3 mHz resonance latitude estimates may arise because this frequency component peaked in amplitude at 0635 UT while the cross-phase continuum was determined over 0630-0800 UT and the resonant frequency at a particular latitude increases with local time. The field line eigenfrequency continuum is an apparently smooth curve extending to the outermost field lines observable with the IMAGE array. This is a typical result

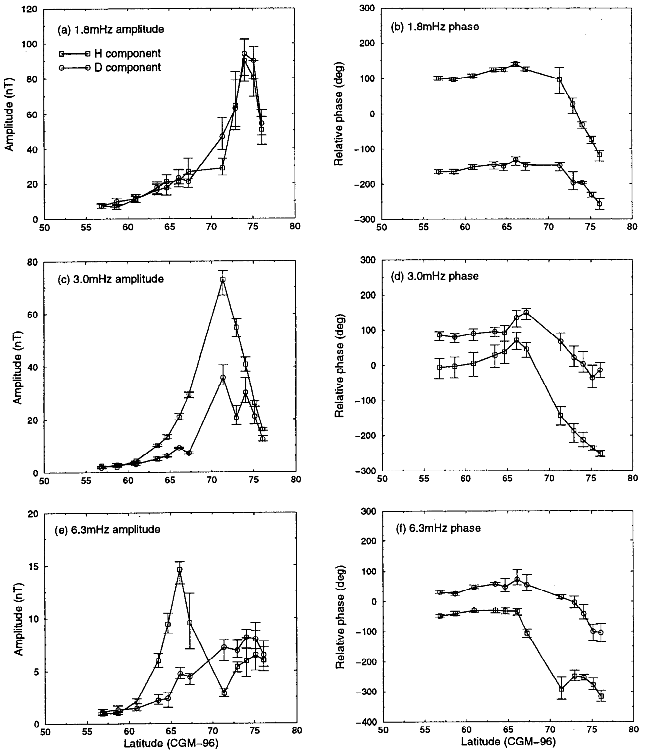

Figure 3. Latitudinal profile plots for the three signal frequencies considered: (a) 1.8 mHz amplitude, (b) 1.8 mHz phase, (c) 3.0 mHz amplitude, (d) 3.0 mHz phase (e) 6.3 mHz amplitude, and (f) 6.3 mHz phase.

obtained for many events. However, on days of higher Kp, no cross-phase continuum could be obtained for the highest latitude stations as the interstation coherence drops to low levels. We interpret this as direct evidence of open field lines on these high latitude stations.

The diurnal variation of field line eigenfrequency for a number of station pairs on this day is shown in Figure 5. Again, this is typical of many other days studied and clearly shows the inverted U-shape, or "arch". The resonant frequency at a particular latitude and local time was also found to move up and down from day to day, depending upon the level of geomagnetic activity. On quieter days, the curves were shifted to lower frequencies.

4. Discussion

There is close agreement between the resonant latitudes of the three major spectral components derived from the complex demodulation analysis (Figure 3) and those predicted by the cross-phase Alfvén eigenfrequency continuum (Figure 4). The FLRs we observe are clearly the response of the local field lines to a monochromatic driver imposed over a wide range of latitudes by some source mechanism, be it the KHI on the magnetopause or a global cavity/waveguide mode. The amplitude peaks shown in Figure 3 represent the local enhancements in power where the driving frequency matches the local field line eigenfrequency. This scenario has been observed for many events and on a number of days, with very low frequency FLRs often apparent.

Particle data from the polar orbiting DMSP satellite network can be used to obtain information on magnetospheric topology [*Newell et al.*, 1989]. Data obtained from the DMSP F12 satellite, located approximately 15^o east of the IMAGE array at the time of the presented event, indicated that the boundary layer extended to a latitude of $\sim 80^oN$.

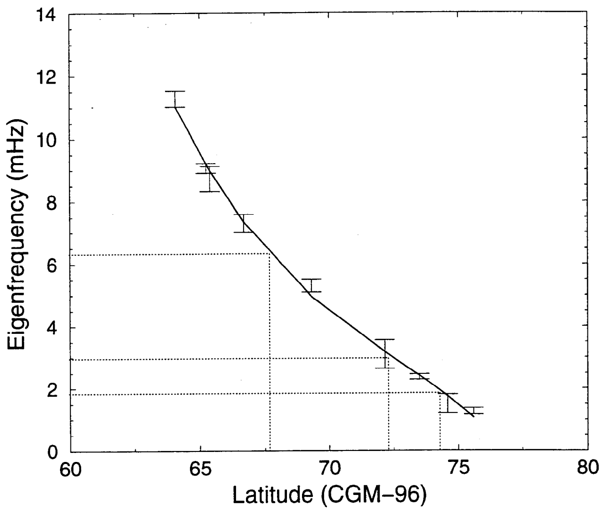

Figure 4. The Alfvén frequency continuum, calculated for the interval 0630-0800 UT, centered on the time of maximum amplitude of the 1.8 mHz signal.

Therefore, the IMAGE stations would be likely to observe only closed field lines at this time. This agrees with the results of Figure 3a which shows that a signal of 1.8 mHz can couple to a resonance on closed field lines at high latitudes.

A study by *Matthews et al.* [1996] showed a 3.3 mHz pulsation to reach a maximum in amplitude at the latitude of the cusp, as determined by radar and satellite measurements. The pulsations also appeared to persist coherently up to 5^o poleward of the cusp, and it was suggested that this may be due to the slow fall off in ionospheric current systems with distance. In contrast, *Ables et al.* [1998], monitoring the cusp topology with Pc5 waves observed at three high latitude ground magnetometer stations, found that pulsation activity collapsed quickly on open field lines, especially during intervals of enhanced geomagnetic activity.

From a survey of the 137 pulsation events presented by *Mathie et al.* [1999] (of which the event described here is one), we have found that under quiet geomagnetic conditions it is possible to observe FLRs at frequencies as low as 1.1-1.3 mHz on the most poleward stations of the IMAGE array ($\sim 76^oN$), which were presumeably observing closed field lines on these days. However, in common with *Ables et al.* [1998], we found that on days of higher Kp (per-

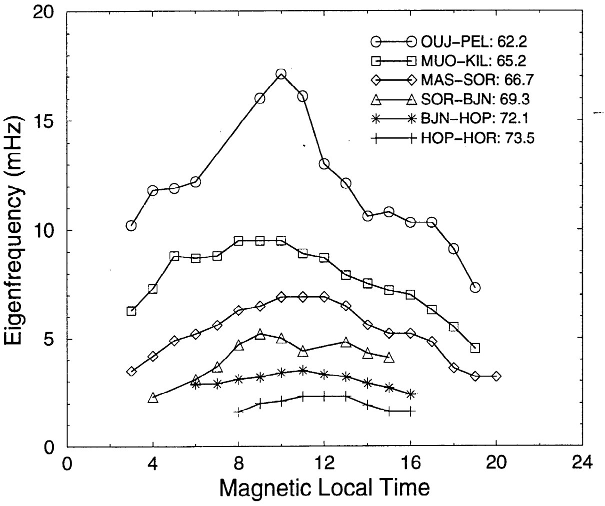

Figure 5. Diurnal variation of the Alfvén continuum for six station pairs of the IMAGE array. The station pairs and midpoint latitudes are indicated.

haps Kp>3) the coherence between waveforms at neighboring stations dropped to low levels on stations poleward of the Scandinavian mainland ($> 70^o N$). On such days, the amplitude response on the mainland stations was often consistent with high latitude resonance characteristics but poleward of the mainland the amplitude response became unpredictable. The corresponding phase estimates became unreliable and showed a large variation at the higher latitude stations. This may indicate an open/closed field line boundary at latitudes of around $71^o - 72^o N$ for Kp>3, or at least suggest that poleward of these latitudes, the field lines are severely stretched and unable to support FLRs.

Figure 5 clearly shows the diurnal variation in field line eigenfrequency. This frequency "arch" has perhaps two possible causes. *Poulter et al.* [1988] showed that the radial motion of a flux tube due to $E \times B$ drift may cause a diurnal variation in field line eigenfrequency, with a small frequency increase ($\sim$ 1 mHz at high latitudes; see their Figure 5) near the subsolar point. However, it is likely that the dominant effect is that of field line stretching. *Kennel* [1995] discusses how an element of magnetospheric convection is driven by a viscous interaction at the magnetopause, which implies a momentum transfer onto closed field lines. This should stretch high latitude field lines, especially on the flanks. We suggest that the very low frequency FLRs we observe are oscillations of these stretched closed field lines. To obtain a first order estimate of the degree of field line stretching, we consider the case of constant Alfvén velocity, such that the frequency supported on a field line is inversely proportional to field line length. For the field line observed by the MAS-SOR pairing (66.7^o, L=6.5) in Figure 5, we see that the eigenfrequency increases from ~3.5 mHz at 0300 MLT to ~7 mHz at 1200 MLT. To first degree, this change indicates that the L=6.5 field line may be up to twice as long in the early morning sector than at local noon.

Finally, we use the observed diurnal variation in field line eigenfrequency to obtain a first order estimate of the plasma mass density in the outer magnetosphere. *Singer et al.* [1981], using the Olson-Pfitzer field line model, calculated the fundamental toroidal mode eigenfrequency over a range of latitudes and at various local times for a density of 1 amu/cm^3. Comparing their results with those observed for the MAS-SOR pair in Figure 5, and considering that period scales as $\sqrt{n}$ where n is the mass density of the plasma in amu/cm^3, we find a plasma mass density of $\sim$ 6 amu/cm^3 for 22 March, 1996. This value compares favorably with that presented by, for instance, *Poulter et al.* [1984], and suggests significant mass loading of the field lines.

In conclusion, our survey of 137 Pc5 pulsation events shows that FLRs represent local amplitude enhancements in the Alfvén continuum and that driving frequencies as low as 1.1-1.3 mHz can couple to FLRs on high latitude field lines during quiet geomagnetic conditions. Further use of the cross-phase technique may indicate the dominant influence upon the diurnal evolution of field line topology and allow for more accurate estimates of plasma density distribution.

Acknowledgments. We thank Lasse Hakkinen at FMI for the supply of IMAGE data and all those who maintain the array. R.A.M is supported by a PPARC studentship. F.W.M received support from a PPARC Visiting Fellowship during this study. I.R.M is supported by a PPARC fellowship.

References

Ables, S., B. Fraser, C. Waters, and D. Neudegg, Monitoring cusp/cleft topology using Pc5 ULF waves, *Geophys. Res. Lett.*, *25*, 1507–1510, 1998.

Beamish, D., H. Hanson, and D. Webb, Complex demodulation applied to Pi2 geomagnetic pulsations, *Geophysics Journal of the Royal Astronomical Society*, *58*, 471–493, 1979.

Kennel, C., *Convection and Substorms: Paradigms of Magnetospheric Phenomenology.* Oxford University Press, New York, 1995.

Lühr, H., The IMAGE Magnetometer Network, STEP International, *4*, 4–6, 1994.

Mathie, R., I. Mann, F. Menk, and D. Orr, Pc5 ULF pulsations associated with waveguide modes observed with the IMAGE magnetometer array, in press *J. Geophys. Res.*, 1999.

Matthews, D., J. Ruohoniemi, J. Dudeney, C. Farrugia, L. Lanzerotti, and E. Friis-Christensen, Conjugate cusp-region ULF pulsation responses to the solar wind event of May 23, 1989, *J. Geophys. Res.*, *101*, 7829–7841, 1996.

McHarg, M., J. Olson, and P. Newell, ULF cusp pulsations: Diurnal variations and interplanetary magnetic field correlations with ground-based observations, *J. Geophys. Res.*, *100*, 19729–19742, 1995.

Menk, F., B. Fraser, C. Waters, C. Ziesolleck, Q. Feng, S. Lee, and P. McNabb, Ground measurements of low-latitude magnetospheric field line resonances, in *Solar Wind Sources of Magnetospheric ULF Waves*, edited by M. Engebretson, K. Takahashi, and M. Scholer. American Geophysical Union, 1994.

Menk, F., C. Waters, and B. Fraser, Field line resonances and waveguide modes at low latitudes; 1. Observations, in press, *J. Geophys. Res.*, 1999.

Newell, P., C.-I. Meng, and D. Sibeck, Some low-altitude cusp dependecies on the interplanetary magnetic field, *J. Geophys. Res.*, *94*, 8921–8927, 1989.

Poulter, E., W. Allan, J. Keys, and E. Nielsen, Plasmatrough ion mass densities determined from ULF pulsation eigenperiods, *Planet. Space Sci.*, *32*, 1069 - 1078, 1984.

Poulter, E., W. Allan, and G. Bailey, ULF pulsation eigenperiods within the plasmasphere, *Planet. Space Sci.*, *36*, 185–196, 1988.

Ruohoniemi, J., R. Greenwald, K. B. Baker, and J. Samson, HF radar observations of Pc5 field line resonances in the midnight/early morning MLT sector, *J. Geophys. Res.*, *96*, 15697–15710, 1991.

Saito, T., Geomagnetic pulsations, *Space Science Reviews*, *10*, 319–412, 1969.

Samson, J., and G. Rostoker, Latitude-dependent characteristics of high-latitude Pc4 and Pc5 micropulsations, *J. Geophys. Res.*, *77*, 6133–6144, 1972.

Singer, H. J., D. J. Southwood, R. J. Walker, and M. G. Kivelson, Alfvén wave resonances in a realistic magnetospheric magnetic field geometry, *J. Geophys. Res.*, *86*, 4589–4596, 1981.

Takahashi, K., and R. McPherron, Harmonic structure of Pc3-4 pulsations, *J. Geophys. Res.*, *87*, 1504–1516, 1982.

Walker, A., J. Ruohoniemi, K. Baker, R. Greenwald, and J. Samson, Spatial and temporal behavior of ULF pulsations observed by the Goose Bay HF radar, *J. Geophys. Res.*, *97*, 12187–12202, 1992.

Waters, C., J. Samson, and E. Donovan, The temporal variation of the frequency of high latitude field line resonances, *J. Geophys. Res.*, *100*, 7987–7996, 1995.

Ziesolleck, C., and D. McDiarmid, Statistical survey of auroral latitude Pc5 spectral and polarization characteristics, *J. Geophys. Res.*, *100*, 19299–19312, 1995.

I. R. Mann, R. A. Mathie, and D. Orr, Department of Physics, University of York, York YO10 5DD, England. (e-mail: rod@aurora.york.ac.uk; ian@aurora.york.ac.uk; david@aurora.york.ac.uk)

F. W. Menk, Department of Physics, University of Newcastle, Newcastle, NSW 2308, Australia. (e-mail: physpuls3@cc.newcastle.edu.au)

(Received November 24, 1998; revised February 8, 1999; accepted February 11, 1999.)