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Period, phase and resonant structure of a pulsation event seen by the ISEE 1 and 2 spacecraft on 2–3 April 1978

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Abstract. Complex demodulation is used to make estimates of the wave parameters of a pulsation event seen by the ISEE 1 and 2 spacecraft. The pulsation was observed in the early morning local time sector on April 2-3 1978 (day 92/3). The pulsation was in the pc4 frequency range and had a strong compressional component. Pulsation activity was observed continuously for about 90 min, over a radial extent of approximately $L=9$ to $L=6$. The observed wave parameters show both temporal and spatial variations. It is shown that the wave period is decreasing with time and that this allows the wave ellipticity observations to be interpreted according to the theory of field line resonance.

Key words: ISEE – Resonance – pc4 – Multisatellite – Second harmonic – Magnetosphere – Time-local – Complex demodulation

Introduction

The theory of field line resonance (Southwood, 1974; Chen and Hasegawa, 1974) was developed to explain pulsation structure seen by high-latitude magnetometer arrays (Samson et al., 1971). Whilst there is an abundance of observations of field line resonance structure on ground magnetometer arrays, such as the IGS arrays in the United Kingdom and Scandinavia, there are comparatively few in situ observations of such structure (for example, Singer et al., 1982). Pulsations observed at geostationary orbit have shown little correlation between the wave forms observed by two satellites if the satellites are too far apart (Hughes et al., 1979), indicating that the pulsations had large azimuthal wavenumbers. However, pulsations seen at the ISEE spacecraft have shown resonant structure (Singer, 1982; Singer et al., 1982). Singer et al. (1982) report several events, including one where the period decreased with time.

Inhomogeneity in the magnetosphere, possible source fluctuations and field line resonance structure would lead one to anticipate both spatial and temporal effects to be evident in the structure of the waveforms. To isolate the spatial from the temporal phenomena, and hence remove the ambiguity they cause, estimates of the wave parameters with greater time resolution than the separation of the two spacecraft are required. Complex demodulation is a technique which allows such estimates to be made and is used here to estimate the pulsation period, amplitude and polarization as functions of time.

A notable feature of the event examined here, and also of many other events observed in situ, is the presence of a large compressive component. As a crude model of field line resonance, one might expect temporal structure in the compressive field line components, associated with energy propagation across field lines, and some spatial structure in the toroidal component associated with the resonance.

The pulsation event in question was seen from 23.30 UT to 2.00 UT on April 2/3 1978 by three satellites, GEOS 1 and the twin satellite ISEE mission. Observations of this event are also to be reported by Hughes and Grard (1984). Activity was also seen on the ground by the IGS UK and Scandinavian magnetometer arrays. Correlation between satellite and ground is poor in that whilst pulsation activity is seen on the ground, the period is greater than that seen in the magnetosphere at the same time. Here only magnetic field observations made by the ISEE spacecraft are considered.

During this time the ISEE spacecraft were inbound from approximately $L=9$ to $L=6$ in the 2.00 local time sector. ISEE 2 was leading ISEE 1 by approximately 10 mins or 2000 km. The orbit was essentially radial with the spacecraft located approximately 5° south of the magnetic equator.

In this paper the wave structure of this event is investigated using complex demodulation. The ISEE 1 and 2 spacecraft are a mother-daughter pair and their orbital separation is small compared with the scale length of the pulsations. The waveforms should, therefore, be highly correlated. The wave parameters observed are then interpreted according to the theory of field line resonance.

Complex demodulation applied to ISEE 1 and 2 data

Complex demodulation has previously been applied to the analysis of pulsations observed on the ground (Beamish et al., 1979). It has proved particularly useful in the analysis of pi2 events, as wave parameters can be estimated over only a few wave cycles (Lester and Orr, 1981).

Demodulation of a time series with an oscillatory component of angular frequency ω by a demodulation frequency of ω_d results in a demodulate

$$X_d(\omega_d, t)=\frac{A}{2}\exp\{-i(\delta\omega\cdot t+\gamma)\}. \tag{1}$$

The phase of the demodulate is

$$\phi_d=\delta\omega\cdot t+\gamma \tag{2}$$

where $\delta\omega=\omega_d-\omega$.
The parameter γ is the phase of the original oscillatory component and A is the time-dependent amplitude of the demodulate. The time resolution is limited by the bandwidth of the demodulation filter, as it is this bandwidth which determines the time interval over which independent amplitude and phase estimates can be made. The frequency of this oscillatory component can be determined from Eq. (2) by calculating the phase of the demodulate. The demodulate amplitude and phase can be combined to calculate the time-local wave azimuth angle and ellipticity. The phase estimate at any point is based on a section of the original time series surrounding that point. The phase estimates can therefore be said to be time-local because they reflect the local behaviour of the time series. The time-local phase of the time series will only have any significance when the signal amplitude rises above the noise level. When forming the time-local phase from the demodulate, an estimate should only be made where the demodulate amplitude exceeds a specified minimum level.

The other point of concern is the level of confidence that can be placed in the demodulate. The waveform is assumed to be non-stationary, so a statistical approach cannot be used to determine the confidence levels. The alternative is to test for self-consistency by repeating the analysis using different demodulation frequencies and using the results to determine the amount of scatter in the data derived from the different demodulates.

Data analysis

The magnetic field data is 4 s averaged data derived from the identical fluxgate magnetometers on board ISEE 1 and 2 (Russell, 1978). Figure 1 shows the waveforms in the Mean Field Aligned coordinate system as defined by Hedgecock (1976). X is radially outwards in the magnetic meridian, Z lies along the ambient field and Y, the azimuthal component, completes the right-handed set. This coordinate system is used throughout this paper.

The waveforms were demodulated at a period of 89.77 s, with a demodulation filter width from 74.0–113.0 s. This gives a filter bandwidth of 4.67 mHz and so a time resolution of 216 s. Phase estimates were derived only where the amplitude of the total wave vector was greater than 0.25 nT.

The error in wave period (see Fig. 3) was estimated by further demodulating at 95 and 83 s. Wave periods were derived using these other demodulates, and the scatter of these points around the wave periods derived from the original demodulate was taken as indicative of the expected error in the wave period. This showed that the wave period could be determined to an accuracy of ±3 s.

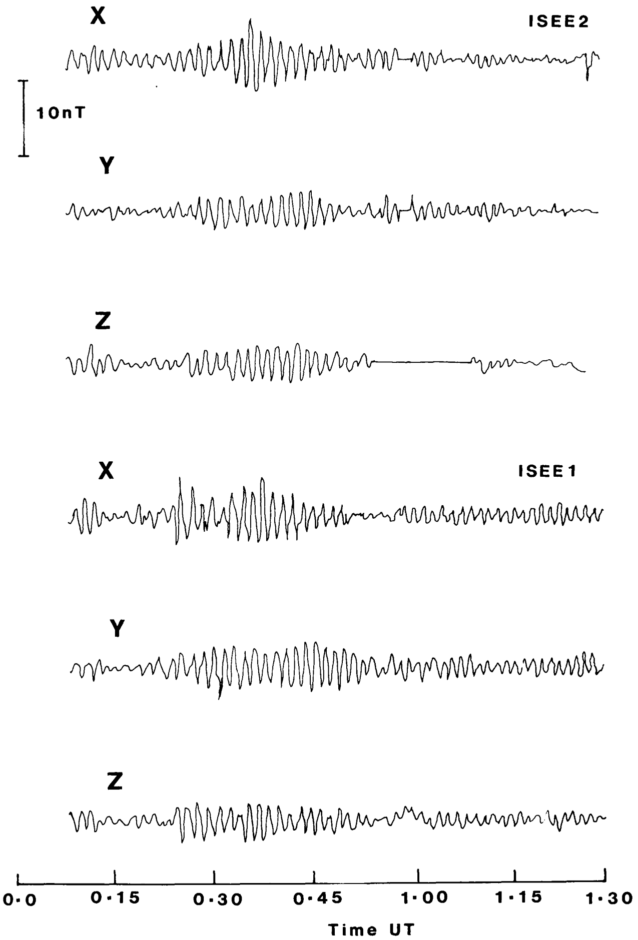

Fig. 1. The waveforms observed by the two spacecraft; X, Y and Z components in MFA coordinates. The data have been high pass filtered at 300 s

Figure 2 shows the wave ellipticities in the $X-Y$ plane and the amplitudes of the X and Y components for both spacecraft. ISEE 1 sees two ellipticity reversals, one at ~0.30 UT and the other at ~1.07 UT. The major point of interest is the difference in ellipticity between ISEE 1 and 2. During the interval 0.30–1.07 UT ISEE 1 observes right-hand polarized waves whereas ISEE 2 observes left-hand polarized waves. The two spacecraft are only 10 min apart in their orbits, which means that for the majority of this interval the two spacecraft observe waves of opposite ellipticity at the same point in space.

Another feature of interest in this event is that the wave period appears to be varying. Indeed complex demodulation shows that the period is in fact varying smoothly. Estimates of the observed wave periods at both satellites are shown in Fig. 3. Also shown is the second harmonic eigenperiod calculated at various times during this interval by Hughes and Grard (1984). Hughes and Grard have used data from the plasma measuring instrumentation on ISEE 1 to estimate the ambient plasma population and then used these estimates to scale the model field line eigenperiods calculated by Cummings et al. (1969).

Both ISEE 1 and 2 observe the same frequency in the X and Z components (see Fig. 3, *top two panels*).

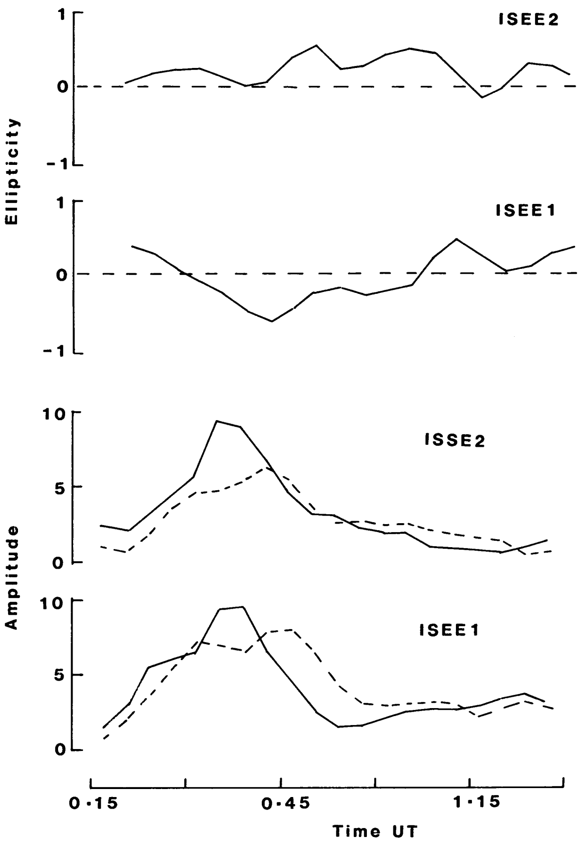

Fig. 2. Ellipticity and amplitude in the $X-Y$ plane. The *top two panels* show ellipticity: 1 and -1 represent left- and right-hand circular polarizations, respectively, 0 = linear polarization. The amplitudes are in arbitrary units, the *solid lines* represent the X components and the *broken lines* the Y components

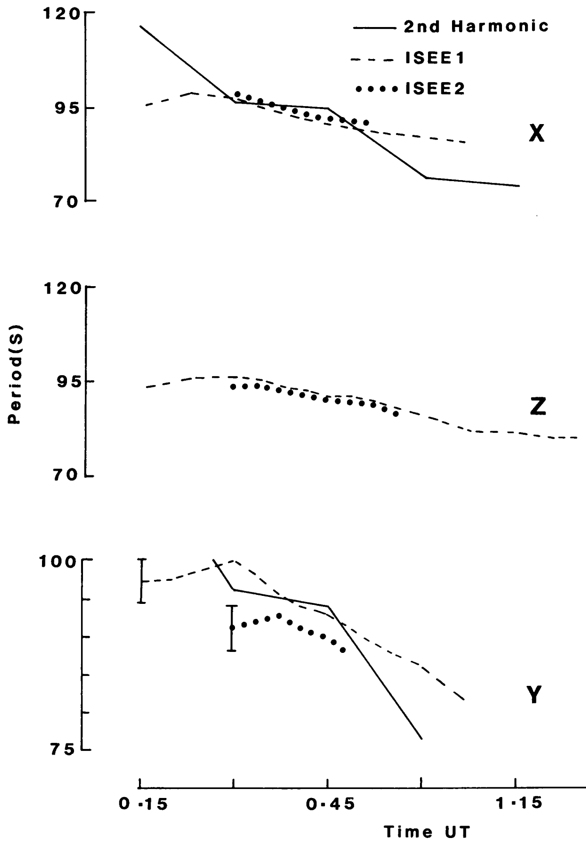

Fig. 3. The observed wave period versus time. The periods in the X and Z components are essentially identical. The *lowest panel*, showing the Y components, is plotted on an expanded scale to show the measured difference and expected error in the wave period.

Furthermore, in these two components the satellites see the same periods at the same time rather than at the same place. However, in the Y, or azimuthal, component it is possible that there may be some spatial structure (see Fig. 3, *bottom panel*); that is, the ISEE 2 curve follows the ISEE 1 curve if it is translated to the right by about 10 min, or the separation of the two spacecraft. The error in the calculated wave periods is 3 s, and so whilst the measured period at ISEE 1 is consistently higher than that measured at ISEE 2 the difference lies just within the error in the determination of the wave period.

This analysis suggests that the Y, or azimuthal, component may exhibit some spatial structure but is unable to demonstrate conclusively that such structure is indeed present. However, the analysis does show that the wave period is varying as a function of time and does show how this variation is observed by both spacecraft.

The morphology of the wave packet structure is shown in Fig. 2. These amplitudes are again calculated by complex demodulation. Both satellites encounter amplitude maxima simultaneously in each of the X and Y components, indicating that the packet structure is temporal rather than spatial. The X component maxima are at ~0.38 UT and the Y maxima occur some 7 min later at ~0.45 UT.

It has been assumed that the phase variations observed by the spacecraft were due to the variations in the ambient wave period. However, there are other factors which might cause variations in the demodulate phase. The spacecraft may be moving through a region where there is a spatially varying phase structure. Such spatially varying structure could occur for two reasons; there may be a resonance, in which case one would expect a 180° phase change, or the phase function of the wave may be modified by the motion of the observer through the inhomogeneous magnetoplasma.

If either of the spacecraft were to fly through a resonant region, then one would expect to see an abrupt phase change over the width of the resonance. At 0.00 UT ISEE 1 is at approximately $L=8.5$ and at 1.30 UT is located at approximately $L=6.5$, a difference of two L shells, or since the spacecraft are located near to the magnetic equator, approximately $2\,R_e$. Resonance widths at pc4 frequencies have been shown to be $\sim 0.6\,R_e$ (Hughes et al., 1978; Singer et al., 1982). During the interval 0.00–1.30 UT the variation of phase at both spacecraft is smooth and continuous; there is no abrupt change which might correspond to the spacecraft traversing a resonant region. Furthermore, the spacecraft separation is $\sim 0.3\,R_e$ with ISEE 2 leading ISEE 1. One would expect to see an abrupt change in the difference in phase between the two spacecraft as

ISEE 2 entered the resonant region first. No such abrupt phase changes are seen in any of the three wave components.

The other possible effect which must be considered is the possible modification of wave phase due to the motion of the spacecraft through the inhomogeneous magnetoplasma. If wave energy is to flow across field lines, there must be some fast mode or compressive disturbance. It is possible that the phase function of the waveforms could be significantly modified if the velocity of the observer or gradient of inhomogeneity were sufficiently large. Inhomogeneity in the magnetosphere occurs as a consequence of the non-uniform magnetic field and the gradient in plasma density.

The magnitude of this effect can be estimated from the ISEE data itself by considering the propagation of a wave of constant frequency through an inhomogeneous magnetosphere. To model the transmission of a wave through an inhomogeneous medium the WKB approximation can be used if the properties of the medium change only slightly over a wavelength. It may be assumed that the wavelength is of the order of the dimension of the plasmatrough. Over this region the wave phase velocity (Alfvén velocity) may vary by a factor of up to 50%. However, this is an upper limit as the wave is probably a second harmonic and may be more localized (see next section), which would improve the approximation. The approximation may not be a very good one but should be sufficient to obtain an order of magnitude estimate of the effect.

For a wave, propagating in the X direction, in a one-dimensional time invariant magnetosphere where the scale length of the inhomogeneity is of the order of the wavelength, then in the WKB approximation

$$\psi(x,t)=\frac{A}{\sqrt{k(x)}}\exp\left\{i\left(\omega t-\int_{x_0}^{x}k(x)\,dx\right)\right\}, \tag{3}$$

where A, x_0 are constants and

$$k(x)=\frac{\omega}{V_p(x)} \tag{4}$$

where $V_p(x)=$ phase velocity.
The frequency and wavenumber are defined by

$$\omega=\frac{\partial S}{\partial t},\quad k(x)=\frac{\partial S}{\partial x} \tag{5}$$

$$\text{where } S=\omega t-\int_{x_0}^{x}k(x)\,dx, \tag{6}$$

i.e. S is the phase function.
The observed frequency, though, is

$$\frac{dS}{dt}=\omega-\frac{d}{dt}\int_{x_0}^{x}k(x)\,dx. \tag{7}$$

For a moving observer $x=x(t)$ and so

$$\omega_{\text{obs}}=\omega-k(x)\cdot\frac{dx}{dt}. \tag{8}$$

The observed period depends only upon the frequency of the source and the ambient field and plasma in the vicinity of the spacecraft. If we allowed temporal as well as spatial inhomogeneity, then an additional term would be required in Eq. (8) which would involve a path integral from source to observer.

The phase velocity is, to a good approximation, the Alfvén velocity

$$V_A=\frac{B}{\sqrt{\mu\rho}}. \tag{9}$$

The ambient field, B, can be estimated from the ISEE 1 magnetic field data. The plasma density (ρ) is that derived by Hughes (personal communication).

The frequency shift is given by

$$\frac{\omega_{\text{obs}}}{\omega}=1-\frac{v}{V_A} \tag{10}$$

where v is the satellite velocity.

Assuming the satellite velocity to be constant and ~5 km/s, then the frequency shift due to spatial inhomogeneity amounts to 1.1% at 0.30 UT and 0.8% at 1.00 UT. The differential frequency shift between these two times is 0.3% and is insufficient to account for the observed period shift of some 10% between these two times. Therefore, the apparent shift in the observed wave period indicated by the behaviour of the demodulate can be attributed only to a shift in the ambient wave period.

Discussion

The curious feature of this event is the apparent anomaly in the wave ellipticities which is observed between the two spacecraft. If the two spacecraft simultaneously observe waves of opposite ellipticity, then one must be located equatorward and the other poleward of a resonant region. The ellipticity observations (Fig. 2, *upper two panels*) indicate that a resonance does indeed lie between the two spacecraft and remains between them for approximately 20 min. The implication of this is that the resonant region is propagating earthward at a similar velocity to the spacecraft. There is no simple spatial or temporal structure which could account for these observations.

However, complex demodulation has shown that the observed wave period is decreasing with time, and that this decrease is derived from the pulsation source rather than any structure within the magnetosphere. This could then explain the curious ellipticity observations. Resonance occurs where the driving wave period equals the field line eigenperiod (plus a small correction for damping). Normally, in the plasmatrough the field line eigenperiod increases with radical distance. Hughes and Grard (1984) show that this basic variation occurs during this particular interval, so in this case the region of resonance will propagate earthward as the driving wave period decreases. During the half-hour period from 0.30 UT the resonant region is not only located between the two spacecraft but is also propagating inwards with a similar velocity.

The nature of the source cannot be inferred from the magnetic field data alone. A Kelvin-Helmholtz instability at the magnetopause is unlikely since the event occurs so close to local midnight. The local time occurrence makes it much more likely that the pulsation is due to an energetic particle instability. Evidence exists that both mechanisms cause pulsation activity (Southwood and Hughes, 1983). Analysis of the ambient plasma population and calculation of the Poynting flux may allow the nature and location of the source to be identified. Detailed comments about the source mechanism are clearly beyond the scope of this paper, although the observation of the variation of the source period with time has important ramifications in our understanding of the mechanisms involved in the generation of pulsation energy.

The variation in source frequency explains the peculiar ellipticity observations and allows this and some of the other features to be explained in terms of the theory of field line resonance. Figure 3 also shows the model field second harmonic eigenperiod calculated by Hughes and Grard (1984). During the interval 0.30–1.00 UT the observed wave period agrees closely with the model eigenperiod. It is in this interval that the resonance lies between the spacecraft. This confirms that the calculated eigenperiod accurately reflects the spatial structure through which the spacecraft are moving. The spacecraft were inbound with ISEE 2 leading, so left-hand polarization indicates that the satellite is equatorward of resonance. Conversely right-hand polarization indicates that the spacecraft is poleward of resonance.

The spacecraft are located near to the magnetic equator, so the large perturbation wave fields indicate an even-mode harmonic. It has, in fact, been shown that this pulsation event is a second harmonic standing wave (Hughes and Grard, 1984). This is consistent with recent work which has shown that second harmonic pulsations are more common than originally believed (Singer et al., 1982).

At approximately 1.05 UT an ellipticity reversal occurs at ISEE 1 and from this time on, with the exception of one irregular point at ISEE 2, both spacecraft see left-hand polarized waves, indicating that both spacecraft are equatorward of resonance. Figure 3 shows that during this interval the wave period observed by ISEE 1 is higher than the calculated eigenperiod. This is consistent with the spacecraft being located equatorward of resonance. Figure 3, though, would indicate that this ellipticity reversal should occur earlier at approximately 0.55 UT, as it is at this time that the observed wave period first becomes significantly higher than the field line eigenperiod. However, the field line eigenperiod is derived from an idealized model and so the observed ellipticity reversal is a more reliable indicator of the position of the spacecraft relative to the resonance. The point of reversal is the point at which the wave becomes linearly polarized. There need not be any abrupt changes in wave parameters at this point because the demodulate phase variation is dominated by the change in wave period. From 0.40–1.10 UT the ellipticity observed by ISEE 1 changes slowly from nearly right-hand to nearly left-hand circular polarization. This is consistent with ISEE 1 flying with a very small velocity relative to a moving resonance, rather than flying through a stationary spatial structure.

Before 0.30 UT both spacecraft observe left-hand polarized waves. During this time one would expect both spacecraft to be poleward of resonance, and so to observe right-hand polarized waves. These observations cannot be explained by invoking the argument used so far to explain the ellipticity observations. It is possible that this inconsistency is due to the spacecraft encountering a region of convecting plasma or the presence of some other irregularity in the plasma population. It may also be possible that the field model (Cummings et al., 1969) is inaccurate at these larger radial distances ($L=8.5$ to $L=8.0$).

It is also evident from Fig. 3 that whilst both spacecraft see the same periods at the same time in the X and Z components, there is a measured difference in the periods seen in the Y components. It is unfortunate that this difference is not fully resolved within the error in the calculation in the wave period. It would only have been possible to determine conclusively whether this difference is a genuine effect or not if either the spacecraft separation or the gradient in field line eigenperiod were greater, so that the effect would have been more enhanced.

Previous studies of satellite data have shown that neighbouring regions of the magnetosphere can simultaneously support waves of different periods, or even waves of different types (see review by Singer, 1982, and references therein). As the period of the source varies it may impart some "shell" structure to the magnetosphere in that the magnetosphere may behave in the toroidal mode as a series of concentric shells each of which can respond as an independent harmonic oscillator (Poulter and Nielsen, 1982; Singer et al., 1982). Most energy is coupled into a field line when that field line is in resonance. When the period changes the point of resonance will shift accordingly, but the field line may retain significant amounts of energy at its resonant period. If this resonant energy in the toroidal mode decays away sufficiently slowly, then a transient spatial structure could be set up with each field line oscillating at its own eigenperiod. The period-time curve for the Y component at ISEE 2 most nearly matches that for ISEE 1 if it is translated to the right by approximately 10 min so that the observed periods align by spacecraft position rather than time (see Fig. 3, *bottom panel*). If the measured difference were significant, then this would be evidence of such spatial structure.

There was also some pulsation activity seen on the ground in the conjugate sector of the magnetosphere, on the IGS UK and Scandinavian magnetometer arrays. Activity is seen at Reykjavik ($L=6.4$), Eidar ($L=6.7$) and less distinctly at Tromsö ($L=6.2$). These data are not presented in detail here because there is no direct correlation with the ISEE data. At Reykjavik and Eidar there is strong continuous pulsation activity in the east-west and vertical field components. Two wave packets are observed, one from 0.00–0.30 UT and one from 0.45–1.15 UT. During the first interval the wave period was found (by complex demodulation) to be 80 s at Eidar and 72 s at Reykjavik. During the second interval the period was found to be 96 s at both stations. Both wave packets at both stations showed no temporal variation in period.

The amplitude maxima occur when there is no distinguished activity observed by the ISEE spacecraft and, moreover, the wave periods observed on the ground are different from those observed at the same time by the ISEE spacecraft. It can only be assumed from this lack of correlation that two distinct events are being witnessed and this is an example of two neighbouring regions in the magnetosphere supporting disparate pulsation activity.

Conclusions

This pulsation event, seen by ISEE 1 and 2, exhibits some curious and interesting features. Spatial and temporal affects combine to create ambiguities which must be resolved before a clear picture of what is happening can be formed. In this paper analysis of the data from the ISEE 1 and 2 magnetometer experiments using complex demodulation is presented. This technique is able to track the dominant spectral component as it changes in time. Apparent anomalies in the observed wave parameters can be explained by using time-local estimates of wave parameters to isolate temporal from spatial effects.

The wave observations can be accounted for by the theory of field line resonance, although there are some anomalous observations which cannot be satisfactorily explained. The frequency of the source is found to be varying with time, and it is suggested that this may give rise to some spatial structure within the magnetosphere.

This event, whilst probably not typical of events seen on the ground, gives some insight into the nature of pulsation sources and processes occurring in the magnetosphere in and around a resonant region.

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