THE SPATIAL CHARACTERISTICS OF LOW LATITUDE Pc 3 GEOMAGNETIC PULSATIONS

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Abstract: An array of four low latitude induction coil magnetometer stations has been used to study Pc 3 interstation phase variations and polarization characteristics over a longitudinal range of 17° at $L=1.8$ and a latitudinal range of 10° from $L=1.8$ to 2.7. Five days of data recorded between March 25–30, 1982 have been analysed. The east-west chain shows generally highest coherency between north-south field components with relatively small interstation phase differences corresponding to low azimuthal wave numbers in the range $|m_{x,y}| \lesssim 6$. The north-south stations show greatest coherency between the east-west field components and slightly higher wave numbers. Azimuthal wave propagation is towards the west in the morning and is associated with left-hand polarization. In the afternoon propagation is eastwards and the waves are right-hand polarized. Propagation in the latitudinal direction is always towards the south, away from the equator. These results are interpreted in relationship to wave source models and it is concluded that they are consistent with generation by field line resonances situated at $L>3$.

1. Introduction

Observations of geomagnetic pulsations at low latitudes ($L<3$) indicate that significant hydromagnetic wave energy penetrates deep into the magnetosphere and the plasmasphere. Statistical studies carried out in the past show that wave energy at low latitudes is primarily in the Pc 3 frequency band (SAITO, 1969; JACOBS, 1970; ORR, 1973). However the origin of these waves has not been established and it is important to determine whether they are generated within or external to the magnetosphere and to identify their generation mechanism.

It is generally accepted that some of the dayside Pc 3 pulsation energy is associated with sources external to the magnetosphere. Statistical studies show that the Pc 3 wave period is strongly correlated with the magnitude of the interplanetary magnetic field while the pulsation occurrence rate is dependent on the orientation of the interplanetary magnetic field (GREENSTADT *et al.*, 1980). Direct evidence for the propagation of external Pc 3–4 wave power into the magnetosphere has been presented by GREENSTADT *et al.* (1983) who show that similar wave frequencies are observed simultaneously by ISEE-1 and ISEE-2 spacecraft in the magnetosheath and the outer magnetosphere respectively. Lower power is seen within the magnetosphere. In contrast to the external source, waves generated within the magnetosphere must originate from instabilities or free energy sources.

Combined studies of spatial and temporal variations in Pc 3 pulsation wave polarization and phase are of vital importance because they are capable of identifying properties which may be related to hydromagnetic wave generation mechanisms. For example, at high latitudes Pc 4–5 polarization rotation changes from left-hand (LH) in the morning to right-hand (RH) in the afternoon (SAMSON *et al.*, 1971) in association with waves propagating away from the noon meridian towards the dawn and dusk terminators (OLSON and ROSTOKER, 1978). These results are consistent with the coupling of Kelvin-Helmholtz instability wave energy to field line resonances in the magnetosphere (CHEN and HASEGAWA, 1974; SOUTHWOOD, 1974). A similar diurnal polarization pattern is seen in Pc 3–4 waves at middle latitudes in the vicinity of the plasmapause (LANZEROTTI *et al.*, 1974) but azimuthal phase relationships are complicated and show no simple pattern (GREEN, 1976; MIER-JEDRZEJOWICZ and SOUTHWOOD, 1979, 1981).

There have not been many wave polarization and phase propagation studies carried out at low latitudes ($L \approx 2$). It has been established that the polarization rotation sense is the same as that observed for Pc 3–5 waves at higher latitudes, namely LH in the local morning and RH in the afternoon (ZELWER and MORRISON, 1972; KUWASHIMA *et al.*, 1979; LANZEROTTI *et al.*, 1981). The northern hemisphere ellipse major axis azimuth direction is in the NW-SE quadrants prenoon and spread over all quadrants in the afternoon (LANZEROTTI *et al.*, 1981). A diurnal pattern of longitudinal interstation phase difference was observed at $L=2.3$ by HERRON (1966) who showed that the station nearer the dark hemisphere usually led in phase. The magnitude of the phase lags was found to be a function of wave period. There have not been any other diurnal phase studies reported at low latitudes and the present study attempts to identify Pc 3 phase and polarization patterns which will lead to the identification of a generation mechanism. A recent but independent study of Pc 3–4 phase

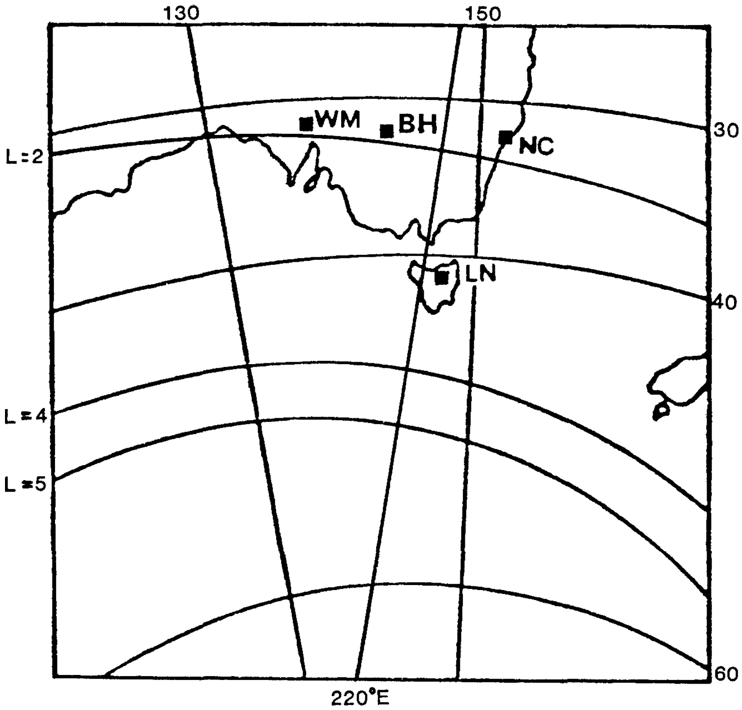

Fig. 1. The University of Newcastle Pc 3 recording station network.

Table 1. Station locations and interstation distances.

	Station locations Geomagnetic Latitude (°S)	Longitude (°E)	L value
Newcastle (NC)	42.0	226.3	1.81
Broken Hill (BH)	42.4	214.5	1.81
Woomera (WM)	41.7	209.1	1.79
Launceston (LN)	52.4	231.1	2.69
	Interstation distances (km)		
WM–BH	425		
BH–NC	1065		
WM–NC	1485		
NC–LN	1120		

variations at middle and low latitudes has been undertaken by Saka (private communication, 1984).

An array of four two component Pc 3–4 induction coil magnetometers was established in South-East Australia to study interstation polarization and phase characteristics (Fraser *et al.*, 1980). The array is shown in Fig. 1 and station locations and interstation distances are listed in Table 1. It can be seen that a geomagnetic longitudinal range of 17° is covered at $L=1.8$ and a latitudinal range of 10° over $L=1.8$ to 2.7.

2. Data and Analysis

The north-south (X) and east-west (Y) components of Pc 3–4 wave signals over a bandwidth of 10–100 mHz were recorded onto slow-speed frequency-modulated analogue magnetic tape along with a 5 s pulse time channel. Accurate timing was provided by chronometers with an accuracy of 10 ms day^{-1}. Data were later digitized in the laboratory with a 5 s sample rate using the recorded time channel pulses and providing a Nyquist frequency of 100 mHz. The resulting $X(t)$ and $Y(t)$ time series for each station were used to calculate dynamic spectra over one day intervals using the FFT algorithm on 10 min subsets overlapping by 5 min and plotted using grey-scale techniques as illustrated in Fig. 2. Wave polarization parameters in the plane of the earth's surface were calculated from smoothed spectral densities using coherency matrix techniques. Information was obtained on auto-power spectra, ellipticity, major axis azimuth direction and the percentage polarization which is the ratio of the polarized power to the total power in the signal. Interstation cross-spectral parameters, namely the cross-phase spectrum and the coherency were calculated using corresponding $X(t)$ and $Y(t)$ data from pairs of stations. The phase results were used to calculate the wave numbers m_x and m_y for selected frequency bands centred on spectral peaks in the Pc 3 band. The angular wave number m value is defined as the phase difference (in degrees) between two stations divided by the longitudinal or latitudinal station spacing (in degrees).

Five days of two component Pc 3 data from the four stations between March 25–30, 1982 were analysed in detail. Magnetic activity over these days ranged from

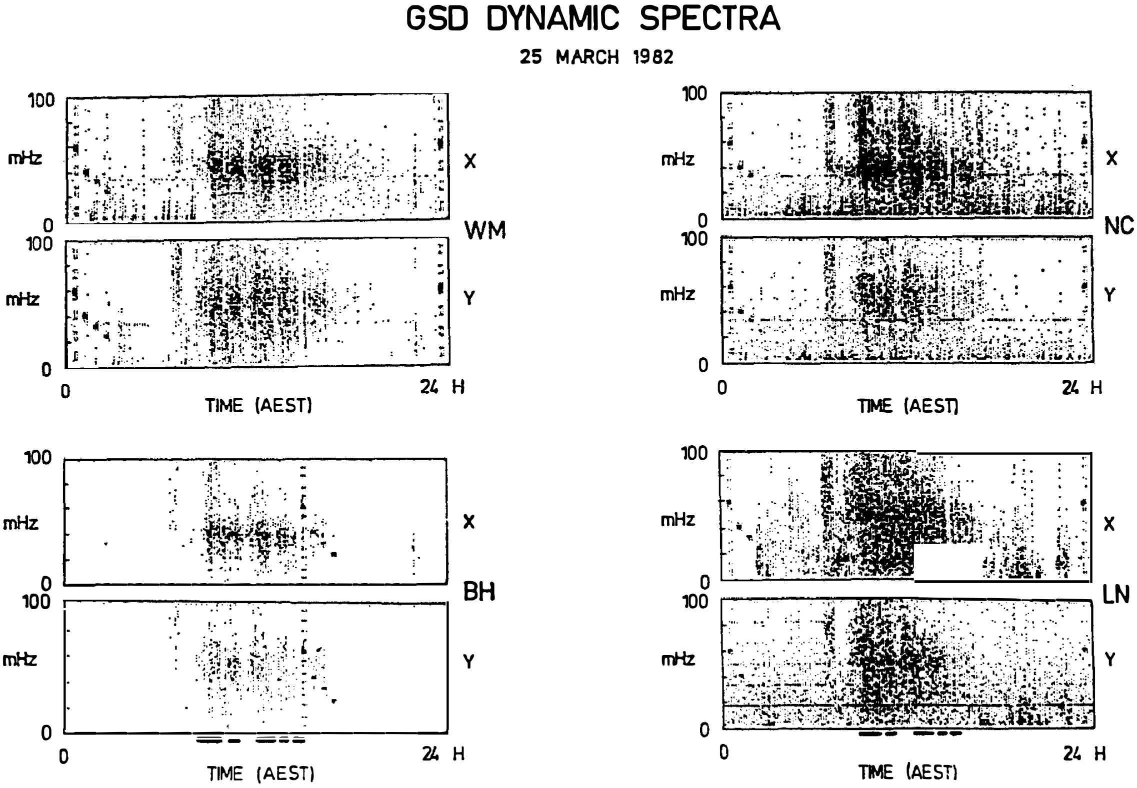

Fig. 2. Dynamic grey-scale spectra showing Pc 3 activity on March 25, 1982. The segments marked with a horizontal line on the time axis have been analysed in detail. Calibration signals commence twenty minutes past local midnight and are seen at each end of the spectra at WM, NC and LN. Continuous horizontal lines in the spectra are interference.

$\Sigma Kp=11$ to 28. These days were the first analysed at the beginning of the recording interval and were not chosen for any special characteristics. Using auto- and cross-spectra the data were organized into frequency bands showing continuous Pc 3 activity over time segments varying in duration from 10 to 90 min. The results of the polarization and phase analyses from all five days show similar characteristics and only one day, March 25 which was moderately disturbed with $\Sigma Kp=28$ will be considered in detail. The dynamic grey-scale spectra for this day on the X and Y components at all four stations are illustrated in Fig. 2. Five time segments during the daytime hours were analysed in detail and these are indicated by the horizontal lines on the time axes in Fig. 2. Continuous Pc 3 activity occurred between 0845 and 1615 h AEST. Australian Eastern Standard Time (AEST) is 150° meridian local time and AEST=UT+10 h. The longitudinal stations (WM, BH and NC) show a constant frequency all day centred around 40 mHz. Activity is more variable at LN where a higher frequency band centred around 50 mHz and of greater intensity than the 40 mHz band is also observed. The Y component shows broader spectra at all stations and this power level is lower than that of the corresponding X component.

3. Wave Polarization

Polarization parameters from the first time segment on March 25, 1982 between

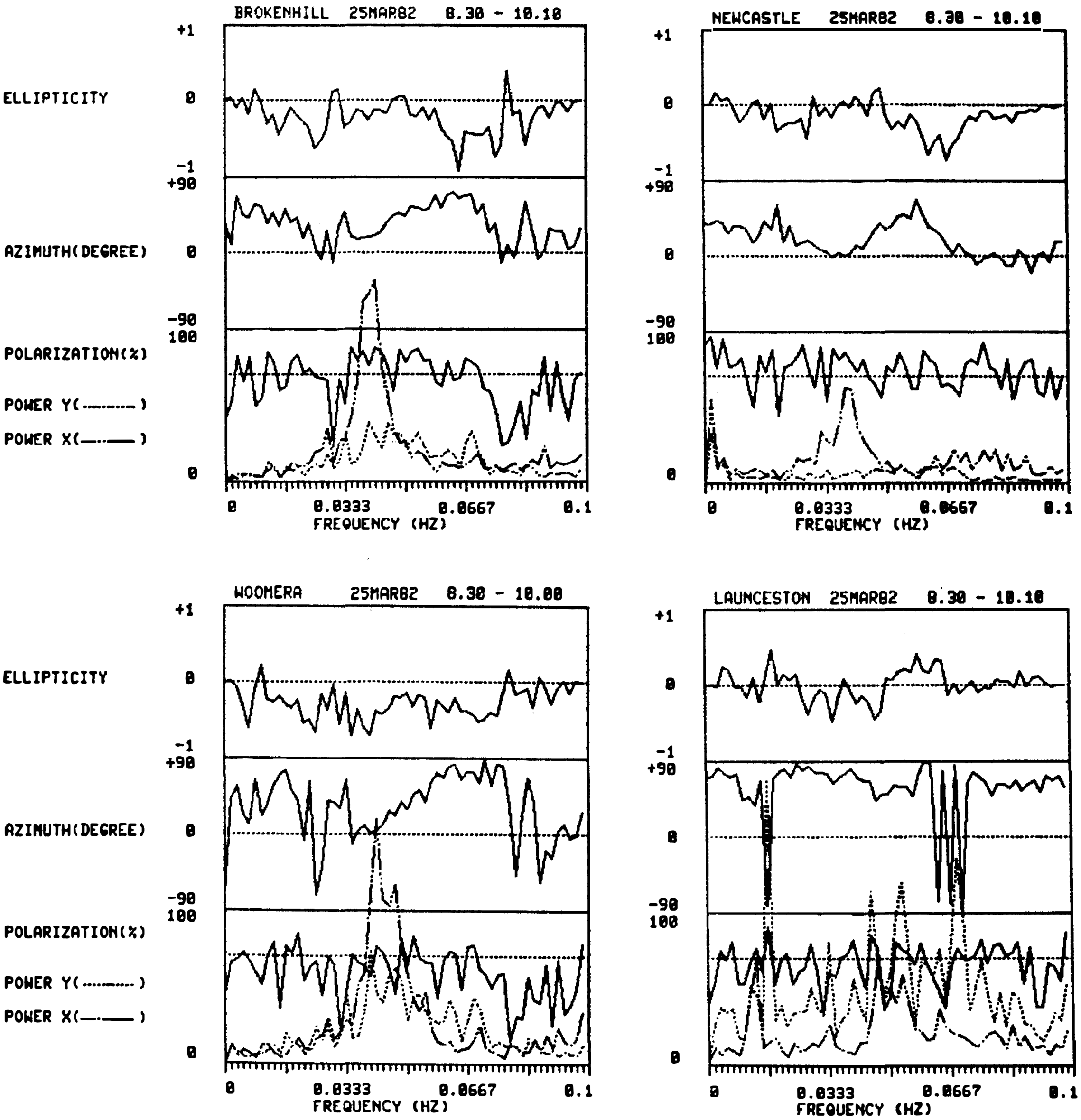

Fig. 3. Polarization parameters from 0830–1010 h AEST, March 25, 1982 at WM, BH, NC and LN. Noise spikes are present in the LN(Y) spectra at 10 mHz and 63–70 mHz. Positive (negative) azimuth angles indicate major axes in the north-east (north-west) quadrant. Positive (negative) ellipticity indicates RH (LH) polarization.

0830–1010 h AEST are plotted in Fig. 3. Polarization ellipticity and azimuth results were considered reliable if the percentage polarization exceeded 70% and significant power was seen in the auto-spectra. It should be noted that the auto power plots in Fig. 3 are normalized to peak X component power at each station and therefore the scales are different in all panels. At a given station, however, the same scales are used for X and Y data. It can be seen from Fig. 3 that ellipticity and azimuth variations with frequency are similar at the three longitudinal stations WM, BH and NC. Ellipticity is generally negative (LH) in the 40 mHz band at WM, BH and LN and near zero at NC. The azimuth angles are all positive (NE quadrant) at all

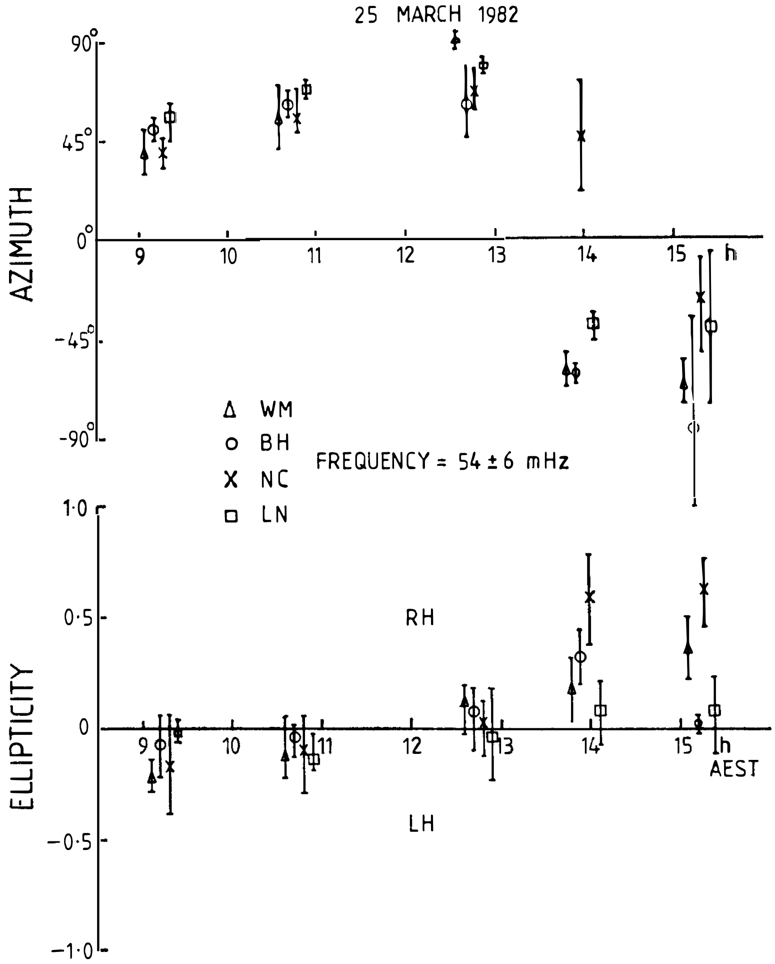

Fig. 4. Diurnal variation in polarization azimuth and ellipticity for March 25, 1982 at WM, BH, NC and LN in the 48–60 mHz band. Positive (negative) azimuth indicates a major axis in the NE (NW) quadrant. Error bars indicate the standard deviation.

stations. Four frequency bands which showed peaks in the auto- and cross-power spectra, namely 27–33, 35–47, 48–60 and 60–70 mHz were selected for diurnal variation studies. Results from the 48–60 mHz band for the five daytime data segments identified in Fig. 2 are plotted in Fig. 4. Individual data points plotted for each station are the average values calculated over all data points in the time segment and are located at the centre of the segment. It can be seen that all wave ellipticities are generally low (≤ 0.5) and polarization is LH prior to noon and RH after noon with a wider spread. Major axis azimuth directions are well grouped and in the NE quadrant before 13 h AEST and, with the exception of NC, change to the NW quadrant with greater variability after 13 h. NC changed azimuth somewhat later after 14 h AEST.

4. Interstation Comparisons

Interstation comparisons using cross-spectral analysis were carried out on WM–BH, BH–NC and WM–NC station pairs to give longitudinal or azimuthal wave

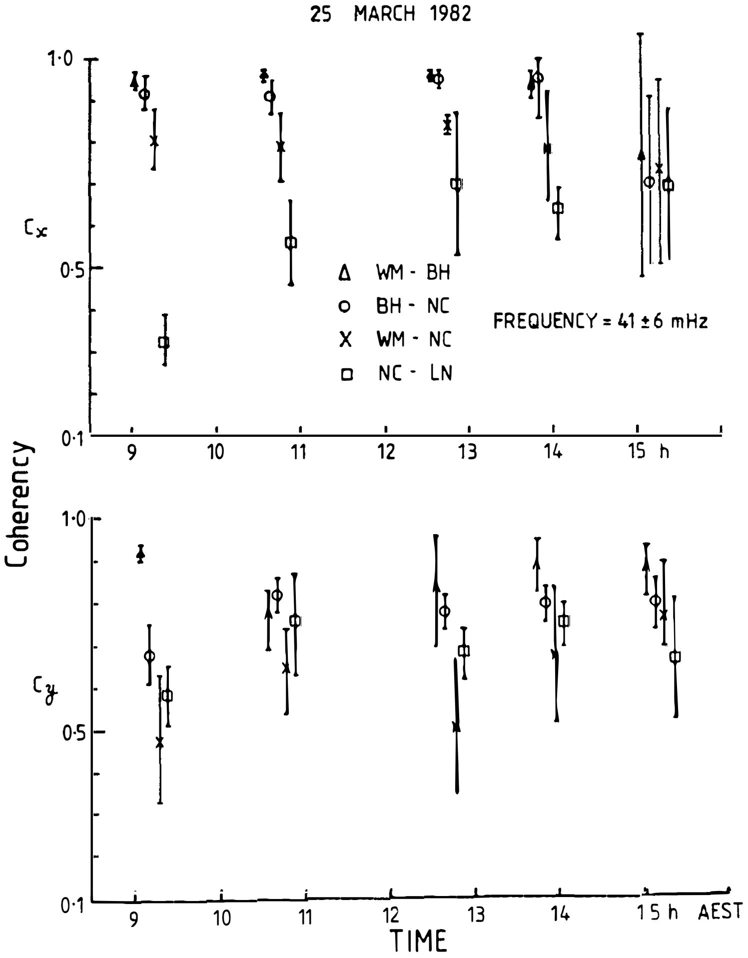

Fig. 5. Interstation wave signal coherency between the indicated station pairs in the 35–47 mHz band on March 25, 1982. Error bars indicate the standard deviation.

properties and on the NC–LN pair to give latitudinal wave properties. Signal coherencies for the X and Y components for these station pairs over the five time segments in the 35–47 mHz band are shown in Fig. 5. Longitudinal coherencies are generally higher than latitudinal coherencies. It can be seen that for longitudinal station pairs the coherency is greater on the X component than the Y component. The reverse is the case, at least during morning hours for the NC–LN latitudinal pair. These results, showing greatest coherency between components perpendicular to the station line are in agreement with the 90° rotation of the Pc 3 waves by ionospheric transmission from the magnetosphere to the ground (Hughes, 1974; Hughes and Southwood, 1976).

Figures 6a and 6b show cross-spectral phase coherency, cross-power and auto-power spectra at pairs of stations for X and Y components in the 1210–1330 h AEST interval on March 25, 1982. Phase data was considered significant for $C_{x,y} > 0.5$ averaged over the signal band. Phases were checked for aliasing using the three longitudinal stations and in all cases the sum of the WM–BH and BH–NC phases were equal to the WM–NC phase. It is important to note from Fig. 6 that Y component coherency is high over a wide band from 25 to 80 mHz even though signal power is often very low. The

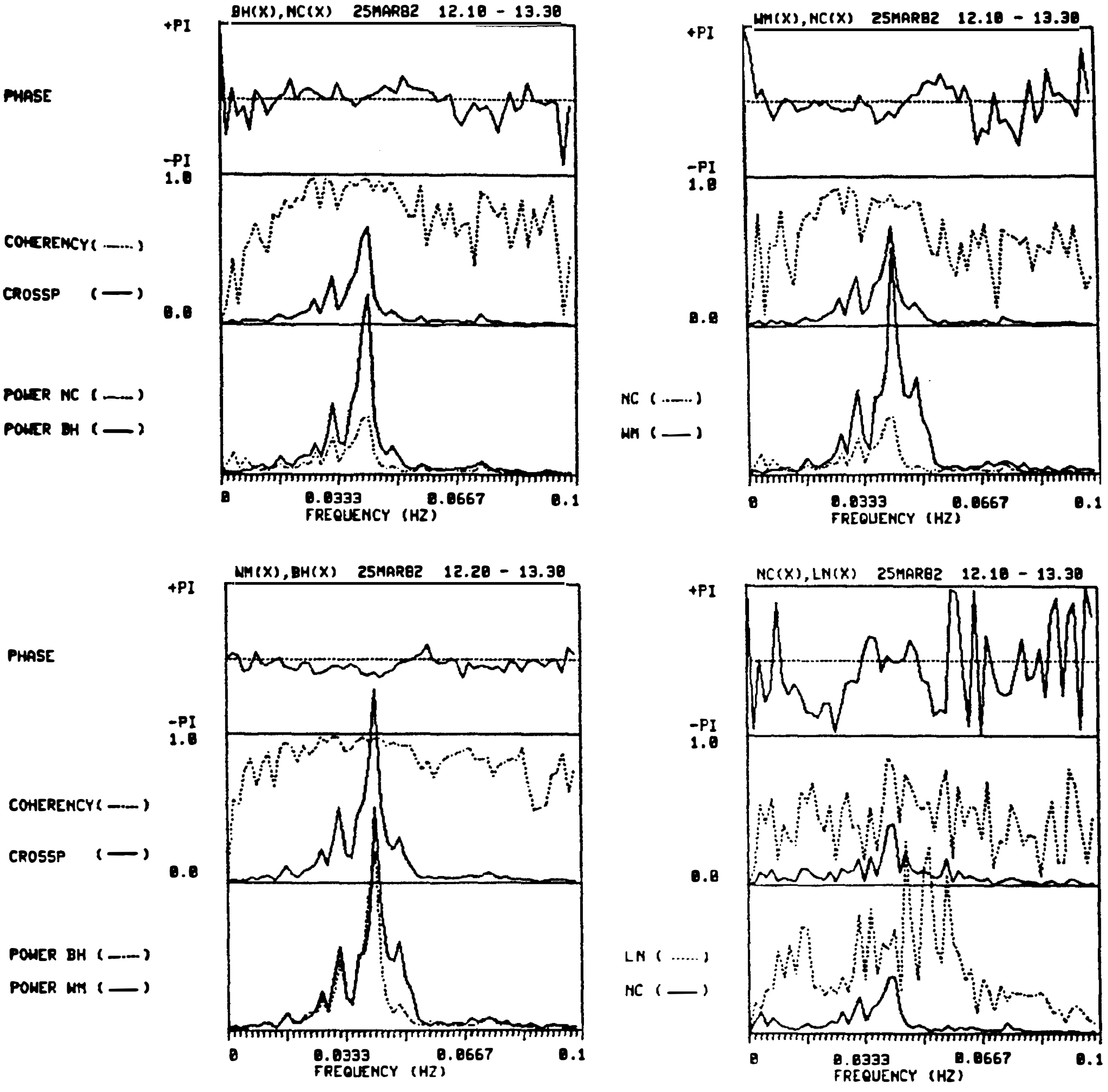

Fig. 6a. X component data.

Figs. 6a, b. Cross-spectral analysis for March 25, 1982 between 1210–1330 h AEST. Interference is present on the LN Y component at 10 and 30 mHz.

autospectral plots here also illustrate the independence of the X and Y components. For example while both components at WM show spectral peaks at 30, 42 and 48 mHz there are also significant Y component peaks at 35, 55 and 62 mHz and an additional lower frequency X component peak at 25 mHz. This independence of X and Y spectra is often seen in the data and may indicate decoupling of toroidal and poloidal wave modes (ORR, 1973).

The wave numbers m_x and m_y were determined for each pair of stations in all five time segments over the four frequency bands used in the polarization analysis. The results for the 48–60 mHz band are shown in Fig. 7. The azimuthal wave numbers are low generally and in the range $|m_{x,y}| \lesssim 6$ indicating long azimuthal wavelengths. Wave numbers are more ordered on the Y component and waves appear to propagate

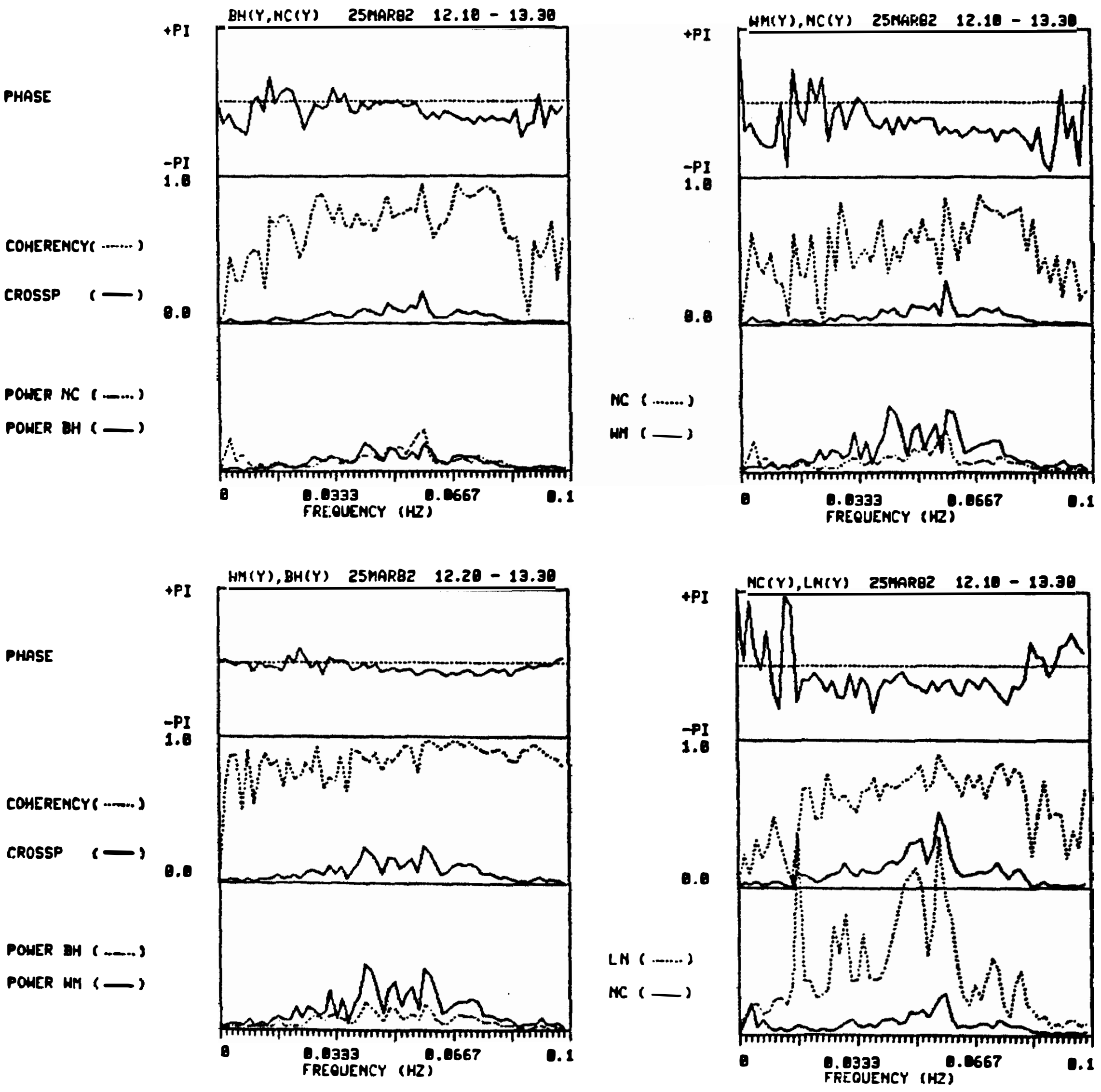

Fig. 6b. Y component data.

westwards in the morning and eastwards in the afternoon with zero wave number around 11 h AEST. On the X component the data are more variable with the reversal much later near 14 h. The Y component latitudinal wave numbers are similar in magnitude to azimuthal values but the X component shows much greater wave number magnitude with $|m_x|=6$ to 12. The latitudinal wave numbers are negative at all times indicating north to south propagation, away from the equator.

5. Wave Number and Ellipticity

The relationship between wave polarization ellipticity and azimuthal wave number is important as it provides information which may be used to identify Pc 3 wave generation and resonance mechanisms. Ellipticity as a function of wave number for all four stations on March 25, 1982 are plotted in Fig. 8 for the 48–60 mHz band. For

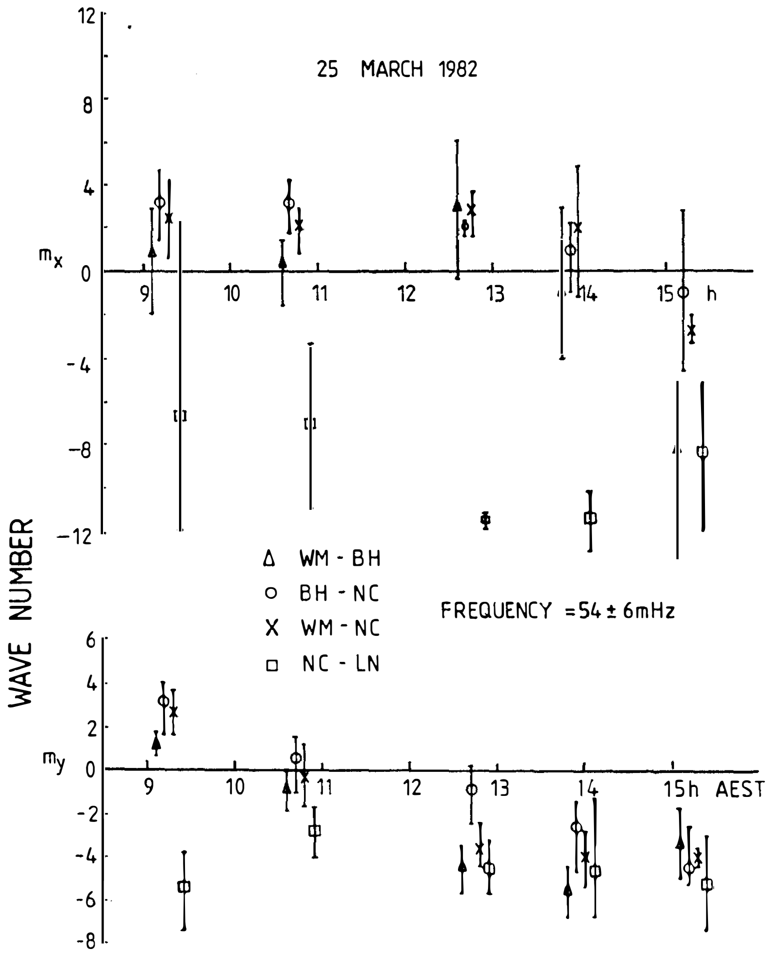

Fig. 7. The diurnal variation in the latitudinal wave number (m_x) and the azimuthal wave number (m_y) for the five time segments in the 48–60 mHz band on March 25, 1982. For azimuthal wave numbers positive values indicate westward propagation. For latitudinal wave numbers positive values indicate northward propagation. Error bars indicate the standard deviation of the mean of each plotted point.

Table 2. Azimuthal wave number–ellipticity relationships.

	Prenoon	Afternoon	
Ellipticity Propagation	LH Westward	RH Eastward	ΣKp
March 25, 1982	75%	72%	28
March 26	67	50	21
March 27	67	83	22
March 28	58	70	11
March 30	67	75	22

the longitudinal stations there is a predominance of negative (eastward) wave numbers associated with positive (RH) ellipticity (13 out of 18 cases) in the afternoon and positive (westward) wave numbers associated with negative (LH) ellipticity (9 out of 12 cases) in the morning. For the latitudinal NC–LN station pair wave numbers are always negative while the polarization rotation reverses from negative to positive near

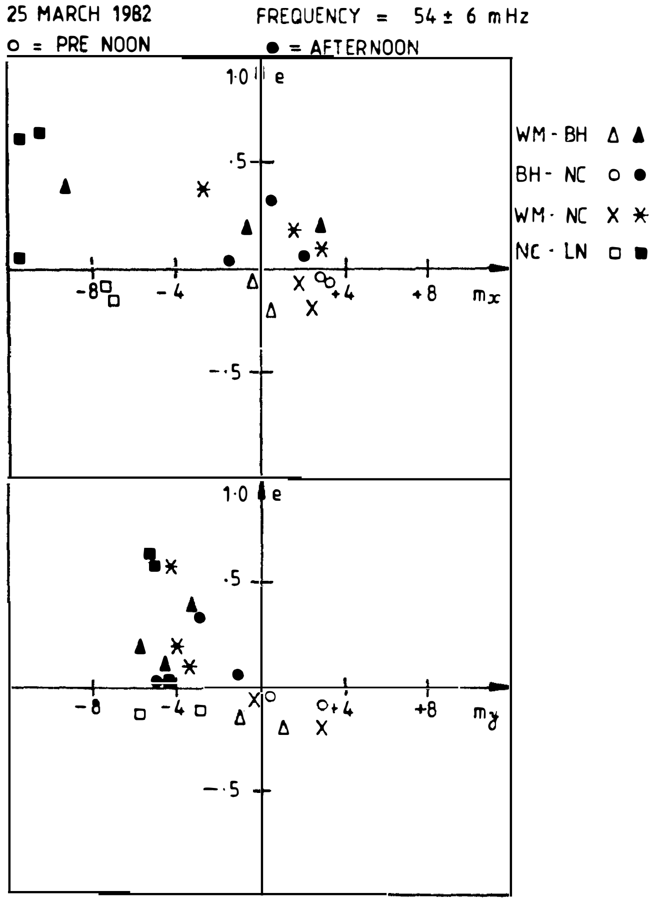

Fig. 8. *The relationship between polarization ellipticity and wave numbers m_x, m_y. Ellipticities plotted are those for the first mentioned station of each pair used in the wave number calculation.*

noon.

The data from all frequency bands on each of the five days analysed are summarized in Table 2 and the results are in general agreement with those illustrated in Fig. 8. The diurnal pattern is seen on days of both high and low magnetic activity. Often the standard deviations calculated over data segments are smallest on days with low magnetic activity. The wave number and ellipticity are near zero and variable around local noon (Figs. 4 and 7) and the reversal in these two parameters could be at any time between 11 and 13 h. Furthermore the ellipticity and wave numbers do not necessarily all switch sign at the same time.

6. Discussion and Conclusions

The wave polarization results illustrated in Fig. 4 and Table 2 indicate LH ellipse rotation in the morning accompanied by major axis azimuth directions in the NE quadrant. In the afternoon RH ellipse rotation is seen and azimuth directions generally change to the NW quadrant. Similar results have been found at low latitudes in a variety of previous studies (Prinkner *et al.*, 1972; Zelwer and Morrison, 1972;

KUWASHIMA *et al.*, 1979; LANZEROTTI *et al.*, 1981). Azimuthal wave numbers at low latitudes (Fig. 7) were found to be low on both the X and Y components and in the range $|m_{x,y}| \lesssim 6$. These are in agreement with the generally low middle latitude Pc 3–4 wave numbers found by HERRON (1966) and MIER-JEDRZEJOWICZ and SOUTHWOOD (1979, 1981) and relate to phase velocities in excess of 500 km s^{-1} and wavelengths greater than 12000 km. In contrast to these results OLSON and ROSTOKER (1978) found Pc 4–5 azimuthal phase velocities of 14 km s^{-1} at high latitudes and related them to the Kelvin-Helmholtz instability. Latitudinal wave numbers are also low with $m_{x,y} = -3$ to -12 indicating north to south propagation away from the equator.

The association of LH wave polarization with westward propagation in the morning and RH polarization with eastward propagation in the afternoon is an important property established by the present study and is considered to be related to the source characteristics of Pc 3 waves observed at low latitudes. Recent studies of waves in the Pc 3 band in the interplanetary magnetic field, the outer magnetosphere and on the ground suggest that some of the daytime energy seen on the ground is produced by sources external to the magnetosphere (GREENSTADT *et al.*, 1983; TOMOMURA *et al.*, 1983; YUMOTO *et al.*, 1985). It has been suggested by YUMOTO and SAITO (1982, 1983) that waves with a significant compressional component propagate deep into the magnetosphere and couple to field line reasonances. ARTHUR *et al.* (1977) have shown that radial Pc 3 events observed by ATS-6 have a significant compressional wave component. However, TAKAHASHI and MCPHERRON (1983) have since found that the radial events are artifacts in the data. More recently TOMOMURA *et al.* (1983) using ISEE data found that compressional oscillations dominate in the magnetosheath around local noon but transverse waves are seen in the magnetosphere. Further spacecraft observations are therefore required in order to confirm the existence of propagating compressional Pc 3 waves within the magnetosphere.

If it is assumed that significant Pc 3 wave energy can penetrate to $L<4$ at low latitudes then there are three possible resonance mechanisms available for wave generation (DOOBOV and MAINSTONE, 1973; YUMOTO and SAITO, 1983). These are collective transverse surface wave eigen oscillations at the plasmapause (L_{pp}); fundamental toroidal mode standing oscillations at $L=1.1$ and $L=1.7$–2.6 and higher order harmonics at $L=2.0$–L_{pp}; and trapped fast mode oscillations in the equatorial plane between the two peaks of the Alfvén velocity at $L=1.7$–L_{pp}. The trapped fast mode oscillations may explain the Pc 3 waves around noon where azimuthal wave numbers $m_{x,y} \approx 0$ but it is difficult to see how they can explain the observed diurnal ellipticity-wave number pattern. The toroidal field line resonance mechanism of CHEN and HASEGAWA (1974) and SOUTHWOOD (1974) appears to be the favoured candidate to explain the present results. In this mechanism the wave polarization characteristics depend on the azimuthal wave propagation direction and the theoretical predictions for a source south (polewards) of the present network agree with the pattern observed in Table 2. Latitudinal wave propagation away from the equator has also been observed by HERRON (1966) and ZELWER and MORRISON (1972) and is in agreement with field line resonance theory. The observation of larger phase variations in the north-south (X) component compared to the east-west (Y) component shown in Fig. 7 is also a property of field line resonance (HUGHES and SOUTHWOOD, 1976). Of the mechanisms suggested by YUMOTO and SAITO (1983). oscillations at the plasmapause or toroidal field line resonance at $L \gtrsim 3$ may best describe the Pc 3 energy source.

Although consideration of the present results favours field line resonance as the mechanism producing Pc 3 waves at low latitudes with the source situated at a higher latitude than the network ($L>3$), the relationship of this source to the plasmapause has not been established. However it is considered that a more detailed study of the present data in light of theoretical predictions will provide additional Pc 3 source properties.

Acknowledgements

This research was supported by grants from the Australian Research Grants Scheme and the University of Newcastle. One of us (I.A.A.) was partly supported by a University of Newcastle Post-graduate Scholarship. The symposium paper presentation was made possible by an exchange visit travel grant from the Australian Academy of Sciences and the Japanese Society for the Promotion of Science.

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(Received May 15, 1984; Revised manuscript received August 23, 1984)