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On some spatial characteristics of ULF pulsations in the Indian region

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Abstract

Employing digitally recorded data on geomagnetic pulsations from a three latitudinal chain of stations in the Indian longitudinal region, spatial characteristics of Pc 3-4 (Frequency ranges, 10 to 100 mHz) are reported. Different techniques of analysis on the three identified frequency bands of the pulsation signals have been used. In the lowest frequency band (10 to 22 mHz), the amplitudes of the signals, in both NS and EW directions in the horizontal plane, are seen to be decreased at the station farthest away from the equatorial electrojet influence as well as at the station close to Sq focus. The cross phase (or time delay) between the latitudes of extreme northern and southern stations, estimated through the gradient technique, has yielded two frequencies, one at 35 mHz and the other at 50 mHz. The validity of the 35 mHz cross phase is discussed in terms of excitation by a broad band source and propagation of signals through the cavity resonance mode at low and equatorial regions. The configuration of three NS- chain of stations network only permits estimation of latitudinal disposition with reference to propagation of wave energy. The latitudinal location of the stations with respect to the FLR phase response is found to be highly variable (m_x or m_y values lying between 3 and 12) and the propagation is inferred to be mostly directed away from the equator. Some hodograph results illustrating wave polarization are presented and discussed.

Introduction

Ultra Low Frequency (ULF) waves, also known as geomagnetic pulsations, can basically be classified into two groups. One is 'exogenic' pulsations of external sources to the magnetosphere which are continuously driven by the solar wind. The other is 'endogenic' pulsations which are excited mainly by transient and abrupt changes of ambient magnetized plasma and/or the free energy stored in the earth's magnetosphere (Yumoto, 1986). A significant part of exogenic Pc 3 pulsations (frequencies, 100 to 22 mHz) observed in daytime is in someway a function of the solar wind. It has been demonstrated that daytime Pc 3 pulsations assume an important role in communicating the solar wind energy into the inner magnetosphere, which is of vital importance in understanding the physics of important aspects of the solar wind- magnetosphere interaction.

It is generally accepted that there are two candidates of primary exogenic sources for daytime Pc 3-4 (10 - 100 mHz) pulsations. One is surface waves excited by the shear flow (Kelvin- Helmholtz type) instability driven by the solar wind at the day-side high latitude magnetosphere boundary (Miura, 1984; Yumoto, 1985). The other is the bow-shock wave phenomenon associated with particle reflected and/or accelerated by the bow-shock (Russel and Hoppe, 1983). However, the Pc 3 pulsations are seen as ground signatures of FLR at low latitudes, it is difficult to see how these waves are associated with surface waves at the day side high latitude magnetopause because of the high damping rate of the waves which attenuates the signals propagating into the middle magnetosphere in the radial direction. Lanzerotti et al. (1981) proposed a possible mechanism to obtain low-latitude waves without excessive damping for excitation by disturbances produced in the magnetospheric cusp, and suggested that these cusp disturbances would propagate to lower latitude via the ionosphere. While studying the roll of the ionosphere in coupling upsteam ULF wave power into the dayside magnetosphere, Engebretson et al. (1991) have shown clear interplanetary magnetic field magnitude control of dayside resonant harmonic pulsations and band-limited very high latitude pulsations, as well as pulsation- modulated precipation of what appear to be magnetosheath/ boundary layer electrons. They have postulated that the modulated precipitation may be responsible for the propagation of upstream wave power in the Pc 3 frequency band into the high latitude ionosphere, from where it may be transported throughout the dayside magnetosphere by means of an ' Ionospheric transistor'. The magnetosonic upstream waves in the 15-100 mHz range that are excited by the reflected ion beams in the earth's foreshock and are transmitted into the magnetosphere without significant changes in spectra have been accepted for their endurance (or maintenance). The impulse at the magnetopause is believed to generate compressional cavity mode resonances and the transmitted Pc 3-4 waves are the main sources of low- latitude pulsations (Wolfe et al., 1985; Yumoto et al., 1985). Thus, Many theories are proposed and modified on ULF wave in Pc 3 class.

As there is a large gap of observational studies in these classes of pulsations at a very low and equatorial regions and the morphological relationships between high- latitude Pc 3 and low- latitude Pc 3 are yet to be conclusively clarified, it is the aim of this communication to bring out few of the spatial characteristics of Pc 3- 4 pulsations. Spatial characteristics including latitudinal propagation, polarization of the signal and Field Line Resonance (FLR) characteristics (at latitudes away from the equator) are studied and discussed here at the Indian longitude sector.

Data and methodology

Three induction coil magnetometers (N-S coil giving the time variations of geomagnetic field in X- component and E-W coil giving similar variations in the Y-component) are deployed at Tirunelveli (Geog. 8.67° N, 77.82° E; Geomag.- 0.87°, 149.32°; L ~ 1.02), a station under the influence of the daytime equatorial electrojet, at Alibag (Geog. 18.63° N, 72.87° E; Geomag. 9.74°, 145.57; L ~ 1.05), a station distant from the influence of the equatorial electrojet and the S_q focal latitude and at Sabhawala (Geog. 30.37° N, 77.80° E; Geomag. 20.93°,151.51°; L ~ 1.25), a station closer to S_q focal latitude. The potential difference induced in the sensor is proportional to the rate of change of the magnetic field along the axis. This is recorded digitally after pre- amplification. Care has been taken to operate the sensors at all stations with a uniform gain factor. The digital output is sampled at intervals of 2 Sec with 80 mV (in the unattenuated range of Frequency range 10-100 mHz) corresponds to 1 nT of field component.

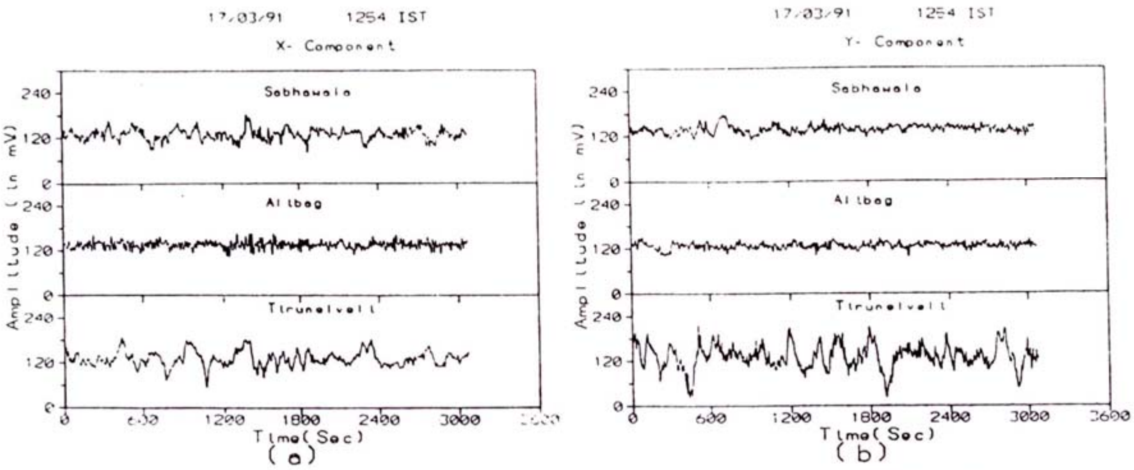

Fig 1. Geomagnetic pulsation event simultaneously recorded in (a) NS (X-) and (b) EW (Y-) Components at Tirunelveli, Alibag and Sabhawala at the noon hours of 17 March 1991. The starting time is indicated at the top of the Figure.

A typical pulsation event in the X- and Y- components was recorded simultaneously at these stations on 17 March 1991 at 1254 IST (IST = UT + 5h 30 min). The daily A_P was 17 and 3 hourly K_P during the interval of event was 2_- and the electrojet was fully developed. This is shown in Fig 1a and Fig 1b. Another event recorded on 04 April 1991 at 1300 IST ($A_P = 50$, $K_P = 3_-$) is shown in Fig 2a and Fig 2b. These simultaneous ULF pulsations at three stations have been analysed to obtain polarization and spectral characters, and latitudinal disposition of the stations with respect to FLR phase response of the signals in selected bands of frequencies. Hodograph, FFT, Complex Demodulation and cross phase spectrum are used to study the variations of polarization and spectral characteristics of the ULF waves with latitudes.

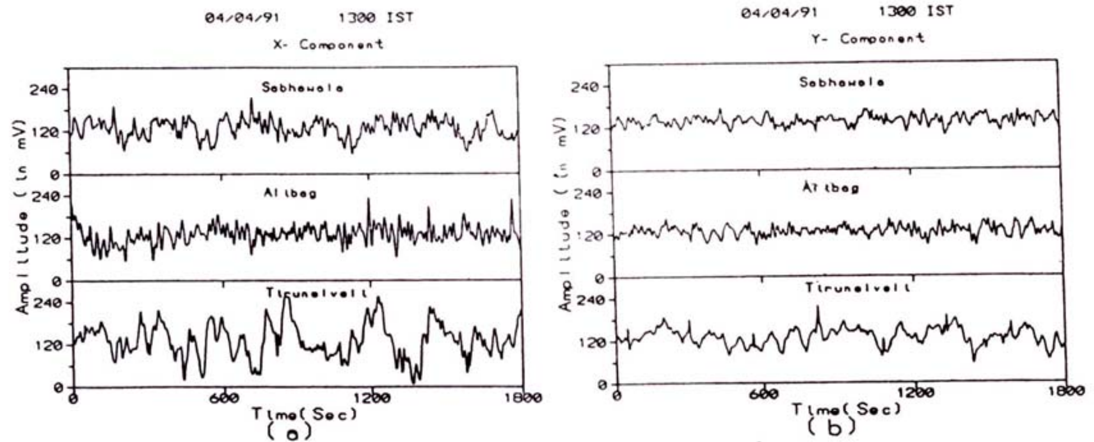

Fig 2. Same as Fig 1 but for the event on 04 April 1991

Results

The electronics of the data logger system use a filter to have unattenuated signals in 10 to 100 mHz frequency range. As FFT in Fig.3 has peaks in different frequencies in the time interval chosen for study and the frequencies are falling in both Pc 3 and Pc 4 ranges, they have been divided broadly in three discrete bands. The three chosen bands are 10-22 mHz (102.4- 46.5 sec; Band 1) which are in Pc 4 ranges, 25-37 mHz (39.4 - 26.9; Band 2) and 44-55 mHz (22.7 - 18.0; Band 3) in Pc 3 ranges. Sine termination filters with number poles 100 were designed for each of three above bands of frequencies and 201 weights are computed numerically. These weights are used to isolate signals from the observed data at these frequency ranges. Temporal variations in Band 2 on filtration at three stations in X- and Y- components on 17 March are shown in Fig 4a and Fig 4b respectively. It can be noticed that, while the amplitudes in the X- component are comparable at all the three stations, the Y- amplitudes are enhanced at the equatorial station (Tirunelveli). Time variations of the signal amplitudes in X- and Y- components in the lower frequency Band 1, confining to Pc 4 pulsation range are shown in Fig 5. It is inferred here that the amplitudes in both the X- and Y- components at Alibag are attenuated at the lower frequencies when compared with those from other two stations. Power spectra for each of the three band passed filtered series are computed and their amplitude spectra in X- are shown in Fig 6. It is noticed that the amplitudes in X- at the three bands are generally similar with a marginal enhancement of amplitudes at higher frequencies at Alibag.

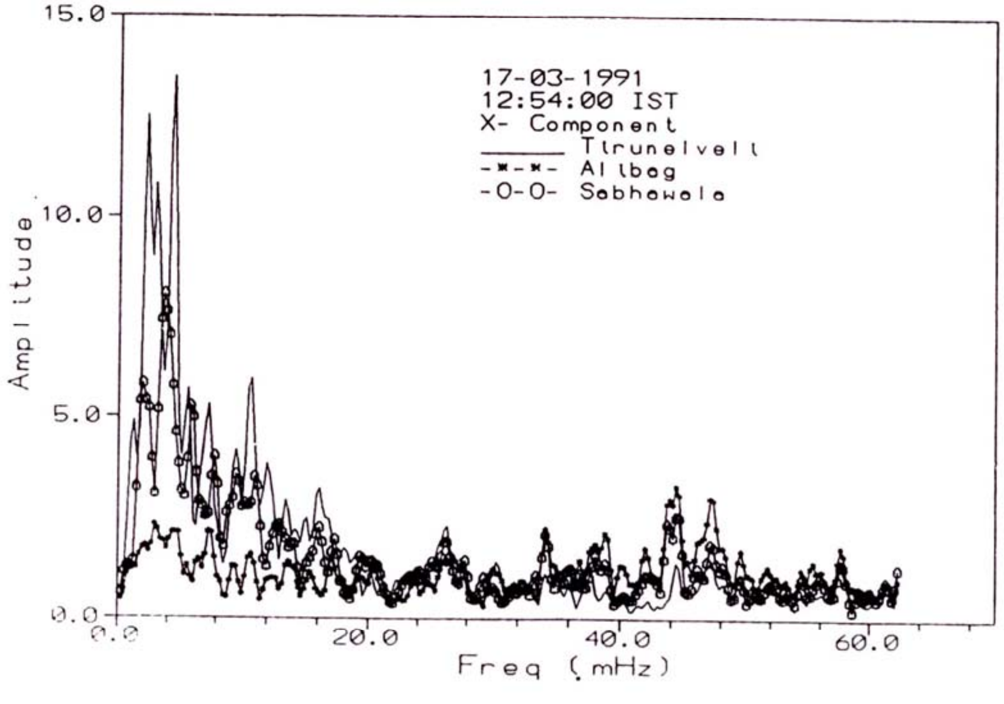

Fig 3. Amplitude spectra of the event on 17 March 1991. Significant signals are seen in the frequency ranges 9.8- 21.5 mHz (102.4 - 46.6 sec), 25.4-37.2 mHz (39.4- 26.9 sec) and 44.9- 55.5 mHz (22.7- 18.0 sec).

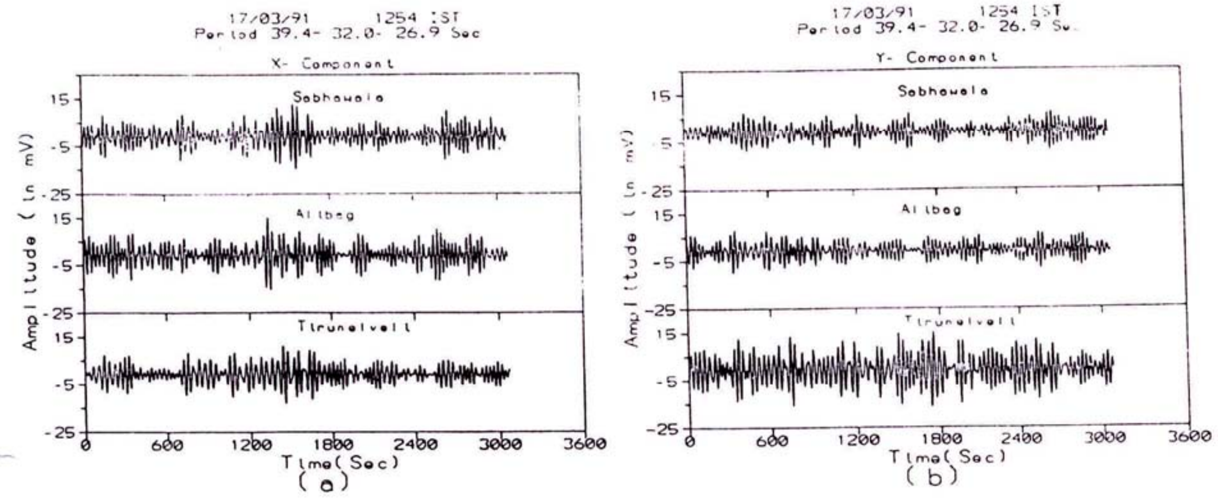

Fig 4. Band pass (in the frequency ranges 25.4 and 37.2 centered at 31.3 mHz) filtered (a) X- and (b) Y- series of the event on 17 March 1991.

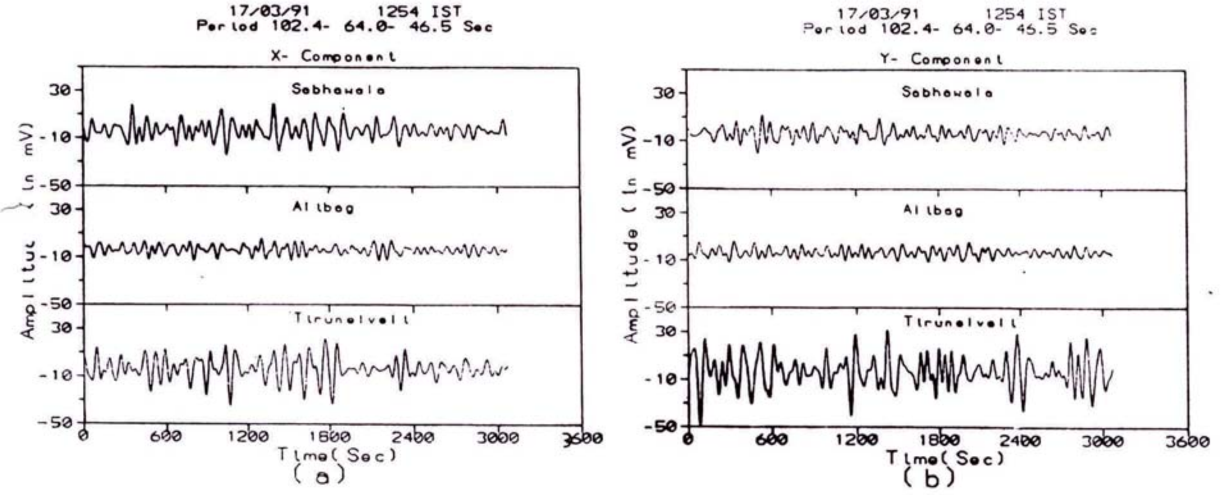

Fig 5. Same as Fig 4 but for the band 9.8- 15.6- 21.5 mHz.

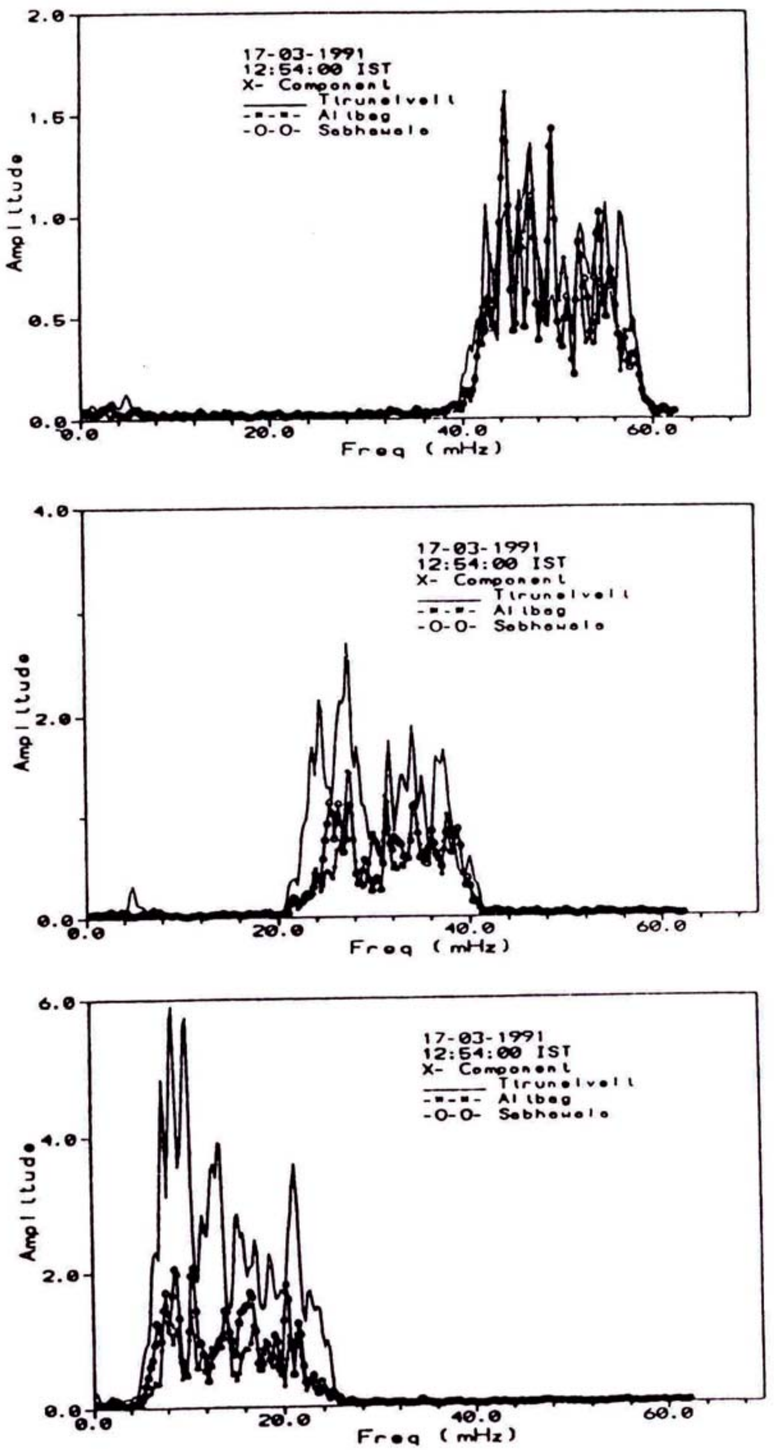

Fig 6. Amplitude spectra of filtered X- Component series on 17 March 1991 at three stations

The spectral estimates of amplitudes and phases are essentially the average parameters indicative of the integrated effect of a frequency component in the entire time length of the data series. However, in nature most physical phenomenon exhibits quasi- stationarity only, (i.e., a signal's frequency, amplitude and phase may vary with time). To understand the temporal behaviour of the signal characteristics, the Complex Demodulation technique, which will provide insight into time local properties of the data series, has been employed. This yields information on the time variation of amplitude and phase in the band of frequency which otherwise would be difficult to visualize, either from the original data time series or the computed amplitude and phase spectra. The variation of demodulated amplitude at the three stations in the X- component over 44 -55 mHz band, centred over the 50 mHz frequency, is shown in Fig 7a. Similar results in respect of the phase are shown in Fig 7b.

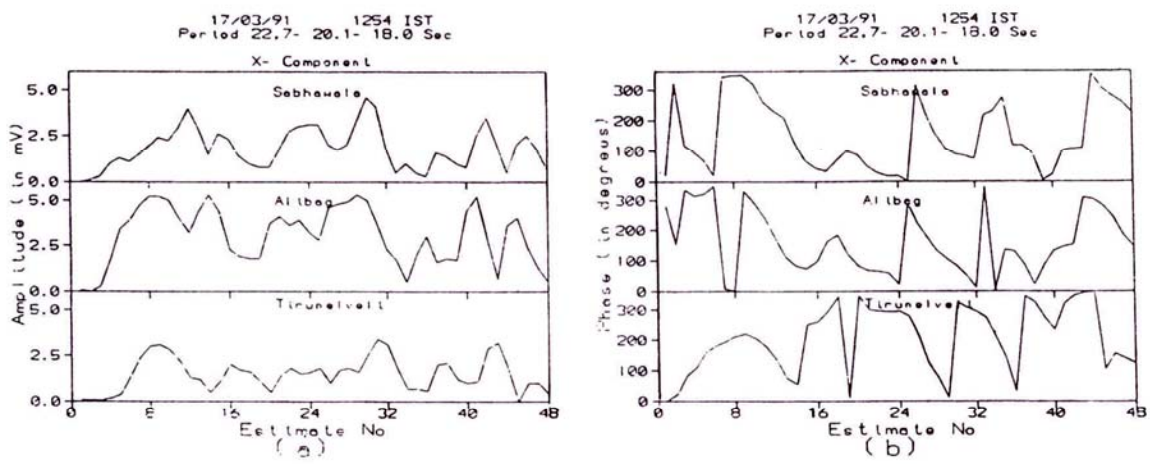

Fig 7. Time variations of (a) amplitude and (b) phase of demodulates of the filtered time seriesat three stations in a band centred at 31.3 mHz frequency on 17 March 1991.

Using numerically filtered pulsation series on 4 April 1991 in the bands centred in Pc 3 ranges at 31 mHz and 50 mHz in the X- component at Tirunelveli (the southern latitude station H_S) and at Sabhawala (H_N, the northern latitude station), the amplitude ratios and differences of amplitudes in the spectra are calculated. These, along with the respective amplitude and phase differences, as a function of frequency in mHz are shown in Fig 8a and 8b. As per the gradient technique enumerated by Baransky et al. (1985), the frequency for which $H_N/H_S = 1$ and $H_N - H_S > 0$ will give the resonant frequency of the field line which crosses the meridian at mid way of the north south- station. It is not proper to estimate the FLR directly from the gradient technique as the inter- station separation between Tirunelveli and Sabhawala is too large to observe field line resonances at the foot of a filed line. The cross spectral in Fig. 8a and 8b satisfy Baransky et al (1985) criteria at 35 mHz and at 50.3 mHz (not shown in the Fig.). These cross phases (or time delays) between the waves seen at equator and 21° magnetic latitude (MLAT) may possibly indicate the phase difference between a compressional mode wave at the equator and a FLR at 21° MLAT. This is further corroborated by obtaining highest coherency and cross power at these frequencies of the waves at the two sites.

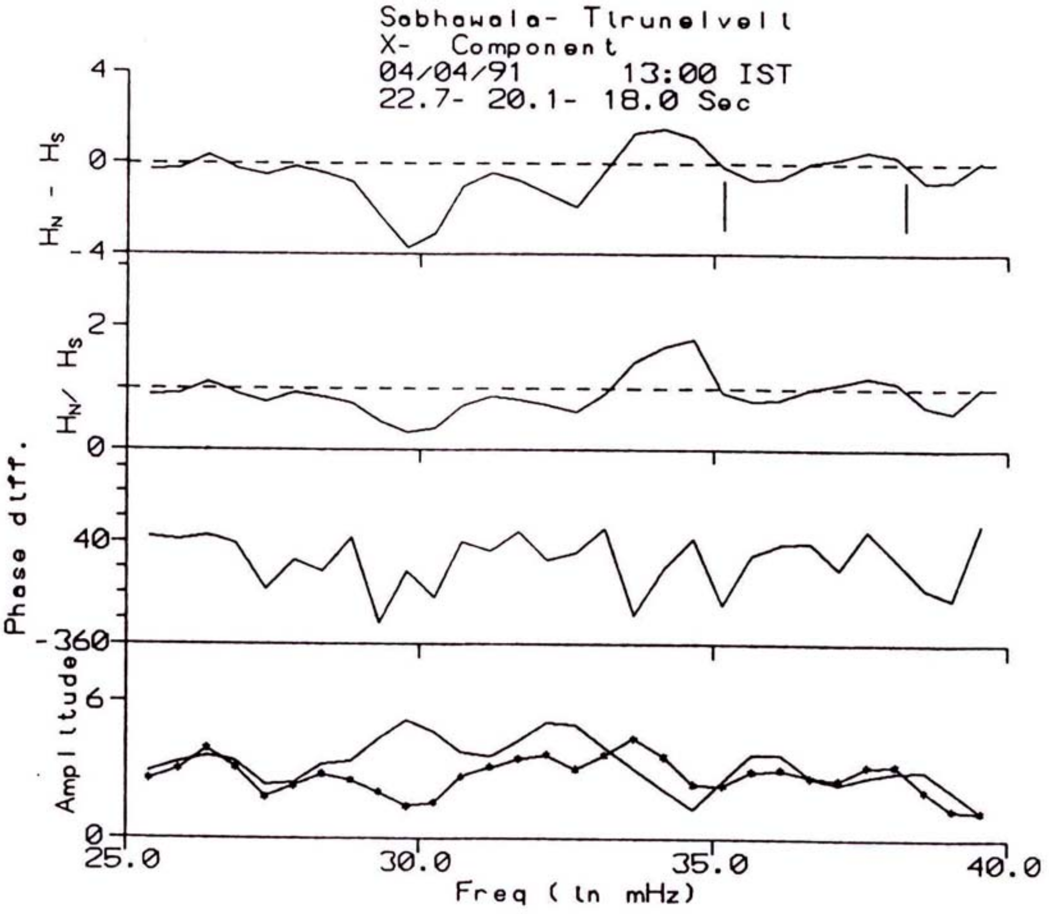

Fig 8. Amplitudes (H_N and H_S), cross phase, amplitude ratios and amplitude differences of 25.4 to 37.2 mHz filtered series of the event at Sabhawala and Tirunelveli on 4 March 1991. The cross phase spectral peaks estimated by Bransky et al (1985) method are shown by vertical lines in the top panel

Towards understanding the propagation of the pulsation wave energies in the three selected bands of frequencies across the latitudes in the Indian region, they are estimated with the help of 'demodulates' obtained through complex demodulation technique. The phase estimates from demodulated signals at each pair of stations where the amplitude maximises within a frequency band have been used to calculate the angular wave number 'm'. The m value is the phase difference (in degrees) between the two stations divided by the geomagnetic latitudinal separation between the stations (in degrees; Ansari and Fraser, 1986). It may be noted here that NS phase differences relate to the latitudinal location of the stations with respect to the FLR phase response. As the three stations are more or less located on the same longitude, EW phases which relate to azimuthal propagation of wave energy could not be estimated. The derived m values from NS pair of stations are listed in Table 1 and they are found to be highly variable (varies between 3 and 12). However, in the majority of cases, from the relative phases, the propagation direction is inferred to be away from the equator.

To bring out the polarization in X - Y plane, the filtered values in the two frequency bands have been shown as hodographs in Fig 9a and 9b. Rotation of the axis of polarization towards NW at Tirunelveli when compared to Sabhawala can be inferred at 31 mHz period band from the results in Fig 9a.

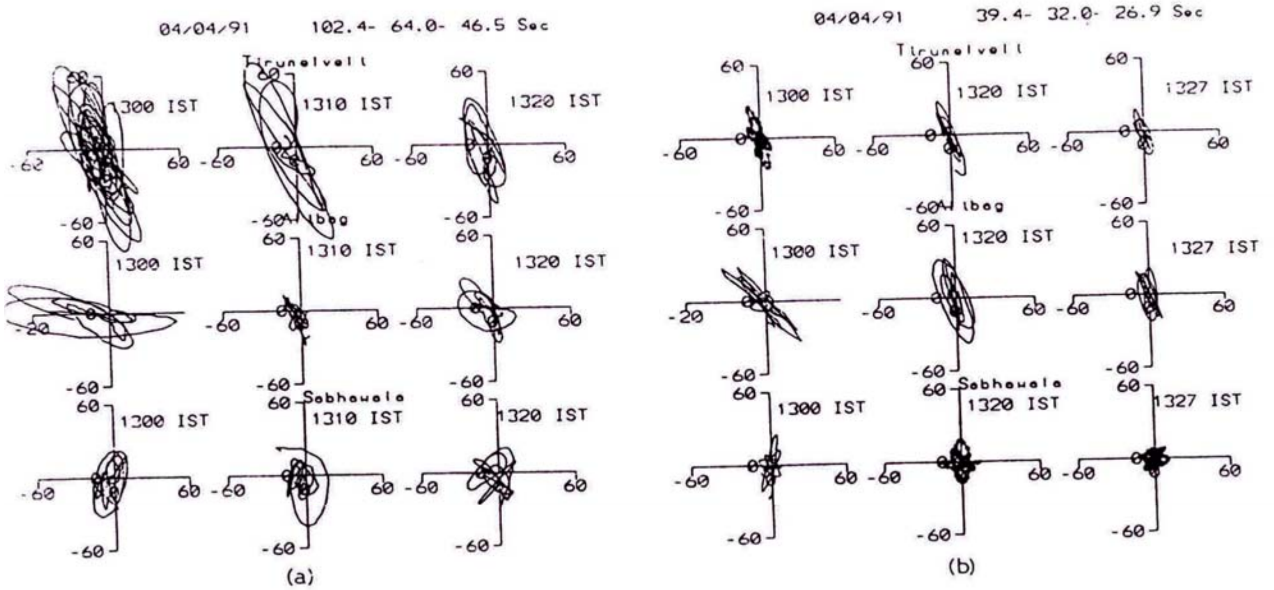

Fig 9. Time variations of the amplitudes of the signals in X and Y (Hodographs) at three stations on 04 April 1991 in the frequency bands (a) 9.8-21.5 mHz and (b) 25.4- 37.2 mHz.

Discussion

In the preceding section, the results on the latitudinal wave numbers of the pulsation wave energy and the estimation of cross phase (time delay) of the waves are reported for the first time, as far as the authors are aware, from the Indian region. The observations from mid latitude station, Alibag, could not be used very effectively as the pairs of stations formed with the other two stations (Sabhawala and Tirunelveli) have not yielded significant cross phase estimates from the gradient technique. The behaviour of Pc 3-4 pulsations at Alibag may not be entirely due to the earth's electromagnetic induction effects as these would be very significant in the vertical component of the geomagnetic field. To reduce the earth's induction effects, Pc 3-4 pulsations in NS and EW components are only recorded and are utilized. In fact, Roy and Rao (1998) have argued that there is a critical frequency below which only the equatorial enhancement of Pc 3-4 signals are noticed and this frequency at Alibag is shown to be proportional to the Resonance frequency of the field line.

Waters et al. (1994) have extensively studied the resonance frequency, resonance width and the damping coefficient of geomagnetic field line resonance in Pc 3-4 from

Table 1 : Estimated latitudinal 'm' numbers

Tirunelveli		Sabhawala		'm' No.
Amplitude	Phase (in degrees)	Amplitude	Phase (in degrees)	
X- Component				m_x
3.7	132	1.3	388	11.85
2.0	58	2.7	270	9.87
1.9	27	3.4	113	4.21
3.7	330	4.9	480	6.94
3.6	33	2.6	250	10.05
2.4	272	2.0	421	6.90
2.2	184	4.0	348	7.59
2.7	326	2.1	443	5.42
3.4	206	2.9	383	8.19
3.2	36	3.6	171	6.25
1.2	246	3.1	423	8.19
4.8	59	6.7	279	10.19
9.7	19	5.0	91	3.30
7.9	117	6.2	277	7.40
2.3	146	5.6	247	4.47
2.8	17	3.1	170	7.08
2.2	232	3.2	389	7.27
1.3	56	2.4	174	5.46
2.8	84	5.0	189	5.79
3.9	339	9.0	511	7.96
10.4	148	10.1	213	3.09
19.7	324	9.1	470	6.29
Y- Component				m_y
2.8	191	4.2	344	7.08
2.6	19	3.6	237	10.09
3.8	97	1.8	276	8.28
5.8	166	2.2	373	9.58
1.6	147	2.7	223	3.52
2.4	106	0.7	224	5.46
5.6	196	8.9	316	5.56
7.0	130	1.7	369	11.06
1.8	10	1.7	80	3.24
1.5	115	2.1	216	4.68
1.7	263	3.6	358	4.40
2.5	117	4.4	302	8.56
3.4	168	4.7	348	8.33
3.1	311	2.6	547	10.91
6.9	176	6.2	415	11.06

ground data from Australian network of stations. Data from three station at L ~ 1.8 have been employed by them for deriving the resonant frequency by gradient technique as well as cross- phase spectrum analysis. They obtained a resonant frequency of 40 ± 1 mHz for the lowest pairs of southern latitudes. The most poleward station with that of equatorward station at L ~ 1.8, has given resonant frequency of 38 ± 1 mHz while the two stations at higher latitudes has given 36 ±1 mHz. Thus, for the interval of their analysis, they have stated that the resonant frequency has decreased with increasing latitude at a rate of nearly 4 mHz per 80 Km at L ~ 1.8. The cross phase association of coherent signals that are recorded on 4 April 1991 between L values 1.25 and 1.02 in the Indian region have yielded 35 and 50.3 mHz. It may be noted that the wider separation of stations employed for the cross phase spectrum analysis here will not permit conclusively identifying the FLR frequency of the waves. The high latitude station (MLAT ~ 21°) coupled with nearby (within 100 km) stations data can only allow such estimation. From the results from 210° chain of stations of Matsuoka et al. (1997), it is evident that the behaviour of Pc 3 is peculiar at the equatorial region. They have shown phase variation of about 150° at the equator relative to those at the low latitudes that are not expected from simple propagation of fast-mode magnetosonic wave from the outer magnetosphere or from field line resonance. From this, it appears that the 35 mHz cross phase frequency may be attributable to the frequency of cavity mode resonance phenomenon whereas the 50.3 mHz frequency corresponds to the FLR at 21° MLAT as is expected in this region from the latitudinal variation of FLR mentioned above.

Further, Yumoto and Saito (1983) and Yumoto et al. (1985) have observationally clarified that the occurrence probability, the correlation coefficient and the standard deviation of Pc 3-4 pulsations at globally separated low-latitude stations ($L < 2.0$) against the compressional Pc 3-4 waves at synchronous orbit. While concluding that the compressional Pc 3-4 waves propagate radially towards the centre of the earth, Yumoto et al. (1985) have shown larger frequency deviations at a narrow longitudinally separated stations where the compressional wave propagate and suggest the existence of various resonant HM oscillations coupled with the compressional source waves in the plasmasphere. This provides further evidence that the 50.3 mHz resonant frequency obtained here may be associated with HM compressional oscillation In any case, these results are to be taken as very preliminary. Identification of geomagnetic field line resonances from other techniques, apart from gradient technique with wider data base can only conclusively prove the results.

Yumoto and Saito (1983) have also theoretically demonstrated that the low-latitude Pc 3 pulsations at L~ 1.2-3.0 on the ground should be the superposition of diverse coupled-resonance oscillations excited by the compressional source waves having finite frequency bandwidth outside the magnetosphere. According to them, these oscillations may be fundamental ($L = 1.7$ to 2.6) and high harmonics ($L = 2.0$ to L_{pp}, where L_{pp} is the L value of the plasmapause) standing field line oscillations, and a trapped oscillation ($L = 1.7$ to L_{pp}) that was named the 'plasmasphere' cavity resonance mode. A new model to explain why selected field line resonances appear to be excited by a broadband source was proposed by Kivelson and Southwood (1986) and Allan et al. (1986). Global eigen modes of compressional magnetospheric cavity resonance were suggested to predominantly couple to and drive on a corresponding set of field line resonance at positions where the cavity eigen periods match the uncoupled field line eigen periods, Menk (1988) demonstrated that Pc 3-4 pulsations over 25 months at station ($L = 2.1$) showed diverse spectral features, which should be associated with respective excitation and propagation mechanisms resulting from many-fold dynamical responses of the magnetosphere to varying conditions of geomagnetic agitation. The 35 mHz cross phase derived at very low latitudes in the Indian region is, thus, the manifestation of cavity eigen periods of global compressional magnetospheric cavity resonance. Different source of agitation of geomagnetic field conditions in respect of the event that occurred on 17 March 1991 may, perhaps, not permitted to estimate the cross phase unambiguously.

For the configuration of stations location, it is possible to derive only the latitudinal location of the stations with respect to the FLR phase response. These FLR phase responses, X (m_x) and Y (m_y), between the pairs of stations are mostly positive, indicating the propagation of wave energy is directed away from the equator. This again is in agreement with field line resonance theory of propagation in very low latitudes. The magnitude of m_x and m_y have, however, shown large scatter and they are in the ranges between 3 to 12. They indicate shorter wavelengths and have to be compared with the azimuthal wave numbers in the Indian region for complete understanding of the propagation of the energy. However, the order of the magnitudes of m_x and m_y are similar to those worked out by Ansari and Fraser (1986) for the Australian latitudes. The azimuthal wave number m_x and m_y are found by them to be low, in the ranges less than 6, in the Australian sector and propagation is directed to the west in the morning and east in the afternoon.

Kuwashima et al. (1979) have pointed out that the diurnal variation of very low latitude Pc3 polarization at Chichijima is different from that low- latitude Pc3 observed simultaneously at Memambetsu in the Japanese longitude, wherein polarization changes from predominantly left-handed in the morning to right-handed in the afternoon. Yumoto (1986) and Saito et al. (1984) have shown that diurnal variations of Pc 3 polarization senses at northern and southern low- latitude stations (latitudes ~ 10° and 29°) are those at the conjugate low latitude stations (latitudes ± 35°) in the sunlight hemisphere. The change of polarization and senses of rotation of vector points shown here (polarization axis Sabhawala mostly NS and at Tirunelveli NW - SE) warrant a thorough search of the diurnal behaviour of these parameters at these latitudes. The low latitude Pc 3 polarization can give a clue to explain azimuthally propagating, ionospheric Pedersen eddy currents induced by inductive electric field of compressional Pc 3 waves at very low latitudes (Yumoto, 1986).

Conclusion

It is attempted to understand the resonant oscillations of magnetospheric field line, which are the important sources of the ULF pulsations from a network of observations in the Indian longitudinal region. Various analysis techniques have been employed on continuous pulsation data to arrive at propagation characteristics.

A close network of stations, ideally between 100 to 50 kms separation and improved time accuracy (at least milli seconds), deployed in the longitudinal and latitudinal sectors on campaign mode will be ideal to work out the nature of propagation of the waves and such networks are contemplated in near future.

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