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Some Features of PCS Magnetic Pulsations in Dakshin Gangotri, Antarctica

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Abstract

Magnetic pulsation data in the Pc5 range (150-600 sec periodicity) in February 1986 at Dakshin Gangotri, Antarctica were analysed through (i) Power spectral methods (ii) 3-Dimensional polarisation (iii) Complex demodulation and (iv) Single station transfer function for the induction vectors. Dynamic spectra showed that the oscillations were confined to basically three bands of frequencies. The anticipated change in ellipticity and polarisation (left handed to right handed) across the magnetic local noon was not observed suggesting that plasmapause location may be further west of the station. For all the three frequency bands the orientation ot the major axis of the ellipticity of polarisation was quite stable as a function of time. The induction arrows computed for 350, 200 and 150 Sec and periodicity point to inland contrary to the expected direction towards the deep oceans, suggestive of some conductive structure in the Antarctic landmass close to the magnetic station.

Introduction

During the Fifth Indian Scientific Expedition to Antarctica, useful magnetic data were collected between 15 January and 28 February, 1986. Fluxgate magnetometer housed in a well insulated cabin was buried below the ground level in the ice-shelf to minimise temperature variations. The output was taken in two modes: (i) for Normal daily variation and (ii) for Magnetic pulsations in the pass-band 1 to 33 mHz (30 to 1000 sec periodicity), The output was fed to a digital data logger with internal crystal-controlled clock system and sampled every 30 sec. Analog records were also simultaneously obtained which clearly revealed the good quality of data, completely free from artificial noise except for duration when the HF communication system was operated.

The period of observations was marked by intense magnetic activity in the subauroral latitude as seen from daily index Ap of magnetic activity. One of the most severe magnetic disturbances in recent times began on 6th February and ended by 9 February, 1986 (Allan, 1986). Ap reached a peak value of 202 on 8th February, 1986. During the recovery phase of the magnetic disturbance, on 9th February, interesting sequence of pulsations were observed lasting almost the entire day. Some significant highlights of the magnetic field variations in the PC5 pulsation range (150 to 600 sec) observed on 9 February, 1986 are presented in this paper.

Importance of Dakshin Gangotri Location

The coordinates of the temporary Indian magnetic station in Antarctica are given in Table I.

Table I. Coordinates of Dakshin Gangotri

Geographic	Lat.	70°05'S
	Long.	12°00'E
Dipole	Lat.	65.5°S
	Long.	54.5°E
Corr. Geomagnetic	Lat.	62.1°S
	Long.	52.3°E
L-Parameter		4.61RE
Geomagnetic local time (MLT)		(UT- 1 hour)

The L-parameter is the equatorial distance (in earth radius units) of the geomagnetic field line originating near ground in southern hemisphere and reaching the conjugate location in the northern hemisphere. It is well known that at the plasmapause (boundary of the plasmasphere region located between 3 and 7 RE) there is an abrupt drop in plasma density by a factor of 100. The plasmapause is also known to have a bulge in the evening sector and its shape and location changes with enhanced magnetic activity. It has been suggested (Rostoker and Samson, 1981) that plasmapause provides a broad range of resonant frequencies over a confined range of L shells due to the presence of the sharp discontinuity in the thermal plasma density. Pulsation amplitudes are known to have a secondary maximum at plasmapause location in addition to the primary auroral maximum.

The number of magnetic stations in Antarctic region located in the region of plasmapause are sparse and Dakshin Gangotri fills a vital gap to provide data from a subauroral latitude location. The significance of plasmapause in magnetic pulsations studies have been highlighted in a number of publications.

Data Analysis

The digital data of 3 component of magnetic field (X-Geographic N-S, Y-Geographic E-W and Z-vertical) at 30 sec. sampling interval were subjected to analysis in several ways:

(i) Power spectra,
(ii) 3-Dimensional Polarisation Analysis,

(iii) Complex Demodulation Analysis for horizontal and anomalous Z-variations and

(iv) Single station transfer function computations for induction vectors at chosen frequencies.

Segments of analog records between 0600 and 2330 UT of February, 1986 are shown in Fig. 1. Due to malfunctioning of the Z-channel upto about 0600 UT, we have confined the analysis between 0600 and 2330 UT. In the following sections we present the results of our analysis under each of the above categories.

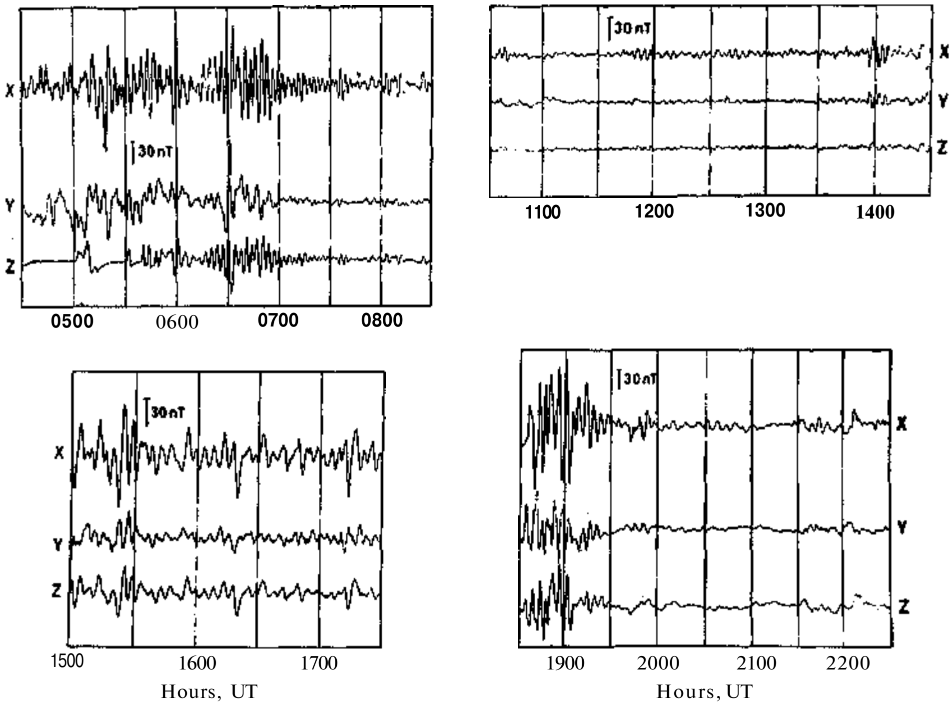


Fig. 1. *Segments of analog records showing magnetic pulsation activity, occasionally of very large amplitudes, on February 9, 1986 at Indian Antarctic station, Dakshin Gangotri*

Power Spectra

The duration 0600-2330 UT of 9 February, 1986 was divided into two time blocks 0600-1430 and 1500-2330 UT giving 1020 discrete samples with $\Delta t = 30$ seconds. Amplitude spectra for the three components for the two segments are shown in Fig. 2. These are computed using Maximum Entropy Method discussed by Ulrych and Bishop (1975), adopting a length of 60 for the Prediction Error Filter chosen based on the Akaike criterion. In both cases, X-component has the largest amplitudes. Despite the significant oscillations seen in Fig. 1, the

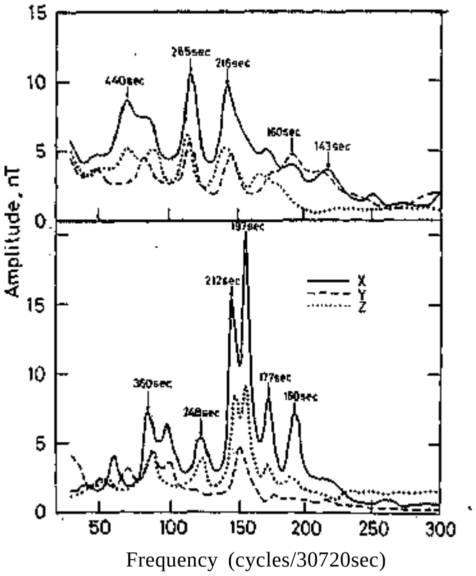
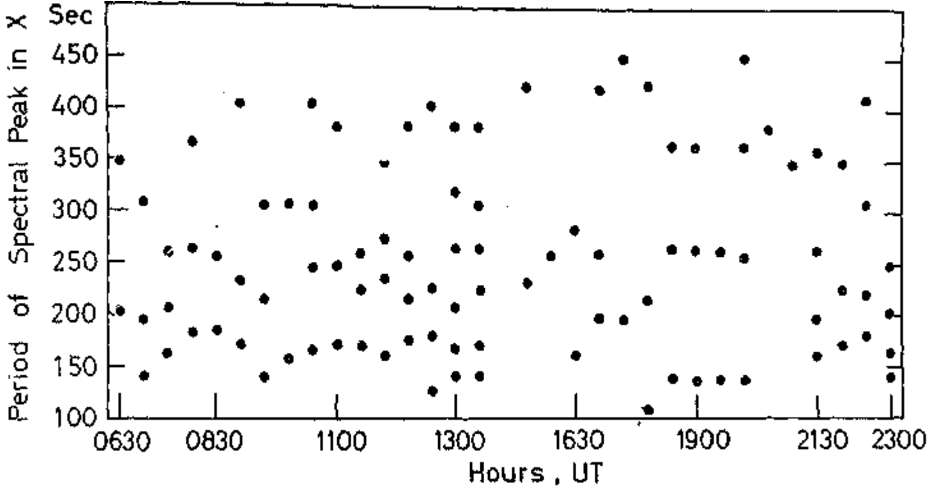


Fig. 2 *Power spectra of magnetic field oscillations in the three components (X, Y, Z) for two segments of data (Top) 0600 to 1430 UT and (Bottom) 1500-2330 UT of 9 February 1986, Dominant periods (in seconds) are indicated. The spectra are derived by Maximum Entropy Method*

spectra are quite smooth with dominant periodicities in the 350-450 sec, 200-250 sec and 150-200 sec ranges only. For determining the degree of relationship between any two components as a function of frequency we also computed the coherence and phase differences for the two segments. It is seen that coherence at most frequencies is significant and uniformly high only for the (X,Z) pair in comparison to the others. Phase differences, on the other hand, vary over a wide range between ± 180°. These results are based on average characteristics integrated over the 8 hour time-span during which many features may change.

In the next step we computed power spectra for one-hour segment, each overlapping by half-an-hour to study the dynamic spectral characteristics. Dominant periodicities observed in individual spectra as a function of time are shown in Fig. 3. Most of the one-hour segment has only 3 to 4 significant peaks between 150 and 400 seconds. Upto about 4000 UT the spectra are more complex in nature. The latter part of the day is marked by simple structure without many significant periodicities. When phase difference and coherence for selected frequencies as a function of time are considered, it is noticed that the phase difference is nearly constant at all hours for the (X, Z) pair in contrast to the other two component pairs and also that the constancy is more pronounced with increased period. This indicates that the horizontal field (in the X,Y plane) has different polarisations at different hours, a fact which proves useful in the geomagnetic induction studies described later. The fluctuations in the three components appear to be coherent for all the hours with the (X, 2) pair aga.n showing coherence close to unity.



Fig, 3. Period-Time dependence of the spectra of 1-hour duration each between 0600 and 2400 UT of 9 February 1986.

Three dimensional polarisation studies

Polarisation properties of magnetic pulsations recorded on surface at different geographical locations are of importance in identifying the nature of the propagating wave, its origin, the medium through which it traverses and helps in testing validity of different theoretical models proposed for ULF waves. Fowler *et al.* (1967) developed a technique for determining the polarisation parameters from the spectra of two components (X, Y) of a plane wave in two dimensions. However,; magnetic field variations show significant oscillations in all the three components and the coordinate system of measurement may be arbitrarily oriented relative to the hydromagnetic waves. It is, therefore, essential to consider all three components in wave analysis. Arthur et *al.* (1976) discussed, in detail, three different techniques for using spectral matrix in wave analysis and concluded that all performed equally well and suggested that the one proposed by McPherron et *al.* (1972) was more useful to detect signal embedded in noise and easier to code for computers. This method is described in brief in the following steps:

(i) Generate a spectral matrix whose elements are auto and cross-power at dominant frequencies derived from specrta of X, Y and Z components.

$$G = \begin{bmatrix} Gxx & Gxy & Gxz \\ Gyx & Gyy & Gyz \\ Gzx & Gzy & Gzz \end{bmatrix}$$

Gxy, Gxz, Gyz are complex and Gyx, Gzx and Gzy are their conjugates.

(ii) From the complex matrix G, isolate the real part (Re G) and perform an Eigen analysis to determine the three eigen vectors. These should be normalized to make the vectors orthogonal. They constitute the column vectors of a transfer matrix, T.

(iii) Perform matrix multiplication $G = T^T GT$ taking care now that the complex spectral matrix G is used. (T^T indicates transpose of T). This step rotates the original coordinate system into the principal coordinate system with the plane wave now in the principal axis system.

(iv) Isolate the upper 2 x 2 submatrix of G' for the subsequent coherency analysis. Let J be the spectral matrix in the principal plane.

$$J = \begin{bmatrix} Jxx & Jxy \\ Jyx & Jyy \end{bmatrix}$$

(v) The following polarisation parameters are then easily determined.

$1/2$
a) Percentage Polarisation = 100 [1-4 det J $(\mathrm{Tr}\ J)^2$]
(b) Ellipticity = tan β where
$\sin 2\beta = 2\ \mathrm{im}\ Jxy/[(\mathrm{Tr}\ J)^2 - 4\ \det J]^{1/2}$
Where Tr J = Jxx + Jyy and det J = (Jxx Jyy) - (Jxy Jyx).
If β is negative the polarisation is left handed.
(c) The orientation of the major axis and the direction of wave propagation relative to original coordinates system is determined from the following relations:

$$\tan \theta_x = (T_{11}^2 + T_{21}^2)^{1/2}/T_{31}$$
$$\tan \varphi_x = T_{21}/T_{11}$$
$$\tan \theta_z = (T_{13}^2 + T_{23}^2)/T_{33}$$
$$\tan \varphi_x = T_{23}/T_{13}$$

Where T_{ii} are the elements of the transfer matrix T. The polarisation parameters are significant only where the coherency defined as:

$$C = \left[\frac{Jxy \cdot Jyx}{Jxx \cdot Jyy}\right]$$

is significant. C = 1 for completely unpolarised signal and C = 1 for completely polarised signal.

To derive the time variations in the polarisation parameters, we utilised the power spectral densities computed for one-hour segment with 30 minute overlap, described earlier, confining our attention to only 3 discrete bands 150-200 sec, 200-300 sec and 300-400 sec. The different polarisation parameters are shown in Fig. 4. Ellipticity for all three bands is dominantly negative at all hours indicating left handed (clockwise in southern hemisphere) polarisation. The magnitude is about 0.5 suggesting that the waves are neither circularly nor linearly polarised at any time.

For Dakshin Gangotri location the magnetic local time is about 1 hour behind UT. For periods less than 200 secs, the ellipticity does show a transition from negative to positive ellipticity near magnetic local noon but there is no demarcation of left handed and right handed polarisation before and after this time. By about 16 MLT again there is a transitory change of ellipticity which cannot be interpreted in terms of any known mechanism.

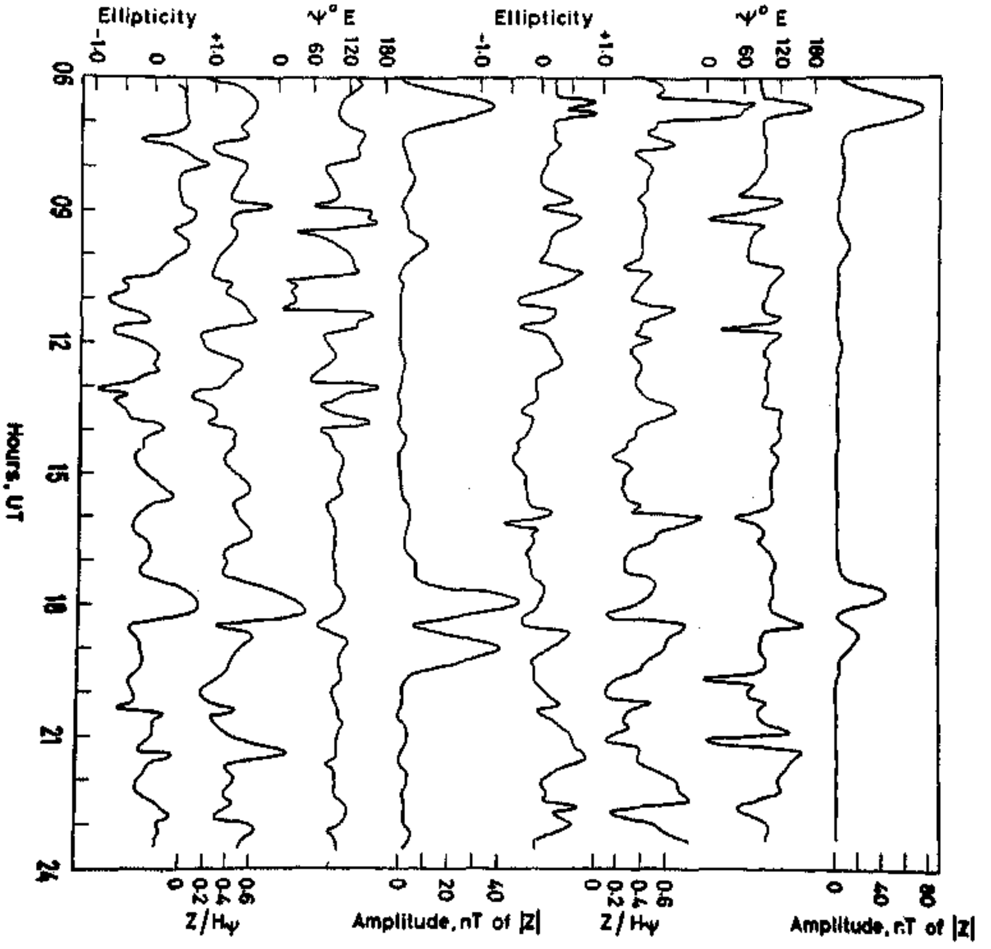


Fig. 4, Polarisation parameters for 3 dominant periodicity bands (Right) 150-200 sec (left) 200-300 sec (Left) (Bottom) 300-400 sec See Text for difinition of the parameters.

For all the three frequency bands, the parameters *Ox* and 0x, defining the orientation of the major axis relative to input coordinate systems are quite stable as a function of time and have the nearly same magnitude. This implies that throughout the day the hydromagnetic waves in the three frequency bands remained unaltered in terms of their principal plane. However, the direction of wave propagation defined by θz and z show greater variability both as a function of time and frequency. In their study of PC3 and PC4 at Siple, Antarctica located near L = 4, Fukunishi and Lanzerotti (1974) found that the wave ellipse in the H-D plane changed direction centred on local noon. The polarisation was dominantly left handed before local noon and right handed after- noon. Lanzerotti *et al.* (1976) and Tonegawa et *al.* (1984) found that for PC5 pulsations the sense of polarisation reverses across magnetic local noon. This was attributed to the reversal of longitudinal propagation direction from westward in the morning hours to eastward in the afternoon hours. In contrast, for the three frequency bands for the PC5 pulsations considered here there is no change either in the sign of the ellipticity or in the major axis parameters, 6x and 0x. Samson (1972) suggested that ground induction effects could vitiate the interpretation of polarisation data and found that the same becomes negligible at the upper limit of mHz (200 sec period). Lanzerotti et *al.* (1976) however, suggest that such induction effects are not of sufficient magnitude to affect the result. According to them any systematic diurnal variation in ellipticity and the tilt angle of the polarisation ellipses could not be attributed to induction effects. Lack of any significant diurnal variation in the present results for three frequency bands in PC5 range could indicate that there could be contamination due to ground induction effect. Alternately, the absence of polarisation reversal across noon could be due to the fact that for the duration of pulsations analysed here, the plasmapause location may be further away from the station. The 3-hourly Kp values for 9th February are 5+, 5-, 50, 6+, 5+ and 40. Adopting the emperical relation L = 6.0 — 0.6 Kp for plasmapause location given by Chappell (1972), we find that plasmapause could be nearer L = 3.0 than near Dakshin Gangotri with L = 4.6. If we assume that the statistical plasmapause location $L = 6.52 - 1.44\ Kp + 0.18\ Kp^2$ given by Orr and Webb (1975) normally valid upto Kp = 4 is correct even for disturbed periods with Kp = 5, the location of plasmapause turns out to be 3.8, again indicating that Indian Antarctic station was well inside the plasmapause. It would be worthwhile to examine the ellipticity and orientation characteristics for periods of magnetic quiescence and for higher frequency bands in PC3 and PC4 range. Efforts are made to increase the sampling interval in the subsequent Antarctic expeditions, to study these bands.

Complex Demodulation Analysis

Complex demodulation permits study of the time variation of the amplitude and phase of any selected frequency band of a data set. Though Bingham *et al* (1967) had described application of Fast Fourier Transform techniques to obtain the demodulates quite a while ago, this missed the attention of geophysicists somehow till Banks (1975) showed how effectively the techique can be utilised in geomagnetic deep sounding. Power and cross spectra calculated from time series represent average characteristics over the entire data length. When the time series are non-stationary in nature, demodulates giving information on 'time-local' properties of the data should be preferred (Banks, 1975). Agarwal *et al.* (1980) showed that the technique reproduces amplitude and phase accurately when more than four continuous sinusoidal cycles are present. They also highlighted how demodulates from a single geomagnetic disturbance provide same information on geomagnetic anomalies as derived from several single events of chosen periodicity conventionally adopted earlier. Beamish *et al.* (1979) applied successfully the technique to geomagnetic pulsations. Banks (1975) had also illustrated how the amplitude and phase demodulates can be combined to derive parameters of the horizontal polarisation ellipse which can be utilised to infer anomalous behaviour of the vertical component. Lilley and Bennet (1972) provide the defining formula for azimuth (ψ) and magnitude ($H\psi$) of the major axis of the horizontal polarisation ellipse and the ratio of minor to major axis. To study the dependence of anomaly of response on the azimuth ψ, it was suggested that ψ should be compared with $Z/H\psi$ rather than with Z amplitude alone (Banks, 1975).

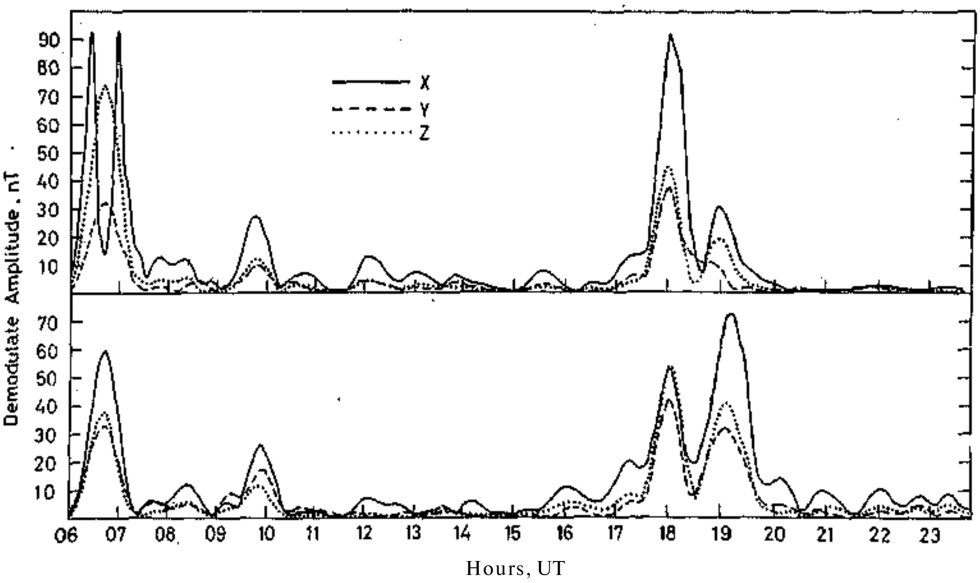


Fig. 5 *Demodulate amplitude of the frequency-band centred on 200 sec (top) and 350 sec (Bottom) periodicities for the three components of the magnetic field for 9 February 1986.*

Following the method outlined by Banks (1975) we computed complex demodulates for two frequency bands centred on 350 sec and 200 sec. The amplitudes are shown in Fig. 5. Large amplitude pulsations in these two bands were present only near 7, 10, 18 and 19 UT. In both cases the X amplitude was the largest and Y the least. Comparison with raw data reveals that the demodulates provide a visual envelope of the raw data indicating that over the whole time span these were the dominating frequencies.

In Fig. 6 are shown the Z amplitude and horizontal polarisation parameters ellipticity and the ratio Z/Hψ for the two bands as function of time. These figures provide details of the relationship between the source azimuth ψ and the response of the anomaly. If the source azimuth is favourable for excitation of Z anomaly then Z/Hψ; ratio shows a peak. ψ angles corresponding to low values of the ratios are indicative of unfavourable azimuths for horizontal field variations.

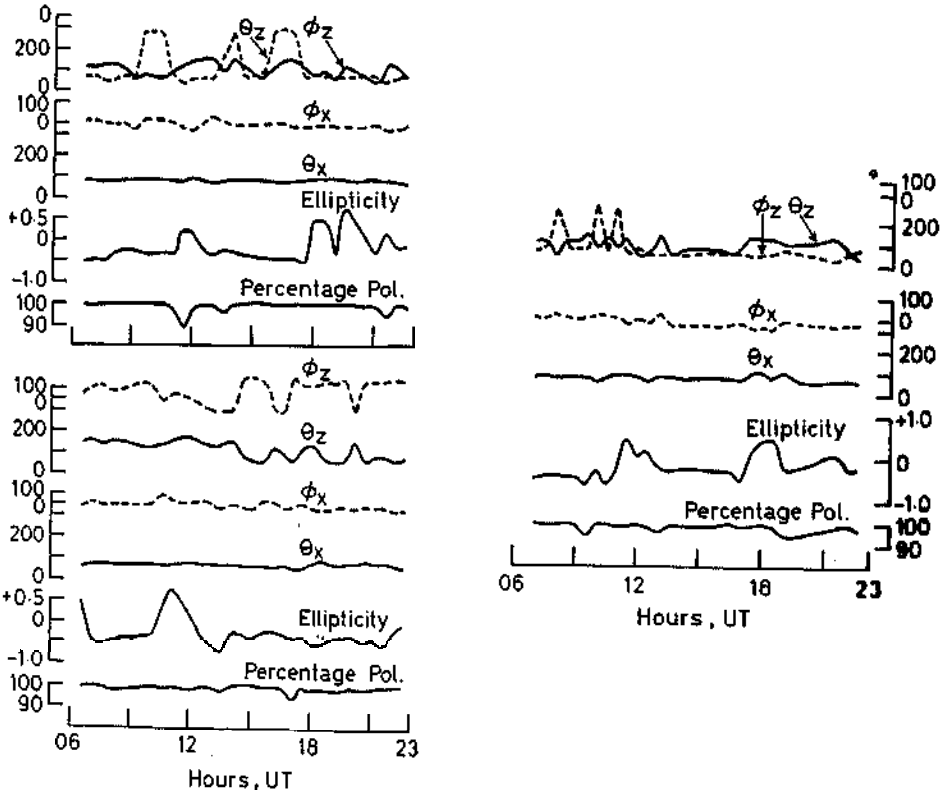


Fig. 6 Horizontal polarisation parameters ψ ellipticity, demodulate Z amplitude and ratio Z/Hψ Junction of time for the two period bands centred on 200 sec (top curves) and 350 sec (bottom curves)

The horizontal polarisation ellipses have variable ellipticity with several transitions from positive to negative values. The azimuth ψ is nearly constant after 1500 UT for both frequency bands but shows sufficient variability during the initial half of the day. These rapid changes can be seen to be related to the enhanced Z amplitudes and corresponding enhanced Z / H Ψ ratios. To ascertain the reality of favourable polarisation angles in the horizontal plane more such events may have to be analysed.

Single Station Transfer Function Analysis

Magnetic pulsation frequencies penetrate to a depth in the upper crust of the earth where many conductivity anomalies are likely to occur. Magnetic pulsations can therefore be a useful tool for probing the crust for lateral conductivity contrasts. Ideally, one needs a close network of magnetometers recording three components of geomagnetic variation over sufficient length of time. Even in the absence of such array, we can still compute induction vectors which point towards the direction of internal current concentration. The single station transfer functions are defined as the complex functions (A, B) which minimize in the least squares sense, the error of the fit to the equation

$$Z(f) = A(f)\ x\ (f) + B(f)\ Y(f) + E(f)$$

where f is the frequency of interest and E is the uncorrelated error part.

The transfer functions A and B can be calculated for any field variation. But in studies related to induction effects, the following assumptions should be valid:

1. The vertical field is totally anomalous without any normal part.
2. The horizontal fields X and Y are not correlated with normal vertical field.
3. The horizontal fields themselves should be approximately close to being normal.

Schmucker (1970) has shown that under these assumptions, we can calculate the induction vector from the auto and cross power spectra of the three components of the magnetic field. The defining equations are:

$$A = \frac{S_{zx}\,S_y - S_{zy}\,S_{yx}}{S_x\,S_y - [S_{xy}]^2}$$

$$B = \frac{S_{zy}\,S_x - S_{zx}\cdot S_{xy}}{S_x\,S_y^{\cdot} - [S_{xy}]^2}$$

Where $S_{x,}S_{y,}$ S_z are the auto power at frequency f and $S_{xy,}$ $S_{xz,}$ and S_{yz} are cross power between (X, Y), (X, 2) and (Y, 2) respectively. It may be noted that $S_{xy} = S_{yx}*$, where * denotes the conjugate.

The transfer functions A and B can be separated into their real and imaginary parts

$$A = A\gamma + i\ A_{im}$$
$$B = B\gamma + i\ B_{im}$$

which can then be combined to form the real (imaginary) induction vectors with

$$\text{amplitude} = (A\gamma^2 + B\gamma^2)^{1/2} \; [\,(A_{im}^2 + B_{im}^2)^{1/2}]$$

$$\text{and orientation angle} = \tan^{-1}(A\gamma/B\gamma) \; [\,\tan^{-1}(A_{im}/B_{im})]$$

Conventionally the induction vectors are computed from several single events like bays, storm sudden commencement etc. to minimise the errors. Banks (1975) demonstrated that complex demodulates (amplitudes and phases) as a function of time over a span of data are also equally well suited. This obviates the necessity of finding similar frequency events over several days of record. We adopted Schmucker's (1970) formulation of computing the real and imaginary induction vectors together with their error terms for 3 frequency bands centred on 350, 200 and 150 seconds. The real parts of A and B give the 'in-phase' response of Z to horizontal field changes and the imaginary parts give the 'quadrature-phase' response. The in-phase induction vector points towards a good conductor in which currents flow in phase with the normal field (Schmucker, 1970).

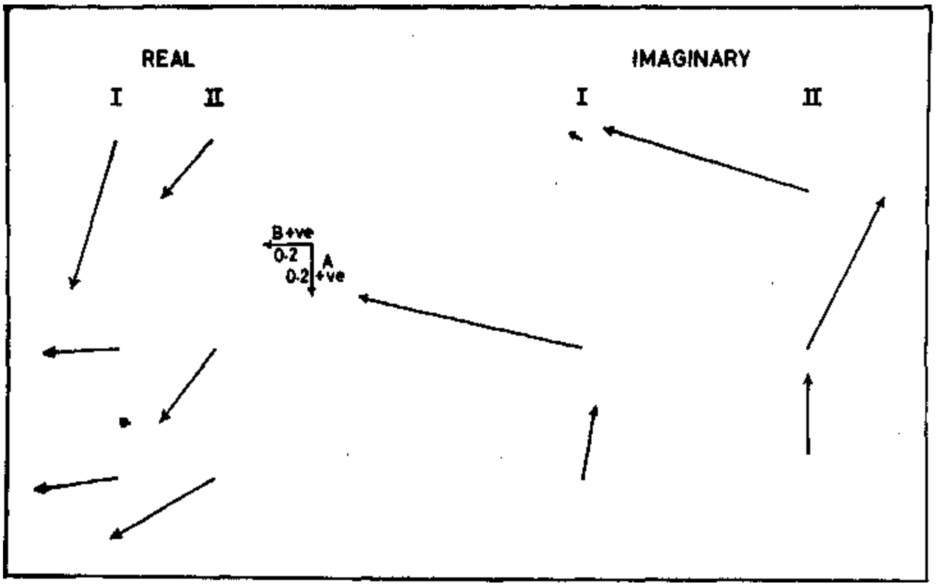


Fig. Amplitude and direction of Induction vectors (Real and Imaginary part) for three frequency bands (Bottom) 150 sec (Middle) 200 sec and (top) 350 sec derived from two sets of demodulates I for 0600-1430 UT and II for 1500-2300 UT.

The vectors were computed using two independent sets of demodulates (i) between 0600 and 1430 UT and (ii) between 1500 and 2330 UT. In Table II are given the parameters of the real and imaginary induction vectors. A sketch showing six real and six imaginary induction vectors with their origin coincident with Dakshin Gangotri location is provided in Fig. 7

Table II. Parameters of Induction vectors

Period	First set (0600-1430 UT)		Second set (1500-2330-UT)	
	Real	Imaginary	Real	Imaginary
350 sec	A = 0.574	-0.020	0.310	-0.240
	B =0.182	0.051	0.225	0.802
	$Resid^2$ = 0.062		0.031	
200 sec	A = 0.013	-0.193	0.276	-0.569
	B = 0.303	0.9199	0.227	-0.295
	$Resid^2$ = 0.123		0.042	
150 sec	A = 0.041	-0.273	0.233	-0.292
	B =0.335	-0.050	0.434	0.004
	$Resid^2$ =0.101		0.055	

Close to the sea coast the real induction vectors are expected to point towards the nearest deep sea as the conductivity is distinctly higher. For Dakshin Gangotri, this implies real induction arrow pointing towards North or North-East direction. Surprisingly, for all the three frequencies the real vectors point to south-west direction towards the continent. This suggests that in the crustal region corresponding to the depth of penetration for the frequency bands (3 to 6.5 mHz) there appear to be a significant lateral conductivity contrast sufficiently in excess of the land/ocean contrast near the coast in the northern side. Further insight about this conducting belt can be obtained if we operate an array of magnetometers from the ice shelf to the interior continent covering a sufficient area.

The 'imaginary' induction vectors are more difficult to interpret. If they point to the same direction as the real vectors it can be inferred that they are probably associated with the same conductivity anomaly. If the quadrature vectors are more dominant, it is indicative of a 90° phase difference between vertical and horizontal components. Fig. 7 shows that the quadrature induction vectors have variable orientation and magnitudes and none in the same direction as the real vectors. According to Gough et a/. (1974) the coast effect for stations close to the sea coast should manifest as quadrature phase vectors directed strongly towards the sea.

During the second expedition spot measurements of total field were made along six 10-15 km long profiles. A magnetic low was interpreted in terms of rift structure on the 10-12°E topographic ridge (Arora et *al.,* 1985). In view of the low amplitude of magnetic anomalies it was inferred that.the anomaly may be related to sediments infilling the rift valley. The presence of hydrated sediments near the measuring sites are expected to affect the induction pattern. The near

SW orientation of the induction arrows can be ascribed to the presence of the thick sedimentary layer, inferred from static magnetic field results.

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