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Induction Arrows Computed for the 210° MM Magnetic Observation Stations

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Abstract

The induction arrows determined from the transfer functions calculated by making use of data on the 210° magnetic meridian geomagnetic observations were obtained at 17 stations. Using high-sensitivity magnetometers and data acquisition with a fast sampling rate (1 sec for every component) makes it possible to analyze the geomagnetic variation fields with various amplitudes and periods from a few seconds to a few hours. The results show that the magnitudes and directions of induction arrows obtained at several stations, especially at the six stations in Australia, are subject to considerable variation between 0.25 Hz (4 sec) and 0.00011 Hz (150 min). Among those stations, the characteristics of geomagnetic variation fields observed at Learmonth, North West Cape, Australia, were examined by using high-pass-filtered records. The frequency dependence of the induction arrows at Learmonth could be due to the concentration and bending of electrical currents induced in the ocean and underlying high-conductivity structure and to the magnetic shielding effect of the subsurface conductive layer in the higher-frequency range.

1. Introduction

During the Solar Terrestrial Energy Program (1990-1997), an international scientific project, ground-based observations of geomagnetic variation fields at a chain of stations along the 210°magnetic meridian (MM) from Siberia, Russia, to Macquarie Island, Australia, were conducted by the Solar-Terrestrial Environment Laboratory (STEL), Nagoya University, in cooperation with Japanese and foreign universities and research institutes. Individual names of the 210°MM magnetic observation groups and organizations concerned are given by YUMOTO *et al.* (1996). The observations began at six stations (three in Japan and three in Australia) in 1990. At present, the three-component geomagnetic variation fields are being recorded simultaneously at 27 210°MM stations in various countries, including 8 stations in Australia.

The primary purpose of 210°MM observations is the investigation of energy and plasma flows from the upstream solar wind through the magnetosphere and ionosphere to the biosphere. Since the geomagnetic variation fields observed on the

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Earth's surface consist of two parts, the inducing field, which originates outside of the Earth, and the induced field, which is caused by electrical currents induced in the Earth's interior, it is important to remove the effects of the induced field from the observed field in order to achieve the above mentioned purpose. In the meantime, it is interesting to study the electrical conductivity structures at and around the 210° MM stations by making use of the 210°MM observation data.

In order to have an overall view of the induced field at each station, transfer functions with various periods from 4 sec to 150 min were calculated. The induction arrows that are determined from the transfer functions show an interesting frequency-dependent feature at most 210°MM stations, especially those in Australia.

In this paper, frequency dependencies of the induction arrows with frequency ranges between 0.25 Hz (4 sec) and 0.000111Hz (150 min) at the six stations in Australia are described, and a possible cause of the results obtained at Learmonth, North West Cape, Western Australia, is discussed in detail.

2. Observation and data analysis

Figure 1 shows the location of the 210°MM stations at which the three-component geomagnetic variation fields were recorded. The station names and those abbreviations are listed in Table 1. Geographic and geomagnetic locations and period of recording for every station are listed in *Reference Manuals of 210° Geomagnetic Data* issued by the STEL in February 1995. The geomagnetic variation fields were analyzed by using data obtained at the 17 stations indicated with solid circles in Figure 1, where recording had begun by 1993.

The three-component geomagnetic variation fields were observed by means of a fluxgate magnetometer with the same data acquisition system at all 210° MM stations (YUMOTO *et al.*, 1992). Because of the high sensitivity (resolution, 0.012nT) of the magnetometer and the fast sampling rate (1 sec) of the recording, it was possible to analyze geomagnetic variation fields with small amplitudes or short periods, such as geomagnetic micropulsations, and to study frequency dependence.

It is known that under the assumptions (*e.g.*, BEAMISH, 1979) that (1) the vertical component of the inducing field (Zn) is small compared to that of the induced

Table 1. The 210°MM station names and those abbreviations.

Station Name	Abbr.	Station Name	Abbr.
Kotel'nyy Isl.	KTN	Koror	KOR
Chokurdakh	CHD	Biak	BIK
Tixie	TIX	Wewak	WEW
Zyryanka	ZYK	Darwin	DAW
Magadan	NGD	Weipa	WEP
St. Paratunka	PTK	Learmonth	LMT
Moshiri	MSR	Birdsville	BSV
Onagawa	ONW	Dalby	DAL
Kagoshima	KAG	Canberra	CAN
Chichijima	CBI	Adelaide	ADL
Lunping	LNO	Katanning	KAT
Guam	GUA	Macquarie Is.	MCQ
Muntinlupa	MUT	Kotzebue	KOT
Yap Isl.	YAP	Ewa Beach	EWA

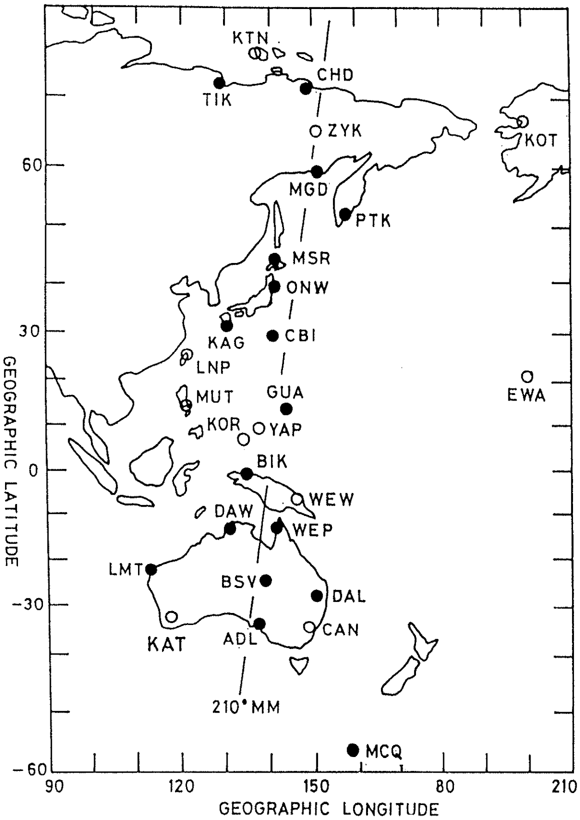

Fig 1. Location map for the geomagnetic observation stations along the 210° magnetic meridian. Seventeen solid circles show the stations at which analyses were made for this paper.

field (Za), (2) there is no correlation of Zn with the north and east components of the inducing field (Hn, Dn), and (3) both Hn and Dn are larger than the components of the induced field (Ha, Da), three-component geomagnetic variations observed at a certain station satisfy the following relation:

$$Z = A \cdot H + B \cdot D$$

where H, D, and Z mean Hn, Dn, and Za, respectively. The coefficients A and B are transfer functions that are calculated from the power spectral analyses of geomagnetic variation data with a suitable time interval (EVERETT and HYNDMAN, 1967). The two transfer functions are complex and are usually represented by real (in-phase) and imaginary (out-of-phase) induction arrows that are defined by the magnitude of $\sqrt{A^2+B^2}$ and the direction of arctan(B/A), respectively. Figure 2 illustrates the relation between transfer functions and induction arrow. The induction arrows point toward a higher-conductivity structure with a lateral discontinuity at which induced electrical currents flow intensely. The magnitudes of those arrows depend on the strengths of the induced currents, so if the assumptions listed above hold true, then the induction arrows give some information on the induced fields and the related conductivity structure at a station.

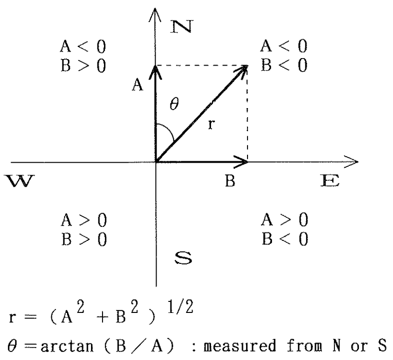

Fig 2. Illustration of an expression of induction arrow from transfer functions.

The transfer functions were calculated by using data with 1-min sampling values and 8-h durations on several different geomagnetically disturbed days: February 9, March 17, September 9 and 17, and November 9-12, 1992; February 7-10, 1993; and August 14, 1994. The simultaneous daily magnetograms observed at the 210° MM stations can be seen in *Daily Magnetograms* (STEP), *210° Magnetic Meridian Network, July – October 1992* and *Daily magnetograms* (STEP), *210° Magnetic Meridian Network, November 1992 – June 1993* which were issued by the STEL in 1993 and 1994, respectively. The results obtained by using the data for September 17, 1992 are shown in Figures 3 and 4, which display real induction arrows at the

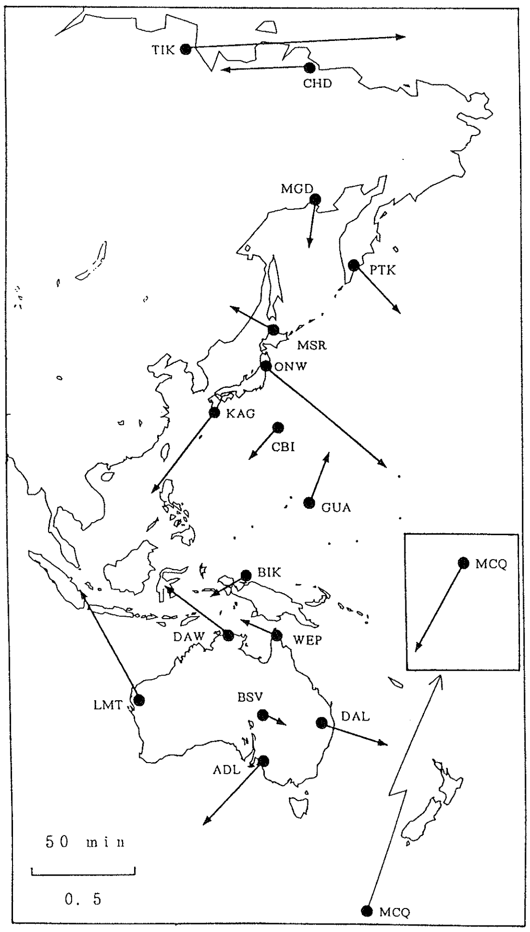

Fig 3. Real induction arrows for 50-min variations. The Macquarie Island arrow is shifted upward.

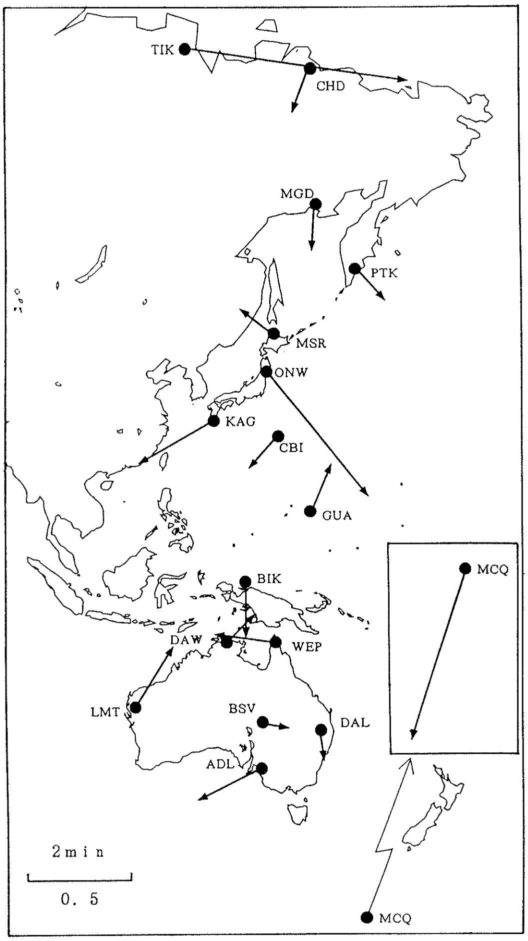

Fig 4. Real induction arrows for 2-min variations. The Macquarie Island arrow is shifted upward. Directions of arrows at Leamonth (LMT), Darwin (DAW) and Dalby (DAL) are different from those at 50-min (Fig. 3).

210°MM stations with variation periods of 50 and 2 min, respectively. Since the calculated imaginary induction arrows were small compared with the real arrows, the imaginary arrows are not displayed in Figures 3 and 4.

The magnitudes of induction arrows at Tixie, Russia, and Macquarie Island, Australia, both located in the polar regions, are extremely large, and vary widely according to the data used, a fact indicates that the assumption of transfer functions (Zn ‹‹ Za) does not hold at a station located in a high-geomagnetic-latitude region that is close to the auroral electrojets. The large differences in direction of the induction arrows at Chokurdakh, Russia, could be explained similarly. The difference between Tixie, Macquarie, and Chokurdakh is the distance from the coast. Chokurdakh is 200 km from the coast line, but Tixie is near the coast, and Macquarie lies on the island, so Tixie may be subject to the coast effect, and Macquarie may be subject to the island effect.

A comparison of the induction arrows for two periods indicates that although the induction arrow at every station shows a frequency dependence, this dependence is particularly noticeable at almost all of the Australian stations. This paper does not discuss induction arrows for each period at every station except the Australian stations. In the following sections, the frequency dependence of induction arrows in Australia, especially at Learmonth, is described in detail.

3. Induction arrows in Australia

Geomagnetic variation anomalies in Australia have been studied by many authors (*e.g.*, PARKINSON, 1959; GOUGH *et al.*, 1974; LILLEY, 1976; WOOD and LILLEY, 1979; WHITE and MILLIGAN, 1985). Recently, CHAMALAUN and BARTON (1993) studied the large-scale electrical conductivity structures of Australia by making use of the induction arrows obtained by themselves and many other authors. They interpreted the cause of geomagnetic variation anomalies in Australia as the coast effect, the current flow in sedimentary basins that lie among the continental cratons, and current concentrations between the specific regions, such as the region of Flinders Ranges anomaly, South Australia. As for the stations discussed here, Adelaide belongs to the region of Flinders Ranges anomaly (*e.g.*, WHITE and POLATAYKO, 1985),

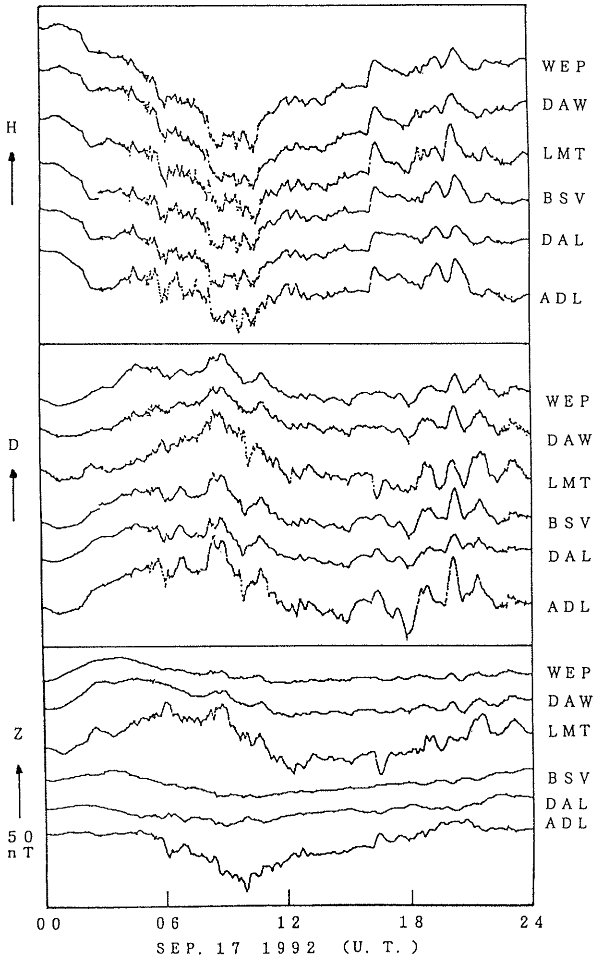

Fig 5. Simultaneous magnetograms for the six stations in Australia on September 17, 1992.

and Birdsville belongs to the Southwest Queensland anomaly (*e.g.*, WOODS and LILLEY, 1980). Most studies of the induction arrows so far, however, have been carried out in the variation period range of more than a few minutes. It may be worthwhile to analyze geomagnetic variations with shorter periods and to examine the frequency dependence of induction arrows in Australia.

There are eight 210°MM stations in Australia, as shown in Figure 1: Weipa, Darwin, Learmonth, Birdsville, Dalby, Adelaide, Canberra, and Katanning. Analyses were made by using the data obtained in 1992 and 1993 at six stations (excluding Canberra and Katanning which are the latest station established [August, 1994 and August, 1995, respectively]). Figure 5 shows three-component magnetograms obtained simultaneously at the six stations on September 17, 1992. H, D, and Z are the horizontal north, east, and vertically downward components, respectively. Although the variations in H appear to be nearly identical at the six stations, differences in the amplitudes and wave forms of D at different stations are perceptible. The variations in Z are quite different, indicating the effect of electrical currents induced in the surroundings of each station. The large amplitude of Z at Learmonth and Adelaide may be interpreted as being mainly due to the coast effect and partly due to the undulation of the electrical conductivity structure beneath the station (*e.g.*, WHITE and HEINSON, 1994).

The induction arrows were determined by 3-min sampling of the data observed on February 8–9, 1993, and 1-min and 1-s sampling on September 17, 1992. Figure 6 shows how the real induction arrows rotate as the period changes from 150 min to 4sec. The 1000-m bathymetric line is also shown in Figure 6. In the longer periods, the induction arrows at Learmonth, Darwin, Weipa, Dalby, and Adelaide tend to point toward the deep ocean because of the coast effect. Although the coast

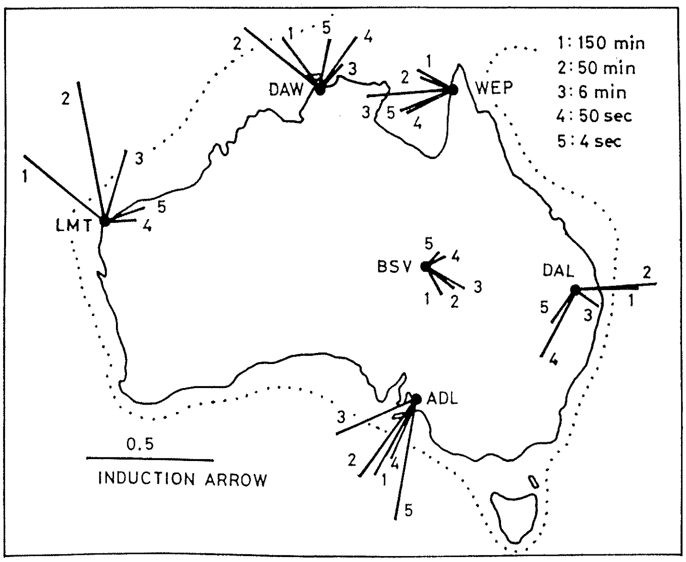

Fig 6. Change in orientation of real induction arrows for five periods that display remarkable frequency dependence. The induction arrows with shorter periods at Learmonth and Dalby do not point toward the deep ocean against the coast effect. The dotted line is the 1000m bathymetric line.

effect seems to be prominent in the shorter periods, the induction arrows at Learmonth and Dalby point in different directions from the ocean as the variation period becomes shorter.

4. High-pass-filtered records

In order to interpret the frequency dependence of the induction arrows that show anomalous behavior against the coast effect in the short periods, the characteristics of short period magnetograms were examined. Lower-frequency and large-amplitude fluctuations, such as the daily variations, were eliminated by means of a numerical high-pass filter with a cut-off period of 50 min (SASAI, 1967). Figure 7a shows high-pass-filtered records for the morning of September 17, 1992, that were obtained in this way.

Figure 7b shows filtered records for the afternoon, and here we see fluctuations with longer periods than we saw in the morning. The amplitudes of H at Learmonth are larger than those at the other stations except Adelaide, which is close to the polar region (L=2.13). The variations of D at stations at approximately the same geomagnetic latitudes, such as Weipa and Darwin, are very similar. However, the amplitudes and phases in variations of D at Learmonth are quite different from those at the same-latitude stations Birdsville and Dalby. D at Learmonth seems to

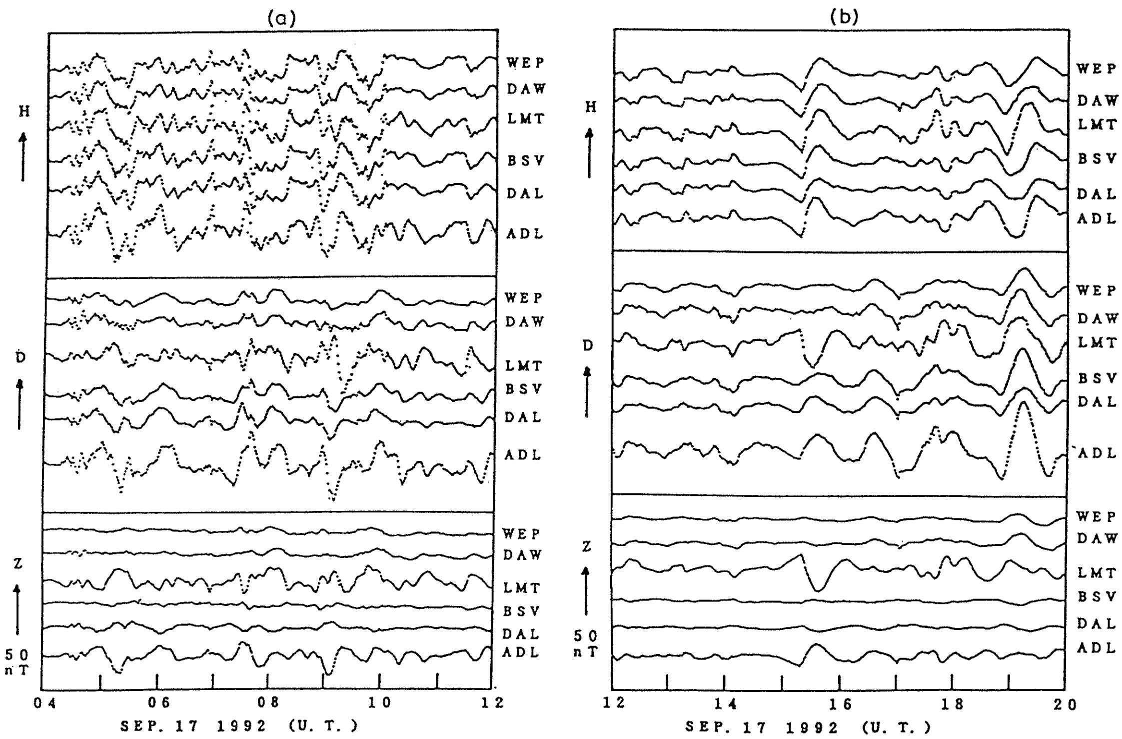

Fig 7. High-pass- filtered records with a cut-off period of 50 min for (a) the morning of September 17, 1992 and (b) the afternoon of the same day.

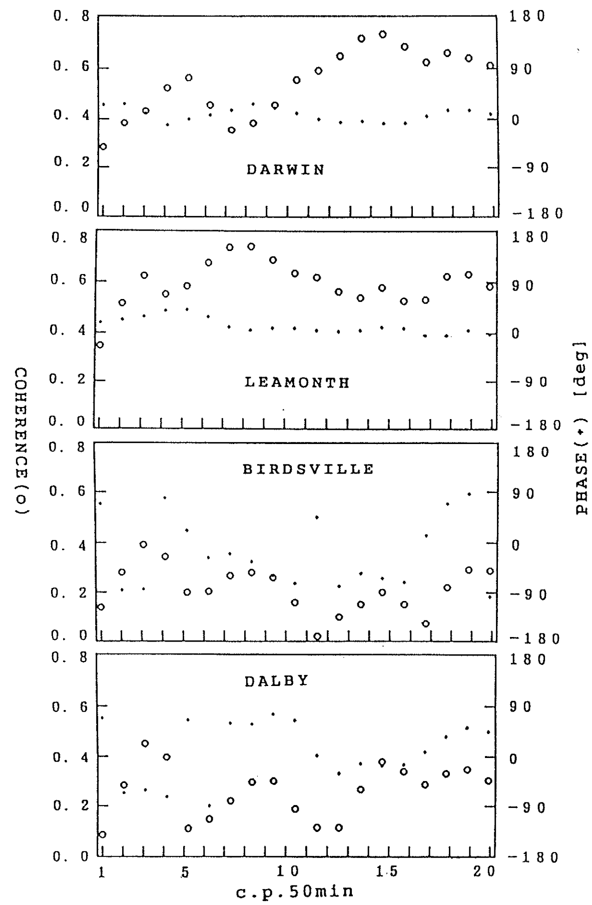

Fig 8. Coherence and phase difference spectra between horizontal northward and eastward variations.

vary out of phase with H and in phase with Z. The amplitudes of Z at Learmonth are extremely large, indicating not only the intense effect of electrical currents induced in the Indian Ocean but also the effect of the high conductivity structure beneath Learmonth.

To gain an overview of the relation between H and D, coherences and phase differences at the Learmonth, Darwin, Birdsville, and Dalby stations are calculated by using the data for September 17, 1992. Figure 8 shows the coherence and phase difference spectra between H and D. For a frequency of more than 2 cycle/50 min (period is less than 25 min), the coherences between H and D at Learmonth and Darwin are good. In accordance with this good coherence, the phase differences at Learmonth and Darwin are small in the higher-frequency range. Figure 8 indicates that at Learmonth and Darwin, H varies coherently with D and vice versa. These facts suggest that as the variation frequency increases, the geomagnetic variation fields observed at Learmonth are suffused with the fields that are caused by electrical currents induced in high conductivity structures, including the ocean.

Figure 9 shows the high-pass-filtered records for a cut-off period of 50s at the four stations. The variations in Pi 2 and Pc 3 geomagnetic micropulsations are

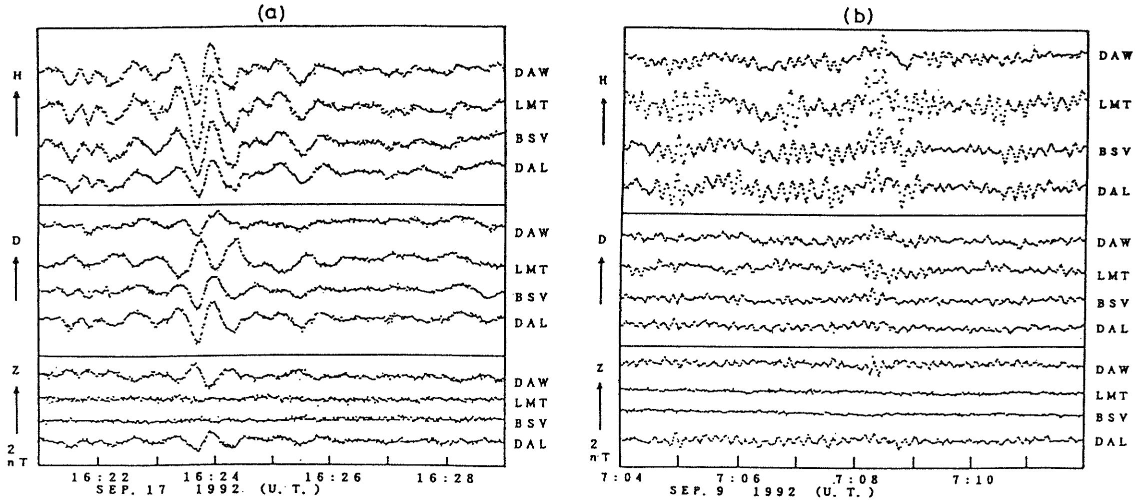

Fig 9. High-pass-filtered records with a cut-off period of 50 sec for (a) Pi 2 and (b) Pc 3 micropulsation phenomena.

shown in Figure 9a and 9b, respectively. In the variations at Learmonth, the amplitudes of H are greater than those at the other stations, and phases in the variation of D are quite different from those at the other stations. Furthermore, D varies out of phase with H, as was seen in the lower-frequency range. It is worth noticing in Figure 9 that the variation amplitude of Z falls to zero in the frequency range higher than 0.025 Hz (period is less than 40 sec), as if there were no coast effect at Learmonth.

5. Discussion

In the preceding sections, the unusual frequency dependences of the induction arrows obtained at Learmonth is described. The main features of geomagnetic variation fields observed at Learmonth are as follows: (1) coherence between H and D is good, (2) H and D vary out of phase with each other, (3) in the lower-frequency range, Z varies in phase with D and out of phase with H, and (4) the magnitudes of Z variation are large in the lower frequency range but become zero in the hlgher frequency range, such as geomagnetic micropulsations. Figure 10a and 10b illustrate the cause of the first three features just mentioned, and Figure. 10c and 10d illustrate the fourth feature. Learmonth is located at the corner of north western Australia. It lies in the middle of the North West Cape (width is about 25 km wide) and faces the Exmouth Gulf, as shown in Figure. 10b, which is supposed to be lying on a shallow ocean as shown in Figure 10c and 10d. EVERETT and HYNDMAN (1967) interpreted the behavior of induction arrows in south western Australia as being due to the coast effect and the underlying higher-conductivity structure. In north western Australia, where the induction arrows are extremely large, the higher-conductivity structure could also be considered to exist beneath the Indian Ocean and deep beneath the Pilbara and Vilgarn craton, which is shown in Figure. 10a, as a shaded area.

In an inducing field that varies towards the south, eastward electrical cur-

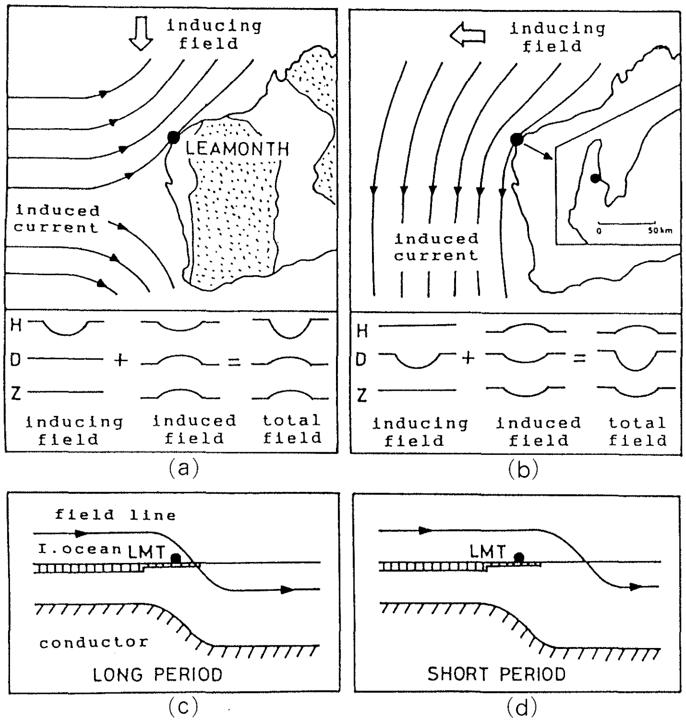

Fig 10. Feature of geomagnetic variation fields observed at Leamonth (LMT): (a) Expected induced current, waveforms of inducing, induced fields, and the sum of both fields (total field) in southward inducing field. Shaded areas show the continental cratons. (b) Expected induced current, waveforms of inducing, induced, and total fields in westward inducing field. Good coherence with H and D, and phase variations among H,D and Z variations at Learmonth are explained by the situations illustrated in (a) and (b). (c) Field line of geomagnetic variation for assumed high conductivity structure, in long period geomagnetic variation. (d) Field line of geomagnetic variation in short period variation. Disappearance of Z variation in the higher frequency range at Learmonth is explained.

rents are induced both in the Indian Ocean and in a shallow high conductivity structure beneath the ocean. The induced electrical currents are bent, and they concentrate on the corner of north western Australia, forming north eastward flows that cause horizontally southward and eastward and vertically downward geomagnetic variation fields at Learmonth as shown in Figure 10a. In the westward inducing field, a situation similar to that shown in Figure. 10b could occur. These illustrations are in accord with observational facts 1,2, and 3 given in the preceding paragraph. In variations with higher frequencies, as a result of the shielding effect of subsurface high-conductivity layers, the variation in Z disappears, as shown in Figure 10d, but the magnitudes of variations in H and D are increased by the induced electrical currents that flow horizontally just beneath the station.

In conclusion, a cause of the frequency dependence of the induction arrows at Learmonth is that the assumptions for transfer function, $Ha \ll Hn$, $Da \ll Dn$ and $Za \gg Zn$, do not hold true because of the induced electrical currents flowing at and around the station. Since the geomagnetic variation fields observed at Learmonth include in-

Table 2. Real transfer functions for three periods and three different data at Learmonth, Darwin, and Dalby.

PERIOD : 1 minute

DATA	LEARMONTH		DARWIN		DALBY	
	A	B	A	B	A	B
SEP. 9 1992	0.011	0.088	-.215	-.155	0.163	0.157
SEP.17 1992	-.240	-.139	-.162	-.090	0.154	0.003
AUG.14 1994	-.090	0.087	-.211	-.170	0.214	-.070

PERIOD : 12.5 minutes

DATA	LEARMONTH		DARWIN		DALBY	
	A	B	A	B	A	B
SEP. 9 1992	-.069	0.096	-.203	-.020	0.136	0.036
SEP.17 1992	-.362	0.030	-.155	0.120	0.061	-.189
AUG.14 1994	-.346	0.143	-.246	0.224	0.131	-.183

PERIOD : 50 minutes

DATA	LEARMONTH		DARWIN		DALBY	
	A	B	A	B	A	B
SEP. 9 1992	-.213	0.371	-.241	0.146	0.050	-.142
SEP.17 1992	-.463	0.231	-.204	0.299	0.038	-.223
AUG.14 1994	-.357	0.466	-.295	0.371	0.046	-.240

tense induced fields, especially in the short-period variations of less than a few minutes, the greatest care must be taken in dealing with the data from Learmonth when one is studying the magnetospheric phenomena.

The causes of frequency dependence at the other stations are not clear. However, a situation similar to that at Learmonth may be occurring at Darwin because of good coherence between H and D. Regarding the frequency dependence at Dalby, since no noticeable feature shows up in the magnetograms, a shallower high-conductivity structure may lie west of Dalby. In the high-frequency variation fields, electrical currents may be induced west of Dalby, and they may overcome the intense coast effect of the Pacific Ocean which lie east of Dalby. Table 2 shows calculated real transfer functions for three stations, three periods, and three different data. Table 2 indicates that the frequency dependences vary more or less with every data.

In order to study frequency dependence quantitatively, a magnetic array study like that conducted around Adelaide (Flinders Ranges anomaly) and Birdsville (Southeast Queensland anomaly) should be conducted in and around Learmonth, Darwin and Dalby.

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