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Micropulsations Recorded by an Array of Magnetic Variometers

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Data recorded at 10-sec intervals by an array of 25 Gough-Reitzel magnetic variometers have been studied for micropulsation activity. The instruments operated simultaneously over an area approximately 500 × 750 km in SE Australia, each instrument recording three components of the geomagnetic variation field. Concurrent recording by the instruments of several cycles of activity of period 7 min has enabled us to map the large-scale spatial variation of the micropulsation components. The resulting patterns are quite smooth; the strongest effect is the spatial variation of the vertical component, which exhibits a 'coast effect' similar to that observed at longer periods. Micropulsation data recorded by arrays of such instruments may yield valuable information on crustal conductivity structure.

Of the wide range of time variations that occur in the geomagnetic field as measured on the surface of the earth, all with periods of greater than about 1 msec have relevance to some aspect of solid earth geophysics. For the analysis of crustal and upper mantle electrical conductivity, variations in the period range of seconds to days are most useful, the longer-period variations penetrating more deeply. The 'geomagnetic depth sounding' method has developed largely by analysis of disturbances of periods of the order of 1 hour, and it was for this purpose that *Gough and Reitzel* [1967] designed a magnetic variometer that made a recording every 10 sec and that was inexpensive enough to be produced in large numbers and thus to be used in array studies. The data of this paper were recorded with an array of Gough-Reitzel instruments, and although it was evident from the earliest tests [see *Gough and Reitzel*, 1967] that the instruments recorded micropulsations faithfully, this paper is believed to be the first analysis of short-period variations recorded over such a large array. Most earlier array analyses have been concerned with longer periods, mainly for the reason already given that longer-period disturbances propagate more deeply; it has therefore been the common practice to digitize the instrument variograms at intervals of 1 min and to smooth out the micropulsations manually [*Reitzel et al.*, 1970].

For the data about to be described, with micropulsation analysis as the main objective, the digitizing interval was taken as 10 sec; that is, every point on a variogram trace was used. The wide spacing of the observing sites, designed to optimize data recorded at about 1-hour periods, means in the case of the present micropulsations a loss of small-scale resolution for the gain of covering such a large area with 25 instruments.

DATA

The data were recorded by an array of magnetic variometers sited inland from the coast of SE Australia (Figure 1) that recorded continuously for three months in early 1971. Micropulsations were only one type of the various events recorded, which included magnetic storms and magnetic daily variations. A code list for the observing stations is given in Table 1, and the exercise is described in more detail by *Lilley and Bennett* [1972]. The micropulsations in question commenced at about 2000 GMT on March 13, 1971. At this time 25 instruments were operating satisfactorily, although individual traces at certain sites were lost. The recorded variograms are shown in Figure 2. The characteristic period of variation (about 7 min) classifies this set as 'giant micropulsations', the Pc 5 type of *Campbell* [1967] and *Jacobs* [1970], with a heavily damped sinusoidal form.

The stacked profiles of Figure 2 were obtained from the original records by manual scaling off a film reader, calibrating, correcting for a small

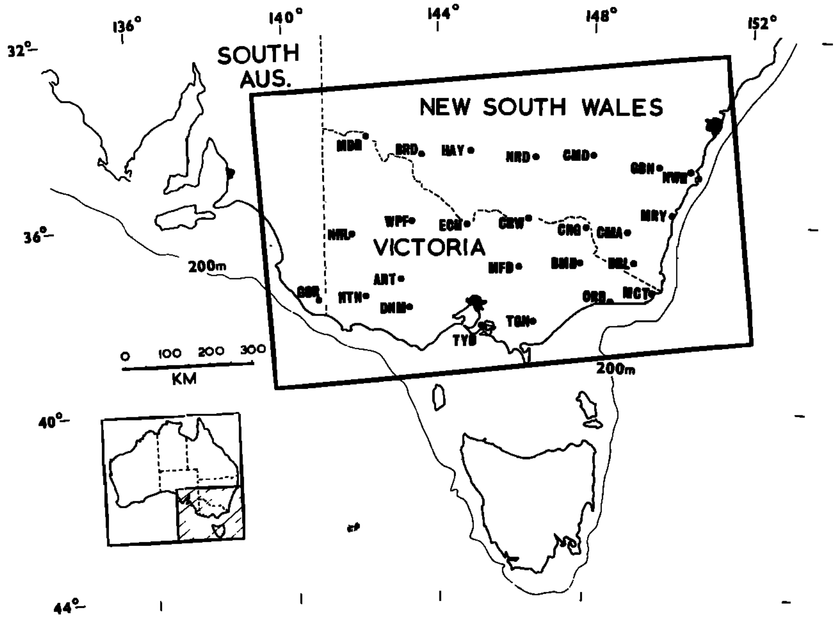

Fig. 1. Map of observing sites in SE Australia. The rectangle drawn is the frame for Figures 4 and 5.

TABLE 1. Observing Stations

Station	Code	Geographic Coordinates
Ararat	ART	37°19'S, 143°00'E
Bombala	BBL	36°55'S, 149°11'E
Benambra	BMB	36°58'S, 147°42'E
Balranald	BRD	34°36'S, 143°34'E
Cooma	CMA	36°18'S, 148°58'E
Cootamundra	CMD	34°37'S, 148°02'E
Corryong	CRG	36°11'S, 147°53'E
Corowa	CRW	35°59'S, 146°22'E
Derrinallum	DNM	37°54'S, 143°11'E
Echuca	ECH	36°08'S, 144°46'E
Goulburn	GBN	34°49'S, 149°44'E
Mt. Gambier	GBR	37°44'S, 140°46'E
Hay	HAY	34°31'S, 144°50'E
Hamilton	HTN	37°39'S, 142°03'E
Mallacoota	MCT	37°36'S, 149°43'E
Mildura	MDR	34°14'S, 142°04'E
Mansfield	MFD	37°02'S, 146°08'E
Moruya	MRY	35°54'S, 150°08'E
Nhill	NHL	36°20'S, 141°38'E
Narandera	NRD	34°42'S, 146°31'E
Nowra	NWR	34°57'S, 150°32'E
Orbost	ORB	37°47'S, 148°36'E
Traralgon	TGN	38°12'S, 146°28'E
Tyabb	TYB	38°16'S, 145°10'E
Wycheproof	WPF	36°04'S, 143°14'E

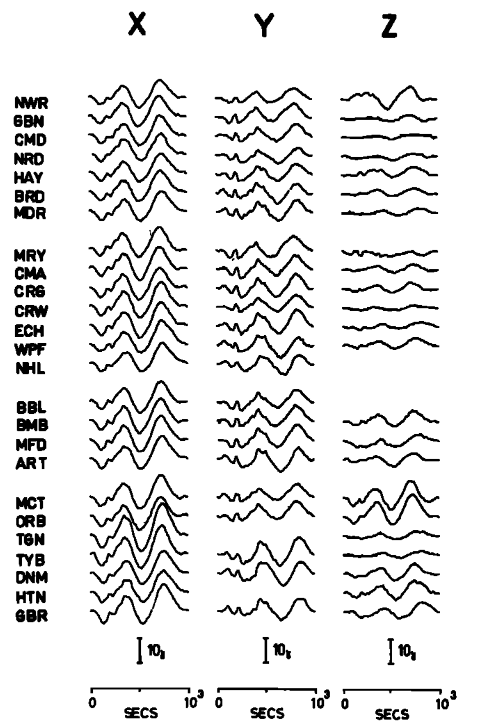

Fig. 2. Stacked variograms for 1000 sec of record at about 2000 GMT on March 13, 1971.

interaction between two sensing elements, and then resolving the readings from magnetic to geographic coordinates. Each profile is therefore a set of digital readings with a digitizing interval of 10 sec. The standard error of each reading is estimated as 0.5 γ, and the error in each time base is negligible, although there may be significant error in the synchronization of the different time bases. The usual methods of timing the variograms were insufficient for this examination of micropulsations, and all records have been timed relative to a sharp transient signal that showed on the north traces just before the signals of Figure 2. In the drafting of Figure 2 this sharp transient signal has been assumed to be instantaneous across the array.

ANALYSIS OF DATA

We have computed Fourier transforms for each profile shown in Figure 2 by taking the value of the signal to be 0 for indefinite intervals before and after the interval shown. Because the data of Figure 2 represent unfiltered series of readings at 10-sec intervals, there is inherent in this process the danger of 'aliasing' errors arising in the transform values. We have guarded against these errors as much as possible by choosing records that appear to be varying smoothly and by choosing pulsations at the long-period end of the micropulsation range. Typical spectra are shown in Figure 3. The strong peak at the 7-min period is to be expected from the even sinusoidal appearance of the variograms. There is no evidence of a frequency displacement of the spectral peak across the survey area.

From the analysis of the errors of Fourier coefficients given by *Whittaker and Robinson* [1946, p. 280], we estimate the probable error of each sine and cosine transform spectral value as 50 γ/Hz. Although they are calculated directly from the sine and cosine transform values, the amplitude and phase values presented in the next section will have probable errors that differ in each case, because the probable error in the phase depends on the magnitude of the amplitude value. The phase to be used is a phase 'lag' in the sense that if a station has a more positive phase value the signal will have been recorded there at a later real time.

MAPS OF FOURIER TRANSFORM PARAMETERS

The Fourier transform parameters of amplitude for period 7 min are plotted for each station and contoured in Figure 4. Presentation of the phase data is not so straightforward, because of the insufficiently accurate timing mentioned above. At each station, however, the three data series X, Y, and Z are timed near-perfectly relative to each other, because all three are recorded simultaneously on film by the same light flash. Consequently it is possible to give the phases of any two components relative to the third; this is done in Figure 4, in which the phases of Y and Z are quoted relative to the phase of X, which is taken as 0. If the transient used as the reference time mark in Figure 2 were in fact instantaneous across the

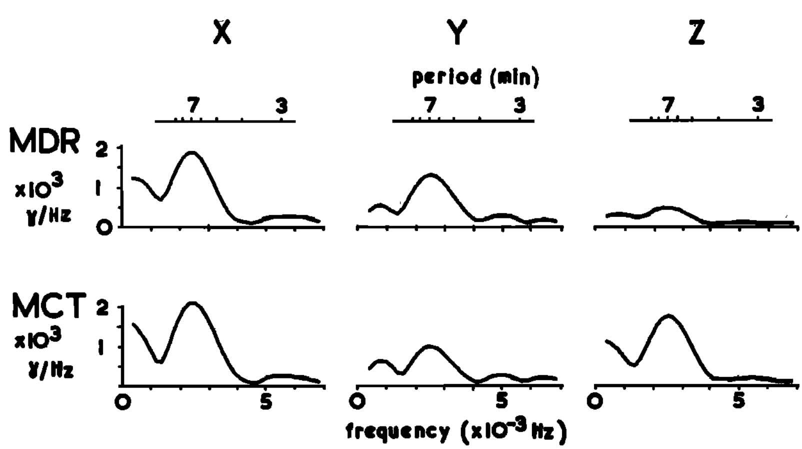

Fig. 3. Typical amplitude spectra for a coastal station (MCT) and a distant inland station (MDR).

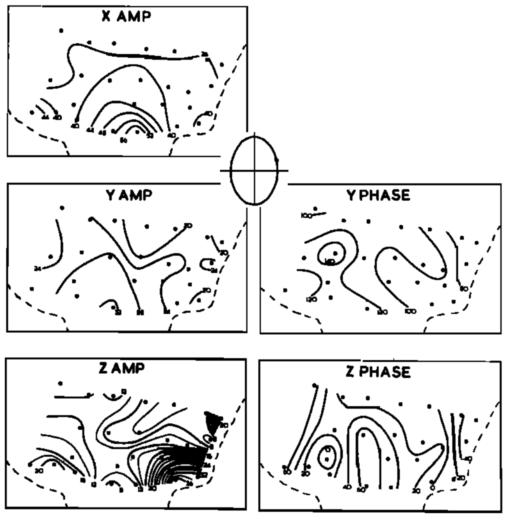

Fig. 4. Fourier transform maps for the micropulsations at period 7 min, with ellipse of horizontal polarization. Units of amplitude are 500 γ/Hz, and units of phase lag are seconds. The broken lines mark the approximate edge of the Australian continental shelf.

array, absolute X, Y, and Z phase maps could be presented. These would show a smooth X phase increase of about 20 sec from east to west across the array, and the $(Y\text{-}X)$ and $(Z\text{-}X)$ phase maps of Figure 4 would be modified accordingly.

The ellipse in Figure 4 is that of horizontal polarization, calculated as described in *Lilley and Bennett* [1972] for stations in the center of the array; it shows the sense of rotation to be clockwise, as is commonly the case for such pulsations in the morning sector of the southern hemisphere [*Jacobs*, 1970, p. 134]. The horizontal polarization shows little change at frequencies on either side of the spectral peak of Figure 3. This pattern, which is to be contrasted with the highly varying polarization of magnetic storms, undoubtedly results from the more simple mechanism by which the micropulsations have been produced [*Campbell*, 1967], as deduced from the sinusoidal appearance of their signals (Figure 2).

Discussion

To interpret the maps of Figure 4 it is instructive to have for comparison the similar maps for a longer period (64 min) obtained from the magnetic substorm data described in *Lilley and Bennett* [1972] and shown in Figure 5. Note that, for the examples shown, the polarization ellipses are similar, except that the senses of rotation are opposite. Comparison of the maps of Figures 4 and 5 shows them to be remarkably similar at first sight, with high Z amplitudes near the coastlines and high X amplitudes in the central southern part of the array. The Y amplitude pattern for 7 min is rather more complicated than the smooth NS gradient at 64 min but can be considered as basically similar to this gradient with some fine detail superimposed, possibly because of the greater sensitivity of the higher-frequency micropulsations to near-surface conductivity inhomogeneities.

The phase of Z on both maps shows marked change across the array. This relationship can be explained for both frequencies by a change in the correlation of Z from being in phase with the onshore horizontal component at the east coast to being in phase with the onshore horizontal component at the SW coast, in the manner demonstrated by *Bennett and Lilley* [1972] for other data from this array. It is a further indication that the large coastal Z anomalies of Figure 4 are due to the conductivity contrast (which may extend deeper than

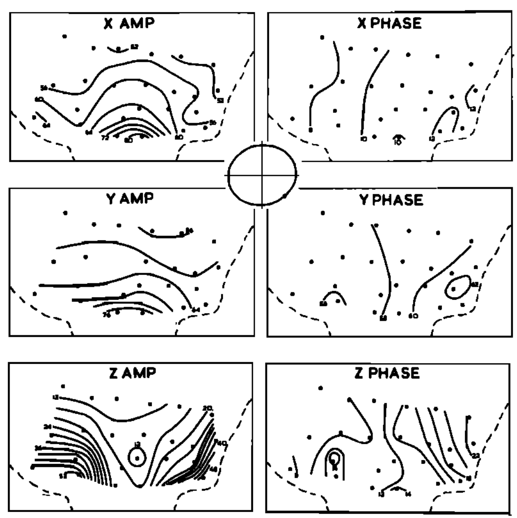

Fig. 5. Fourier transform maps for April 11, 1971, 1500–1800 GMT at period 64 min, with ellipse of horizontal polarization. Units of amplitude are 540 γ/Hz, and units of phase lag are minutes. The broken lines mark the approximate edge of the Australian continental shelf.

the seawater) at the ocean-continent interface.

There is therefore evidence that the observed Z pattern at 7 min is produced to a large extent by a coast effect. The only unusual feature in this result is the low Z amplitude at the station of MRY on the east coast. Comparison of the MRY data with that recorded at coastal station NWR farther north shows NWR to have a much stronger Z amplitude and MRY to have a slightly stronger Y amplitude. No particular phase structure is associated with these differing amplitude responses, but the effect is considered quite genuine. *Schmucker* [1970, p. 53] notes that some of his Californian coastal sites show unusually low Z amplitudes for micropulsations; he attributes this characteristic to the fact that ocean eddy currents diffuse into the continental coast. Possibly a similar phenomenon takes place on the Australian east coast.

On both Z phase maps there is a feature in the SW corner of the array centered on Ararat (ART) that coincides with the anomaly considered in *Lilley and Bennett* [1972] to be possibly associated with the recent volcanics of the area. For both this and the feature at MRY a denser siting of observing stations is needed to define the anomalies more clearly.

The phase of the horizontal components on both maps is small and varies smoothly across the array, although the 7-min map appears to show phase increasing westward whereas the 64-min map shows phase increasing eastward. This difference may possibly be evidence of the different source mechanisms involved, although the inaccuracy in timing the phase maps of Figure 4 must be remembered. The general similarity of the horizontal amplitude maps suggests that the source of the micropulsations could be represented for the purposes of geomagnetic depth sounding by an ionospheric current system similar to that often constructed for magnetic substorms.

The general consistency of large-scale pattern in the maps of Figure 4 is taken to demonstrate that for geomagnetic midlatitudes it is possible to perform a valid analysis of micropulsation data recorded by large variometer arrays; also it is evident that micropulsation components vary systematically over areas of such size. The variation due to general latitudinal dependence may be less than that due to the earth's conductivity structure. The conclusion is reached that an analysis of micropulsations recorded by an array of Gough-Reitzel instruments may be a rewarding exercise for the purpose of investigating crustal conductivity structure. In a later paper the conductivity structure of the earth beneath the area involved will be investigated, including the observational frequency range obtained from similar analyses of magnetic storms and daily variations.

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