Spectral characteristics of low latitude Pc3 geomagnetic pulsations in south-east Australia

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MS received 8 March 1985; revised 17 October 1985

Abstract. Geomagnetic pulsations in the Pc3 period range (10–45 sec) were recorded simultaneously in south-east Australia using an array of four low latitude induction coil magnetometers over a longitudinal range of 17° at $L = 1.8$ to 2.7 . Geomagnetic data from March 25 to September 21, 1982 were digitized and spectral studies were carried out from Grey scale digital (GSD) dynamic spectra and contour sonagrams. Similar wave spectra were generally seen at the three stations WM, BH and NC in the same latitude with Pc3 waves mostly being observed in the 40–45 mHz band. In addition the higher latitude station (LN) also showed lower frequency Pc4 bands (~ 10 mHz) on some days but higher frequency bands (60–80 mHz) on others. Sometimes completely different wave frequencies were observed on the X and Y components with the stations in the same latitude generally showing similar spectra on the corresponding components. Dynamic spectra also indicated that wave energy often turned off and on abruptly over short intervals of time implying solar wind control and Pc3 pulsation activity. A band harmonic structure was occasionally seen in wave spectra at the azimuthal stations mainly on the X component during the local afternoon with a harmonic spacing (Δf) of ~ 10 mHz.

Keywords. Geomagnetic pulsations; Grey scale dynamic spectra; contour sonagrams; induction coil magnetometers.

1. Introduction

Geomagnetic pulsations of the Pc3 type are daytime phenomena with a maximum occurrence around noon (Saito 1964). At low geomagnetic latitudes the amplitude of a typical Pc3 event is 0.1 nT (Orr 1973). Dynamic spectra in the frequency-time domain provide the most convenient method for examining the general properties and interstation similarities of geomagnetic pulsations. This technique has been widely employed within the Pc1 pulsation range (Kokubun 1970) but the difficulty in obtaining the large record to replay tape recorder speed-up ratio has restricted its use in the dynamic spectral studies of the longer period (Pc3–5) pulsations. However Saito *et al* (1979) developed the P-HISSA (power-spectrum-type high speed spectrum analyzer) which is capable of producing dynamic spectra over all the Pc3–5 bands. The present paper describes the spectral studies of low latitude ($L \leq 3$) Pc3 geomagnetic pulsations (period range 10–45 sec) data recorded in south-east Australia.

2. Data and analysis

Data acquisition involved the use of induction coil magnetometers employing digital analysis techniques. Four recording stations, three spaced in longitude along a latitude

and the two separated in latitude along a longitude, were used. A geomagnetic longitudinal range of 17° was covered at $L = 1.8$ and a latitudinal range of 10° over $L = 1.8$ to 2.7 . The stations were situated at Woomera (WM) (41.7°S , 209.1°E geomagnetic), Broken Hill (BH) (42.4°S , 214.5°E), Newcastle (NC) (42.0°S , 226.3°E) and Launceston (LN) (52.4°S , 231.1°E).

The geomagnetic north-south (X) and east-west (Y) components of Pc3-4 wave signals in the 5–100 mHz were recorded using slow speed analog magnetic tapes employing a frequency modulated recording system. Brief details of the recording and analysis instrumentation have been given by Ansari (1984). Both analog and digital analysis procedures were applied to the recorded data (Ansari 1984). Data from March 25 to September 21, 1982 was digitized in the laboratory with a 5s sample rate using the recorded time channel pulses and providing a Nyquist frequency of 100 mHz (Ansari 1984). Digital sonagrams from the $X(t)$ and $Y(t)$ time series of all the data for each station over one day (24 hour) intervals were constructed using the maximum entropy method (MEM) on 10 minute subsets overlapping by 5 minutes. A detailed analysis of the digital sonagram characteristics was then carried out and ten days of data were selected for detailed analysis. These are March 25–28, 30; May 27, 29–31 and June 1, 1982.

For all these days Grey scale digital (gsd) dynamic spectra (see figure 1) were constructed using a 64 K RAM CP/M based microcomputer system and a CIRRON 1550 dot matrix printer with graphics capability (see appendix). In order to obtain a simpler and averaged visual representation of frequency-time structure, contours (see for example figure 2) of four-hour duration at four different power spectral levels were

Figure 1. gsd dynamic spectra showing Pc3 activity on March 25, 1982. 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.

Figure 2. Contour sonagram showing Pc3 activity on the X component at the four stations WM, BH, NC and LN on March 25, 1982 between 0800–1600 hr AEST. The segments marked with a horizontal line on the time axis show continuous pulsation activity.

plotted employing the FFT method on a Tektronix 4025 graphics terminal and a 4612 hard copy unit (for details see Ansari 1984).

Although the frequency response of Pc3 recording equipment (Ansari 1984) is identical at all the four recording stations, the amplifier gains at the four stations were not necessarily the same and consequently the dynamic spectra presented are not normalized with respect to amplitude. Therefore it is not possible to compare the power spectral intensity between the stations from the spectrograms. However at a given station the *X* and *Y* signal channel gains are always identical and the spectral intensity between components can be directly compared. In general, there appears to be a higher signal amplitude on the *X* component than on the *Y*.

In obtaining the GSD spectra fixed levels (0–256) of PIXEL data were used (appendix). Therefore the GSD technique provides a uniform response for all the spectra from all the four stations. However the 256 levels are scaled to range between the maximum and minimum signal intensities for the contour sonagrams and therefore different stations and different days will be portrayed at different intensity levels. This is done in order to emphasize the frequency time structure. All the GSD dynamic spectra are obtained over a time range of 25 hours (0000 hr AEST of the current day to 0100 hr AEST of the next day) and a linear frequency span of 0 to 100 mHz. Time is always stated in Australian Eastern Standard Time (AEST). AEST = UT + 10 hr. The contour sonagrams are separately obtained in four-hour data sections. These sections have the same intensity range and are joined to form a total data span of eight or twelve hours (see for example figure 2). Again a frequency range of 0 to 100 mHz is employed. As the signal intensity level is higher in the *X* component, the contour sonagrams of the *X* component only are shown. The horizontal bars at the bottom of each contour sonagram figure show the durations of Pc3 activity on that day.

Interstation comparison using cross-spectral analysis techniques were carried out on WM-BH, BH-NC and WM-NC station pairs to give longitudinal wave properties and on the NC-LN pair to give latitudinal wave properties. Plots of cross-spectral phase, coherency, auto-power and cross-power spectra at pairs of stations for *X* and *Y* components in all data intervals for all selected days were also constructed (see for example figure 15, referred to later).

3. Results

Detailed spectral studies were carried out for all the ten selected days. The results relating to some days of data are presented here.

3.1 March 25, 1982

The GSD dynamic spectra and the contour sonagrams showing Pc3 activity on March 25, 1982 are shown in figures 1 and 2 respectively. The LN *Y* component spectra in figure 1 show interference bands because these data were not filtered. This day is an example of a moderately disturbed day with $\Sigma Kp = 28$ – and the range of *Kp* values during the interval of Pc3 occurrence is from 3 – to 4 –. Figure 2 clearly shows that almost continuous Pc3 activity occurred on this day from about 0845 hr AEST to 1515 hr AEST at a constant frequency centred around 40 mHz at WM, BH and NC. Activity is more variable

at LN. A higher frequency band centred around 50 mHz and of greater intensity than the 40 mHz band is also observed at LN. The 60 mHz signal (figure 1) occurring at BH between 1520 to 1540 hr AEST is the calibration signal which is normally recorded at all other stations.

3.2 March 26, 1982

The spectrograms for this day are shown in figures 3 and 4 respectively. It is again a moderately disturbed day with $\Sigma Kp = 21$ and the Kp value during the interval of Pc3 occurrence ranges from 2+ to 3. This day is an example of fairly low Pc3 activity with only three bursts occurring. The frequency bands at WM, BH and NC are centred about 30–40 mHz (figure 4). At LN the higher frequency band centred on 40 mHz is present between 1000 hr and 1100 hr AEST while a higher frequency band centred on 60 mHz and not seen at the other stations is predominant at LN between 1400 hr and 1500 hr AEST. Figures 3 and 4 clearly show low frequency (0–10 mHz) instrumentation noise at NC.

3.3 May 27, 1982

Shown in figures 5 and 6 are the GSD dynamic spectra and the contour sonagrams for May 27, 1982. The activity pattern on this day is similar to that of March 25. The range

Figure 3. GSD dynamic spectra depicting Pc3 activity on March 26, 1982.

Figure 4. Contour sonagram showing Pc3 activity between 0700-1500 hr AEST on March 26, 1982.

Figure 5. GSD dynamic spectra depicting Pc3 activity on May 27, 1982.

of K_p values during the Pc3 occurrence period is 3+ to 5-, and $\Sigma K_p = 39$ - indicating a magnetically disturbed day. Figure 5 clearly shows that there is a broader band signal on the Y channel than on the X channel. The contour sonagrams show that at WM the X component band is centred at about 50 mHz. At BH between 1130-1330 hr AEST there are two frequency bands centred on 40 and 50 mHz. At NC, however, the lower frequency band predominates. At LN there is activity in both bands with additional activity centred around 50 mHz. Higher frequency signals around 80 mHz are also seen at LN and to a lesser extent at the other stations. These may be higher order harmonics.

3.4 May 29, 1982

The GSD dynamic spectra and the contour sonagrams for this day are shown in figures 7 and 8 respectively. This is a magnetically active day with $\Sigma K_p = 38$ + and the range of K_p values during the Pc3 occurrence is 4+ to 6. It is obvious from the spectrograms that Pc3 activity continues throughout the day over a wide range of frequencies. At WM there is a dominant activity centred around 30-50 mHz between 0630 hr and 1800 hr AEST and showing a gradual decrease in frequency with time. Activity consisting of a double frequency band centred between 40 and 60 mHz persists between 0900 hr and 1100 hr AEST. The pulsation activity at BH and NC is essentially the same where a frequency band centred around 40 mHz dominates between 0630 hr and 1800 hr AEST. At LN the Pc3 activity is of a broader band (40-70 mHz) between 1000 hr and 1400 hr

Figure 6. Contour sonagram showing Pc3 activity between 0900–1700 hr AEST on May 27, 1982.

Figure 7. GSD dynamic spectra depicting Pc3 activity on May 29, 1982.

AEST and shows common activity with the other stations only at the lower frequencies. There is a 10 mHz Pc4 band present at LN between 0900–1000 hr AEST. Between 0600 hr and 0930 hr AEST high frequency activity in the 60–80 mHz band is also seen.

3.5 May 30, 1982

Figures 9 and 10 depict the GSD dynamic spectra and the contour sonagrams of May 30, 1982 from the data recorded at all the four stations. The range of Kp values during the Pc3 occurrence period is 4– to 4+, and $\Sigma Kp = 34$. The spectrograms show that Pc3 pulsation activity is strongest in the afternoon at WM, BH and NC. The same frequency bands in the 30–60 mHz range are seen at all the four stations. However additional activity is seen at LN at 20 mHz.

3.6 May 31, 1982

The spectrograms for this day are shown in figures 11 and 12. This is also a magnetically disturbed day with $\Sigma Kp = 35$ and the range of Kp values during the Pc3 occurrence is 4 to 6–. The spectrograms show that at WM, BH and NC most of the pulsation activity during the period of occurrence lies between 40 and 60 mHz. This band does not show any significant energy at LN until after 1300 hr AEST. However pulsation activity consisting of a lower frequency Pc4 band at 10–30 mHz is apparent after 1030 hr AEST.

Figure 8. Contour sonagram showing Pc3 activity between 0600–1800 hr AEST on May 29, 1982.

Furthermore, variable frequency activity is seen at LN between 0700 hr and 1000 hr AEST. It does not relate to any great extent to activity at the other stations.

3.7 June 1, 1982

The GSD dynamic spectra and the contour sonagrams for this day are shown in figures 13 and 14 respectively. This is an example of a moderately disturbed day with

Figure 9. GSD dynamic spectra depicting Pc3 activity on May 30, 1982.

$\Sigma Kp = 27+$ and the range of Kp values during the interval of Pc3 occurrence is 3 to 4. Activity is similar to that of the previous day (figures 11 and 12). The spectrograms show that at WM, BH and NC the Pc3 pulsation activity consists of a broad frequency band over the range 20–60 mHz. Activity between 30–60 mHz and similar to WM and BH is observed at LN between 0700 hr and 1100 hr AEST. However after 1030 hr AEST Pc4 activity at 10–20 mHz predominates at LN. This pattern of activity is not observed at other stations.

4. Discussion and conclusion

4.1 General features

It is generally accepted that at a given station there appears to be a higher signal amplitude on the X component than on the Y component. This has been found to be so in the majority of cases and examples can be seen in the GSD spectra in figures 1, 3, 7, 9, 11 and 13. However, exceptions sometimes do occur. An example is seen in the spectra of May 27 (figure 5) where greater power on the Y component is a general feature all day. Although the powers plotted between stations are relative, LN generally shows the greatest signal power. This is supported by the generally higher upper limit used for GSD spectra and contour sonagrams and is expected since this is the higher latitude station. This is in agreement with the observations that the signal amplitude of Pc3 pulsations increases with latitude at middle latitudes (Saito 1969).

Figure 10. Contour sonagram showing Pc3 activity between 0700–1900 hr AEST on May 30, 1982.

It can be seen from the spectrograms that Pc3 pulsations are daytime phenomena with the activity occurring in the daylight hours from 0600 to 1800 hr AEST. This occurrence behaviour totally agrees with the classical Pc3 results reported in the literature (see for example Saito 1969; Jacobs 1970; Orr 1973 and others). However Pc3 activity at LN often starts earlier in the day. An example of this behaviour can be seen in the spectra of May 19 (figure 8). This behaviour also appears in the statistical results (Ansari 1984). Generally the same type of continuous pulsation activity has been observed throughout the day at all the four stations. On some days activity during the morning hours appears to be more continuous than the afternoon activity which may

Figure 11. GSD dynamic spectra depicting Pc3 activity on May 31, 1982.

appear in bursts. An example is seen on May 31 in figure 12 at WM and LN. On other occasions activity is reasonably continuous throughout the day (March 25) or is burst like (March 26). The latter has low magnetic activity ($\Sigma Kp = 21$) and such activity is typical for relatively quiet days.

An important feature which has been noticed in the spectra is that Pc3 activity appears and disappears at almost the same time at all the stations and often there are very abrupt signal cessations and commencements. Such behaviour is easily seen in the GSD dynamic spectra of May 30 (figure 9) in the 40–60 mHz band at 0730–0740, 0815–0840, 1010–1030, 1100–1140, 1245–1330, 1420–1515, 1600–1625, 1640–1645 and 1700–1730 hr AEST. It is also of interest to note that the 20 mHz band at LN also follows the same pattern in the afternoon. There appears to be some overriding mechanism which can control the wave generation resonances in all pulsation bands and which is independent of station location. It could be associated with solar wind control of pulsation activity and in particular a change in the θ_{XB} (angle of the interplanetary magnetic field from the sun-earth line) which appears to control some Pc3 occurrence activity. Other examples of this signal dropout at single closely spaced stations have been observed at low latitudes by Medford *et al* (1982).

Finally the general feature emerging from the interstation comparison of the spectrograms is that stations along a latitude (WM, BH and NC) show greater frequency-time similarities than stations (NC and LN) along a longitude which are often quite different.

Figure 12. Contour sonagram showing Pc3 activity between 0700–1900 hr AEST on May 31, 1982.

4.2 Frequency structure

In general Pc3-4 spectra consist of one or more frequency bands. The spectra of May 21 and June 1 present excellent examples of multiple frequency bands. On close examination the GSD dynamic spectra and the contour sonagrams (figures 11 to 14) show four frequency bands for each of these two days. These bands can be seen more clearly in the X components of the cross-spectral plots for the longitudinal stations in figures 15 and 16 for the respective days. On May 31 there could be five peaks present on the X component at WM, BH and NC and they occur at 25, 37, 44–46, 50–52 and 58 mHz

Figure 13. GSD dynamic spectra depicting Pc3 activity on June 1, 1982.

between 0940–1020 hr AEST. There are two large peaks at LN corresponding to the 25 and 44–46 mHz bands but the higher bands are absent at this station. The Y component at the longitudinal stations shows completely different activity over a broader frequency range. Peaks can be identified from the cross-spectra at 15 and 30 mHz. At LN these bands are also present but the greatest power is seen at 44 and 50 mHz in agreement with the X component higher frequency peaks. Minor peaks at these frequencies are seen at the other three stations. On June 1, peaks occur on the X components at 25, 35, 45 and 55 mHz between 1400–1450 hr AEST. Large power is also seen in the lower band at LN but high frequencies are absent. A Pc4 band at 8 mHz appears at LN. On the Y component the lowest band (25 mHz) is seen at the longitudinal stations but not at LN. Earlier band structure results have been reported at ground based stations (Duncan 1961; Tonegawa *et al* 1983) and in space (Takahashi and McPherron 1982).

Another general feature emerging from the study of the pulsation spectra is that Pc3 frequencies seen at longitudinal stations (WM, BH and NC) are generally centred about 40–45 mHz. The majority of data analyzed show this pattern. Examples are found in the spectra of March 25, 27, 28, 30 and May 29 and 30. By comparison Lanzerotti *et al* (1981) observed Pc3 frequencies in the range 40–50 mHz at $L \sim 1.9$. Arthur *et al* (1973) and Arthur and McPherron (1975) have reported average peak frequency of 40 mHz for Pc3 waves observed on the ground and on the ATS-1 satellite at $L = 6.6$. Also significant power in the frequency band of 40 mHz can easily be seen in the D

Figure 14. Contour sonagram showing Pc3 activity between 0700–1900 hr AEST on June 1, 1982.

component of the digital dynamic spectra of Pc3-4 data recorded at Sanae ($L \approx 4$) as reported by Barker (1977).

Sometimes Pc3 activity in lower and higher frequency bands has also been observed. The spectra of the data of March 26 (figures 3 and 4) are good examples of a lower frequency band where the frequency is centred about 30 mHz. The spectra reported by Barker (1977) also show significant power at a frequency of about 30 mHz. An example of a higher frequency band in the present study is seen in the WM spectra of May 27 (figure 6) where the frequency is centred at 50 mHz. The dynamic spectra of ULF X component reported by Kuwashima *et al* (1979) clearly show similar behaviour and an

Figure 15a. Cross-spectral analysis for May 31, 1982 between 0840–1020 hr AEST, X component data.

average frequency of 50 mHz at all three Japanese stations. It is interesting to note that the Pc3 pulsation spectral properties at low and higher latitudes are the same.

The spectra of LN usually consist of slightly lower Pc3 frequencies centred about 35–40 mHz and often include a strong Pc4 band. However sometimes higher frequencies can also be seen at LN. An example is May 27 (figure 5) where broad band activity is seen between 40–100 mHz.

A detailed comparison of peak signal frequencies among the azimuthal components shows that the average pulsation frequently is slightly higher at WM, the most westerly station, than at BH and NC. An example can be seen in the data of May 27 (figure 5). This behaviour was observed in four of the ten selected days, namely March 27, 28, 30 and May 27.

The frequency-time structure of the data under investigation has shown that all days and stations show either constant or gradually falling frequencies with time during the day. This is a common feature previously identified in Pc3 studies at all latitudes (Barker 1977).

Figure 15b. Cross-spectral analysis for May 31, 1982 between 0840-1020 hr AEST, Y component data.

It can be seen from the cross-spectral plots that there are often different frequencies observed on the X and Y components. An example of this is seen in the cross spectral plot of June 1 between 1400-1450 hr AEST (figure 16). Furthermore the frequency band and the cross power spectrum of the Y signal generally are restricted in the longitudinal pairs of stations and sometimes multiple frequency bands are observed on the X component but not on the Y (for example see figure 16).

4.3 Harmonic structure

Another very interesting feature of the Pc3 spectra observed is that they sometimes show multiple frequency peaks with nearly constant separation between successive peaks. Takahashi and McPherron (1982) have reported this harmonic structure in their study of Pc3-4 from the ATS-6 satellite and have explained the results as the higher order

Figure 16a. Cross-spectral analysis for June 1, 1982 between 1400–1450 hr AEST, X component data.

harmonics associated with toroidal field line resonance and eigen frequencies calculated by Cummings *et al* (1969). An example of harmonic structure observed in the present data is seen in the pulsation spectra of June 1 between 1400–1450 hr AEST (figure 16). Harmonic structure is easily seen in the X components of the azimuthal pairs of stations WM, BH and NC where the spectral peaks at 35, 45 and 55 mHz are separated by a constant frequency difference of 10 mHz. From the present results it appears that the same multiple bands are seen at longitudinal stations and on both components but are more apparent on the X component. Frequencies may be different between components which may be expected for resonant waves since the poloidal (radial) and toroidal (azimuthal) modes have different eigen periods (Jacobs 1970). The observation of harmonic structure with $\Delta f = 10$ mHz can be explained by a standing Alfvén wave consisting of many discrete harmonic frequencies (Takahashi and McPherron 1982). They have observed the harmonic events with $\Delta f = 14$ mHz prenoon and 10 mHz afternoon in the azimuthal (east-west) component. The present observations are best

Figure 16b. Cross-spectral analysis for June 1, 1982 between 1400-1450 hr AEST, Y component data.

seen in the north-south components. This may be explained by taking into account 90° rotation of the polarization major axis azimuth by the ionosphere which occurs when signals are transmitted to the ground (Hughes and Southwood 1976). Tonegawa *et al* (1983) have also reported harmonic structure in Pc3 frequency range (20-80 mHz) on the ground at high latitudes.

Acknowledgements

This research was supported by grants from the Australian Research Grants Scheme and the University of Newcastle. One of the authors (IAA) was supported by a University of Newcastle Scholarship and is also thankful to the Department of Electrical and Computer Engineering of the University of Wollongong for assistance.

Appendix

Grey scale digital (GSD) dynamic power spectral plotting

The power spectral density was calculated using FFT methods. The distribution of power spectral density is scanned to determine the minimum and maximum power for scanning of the upper (black) and lower (white) limits for the grey scale plot. The dc spectral component is set to zero. The maximum and minimum power values are used for linearly scaling the power density to a level from which a half-tone grey scale picture can be plotted.

Unlike the usual printer where lights and lenses are used to perform the half-toning process in an analog fashion, the Grey Scale software accepts the scaled pixels and processes them digitally using a 32 nib (dot) half-toning screen to produce a raster line with 33 levels of grey shading (0–32 nibs on/off). Horizontal and vertical replication is used to obtain the grey scale plot of the required size. The density of nibs on the printer is currently 132/inch horizontal by 72/inch vertical. A replication ratio of 2:1 is used to overcome the difference in horizontal and vertical nib densities.

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