Long Term Changes in the Amplitude and Phase of the Semiannual and Annual Variations in Low Latitude Geomagnetic Field

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The technique of complex demodulation is applied to low latitude geomagnetic field data to isolate the long term changes in the amplitude and phase of the semiannual and annual variations. The phase for semiannual variation is in close agreement with that anticipated from equinoctial hypothesis. The amplitude does not show significant dependence on the 11-yr solar cycle. Comparable time variation for all the hours of the day leads to the conclusion that the semiannual variation originates in the disturbance field. A regular oscillation with a 6–7 year periodicity and a long-term variation of the amplitude of annual oscillation corresponding to 14 LT appear as new results.

1. Introduction

One of the most well established features of geomagnetic activity has been its semiannual oscillation with equinoctial maxima. The basic mechanisms to explain the March/September enhancement in geomagnetic activity have broadly been classified into 'axial' and 'equinoctial' hypotheses. In 'axial' mechanism postulated by CORTIE (1912) and supported by several authors (for e.g. PRIESTER and CATTANI, 1962) the varying heliographic latitude of the earth is the crucial factor with most favourable positions on March 5 and September 7. In the 'equinoctial' mechanism (BARTELS (1932), supported by MCINTOSH (1959) and others) the enhanced activity in March and September is attributed to the near normal inclination of the sun-earth line and the dipole axis of the earth. The predicted dates for highest activity would be March 21 and September 23. Several investigations have been carried out to identify the most probable mechanism but the proximity of the two dates have led to ambiguous results. GUPTA and CHAPMAN (1967), after an extensive analysis of C_p data found that the equinoctial hypothesis was more appropriate than the axial hypothesis to explain the semiannual variation of magnetic activity. At low latitudes the signature of magnetospheric currents are uncontaminated by the strong auroral electrojets and they can be usefully utilised for studies related to alternate claims of generating mechanisms. The magnetic field data could also be analysed to yield finer resolution than indices of activity. BHARGAVA (1972a) initiated a new approach to study seasonal changes of low latitudes geomagnetic field by confining the surface observations to one hour at a time. In a series of papers (BHARGAVA, 1970, 1972a,

1972b; BHARGAVA *et al.*, 1973) he showed that the semiannual oscillation has the largest signal around 8 hrs LMT at several low latitude stations with a secondary maximum in the late evening hours. The daytime signal has significant contribution from quiet-time ionospheric currents (S_q) whereas the night time oscillation appeared to be purely magnetospheric in origin. A similar feature was observed for the annual component (1 cycle/year) of the low latitude geomagnetic field with strongest signal appearing just after local noon.

With the availability of spacecraft observations of solar wind parameters and Interplanetary Magnetic Field (IMF), the crucial role of the north-south component (B_z) of IMF in solar wind-magnetosphere interaction became evident. RUSSELL and MCPHERRON (1973) attempted to model the semiannual variation in geomagnetic activity simply in terms of the magnitude and direction of B_z . They assumed that when B_z was northward ($B_z > 0$) the interaction was zero and when southward, the interaction was proportional to the strength of B_z . According to them, when the IMF is directed along the archmedian spiral direction in the solar equatorial plane, the sun-earth geometry is such that IMF directed toward (away from) the sun will have a dominant southward component in March (September). This is brought about by the fact that the IMF is ordered in the Solar-Equatorial Coordinate (GSEQ) system whereas the interaction with magnetosphere is ordered in the Solar Magnetospheric System (GSM). The Russell-McPherron model predicts peak activity not near the equinoxes but on April and October 5. In a way, Russell-McPherron mechanism is a combination of the 'Axial' and 'Equinoctial' hypotheses. In a recent paper, GREEN (1984) applied the technique of complex demodulation to the long series of A_a and A_p indices to examine the long term modulation of the semiannual variation. His results for phase variations clearly indicated support for equinoctial mechanism. The index A_a of magnetic activity is derived from just two observatories which are not truly anti-podal (the local time difference is less than 10 hours) and solely temporal averaging does not eliminate additional local and regional anomalies (SIEBERT *et al.*, 1983). In deriving planetary index A_p , the quiet day contribution gets eliminated. Also A_p and A_a are measures of sub-auroral zone activity and therefore have contribution from both equatorial ring current and auroral electrojets.

In this paper, we study the time variations of the phase and amplitude of semiannual component in low latitude geomagnetic field confining the data to one hour at a time to get insight into the dominant generating mechanism as a function of time of the day and solar activity. In addition, we also examine the variability in the same parameters for the annual component which has been shown to have a distinctly different generating mechanisms (BHARGAVA and RANGARAJAN, 1977).

2. Data and Method of Analysis

The data utilised for the present study are the mean monthly hourly values derived from observations on all days at Alibag (dipole lat 9.5° N) a low latitude station outside the influence of the equatorial electrojet and a key observatory recently included in the derivation of D_{st} index, indicative of magnetospheric ring

current intensity. The period of analysis was 1924 to 1984. Trend and longer period variations, of no interest to the present investigations, were eliminated through a high pass digital filter with unit response for periodicity shorter than 12.5 months. The well documented technique of complex-demodulation (BANKS, 1975; AGARWAL *et al.*, 1980) was applied to time series constituted by data for individual hours. This provides a method of studying the 'time-local' variation of phase and amplitude of the central frequency of a chosen filter band. It may, however, be noted that in the method outlined by BANKS (1975), the time variations of the 'phase' will not be accurate if the frequency (ω') chosen as the central frequency for demodulation is not exactly the same as the real frequency (ω_0) embedded in the series. In fact the two are related as

$$\phi(\omega') = -\delta\omega \cdot t + \phi(\omega_0)$$

where $\delta\omega = \omega' - \omega_0$ and t is time.

If there is more than one dominant frequency in the band considered for demodulation the phase progression with time is neither constant nor has it only a linear trend. To overcome this constraint which springs up in analysis of semiannual variation (6 month periodicity) using conventional Cooley-Tukey algorithm for Fast Fourier Transform where $N=2^K$, we adopted a modified version of FFT using $N=2^{K_1} \cdot 3^{K_2}$ where K_1 and K_2 are integers. YFANTIS and BORGMAN (1981) have listed relevant computer programmes of Fast Fourier Transform for such values of N which are products of suitable powers of 2, 3 and 5. Both annual and semiannual periodicities appear as exact harmonics if we consider $N=720$ or $N=768$. For better resolution and facility of computation we adopted the latter value so that semiannual component (SAV) appears as the 128th harmonic and the annual (AV) as the 64th harmonic of the fundamental periodicity covering the data length.

3. Results and Discussion

Power densities of the SAV and AV as a function of local time derived from the Fourier spectra are depicted in Fig. 1. The local time profile is just the same as shown and discussed earlier by BHARGAVA (1972a). The morning maximum reduces in magnitude when data is restricted to quiet days as shown by Bhargava and the evening peak vanishes (not shown here).

In Fig. 2 are shown the demodulate amplitude variations of semiannual signal over the entire interval 1925–1983 for some selected hours of the day. The representative hours chosen correspond to peak power (8 LT), least power (14 LT) late evening secondary peak (22 LT) and predawn hour (4 LT). It may be noted that in the method adopted for processing prior to spectral estimation the nature of the first 3–4 cycles (covering about 2 years) initially and in the end gets altered and, therefore the values are not realistic. The amplitudes and phases pertain to the band of periodicities between 4.8 and 8.0 months for SAV and 16 and 9.6 months for AV. However, in the spectra for individual hours, the dominant peaks were only at annual

Fig. 1. Power density @ 1 cycle/year and 2 cycles/year, of horizontal intensity at Alibag on a function of local time (75° EMT).

and semiannual periodicities with negligible power densities at adjoining frequencies in the band, and therefore the contamination is minimal.

One of the most striking features of this diagram is the fact that even for 14 LT where average power at SAV periodicity was close to zero (cf. Fig. 1), the demodulates indicate significant amplitude for some epochs like 1947–1948, 1957–58 and 1967–68, years of enhanced solar activity. The time variations of amplitude for the two hours 8 and 22 LT where distinctly different mechanisms were suggested to be operative (BHARGAVA, 1972b) are comparable. This leads to the conclusion that at all hours of the day the dominant component of SAV is of disturbance origin. Though there is an apparently clear relationship of the amplitude with solar activity, closer scrutiny reveals several interesting differences such as the significant enhancement near solar minimum in 1976–77 and the absence near solar maximum of 1937 and 1969 in most of the curves. Computation of correlation between annual sunspot numbers and amplitude for the representative hours gave not-so-striking value close to +0.4, but significant statistically at 95% confidence level. There is an indication of an embedded long-term periodicity of about 40 years as seen from the 8 LT plot.

This complex behaviour of the 11-yr modulation of the SAV amplitude is similar to that found for A_a index by GREEN (1984). However, Green reported a significant enhancement between 1938 and 1966 without solar-cycle modulation, which is conspicuous by its absence at low latitudes. In his study of the solar control of the

Fig. 2. Yearly values of demodulate and phase of amplitude semiannual variation in H at Alibag for some representative hours of local time. The dotted curve corresponds to variation of annual mean R_s . The three horizontal lines on 08 LT plot correspond to phase anticipated from axial, equinoctial and R.M. hypotheses.

amplitude of SAV in K_p index for 1932–1971 MURAYAMA (1974) found that the amplitude decreased and phase moved to later part of the year when solar activity increased. In contrast GREEN (1984) found that the correlation of SAV in A_a index with solar activity was only marginally significant and positive. Our results for the low latitude field are in conformity with this rather than that for K_p of MURAYAMA (1974). This difference could be attributed to the different natures and representative characteristics of K_p and D_{st} indices. Low latitude field variations should be more similar to D_{st} index rather than K_p index.

Time variations in phase of the demodulates at SAV periodicity band for representative hours of local time are also shown in Fig. 2. The abrupt discontinuities occasionally noticed are the result of plotting the data between 0 to 360°. Phase angles correspond to epoch of maximum of the field. The chief point of interest in this is the near constancy of phase for four hours centred on 8 LT. For other hours the variability is more prominent, especially for years after 1965. However, for all the hours the phase variations are quite similar and the average values are all comparable.

Superposed on the 8 LT curve are three lines representing anticipated phase angle if the semiannual signals were only due to (i) Axial (top) (ii) Equinoctial (middle) or (iii) Russell-McPherron (bottom) hypotheses. The plot clearly indicates that for most of the years the phase angle corresponds to equinoctial and/or R.M. mechanism. It may be noted that the phase angles have less reliability when the amplitudes are insignificant. The points well outside the three lines on 8 LT plot do indeed correspond to low amplitudes. The mean phase angle corresponds to March/September 23 ± 2 days quite close to the predicted days based on equinoctial hypothesis.

It is realised that mere averaging of the phase angles without weightage for the corresponding amplitude of the signal may not lead to meaningful value. CHAPMAN and BARTELS (1940) describe a method of estimating the total variability using harmonic dials and probable ellipses. According to them, if the number in a cloud of points inside and outside the probable ellipse are nearly equal, Gaussian distribution for the cloud may be validly assumed. If the major axis of the probable ellipse is close in direction to the average vector then the variability may be ascribed mainly to amplitude changes whereas if the two are normal to each other, phase variability may be considered more dominant. The phase (epoch of minimum) and amplitude of the SAV demodulates are plotted in a harmonic dial in Fig. 3. The average vector and the probable ellipse for the cloud of points are also shown. The points inside and outside ellipse are nearly equal. The average vector has a phase corresponding to March 21 and the major axis of the probable ellipse is along a direction with phase corresponding to March 25. From the constancy of phase, we can, therefore, conclude

Fig. 3. Scatter plot of yearly vectors (amplitude and phase) of the SAV. The continuous line is the average vector and the dashed line is the major axis of the probable ellipse for the cloud of points. The phase corresponds to first minimum in the SAV.

that the most dominant mechanism for low latitude semiannual variation is 'Equinoctial'. It may be mentioned that BOLLER and STOLOV (1970) invoked the Kelvin-Helmholtz instability at the magnetopause to account for the semiannual variation with greater probability of the instability when the dipole axis is normal to the sun-earth line. This proposition is again an 'Equinoctial' mechanism.

MURAYAMA (1974) obtained a phase close to March 23 from his analysis of SAV in ΣK_p but he explained this feature to be the superposition of two vectors—one corresponding to 'axial' mechanism depending on heliographic latitude of the earth and the second on Russell-McPherron effect due to dominant seasonally dependent southward B_z . RUSSELL (1975) found that if the R-M hypothesis is modified to incorporate modulation of dominant IMF polarity (ROSENBERG and COLEMAN, 1969) and modulation of solar wind velocity, IMF strength etc. with heliographic latitude, then Murayama's results were in good agreement with R-M hypothesis.

GREEN (1984) showed that for his long series of A_a data and shorter span A_p data there is scatter in the phase of the semiannual signal without any systematic long term variation. Our results for the phase of SAV signal at low latitudes is again in close conformity with Green's findings for subauroral zone indices, just as shown for the amplitudes. There is, however, no possibility to delink the two mechanisms as done by MURAYAMA (1974) in the present analysis.

4. Annual Variation

Though the principal aim of the paper was to identify the precise nature of the phase variations in semiannual signal as a function of time and infer the most probable operative mechanism, the computations, without additional labour, also yield useful information on the amplitude and phase changes in the annual component. BHARGAVA and RANGARAJAN (1977) clearly showed that the annual wave in geomagnetic field at low latitudes is a composite of (i) base level oscillation due to summer/winter differences in the winds (ii) S_q currents during day time showing strong seasonal dependence and (iii) a small but significant part due to disturbance. MALIN and ISIKARA (1976) suggested that the mean midnight field oscillation with annual periodicity is brought about by the varying mean latitude of the equatorial ring current. Earlier CURRIE (1966) showed that the generating mechanisms of annual and semiannual lines were different, that an ionospheric dynamo action was probably responsible for annual variation and that it was a seasonal effect caused by amplitude modulation in solar radiation incident on the summer and winter hemisphere. BHARGAVA (1972c) studied the local time dependence of the amplitude and phase of the annual wave at several low latitude stations and showed that the day time component is purely of ionospheric origin while the late evening component could be due to magnetospheric oscillations. The time variations in the amplitude demodulate of AV for the years 1925–1983 are shown in Fig. 4 for representative local times. 8 and 14 LT corresponds to least and greatest power density for the annual signal respectively (as seen from Fig. 1). The following interesting points can be noted from the diagram:

Fig. 4. Yearly value of the demodulate and phase of amplitude annual variation in H at Alibag for some representative hours. The open circles on 14 LT plot is the 11-yr overlapping mean curve. The dotted curve corresponds to variation of annual mean R_z .

(i) Even when average power is least, there is a clear annual variation in several individual years' data.

(ii) There is a systematic oscillation of the amplitude not related to solar activity with a periodicity of about 6 years. This is seen for all the hours indicating that the entire daily variation curve undergoes this systematic oscillation.

It is interesting to note that FUJITA *et al.* (1986) had, earlier, found a similar periodicity (5 year) in the difference of night time total field intensity at two stations in Japan. They attributed this to the variation in equatorial ring current with two peaks in a solar cycle. The slight difference in the average periodicity between our results and that of Fujita *et al.* may be due to different epochs considered for analysis. It is also to be noticed that one finds the periodicity to be present throughout the day.

(iii) For the few hours centred on 14 LT where the annual line in the spectrum is the strongest, the demodulates have a clear long term change as seen from the 11-yr overlapping mean curve. This long term trend is absent when data is confined to the night hours. This suggests that the ionospheric winds in the two hemispheres perhaps undergo systematic long term variability.

Demodulates of phase are also shown in Fig. 4. For 14 LT, the phase is uniformly constant with a mean value corresponding to peak in mid June consistent with earlier results for northern hemisphere station given by several authors. In contrast to the amplitude demodulates, the phase variations do not show long term changes clearly indicating that the modulation is confined only to strength of the winds responsible for AV and not to the time of the year. For most of the other hours of the day the variability is larger; however for the years between 1940 to 1970 the phase seems stable.

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