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# Multiple Timescales in the Fluctuations of the Equatorial *Dst* Index through Singular Spectrum Analysis

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The equatorial *Dst* index for the period 1957–1994 is analysed using the data-adaptive, noise-reducing technique of Singular Spectral Analysis (SSA) in many time scales covering annual, monthly, daily and hourly mean values. The salient features of the results are (i) the presence of a long term trend and a none-too-consistent and weak solar cycle variation in phase opposition with the solar activity, (ii) a well defined ~44 month oscillation with almost constant amplitude throughout the period of analysis with no dependence on solar activity, (iii) an intermittantly strong quasibiennial oscillation with largest amplitudes in the recent years 1990–1993 and (iv) the consistent presence of annual variation with some amplitude modulation and a semiannual variation whose amplitude is independent of solar activity. Daily mean values of *Dst*, during an interval of intense recurrent activity, shows differences in its periodic behavior compared to the *AE* and *Ap* indices. An index of middle latitudes, recently proposed, is shown to behave somewhat differently from expectations probably because of inadequate compensation for the quiet day component. Storm time changes in *Dst* index, as brought out by the analysis of 10 long-duration severe geomagnetic disturbances are characterised by periodicities of about 20 hours and 40 hours, in two separate spectral bands. This is suggested to be due to the corresponding fluctuations in the energy injection into the ring current. In most cases, the singular spectra indicate that only about 60 percent of the total variance in the *Dst* index could be accounted for by regular variations and the rest corresponding to a large "noise floor" in the spectra.

## 1. Introduction

The equatorial *Dst* index was devised as an index to reflect geomagnetic activity directly related to the equatorial ring current. Description of the method adopted to derive the index, its merits and demerits are given in Mayaud (1980) and Rangarajan (1989). Campbell (1996a) suggests that "the basic idea for the *Dst* is that the global part of a geomagnetic disturbance is what remains after local variation features and baseline values are removed from low latitude station records". The hourly *Dst* values may be considered to be sensitive only upto about 1–2 nT taking into account the procedures involved in elimination of long term and seasonal quiet time trends and averaging over four stations and therefore, oscillations with amplitudes better than a nanotesla or so only may be important. Hourly values of the *Dst* index covering the period 1957 to 1994, following the initial efforts of Sugiura (1964), are now available on CD-ROM from the World Data centers. Interestingly, in recent times it is being emphasized that *Dst* should not be taken to be a simple representation of the ring current of a storm because other sources too contribute to the index formulation. Such understanding represents a major change from the older concepts (Campbell, 1996b). Campbell (1996a) showed from several case studies, that the amplitude-time displays of the *Dst* index may be considered to be due to the cumulative effect of several distinctive time series processes each with its own characteristic distribution in time leading to the observed log normal distribution. This aspect of the index, however, is not central to our investigation.

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Some well defined periodicities like the semiannual and annual oscillations in the index have been analysed in detail by Mayaud (1978), Rangarajan and Bhargava (1981) and others. A quasibiennial oscillation in the *Dst* index was detected by Sugiura and Poros (1977) who found an analogous periodicity in the sunspot number also. Recently, Araki *et al.* (1996) suggested that the annual mean value of the *Dst* index, apart from being inversely correlated with the solar activity also exhibited a possible half a solarcycle periodicity.

The index has also been successfully utilised to quantify the energy transfer from the solar wind into the magnetosphere and to establish empirical relationship between IMF/solar wind parameters and the strength of the equatorial ring current (Burton *et al.*, 1975; Feldstein *et al.*, 1984). Though largely identified as an index of the ring current intensity, *Dst* exhibits sustained intervals when it remains positive, indicative of the fact that the magnetic effect of the westward flowing ring current is more than offset by the magnetopause currents caused by enhanced solar wind dynamic pressure. The relationship between the dynamic pressure at the magnetosphere boundary and the *Dst* index has been discussed (Araki, 1992; Araki *et al.*, 1993).

In sharp contrast to the intense bursts of activity in the auroral electrojet indices like *AL* or *AE*, the *Dst* index changes relatively slowly so that hourly values provide adequate time resolution to study most of the evolutionary features. In this investigation, we analyse the *Dst* index covering the period 1957 to 1994 to detect well defined periodicities in different spectral bands using successively annual mean values, monthly mean values, daily values and hourly values. Over an interval of time marked by clear recurrence in geomagnetic disturbance, the oscillations in the *Dst* index are compared with *Ap*, *AE* and a new index *Ah* proposed by Russian scientists to represent geomagnetic activity at midlatitudes. The results reported may be considered complementary to the publication of Gonzalez *et al.* (1993) who analysed the monthly and daily mean values of *Ap* index covering the period 1932 to 1982, through power spectrum analysis using the conventional correlation cosine transformation procedure (Blackman and Tukey, 1958). Earlier, a similar analysis of antipodal observatories' *Aa* index covering a 103-year span was also done through spectral methods by Delouis and Mayaud (1975).

In identifying clear oscillations and their evolution in time, rather than taking recourse to the spectral analysis technique of either Blackman and Tukey (1958) or fast Fourier transform, we adopt the recently developed data adaptive technique called Singular Spectral Analysis (SSA). It is well known that the spectrum can only yield average contribution of a specific oscillation to the total variance and the phase information is lost in deriving the power density. Vautard and Ghil (1989) have highlighted how SSA provides quantitative and qualitative information about the deterministic and stochastic parts of a time series. Their development was a modification of the originally proposed application to the problems of dynamical systems theory by Broomhead and King (1986). In a further development of the method particularly to be used as a tool for short noisy chaotic signal, Vautard *et al.* (1992) provided an approach to generate the so called Reconstructed Components (RC) covering the entire data span instead of the Principal Components (PC) which fall short by the length of the embedding space, as described later. Among the major advantages of the SSA listed by them, the following deserve particular attention for the analysis of geophysical time series.

SSA extracts important components of the variability even when the system is non-stationary. The method generates data adaptive filters, whose transfer functions highlight regions where sharp spectral peaks occur and thus helps reconstruction of the original time series with just a few principal components close to the spectral peaks. In contrast to the Fourier components, the principal components need not be sinusoidal in nature. The resolution of spectral peaks in a short noisy time series will be obviously improved if the noise in the series can be substantially eliminated without losing part of the signal as well. SSA does precisely this by decomposing the original time series into its significant signal components with least noise. In a recent investigation, Keppenne and Ghil (1992) could successfully predict the southern oscillation index by a combination of noise reduction through SSA and low order autoregressive modelling by maximum entropy method (MEM) outlined by Burg (1968). Just recently Dettinger *et al.*

(1995) have given the details of a SSA toolkit for use on personal computers. The complete software package can be obtained from them on request.

## 2. Analysis

The method, in brief, is described next. We begin with a finite time series $y(t)$ of length $N$.

$$y(t) = y(K \cdot ts), \quad K = 1, 2, 3, \ldots, N$$

and $ts$ is the sampling interval. This series after normalization using the mean ($Y$) and standard deviation ($\sigma_y$) yields the series

$$X(t) = \left(y(t) - Y\right) / \sigma_y, \quad t = 1, 2, 3, \ldots, N.$$

The sampled time series is then embedded in an $M$-dimensional space taking as state vectors, the consecutive sequences of $X(t)$

$$Z = \begin{bmatrix} X_1 & X_2 & \cdots & X_M \\ X_2 & X_3 & \cdots & X_{M+1} \\ & & \cdots & \\ & & \cdots & \\ X_{N-M+1} & & \cdots & X_N \end{bmatrix}$$

The matrix so derived is called the Trajectory matrix. For different choices of $M$, we have different trajectory matrices. However, $M$ should be larger than the autocorrelation time (the lag at which the first zero occurs). According to Broomhead and King (1986), the reconstruction of the attractor is then guaranteed under certain hypothesis on $M$ (the viewing window), $ts$ (the sampling rate) and the smoothness of the time series. From the trajectory matrix, we can generate correlation matrix taking the product of each column with all the others successively. These are, in effect, the lagged autocorrelation coefficients and the matrix turns out to be Toeplitz (whose all diagonal elements are equal).

The eigen values of this matrix are then evaluated in descending order of magnitude together with the corresponding eigen vectors. As the matrix is positive symmetric Toeplitz, the eigen values will all be positive. Ideally, the number of non zero eigen values will correspond to the number of independent variables in the system. In the presence of noise in the data, the other eigen values will be close to zero defining a noise floor (e.g., see Sharma *et al.*, 1993). Eigen vectors significantly above the noise level define the Principal Components (PC) as the projection of the time series along the directions of each of the significant eigen vectors. In other words, the eigen vectors serve as data adaptive filters. When quasiperiodic fluctuations are present in the time series, the eigen vectors appear as even/odd pair in phase quadrature, with corresponding eigen values nearly equal in magnitude. As the PCs are filtered versions of the original time series with the $M$ elements of the eigen vectors serving as appropriate filter weights, the resulting series would only be of length $(N - M + 1)$. Vautard *et al.* (1992) have given a method to extract a series of length $N$ corresponding to a given set of eigenelements which they call as Reconstructed Components (RC). The relevant formulae for the $k$-th component are

$$R(X_i)^k = (1/i)\sum_{j=1}^{M} a_{i-j}^k E_j^k \qquad \text{for } 1 \le i \le (M-1)$$

$$= (1/M)\sum_{j=1}^{M} a_{i-j}^k E_j^k \qquad \text{for } M \le i \le (N-M+1)$$

$$= \left(1/(N-i+1)\right)\sum_{j=1}^{M} a_{i-j}^k E_j^k \qquad \text{for } (N-M+2) \le i \le N$$

where $E_j^k$ are the $M$ eigen elements of the $k$-th component and

$$a_i^k = \sum_{j=1}^{M} X_{i+j} E_j^k \qquad 1 \le i \le (N-M).$$

The percentage of the total variance accounted by each of the reconstructed component can be computed from the ratio of the individual eigen value to the sum of all the $M$ eigen values which then gives an immediate idea of the relative importance of a particular component to the time series.

The *Dst* index has been analysed separately in terms of the annual and monthly mean values for the period 1957 to 1994 using appropriate maximum lags for the autocorrelations (with $M$ not exceeding $N/3$ as recommended by Vautard *et al.* (1992)). For a selected period of interest and significance, the analysis is carried out using daily mean values and for a careful choice of days covering major geomagnetic disturbances when the daily mean *Dst* index exceeded –70 nT for four consecutive days, SSA was attempted on the hourly values. The embedding space has been chosen appropriately in each case, keeping in mind the fact that (i) too small a value will provide less information and coalascence of adjacent spectral peaks whereas too large a value would cause instability and (ii) SSA would not resolve periodicities longer than the window length. In general, for oscillations longer than the window size, the even and odd eigen vectors will represent an overlapping mean and trend respectively (Subramaniam Moten, 1993).

In the coming sections, we discuss the time variations of the significant components in the *Dst* index sequentially beginning with annual mean values through monthly and daily values to hourly values.

## 3. Results and Discussion

### *3.1 Annual mean values of Dst*

Figures 1(a) and 1(b) show the annual mean sunspot number and the *Dst* index for the period 1957 to 1994. No clear periodicity is evident in *Dst*, though an inverse correlation of the geomagnetic index with the solar activity index is seen. As suggested by Araki *et al.* (1996), it appears that for every solar cycle, there are two depressions in the *Dst* index suggestive of a 5–6 year periodicity. The most noteworthy feature, of course, is the large change between 1960 and 1965. The only positive value (2 nT) was registered for the year 1965 and never ever afterwards. This series of 38 values were subjected to SSA with a choice of 13 as the length of the viewing window ($M$). The singular spectrum covering this embedding space is shown in Fig. 1(c). The spectrum does not indicate a well defined noise floor which suggests that the time variations in the annual *Dst* index could not be simple in structure nor is it composed of many periodic oscillations, for in that case, we should see successive eigen values of nearly equal magnitude (as for e.g. 5 and 6). The variance of the fluctuations accounted by all the 13 eigen vectors add upto only 78%, of which the trend and long term periodicity accounts for 64%. To avoid clutter, we have not shown individual eigen vectors corresponding to the thirteen components. But, based on the singular spectrum (Fig. 1(c)), reconstructed components corresponding to 1, 2 and 3 were combined together as also that of 5 and 6.

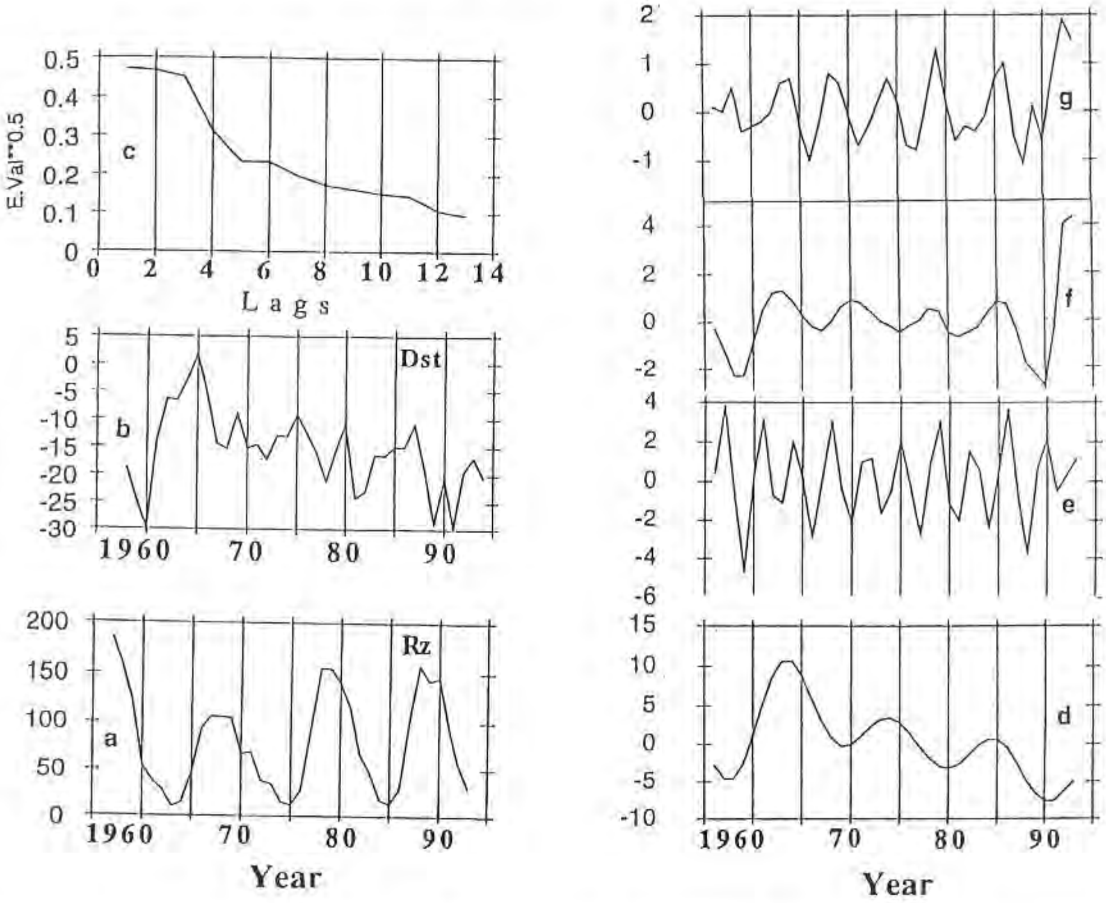

Fig. 1. (a) Annual mean values of sunspot number. (b) Annual mean values of the *Dst* index. (c) Singular spectrum defined by the square root of the eigen value (Eval**0.5) corresponding to the time series of annual mean *Dst* with maximum lag = 13. (d) Reconstructed Component (RC) corresponding to principal components (PC) 1 + 2 + 3 indicative of trend and longer period variations. (e) RC corresponding to PCs 5 and 6 indicating the time variation of the ~44 month oscillation. (f) RC corresponding to PC 4. (G) RC corresponding to PC 7.

Time variations of the *Dst* corresponding to these two components are shown in Figs. 1(d) and 1(e). The first indicates, as mentioned above, the long period trend on which the 11-year oscillation would be superposed by the 2nd and 3rd components. The amplitude of the solarcycle variation barring the initial epoch is about 5 nT. The declining long term trend seen in this component could be indicative of one half of a larger periodicity of about 80 years (the Gleissberg cycle). If so, the feature of the only positive annual mean *Dst* index could be expected only much later. The 11-yr periodicity, seen in Fig. 1(d) is distinctly in phase opposition to the solar activity cycle, with peaks corresponding to solar minima. Components 5 and 6 together provide the only significant periodic fluctuation of note in the time series of the annual mean values.

In Fig. 1(e), corresponding to the Reconstructed Components 5 and 6, we see the consistent presence of a near four-year periodicity in the *Dst* index, with amplitudes almost constant and independent of solar activity. Since spectra of *Ap*, IMF polarity and occurrence of intense storms etc. have been shown to have similar periodicities (Gonzalez *et al.*, 1993 and references therein), this is analysed later with better time resolution in the monthly mean values. For the purpose of visualization of their relative importance, components corresponding to the fourth and seventh eigen vectors are indicated in Figs. 1(f) and 1(g). But for an anomalous rise in the end, the 4th component has no significant amplitude in its ~7 year oscillation. However, Gonzalez *et al.* (1993) note that "It was shown that the yearly distribution of intense storms has two peaks around solar maxima with an average time separation of 3 to 4 years. This hypothesis would be further confirmed if the complementary peak in solar cycle of 8 to 7 years were found. Perhaps the resolution was not sufficient as 11 years period is so dominant". In view of the above, this could well be a real oscillation present rather weakly in the *Dst* index and could be detected out only because of the methodology adapted. An analysis of *AE* or *Ap* index in a similar fashion will confirm the presence of a four year cycle in geomagnetic activity unambiguously.

The seventh component (Fig. 1(g)) has an amplitude of just about half a nanotesla and all subsequent ones are weaker still. In a recent analysis of geomagnetic storms by Taylor *et al.* (1994) based on the intensities defined by *Dst* index, it is shown that the interplanetary parameters responsible for geomagnetic disturbances of different categories could be considerably different. Since the solar and interplanetary causes are not highly periodic in this time scale, the consequent geomagnetic effects too will tend to be random with periodicities corresponding only to the most ordered of the causative phenomena, when annual mean values are taken into account. It may be concluded that the time series of the annual mean *Dst* index is fairly random in nature and embedded periodicities are confined only to the solar cycle and a near four-year cycle. The reason for the randomness in the index could be attributed to the diversely different causes of geomagnetic storms such as solar flares, high speed streams from coronal holes, coronal mass ejections etc. (as also some storms whose solar causes are not precisely known) each contributing only in a particular phase of the solar cycle.

### *3.2 Monthly mean values of Dst*

The papers on SSA by Vautard and colleagues have appeared in journals, not easily available to readers of JGG. Hence to provide a full flavour of the methodology of SSA, particularly in respect of the nature of the eigen vectors which define the principal components, we give in Fig. 2 the singular spectrum (square root of the normalised eigen value as a function of the order of the viewing window or lags), and the first fourteen eigen vectors with 72 elements for a time series of length 456 months. The singular spectrum reveals a clear noise floor after a lag of 15. The eigen vectors bring out some of the salient features of the technique of SSA as detailed below:

The first pair of even and odd eigen vectors do not cover periodicities within the window frame and should, therefore, represent trend and smoothed running mean of the data. Vectors 3 and 4, 5 and 6, 7 and 8 constitute eigen pairs in quadrature and can be expected to provide quasi-periodic fluctuations in the data. From the number of cycles in the length of the window, we know that they should correspond respectively to the semiannual, ~44 month, and annual oscillations. In terms of their relative importance, components 1 and 2 account for 24%, the semiannual and annual variations account for 11 and 6% respectively, but the annual variation is less important than the ~44 month periodicity (corresponding to the 5th and 6th eigen pair) which accounts for nearly 9% of the total variance. Apart from these principal oscillations, a quasibiennial oscillation with a period of ~22 m (12th and 13th vectors) and a periodic variation of 15.4 m (10th and 11th vectors) can be considered significant. As mentioned earlier, low order autoregressive model was used in computing the Maximum Entropy Spectrum of the reconstructed components appropriately added and the periodicities indicated were derived from the spectral peaks.

Time variations of the reconstructed components with decreasing order of periodicities are shown in Figs. 3(a)–3(f). Perusal of Fig. 3(a) reveals that the conclusions regarding long term variation in the *Dst* index arrived at from the annual mean values are replicated in the trend of the monthly series with peak close to 1965 and a possible trough near 1992. The 11 year solar cycle (Fig. 3(b)) shows a large variability in both amplitude and phase and but for the initial cycle, it is not noteworthy. The average double amplitude turns out to be less than 5 nT.

### *3.3 ~44-month component*

The 44-month fluctuation in the *Dst* index (Fig. 3(c)) is strongly present almost throughout the time span considered for analysis. The only weakening of the signal is seen near the years 1973–1974 which were, perhaps, the only interval of time with conspicuous recurrence in geomagnetic activity (as discussed in greater detail later). It can, therefore, be concluded that the coronal holes or high speed recurrent streams are the inhibiting factors for the 44-month signal in equatorial geomagnetic activity, while all other solar

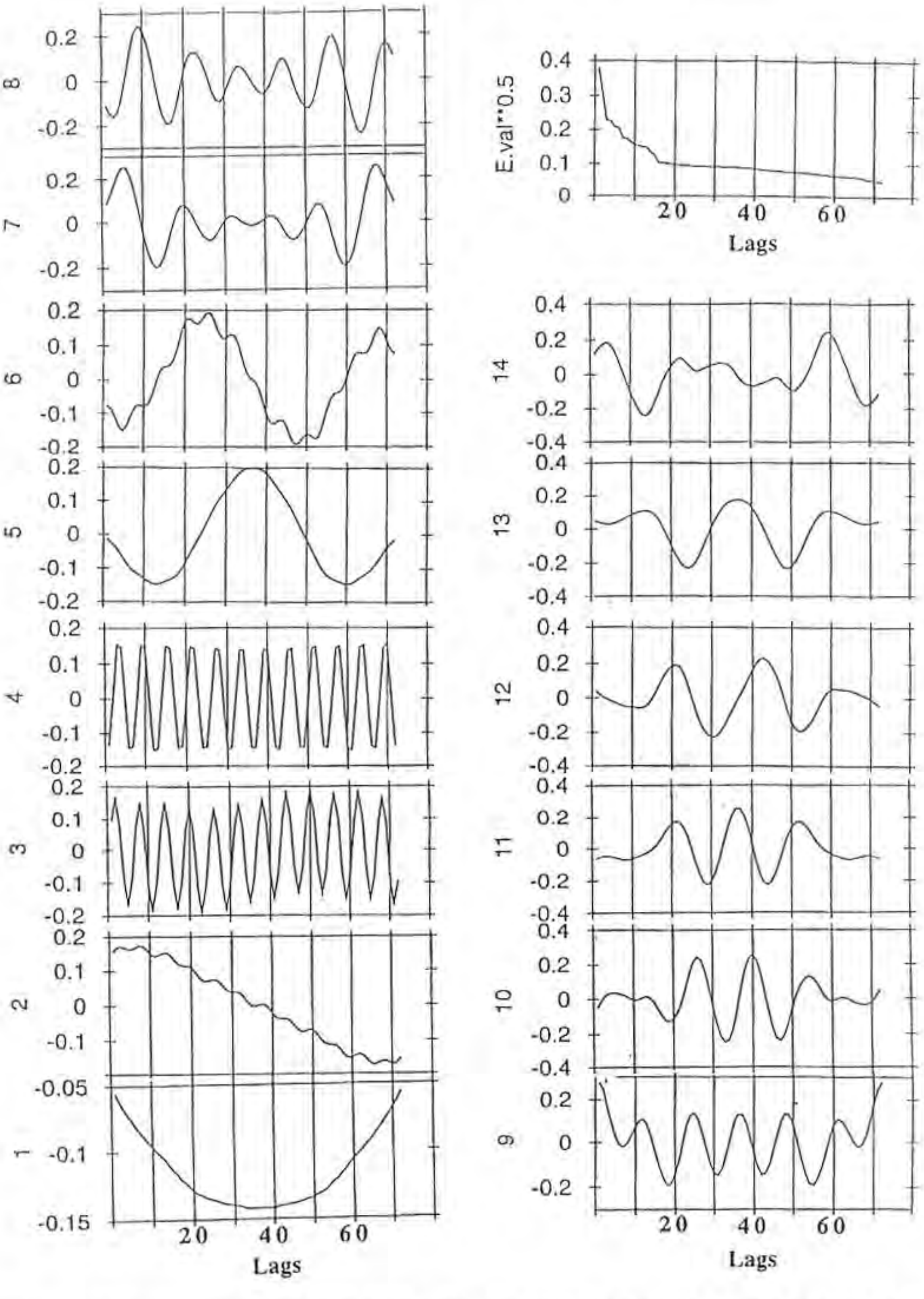

Fig. 2. The singular spectrum corresponding to 456 mean monthly values of *Dst* with a viewing window of 72 (top right). The first 14 eigen vectors derived from the autocorrelation matrix are shown to highlight the eigen pairs whenever periodic oscillations like semiannual (3 and 4) or 44 months (5 and 6) are present.

causes do not seem to diminish its significant presence in all phases of the solar cycle. Recurrent geomagnetic disturbances during declining phase of the solar cycle could be attributed to the solar magnetic sector boundary crossings (Sheeley *et al.*, 1976). It is interesting to note that Gonzalez and Gonzalez (1987) could detect an analogous periodic variation of 3.7 years in the polarity of the Interplanetary Magnetic Field. Gonzalez *et al.* (1990) found that intense geomagnetic storms tend to occur on either side of the solar maximum with average time separation of approximately 3 to 4 years. Now, sector boundary crossings are usually associated with moderate geomagnetic disturbances. Therefore, the sustained presence of the ~44-month periodicity in the *Dst* index can be supported by different mecha-

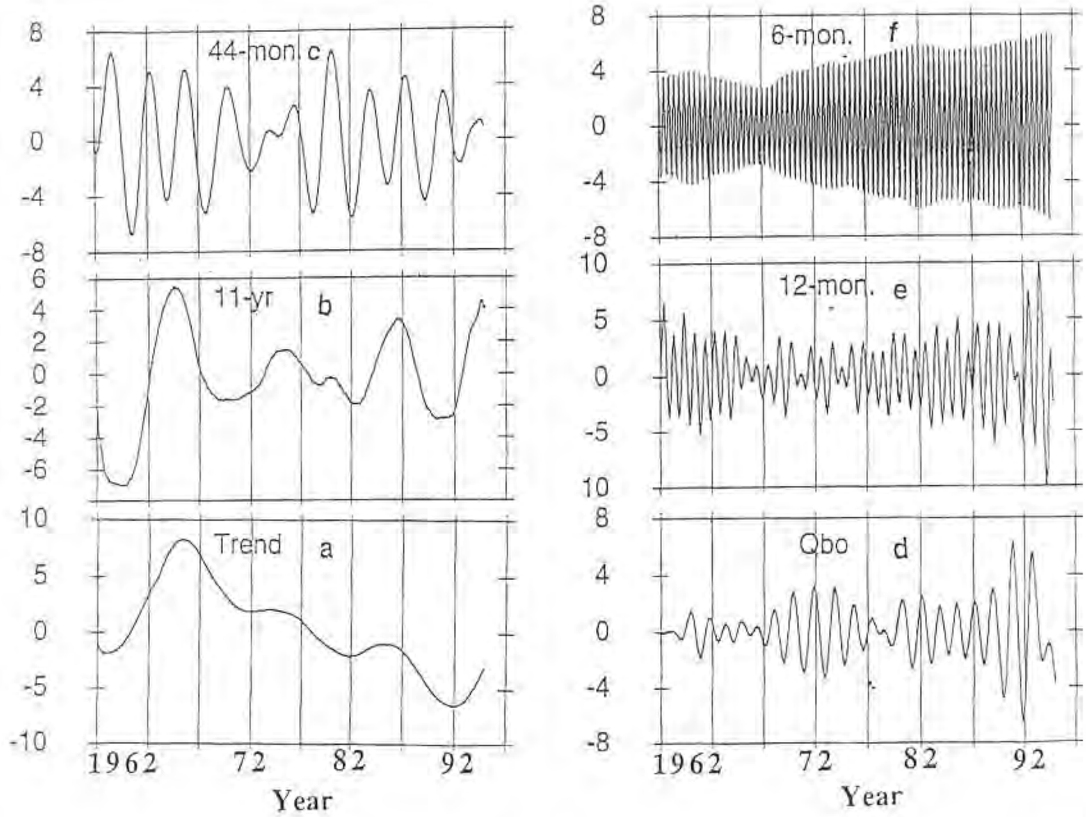

Fig. 3. (a) Reconstructed Component (RC) corresponding to PC 1 to indicate trend. (b) RC corresponding to PC 2 indicating 11 year cycle. (c) RC corresponding to PCs 5 and 6 showing time variation of the ~44 month oscillation. (d) RC corresponding to PCs 12 and 13 showing QBO. (e) RC corresponding to PCs 7 and 8 showing annual variation. (f) RC corresponding to PCs 3 and 4 showing semiannual variation.

nisms in different phases of the solar cycle. In view of the presence of this signal in *Dst* index (present analysis) and in *Ap* (Fraser-Smith, 1972; Gonzalez *et al.*, 1993) and in *Aa* indices (Delouis and Mayaud, 1975), it may be considered to be global in nature, except for, perhaps, the polar cap region, where the vertical component may exhibit this periodicity in view of its significant correlation with the polarity of the Interplanetary Magnetic Field.

### 3.4 *Quasi-biennial oscillation (QBO)*

The quasibiennial oscillation in *Dst* index (Fig. 3(d)) has a periodicity of about 22 months, instead of the nominal ~26-month periodicity in the stratospheric ozone or other atmospheric parameters. Sugiura and Poros (1977) suggested that the cause of the QBO in *Dst* is the Sun, whereas some of the recent analyses (Olsen, 1994) suggest that it could be due to the coupling processes between the middle atmosphere and the ionosphere so that the strong QBO at stratospheric heights can leave measurable signal at ionospheric heights. QBO in quiet day geomagnetic *H* component was indeed identified earlier by Yacob and Bhargava (1968). Rajarao and Joseph (1971) found that the amplitude of the QBO in *Sq*(*H*) is apparently dependent on the longitude and latitude of the station whose data were analysed. Stacey and Westcott (1962) has indicated that QBO, while periodic in nature, could be randomly excited. In the *Ap* spectra, however, the QBO has an associated periodicity of 24.4 months (Gonzalez *et al.*, 1993), but we believe the better resolution and noise reduction inherent in SSA methodology should give the more precise value and an analysis of *Ap* index in a similar fashion should give a matching periodicity. From the unambiguous two-year variation in the north/south asymmetry of the cosmic rays, Rogava and Shatashvili (1990) inferred that there were variations of similar nature in the solar wind velocity. They also found that geomagnetic activity indices showed clear 24-month periodicity between 1968–76 and again from 1979–86.

The present results of the ~22 month periodicity in *Dst* and its varying amplitude are consistent with the earlier findings of Rangarajan (1985) who identified the same periodic variation in the geomagnetic disturbance component present intermittantly at a low latitude station Alibag whose dipole latitude (9.5 deg. N) is similar to the *Dst* stations.

The presence of the signal in *Dst*, encompassing nearly 40 years, clearly lends support to Sugiura's suggestion regarding its solar cause. Even if there are other contributory causes, their significance in *Dst* would be minimized because (i) the quiet day component is eliminated in deriving the index and (ii) data from four different locations are averaged in Universal Time in deriving the index. The least amplitudes are observed during the period when the *Dst* index itself was lowest (e.g. 1964–65) and the largest amplitudes are noticeable in the current solar cycle from its maximum in 1989 and the subsequent declining phase.

### 3.5 *Annual variation*

Annual variation in the *Dst* index is depicted in Fig. 3(e). This and the UT variation in the *Dst* index was studied by Mayaud (1978) who found that the double amplitude of the annual wave for the period 1957–1974 was about 4–5 nT, with a marginal increase in the amplitude when the effects of very large magnetic storms are not included in the analysis. He supported the hypothesis of Malin and Isikara (1976) that the annual variation in the index is caused by the northward (southward) swing of the average latitude of the ring current in winter (summer) solstice and the fact that the 3 of the 4 *Dst* stations are in the northern hemisphere. Analysing the annual variation in *Dst* index as a function of the IMF polarity, Oksman and Kataja (1981) suggested that the annual variation in the ring current intensity may not be much but the observed difference in magnitude between solstices could be due to the influence of the magnetospheric boundary currents, which tends to decrease the influence of the ring current. An annual variation of less than one earth radius in the stand-off distance could produce the observed annual wave. Larger size of the magnetosphere could also be the result of enhanced ring current whose field adds to the main geomagnetic field in the outer magnetosphere leading to a stronger geomagnetic field encountering the oncoming solar wind (Siscoe, 1979). The average double amplitude of annual variation observed here is about 5–6 nT and one can notice some epochs where the signal is diminished and some where it is enhanced. The small amplitudes occur once again during 1964–66 and as with QBO, the largest amplitudes are seen for intervals beginning from the solar maximum of 1989. No clear solar cycle dependence, however, could be inferred.

Irrespective of the cause, the present results suggest variable amplitude for the annual change in the *Dst* index which is not directly related to either intense geomagnetic storms (expected during high solar activity) or due to moderate disturbances, expected during the declining phase. It appears to be largely due to the changes in either the strength or the distance of the magnetospheric boundary currents.

### 3.6 *Semiannual component*

According to Mayaud (1978), the semiannual variation in *Dst* cannot be attributed to the mechanism of K-H instability at the magnetopause (Boller and Stolov, 1970) as the expected phase shift across the solstices of the diurnal variation and the absence of the signal during equinox was not seen in the daily variation of *Dst*. He found that the amplitude of the SAV decreased marginally from 4.2 to 3.2 nT when large geomagnetic disturbances were eliminated from the analysis indicative of the relative contribution of the geomagnetic disturbances to this oscillation. Recently, Taylor *et al.* (1996) found that storms not associated with a sudden commencement exhibited a clear semiannual variation in their occurrence whereas there is no seasonal dependence in the occurrence frequency of SSC storms. When the SSCs associated with intense storms (with $Dst < -200$ nT) were considered, equinoctial maxima in occurrence is noticed but the statistics is very small. The distinguishing parameter of SSC from gradual commencement storms is the solar wind dynamic pressure. They conclude that the heliospheric latitude model (McIntosh, 1959; Boller and Stolov, 1970) of seasonal change in geomagnetic activity is relatively ineffective in modulating the seasonal variations in the occurrence of magnetic storms.

Yet another suggestion for the semiannual variation in geomagnetic activity was proposed by Russell and McPherron (1973). According to them, the IMF is ordered in the solar equatorial system (GSEQ) while the interaction of the solar wind with the geomagnetic field is ordered in the geocentric solar magnetospheric coordinate system (GSM). The semiannual variation is caused by the projection of the $Y$ component of IMF in GSEQ into an effective $Z$ component in GSM leading to two annual components: one corresponding to the IMF "Toward" polarity with spring maximum and the other to "Away" polarity with fall maximum.

Semiannual variation in the *Dst* index, depicted in Fig. 3(f), has features more or less similar to the annual variation except that the amplitudes never tend to zero. Beginning from the solar minimum of 1964–65 there is a progressive enhancement of amplitude, once again indicating lack of solar cycle dependence. Since there is no clear evidence of any solar cycle dependence of the R-M model for SAV, it is likely that the observed variation in *Dst* index is largely due to this mechanism, though others like SAV in intense storms could also be contributing factors.

### *3.7 Daily mean values of Dst*

A complete analysis of daily *Dst* index by SSA would be a difficult task and the results too complex for interpretation as the data length will be too long (38 years) and the choice of the embedding space too correspondingly large. Solar processes in different epochs of solar activity will lead to severe mix-up of the final signature in the ground-based *Dst* index. It may also be noted that SSA is most suited for short, noisy data series as shown by Vautard *et al.* (1992). Therefore, we confine our attention to the recurrent disturbances in geomagnetic activity and, in this section, carry out a comparative study with other indices of activity like *Ap* and *AE*. In addition, we use a new index called *Ah* index devised by the Russian scientists (Semenov, 1992). It is aimed to be an index of geomagnetic activity at middle latitudes, derived from the maximum excursion in an UT hour of the magnetic element in the horizontal plane, measured at Lvov magnetic observatory (geomag. Lat. 45.1 deg.). The sum of the 24 hourly indices for a day and the sum of eight *Kp* values for each day seemed to correlate very well for the test period of 1967, when they also used Memambetsu (36.5 deg. Lat.) and Tucson (39.7 deg. Lat.) for longitude averaging. In the published catalog of the indices, no attempt has been made to eliminate the quiet day component at each hour and only one station is used. It is stated that "the data is distributed for practical testing of the index", which is what is attempted here.

### *3.8 Choice of an interval of strong recurrence*

In order to study fairly noise-free 27-day signal of recurrent activity, it is essential to select an interval free of disturbances from other solar transients. One such interval has been identified by Hansen *et al.* (1976) who found that the period extending from middle of Dec. 1973 to end of June 1974 shows a highly persistent recurrent pattern without any SSCs. Flares and other transient solar activity were totally absent. Van Hollebeke *et al.* (1981) studied the relationship between energetic particle events and high speed solar wind for this interval during which two well-defined recurring high speed streams were seen to persist for nearly 10 solar rotations. Tsurutani *et al.* (1995) have recently examined the interplanetary origin of geomagnetic activity in declining phase, once again using the same interval, characterizing the period as "the cleanest, most unambiguous examples of recurrent streams".

We choose the period beginning from Dec. 18 1973 upto June 24, 1974 corresponding to seven solar rotations and subject the daily mean values of the four parameters—*Dst*, *Ap*, *AE* and *Ah*—to SSA.

### *3.9 Reconstructed components of daily values of Dst*

The singular spectra and the reconstructed components corresponding to the principal oscillations in the time series are depicted in Fig. 4. The singular spectra (Fig. 4(a)) shows clearly that *Dst* and *AE* have distinctly different compositions while *Ap* spectrum has some resemblance to both, as would be expected from the physics the three indices represent. The mid-latitude index *Ah* should have an associated spectrum close to that of *Dst* but we find that it is rather unique, neither resembling that of *Dst* nor that

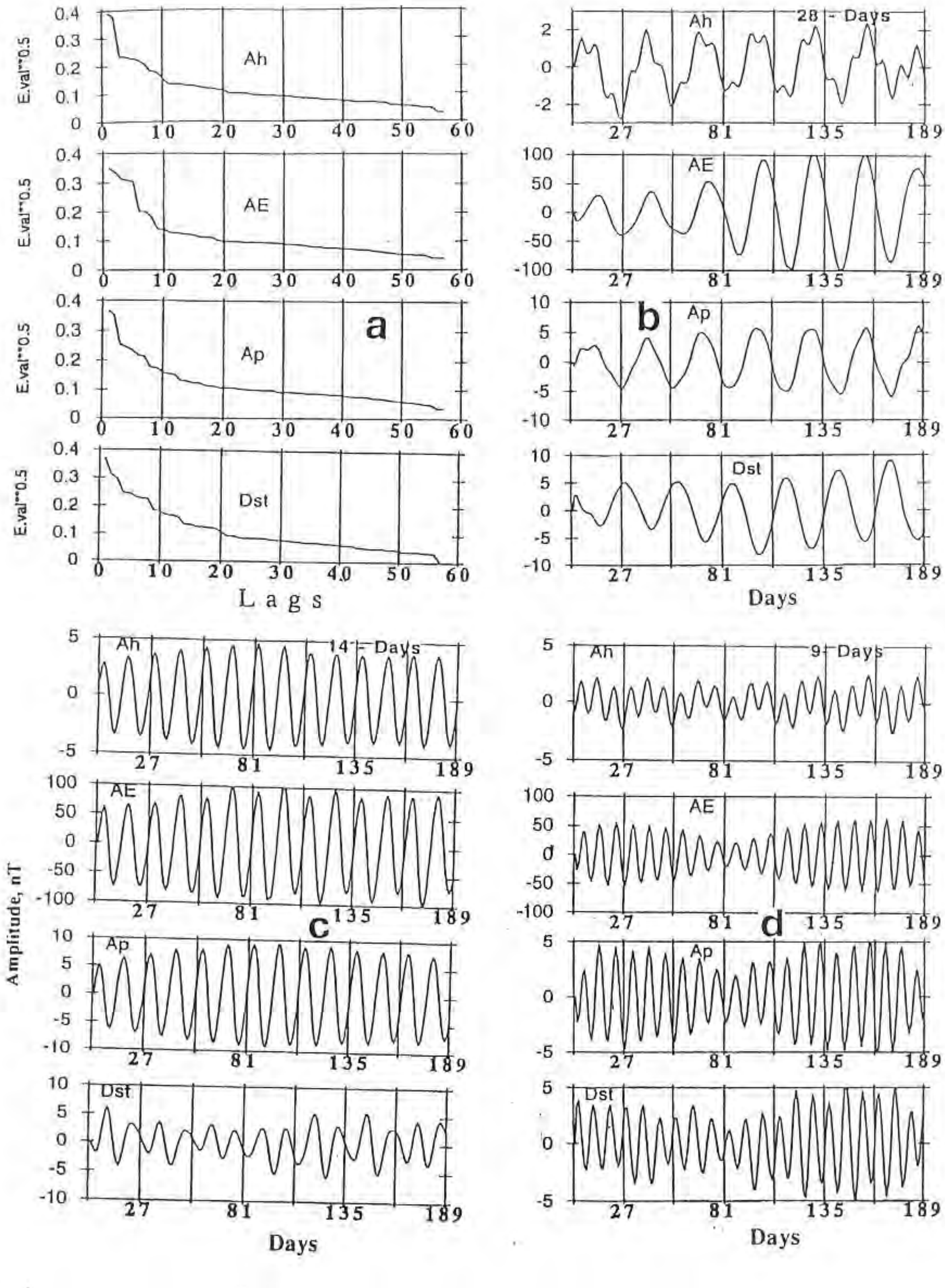

Fig. 4. Singular spectrum corresponding to 189 daily mean values of *Dst*, *Ap*, *AE* and *Ah* indices covering the interval Dec. 18, 1973 to June 24, 1974 (top left). Reconstructed components combining appropriate PCs for ~28 day, ~14 day and ~9.5 day variations are shown in other panels for the four indices separately. Day No. 1 corresponds to Dec. 18, 1973.

of *AE* fully. The noise floor is reached earlier in comparison to the other three indices. It should, however, be mentioned that for all the four indices less than 60% of the total variance is accounted by the first seven significant components indicative of the large fraction of unexplained variance. A noteworthy distinction between *AE*, *Ap*, *Ah* on one hand and the *Dst* index on the other is that the first eigen pair in the case of the three indices represent the periodicity of 13.5 days (half a solar rotation) whereas in case of *Dst* the first corresponds to a long period (135-day) oscillation and the second and third eigen pair correspond to

28-day periodicity (full solar rotation). The longer period oscillation manifests as the third and fourth eigen pair in *Ap* and *AE* data whereas in *Ah* it is relegated to the 7th component. The variance accounted by the solar rotation (half a solar rotation) periodicity is 19% (12%) for *Dst*, 12% (26%) for *Ap*, 19% (24%) for *AE* and 10% (29%) for *Ah* indices. It is thus clear that though two recurrent streams persisted in the interval analysed, one of them was more successful in energy injection into the ring current in comparison to the other whereas the substorm processes were equally affected by the two streams.

The reconstructed components for the 28-day, 14-day and 9-day periodic fluctuations are shown in Figs. 4(b)–4(d). Average amplitudes and phases of these variations and the ratio for each pair of the four parameters, derived from cross spectral analysis using fast Fourier transform, are given in Table 1. Examination of Fig. 4 and Table 1 indicates that the 14-day periodicity in *Dst* index is substantially diminished in comparison to *Ap* and *AE*, whereas the 28-day oscillation is about the same in *Ap* and *Dst* with *AE* having a 10-fold enhancement in magnitude. In their exhaustive analysis of the features of the variations of *Dst*, *AE* and IMF/solar wind parameters, Tsurutani *et al.* (1995) find that the *AE* index has remained anomalously high throughout, mainly caused by chains of consecutive substorms caused by southward component of large amplitude Alfven waves within the corotating stream and that the substorm activity is most intense near the peak speed of the stream where the Alfven wave amplitudes are the greatest. *AE* reaches peak intensity within about 12 hours of the *Dst* decrease in main phase but *AE* remains high even when *Dst* generally recovers. Thus, the periodic behaviour associated with the corotating streams, even if they were two per solar rotation, of the *Dst* index would be different compared to *AE*, as seen here. *Ap* being a subauroral activity index will also tend to mimic *AE* variations to a larger extent compared to *Dst*. Akasofu (1981) pointed out that during moderate geomagnetic disturbances, there is a linear relation between *AE* and *Dst*, whereas when modulus of *Dst* exceeds 50 nT, the relation breaks down with *AE* leveling off or tends to decrease. He noted that the leveling of *AE* is a real feature and not due to the equatorward expansion of the auroral oval. This view was contradicted by Feldstein *et al.* (1994) when they found that for a proper choice of *AE* stations including subauroral latitude locations for intense storms, the auroral electrojet index continues to show a linear relation with *Dst*. However, they found that only a minor fraction of the solar wind energy influx into the magnetosphere loads into the ring current in contrast to the auroral electrojets. We find that the ratio of *AE* to *Ap* for all the harmonic components is about the same whereas the ratio of *AE* to *Dst* is substantially larger for the second harmonic (half a solar rotation) compared to the 28-day periodicity.

Table 1.

| Period | *Dst* | | *Ah* | | *Ap* | | *AE* | |
|---|---|---|---|---|---|---|---|---|
| | Amp. | Phase | Amp. | Phase | Amp. | Phase | Amp. | Phase |
| 28.44 d | 8.1 nT | 107° | 2.9 nT | 296° | 13.2 nT | 295° | 94.1 nT | 280° |
| 13.47 d | 6.0 nT | 291° | 4.6 nT | 113° | 18.6 nT | 49° | 104.5 nT | 43° |
| 9.14 d | 5.7 nT | 130° | 2.6 nT | 4° | 10.6 nT | 355° | 54.8 nT | 352° |

| Period | Ratio of amplitudes | | | | | |
|---|---|---|---|---|---|---|
| | *AE*/*Ap* | *AE*/*Ah* | *AE*/*Dst* | *Ap*/*Ah* | *Ap*/*Dst* | *Dst*/*Ah* |
| 28.44 d | 7.13 | 32.44 | 11.62 | 4.55 | 1.62 | 2.79 |
| 13.47 d | 5.61 | 22.72 | 17.42 | 4.04 | 3.10 | 1.30 |
| 9.14 d | 5.16 | 21.07 | 9.61 | 4.08 | 1.86 | 2.19 |

Note: Period, amplitude and phase are derived from cross spectral analysis of pairs of parameters using FFT. The amplitude of *Ap* has been taken in nT (instead of the usual 2 nT unit for immediate comparison).

The reconstructed components of *Ah* for 28 and 9 days are not clear sinusoidal oscillations, mainly because they account for much less of the total variance and also because in the individual reconstructed component there is a contamination by the other periodicity. It may be noted that we combine components 3 and 5 for the ~9-day oscillation and components 4 and 6 for the ~28-day oscillation. The corresponding periodicities derived from Maximum Entropy Method (MEM) spectra in these cases do not give same values suggestive of dual peaks in each case. Only the 14-day component, appears comparable to *Ap* and more in magnitude than that for *Dst*. In the spectrum, the ratio of *Ap* to *Ah* is practically the same for all the periods, whereas w.r.t. *Dst* the ratio diminishes to near unity (indicative of equal amplitudes) for the first harmonic of the solar rotation. A linear regression analysis of *Ah* and *Dst* indices for this interval gives a correlation of –0.648 suggesting that only 40% of the variation in the two indices can be considered common. Correlation coefficients for other pairs are: *(Ap, Ah)* 0.916; *(AE, Ah)* 0.883; *(Dst, Ap)* –0.788; *(Dst, AE)* –0.770; *(Ap, AE)* –0.913.

It may be concluded, from the results for *Ah* indices, particularly from the weakening of the 28-day signal that even at middle latitudes corresponding to Lvov station, the substorm influence is more dominant than the equatorial ring current effect. How much of the individual characteristics of *Ah* is due to its representing middle latitude geomagnetic activity and how much is due to contamination by non-removal of the quiet day component in its derivation is difficult to isolate. It does appear, however, that when properly evaluated with appropriate averaging over longitudes and removal of *Sq* component, this index will prove beneficial to quantify the extent of the influence of the auroral electrojet at middle latitudes, particularly as a function of the intensity of *AE* index. Because the interval chosen has been marked by a consistent pattern of high speed solar wind stream, no amplitude modulation is seen over the seven solar rotations, except in case of the third harmonic, which weakens in the third and fourth rotations. In *Dst*, the 14-day periodicity shows some variability in amplitude, not seen in *AE* or *Ap*. This could be due to the fact that for several days prior to the appearance of the high speed solar wind streams, the index has positive values, whereas, as mentioned earlier, *AE* remains high throughout (Tsurutani *et al.*, 1995).

The observed differences in detail of the 28-day oscillation and its harmonics in the four indices should help in establishing the relative enhancements at different latitudes due to the energy transfer from the solar wind into the magnetosphere.

It will be interesting to carry out a detailed study using higher resolution data covering the onset/end of each of the high speed stream to understand how the geomagnetic activity at different latitude zones respond to the same driving force and this will be attempted.

### *3.10 Hourly mean values of Dst*

The variation in the hourly *Dst* could be very large ranging from positive values of about 50 nT to negative values in excess of 500 nT as observed during intense geomagnetic storms like the March 1989 event. A cursory examination of the plots of *Dst* values given by Sugiura and Kamei (1991) immediately reveals that there are no distinct periodic variations in the time scales of hours, but during periods of geomagnetic disturbances there could be such oscillations. Interplanetary conditions responsible for large geomagnetic storms have been discussed earlier (Burton *et al.*, 1975; Feldstein *et al.*, 1984; Gonzalez *et al.*, 1990 and others). Tsurutani *et al.* (1992) examined 5 largest storms during 1971–1986 and found that all the storms were associated with high speed solar wind streams led by collisionless shocks. The causative solar flares for the streams could also be identified. Extreme value of southward *Bz* was responsible rather than solar wind speed for these storms. Six of the most intense storms, according to them, were during 1957 and 1960, a period when corresponding solar wind/IMF data were not available.

Feldstein *et al.* (1994) find that during the main phase when the ring current develops sharply, there is dissipation in the auroral ionosphere and the energy loaded into the ring current is closely connected to this. *AE* indices during storms often exhibit fluctuations for several hours. They also find that the asymmetry in the ring current depicted by ASY index drops to low values when *Dst* is largest and that the asymmetry is more sensitive to IMF *Bz* than to the symmetric ring current, DR. Periodic changes in *Bz*—both in direction and in magnitude—and/or contraction/expansion of the magnetospheric cavity by fluctuating solar wind velocity can cause the observed periodic changes in the *Dst*. In modelling the *Dst* variations as a function of interplanetary parameters, Feldstein *et al.* (1984) emphasized that energy transfer into the ring current is possible even during northward orientation of the IMF and that solar wind velocity, particularly square of the solar wind velocity, correlates fairly well with the energy in the ring current. They also suggest that there is a quasi-steady state quiet current when the ring current decay is compensated by the certain level of injection and this level may vary during a storm.

As we are looking for quasiperiodic fluctuations in hourly time scale, we select our storm interval based on the criterion that at least for four consecutive days the daily mean value of *Dst* should be less than –70 nT. The time series considered for analysis begins when the hourly *Dst* indicates the beginning of a sustained decrease and the series is ended when at least three consecutive values of hourly *Dst* is greater than –50 nT without any clear further disturbance. Table 2 gives the storm onset and the duration considered for each of the storms.

Since our criterion for selection is not the magnitude of the largest of hourly value of *Dst*, the storms analysed here differ from the list of great magnetic storms examined by Tsurutani *et al.* (1992) for example. However, the maximum negative hourly value of *Dst* for each of the 10 storms was in excess of 280 nT with a value of 589 nT as the highest for the March 1989 storm.

Even if the length of the time series is different, we adopt a uniform maximum lag of 48 hours, so that periodic fluctuations with time scales of two days and less could be seen, apart from the large scale trend defining the phases of the storm. Table 2 also lists the variance accounted by the first six principal components and the corresponding periodicities determined from a low order Maximum Entropy spectrum.

The first six reconstructed components for the 10 geomagnetic disturbances are shown in Fig. 5. They are grouped in three categories: the bottom four are characterised by fluctuations throughout the period of analysis; the middle four have superposed fluctuations in the initial part but weaken or die down during the latter part and the two unique cases of Sep. 1957 and Mar. 1960 which have in their sixth component distinctly different periodicities (one having higher frequency and the other lower frequency than the remaining 8).

The first two components indicate the time profiles of the smooth change in *Dst* index for each of the storms. While most are marked by a clear decrease in the first 24 hours, the epochs of minimum and the

Table 2.

| Start UT | Total duration (hrs) | Percentage a/c by comp. (periodicity from MESA) | | | | | |
|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 |
| Sep. '57 02d 04h | 136 | 32 (Tr) | 29 (96) | 16 (38.4) | 9 (40.0) | 4 (26.7) | 1.5 (12.8) |
| Jul. '59 15d 01h | 125 | 32 (60) | 27 (Tr) | 13 (33.1) | 13 (29.1) | 6 (19.2) | 3.0 (19.2) |
| Mar. '60 30d 15h | 133 | 38 (Tr) | 35 (107) | 6 (41.7) | 5 (19.2) | 5 (29.1) | 4.0 (30.0) |
| Oct. '60 05d 21h | 110 | 41 (Tr) | 34 (Tr) | 12 (50.5) | 3 (31.0) | 2 (22.9) | 1.6 (—) |
| Nov. '60 12d 17h | 141 | 30 (76) | 26 (48) | 17 (32.0) | 12 (32.0) | 5 (21.8) | 2.4 (21.8) |
| May '67 25d 13h | 117 | 27 (80) | 25 (Tr) | 18 (107) | 13 (31.0) | 8 (21.8) | 4.5 (20.0) |
| Feb. '86 07d 09h | 142 | 40 (160) | 30 (Tr) | 7 (56.5) | 5 (25.3) | 4 (24.0) | 2.6 (20.4) |
| Mar. '89 12d 16h | 137 | 32 (54) | 29 (Tr) | 16 (38.4) | 7 (30.0) | 4 (21.8) | 3.6 (19.6) |
| Apr. '90 09d 10h | 158 | 35 (56) | 29 (Tr) | 17 (40.0) | 6 (30.0) | 3 (21.3) | 2.5 (20.4) |
| Mar. '91 24d 05h | 120 | 33 (137) | 24 (107) | 16 (36.9) | 10 (33.1) | 3 (20.9) | 2.4 (19.6) |

Percentage of total variance accounted for by the first six principal components (and the periodicities in brackets) for 10 geomagnetic disturbances with the magnitude of daily mean value of the *Dst* index exceeding 70 nT for four consecutive days. Time of beginning of the decrease in the index and the number of hours for which data were included in the singular spectrum analysis are indicated.

Tr: Stands for long term trend (comes as the first estimate in the spectrum).

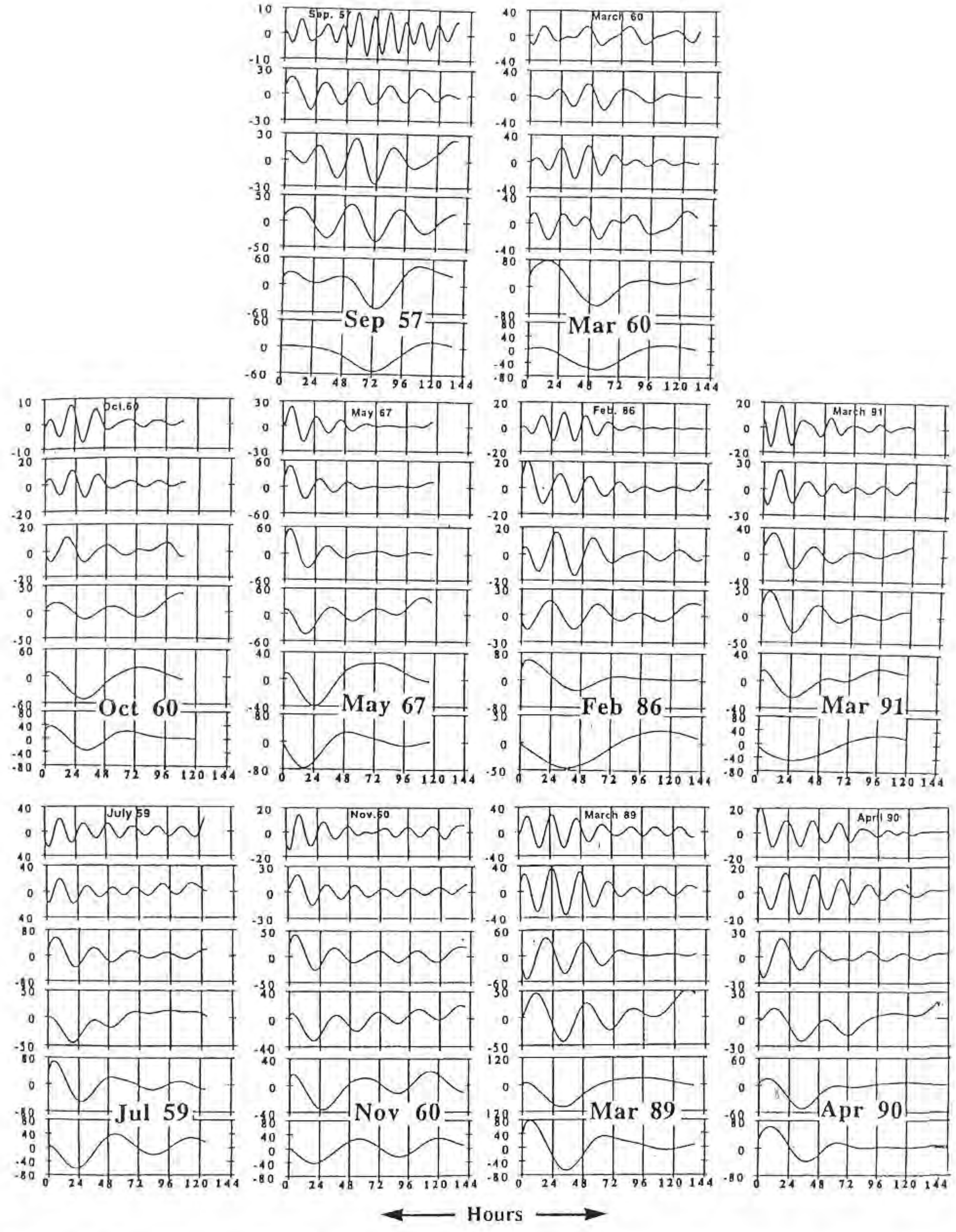

Fig. 5. First six reconstructed components derived from singular spectrum of mean hourly values of *Dst* corresponding to 10 major geomagnetic disturbances when mean daily values of *Dst* were –70 nT or less for four consecutive days. The storms are grouped according to the nature of the oscillations seen in common. The abscissae are hours from the beginning of first decrease in hourly values upto the time when at least three values of *Dst* > –50 nT were observed in the recovery phase.

nature of the recovery is somewhat unique for each storm. This reflects the initial energy injection into the ring current and its subsequent decay as a function of storm time does not form any identifiable pattern. But what appears to be most significant is that the remaining four components for all the storms are marked by well defined oscillations—often in phase quadrature— suggestive of periodic oscillations in the ring current intensity both during its development phase and the decay phase. The third and fourth components correspond, in general, to a periodic variation of 30 to 45 hours. The fifth and sixth correspond to fluctuations in a narrower range of period between 19 to 22 hours. Neither of these is really close enough to 24 hours to suggest that the oscillations may be due to improper elimination of *Sq* component in the derivation of the index. Since they are seen in almost all the samples considered, it may be asserted that periodic energisation of the ring current with time scales of 20 and 40 hours is a reality. It is interesting to observe that Tsurutani *et al.* (1995) do mention that "*Dst* generally recovers but with small periodic ring current injections".

Fluctuations in the period range of 20 or 40 hours in either the solar wind electric field and/or the solar wind velocity or the changing level of steady injection (constituting the quiet time proton belt) could be the mechanism responsible for the observed periodicities in the *Dst* index during severe magnetic disturbances. It is also likely that the location of the ring current undergoes periodic changes matching with this time scale. These aspects need to be investigated with greater vigor. To understand what causes these periodic inputs into the ring current, we may have to examine individual storms in conjunction with the interplanetary parameters restricting the analysis to bands of frequencies at a time. This will be done for storms for which continuous interplanetary data is available.

## 4. Conclusions

The equatorial *Dst* index has been analysed in different time scales, using the method of Singular Spectrum Analysis which isolates significant components in the time series decreasing the noisy part substantially. The mean annual values and monthly mean values indicate clearly the presence of a near-permanent oscillation of 44 month periodicity, independent of solar activity. Perhaps, the strong presence of corotating high speed solar wind streams is the only inhibiting factor for this. The 11-year cycle in the *Dst* index is rather weak with an amplitude of less than 5 nT and in phase opposition with the sunspot number/solar activity. The large change in the index in the initial part from 1957 to 1965 is not seen in later years, suggestive of longer term modulation of the index. A quasibiennial oscillation in the index is shown to be present intermittantly and it can be attributed to solar causes, as the quiet day field is eliminated in the derivation of the index. Annual and semiannual oscillations are a near permanent feature of the index but they have no dependence on solar activity. Recent years are shown to be marked with much larger amplitude of variation of these signals and, therefore, can be studied in greater detail in relation to interplanetary and solar wind parameters.

During periods of strong recurrence in geomagnetic activity, clear differences between the equatorial *Dst* index and the indices representing subauroral, auroral and midlatitude regions are brought out. In particular, it is shown that when two streams per solar rotation were persistent, the energy input into the ring current is larger for one relative to the other, in contrast to the loading of the auroral electrojet which is of about the same magnitude, as manifested by a strong ~14-day spectral line in *AE* index. The index *Ah*, meant to represent geomagnetic activity at middle latitudes, has time variations more similar to changes in higher latitudes than to that close to the geomagnetic equator. Apparently it needs further refinement to be used on a regular basis as the other three indices.

During typically long lasting severe geomagnetic disturbances, significant oscillations in two frequency bands are shown to be present with periods of about 20 and 40 hours. These may well represent the oscillations in solar wind velocity, interplanetary electric field or the steady injection into the magnetosphere which maintains the quiet time proton belt. It is suggested that much more exhaustive analysis by the same methodology needs to be carried out for individual geomagnetic disturbances to identify the most likely mechanism responsible for the fluctuations in the *Dst* index.

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