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J. L. Le Mouël, F. Lopes, V. Courtillot. Singular Spectral Analysis of the aa and Dst Geomagnetic Indices. *Journal of Geophysical Research Space Physics*, 2019, 124, pp.6403-6417. 10.1029/2019JA027040 . insu-03586616

HAL Id: insu-03586616

<https://insu.hal.science/insu-03586616>

Submitted on 24 Feb 2022

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JGR Space Physics

RESEARCH ARTICLE

10.1029/2019JA027040

Key Points:

- Singular spectrum analysis reveals trends and quasi-periodic oscillations in the aa and Dst series of geomagnetic activity
- The ~22-, ~11-, and ~5.5-year components are common to the four indices. These “pseudo harmonic” components are evidence of solar activity
- SSA components vary in frequency and amplitude. The phase relationships of any two components over time can be studied in detail

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Citation:

Le Mouél, J. L., Lopes, F., & Courtillot, V. (2019). Singular spectral analysis of the aa and Dst geomagnetic indices. *Journal of Geophysical Research: Space Physics*, 124, 6403–6417. <https://doi.org/10.1029/2019JA027040>

Received 14 JUN 2019

Accepted 26 JUL 2019

Accepted article online 16 AUG 2019

Published online 20 AUG 2019

Singular Spectral Analysis of the aa and Dst Geomagnetic Indices

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Abstract We apply singular spectrum analysis in order to identify trends and quasi-periodic oscillations in the aa and Dst series of geomagnetic activity. We also analyze the sunspot number International SunSpot Number (ISSN) and the number of polar faculae Polar Faculae (PF). Singular spectrum analysis provides the eigenvalues and therefore trends and oscillatory components of the four series. ISSN is dominated by a trend (the Gleissberg cycle), followed by 10.6, 35.5 years, two ~8-year components, 21.4 and 5.3 year. aa shows the same trend, a ~47-year component, then 10.8, 32.3, 21.8, and a series of three close components at 10.6, 12.2, and 9.2 years, followed by a 6 month seasonal component. PF is dominated by the 20.7-year period, followed by 10.2, 8.3, 41, and 31 years, then a 5.2 year component. Dst is dominated by a trend, then a strong 6-month component; next are found a 47-year component, the 10.6 years and a second seasonal line at 1 year. The ~22-, ~11-, and ~5.5-year components are common to the four indices. These “pseudo harmonic” components are evidence of solar activity. Singular spectrum analysis identifies components that vary in frequency and amplitude. The phase relationships of any two components over time can be studied in detail. An illustration is given by the remarkable phase coherency of the 5.3-year component. But the components are neither truly periodical nor exact multiples of each other. These differences reflect the complex mechanisms that govern solar-terrestrial relationships.

1. Introduction

Long series (several decades and sometimes more than a century long) of daily (then hourly, then minute) mean values of the geomagnetic field components (the North, East, and vertical components X , Y , and Z) have been available from magnetic observatories all over the world. Based on these, geomagnetic indices have been constructed, with the aim of monitoring “short term” features of the external geomagnetic field, that is, with an origin external to the solid Earth. Most of the indices were built at a time when computing facilities were poor or even absent, compared to what has become available by the end of the twentieth century. They required skill in their operation. Nowadays, it might be easier to propose new indices still based on magnetic components or even to use these components (X , Y , and Z) directly in the analysis (e.g., Blanter et al., 2014).

There are two quite distinct families of indices; in both cases, the indices used at present are the successors of former indices. On one hand, the so-called Dst and AE indices are inspired by the u indices of storminess (Mayaud, 1980); on the other hand, range indices, either the local R and Q or the planetary K_p , am and aa , are derived from the K index (Mayaud, 1980).

The study of solar-terrestrial relationships has been a topic of great interest to external geophysics for well over a century, as these indices are expected to allow one to study separately different mechanisms by which energy is dissipated in the magnetosphere (Rostoker, 1972). They now carry renewed interest linked to space weather research. A number of authors have identified significant spectral lines in geomagnetic indices and suggested mechanisms by which these are generated (e.g., Cliver et al., 1998, 2000; Courtillot et al., 1977; Delouis & Mayaud, 1975; Gonzalez et al., 1978; Gonzalez & Mozer, 1974; Le Mouél, Blanter, Chulliat, & Shnirman, 2004; Le Mouél, Blanter, & Shnirman, 2004; Malin & Isikara, 1976; Mayaud, 1978; Prestes et al., 2006; Shnirman et al., 2009). We return to several of these earlier works in the discussion section.

In a series of previous papers, we have analyzed centennial series of a number of geophysical and physical parameters using an adapted version of the powerful method of singular spectrum analysis (SSA). We found strong evidence of solar signatures in the Earth’s mantle rotation pole position (Lopes et al., 2017), in the length of day (Le Mouél, Lopes, Courtillot, & Gibert, 2019) and in a number of climate indices (Le Mouél,

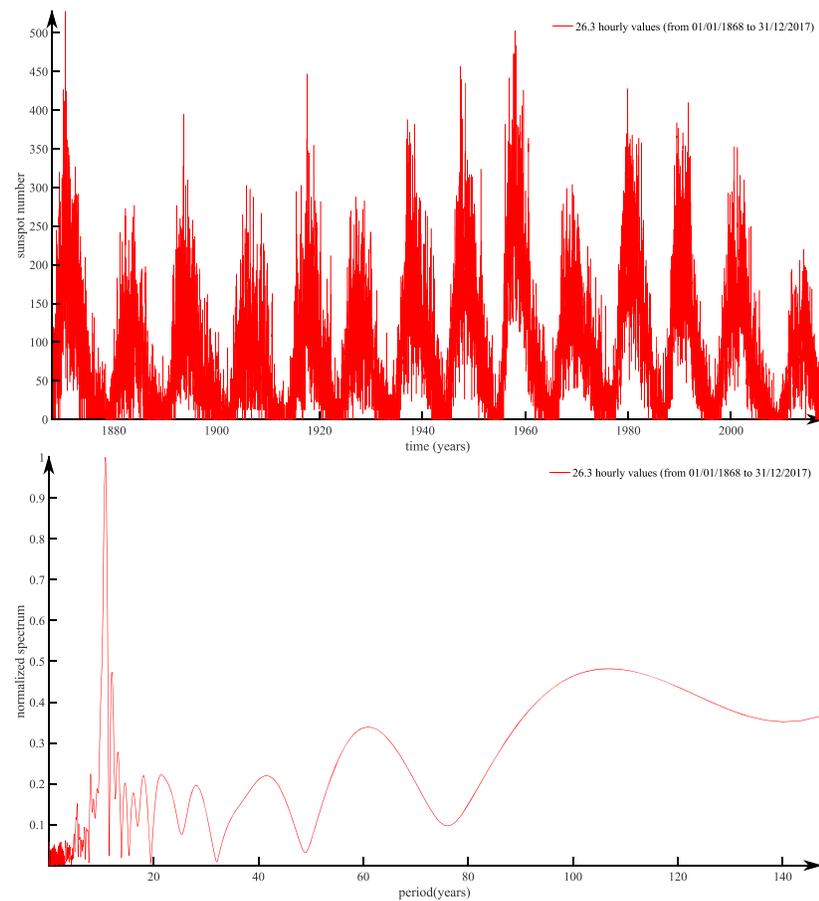


Figure 1. (top) The ISSN (26.3-hourly values) time series (1868–2017). (bottom) Its Fourier spectrum.

Lopes, & Courtillot, 2019). We apply in this paper the same method to the series of aa and Dst geomagnetic indices, with the hope to bring some new information on these classical, already long-lived geomagnetic tools.

More precisely, we analyze the 3-hourly data from the aa index series (1 January 1868 to 31 December 2017) and the Dst index hourly data (1 January 1957 to 31 December 2014). We compare these to the SSA analysis of ISSN spot number (1 data point every 26.3 hr; 1 January 1868 to 31 December 2017; <http://www.sidc.be/silso/datafiles>) and polar faculae PF (1 point per month; 1 August 1906 to 1 August 2006; <http://www.solar-dynamo.org/data.html>; sampled here at a daily interval). They are displayed, together with their Fourier transform in Figures 1 and 2. But first, we discuss the K index from which the range indices are derived.

2. The K, aa, and Dst Indices (Data and Method)

2.1. The K index

The K index was introduced by Bartels (1938) at Niemegek observatory. At this time, geomagnetists began to feel that a daily index was not sufficient, and a strong request came from the International Union of Scientific Radio-telegraphy. The K index is defined as the maximum range of the irregular variations (in nT) in the two magnetic components H (horizontal) and D (declination) observed over a 3-hr interval, after eliminating the SR regular variation generated by the atmospheric dynamo. K is ranked in one of the range classes, as defined in each observatory. A number $K = 0$ to 9 is assigned to each range class. Mayaud (1980, pp. 18 to 40) points out in his monograph the many questions raised by the definition, meaning and use of K, asking first “what is the physical meaning of this range?” and answers them at length.

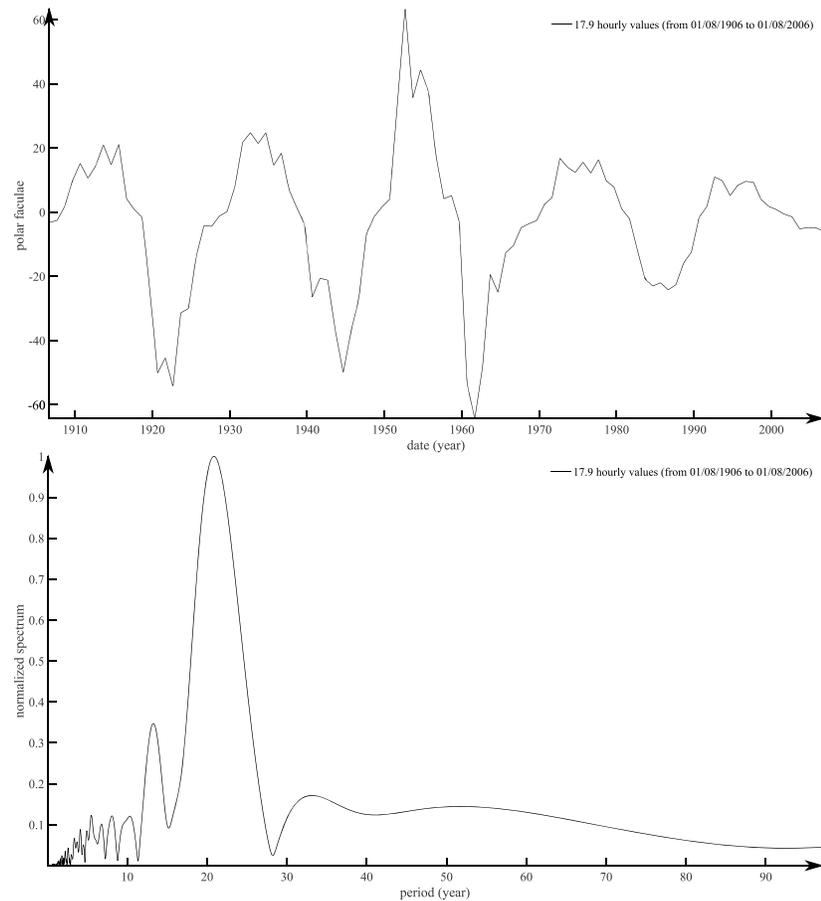


Figure 2. (top) The PF (17.9-hourly values) time series (1906–2006). (bottom) Its Fourier spectrum.

We note that the 3-hr range index K was the first to be proposed at an international level (Bartels, 1940; Bartels et al., 1939). The conception of this index undoubtedly originates in previous attempts to characterize magnetic activity but, in addition, takes advantage of the observational experience acquired in many geomagnetic observatories over several decades (Mayaud, 1978). It became apparent in the late 30s that a daily index was insufficient whereas a 3-hr interval at constant time intervals was deemed sufficient. It was also obvious that the beginning and end of the time intervals should be reckoned in universal time (0h00–3h00 UT, etc.).

Because the 3-hr indices K are defined with a roughly logarithmic scale, they are not suitable for simple averaging. To convert them to a roughly linear scale, the a index (in nT) is defined from the K index by use of a table depending on the observatory; this is a reconversion to an equivalent range measured in magnetic units.

2.2. The aa Index, a Planetary Index Derived From K

A request from the British Royal astronomical society presented at the Madrid 1969 IAGA meeting by S. Chapman is at the origin of the aa index. The aim was to extend the index series backwards, that is, before 1884. The availability of long records at two almost antipodal long-lived observatories (Greenwich and Melbourne) made it possible to obtain a reliable, quantitative time series if K scalings of their records could be performed. The necessary work was undertaken and resulted in a new index aa adopted by IAGA at the 1975 Grenoble meeting; aa is expressed in nT in successive 3-hr UT time intervals, with $aa = a_n$ (Greenwich) + a_s (Melbourne). The small number of observatories involved (only two subauroral ones) was of course imposed by the desire to go back in the past as far as possible. Note that, because the two observatories are almost antipodal, aa cannot be expected to monitor auroral disturbances. In this paper, we analyze

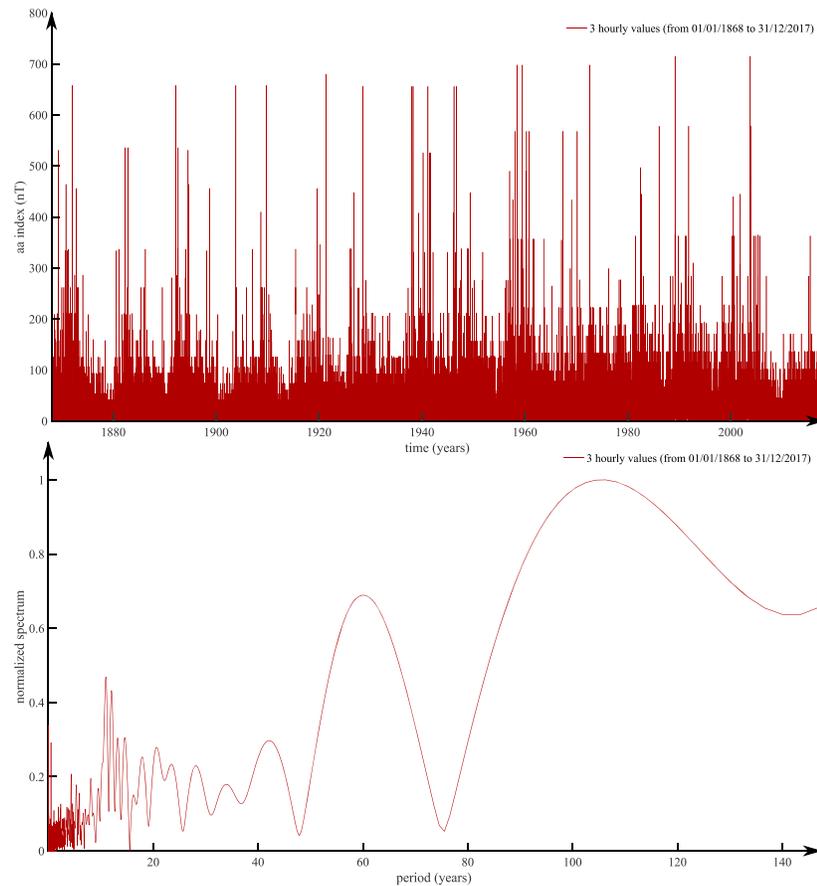


Figure 3. (top) The aa (3-hourly values) time series (1868–2017). (bottom) Its Fourier spectrum.

the 3-hourly aa index series from 1 January 1868 to 31 December 2017; the data are found at http://isgi.unistra.fr/data_download.php website. They are displayed in Figure 3.

2.3. The Dst Index

The Dst index uses recordings of the horizontal component (H) of the geomagnetic field at the four observatories of Hermanus, Honolulu, Kakioka, and San Juan, located at low to midlatitudes. The index is calculated at the data analysis center for geomagnetism and space magnetism, Graduate School of Science, Kyoto University (Kyoto, Japan), and maintained at the world data center WDC-C2. The four observatories “were chosen on the basis of quality of observations and because they were far enough from the equatorial and polar electrojets and distributed in longitude as evenly as possible” (Menvielle & Marchaudon, 2007; Sugiura & Kamei, 1991). The Dst index was devised in order to study the temporal development and intensity of magnetic storms and the ring current (Mayaud, 1980). Its construction comprises two steps: the removal, at each observatory, of the secular variation of the main geomagnetic field and the removal of the quiet day variations. Both are calculated using the five quietest days of each month. In this paper, we analyze the Dst monthly index series from 1 January 1957 to 31 December 2014; the data are found at http://isgi.unistra.fr/data_download.php website. They are displayed in Figure 4.

2.4. Aim and Method of Analysis

Our aim in this paper is not to give a comprehensive discussion of what aa and Dst are intended to measure and how they manage to fulfil this objective through scalars, and over a period during much of which there were no computers. We refer once again to the “Bible,” Mayaud’s (1980) treatise on magnetic indices, for a deeper understanding of the nature of these indices. What we wish to do is to present the results of an analysis of the long aa series (and somewhat shorter Dst series) using a powerful version of SSA analysis. We

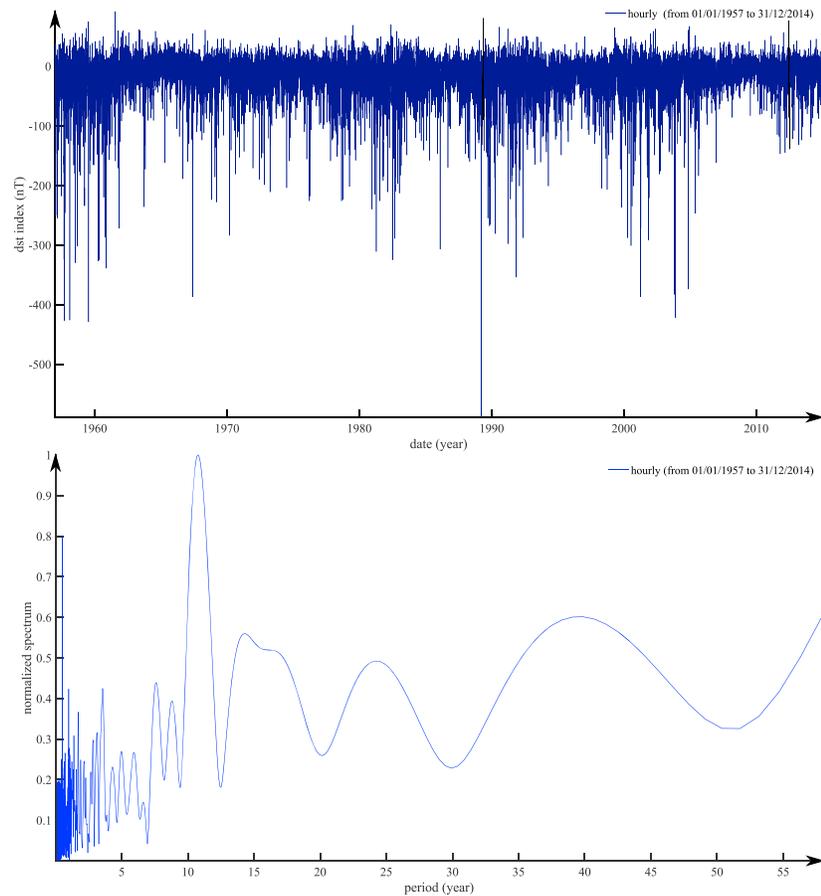


Figure 4. (top) The Dst (daily values) time series (1957–2014). (bottom) Its Fourier spectrum.

Table 1

Lists of the Successive (Pseudo-) Periods and Relative Intensities of the SSA Components (Eigenvalues) of the ISSN, PF, aa, and Dst Indices as a Function of the Rank of the Eigenvalues

Rank of comp.	ISSN ^a		PF ^b		aa ^c		Dst ^d	
1	105.2	11.53%	20.66	52.43%	108.74	0.98%	39.89	4.28%
2	89.95	8.13%	10.19	16.1%	71.82	0.57%	0.5003	1.57%
3	10.59	10.31%	8.29	10.16%	47.21	10.16%	47.28	0.78%
4	8.06	1.67%	41.05	4.24%	10.78	15.23%	10.62	2.51%
5	35.53	1.62%	31.08	3.76%	32.33	4.24%	0.9953	0.98%
6	7.97	1.31%	5.2	1.62%	21.75	3.76%	3.53	0.82%
7	21.36	1.08%	2.57	1.31%	10.62	1.78%	1.72	0.77%
8	5.3	2.94%	1.81	1.08%	12.16	0.52%	14.6	0.32%
9	6.41	1.14%	1.42	2.94%	9.18	1.08%	5.5	0.33%
10	4.74	0.45%	1.22	1.14%	0.5	1.28%	1.39	0.64%
11	3.25	0.4%	0.7693	0.45%	22.29	1.14%	5.17	0.3%
12	3.55	0.72%	0.6899	0.4%	15.56	0.45%	1.24	0.6%
13	1.05	0.98%	0.6188	0.72%	8.22	0.4%	2.14	0.59%
14	4.08	0.32%	0.5667	0.98%	9.41	0.72%	0.7165	0.57%
15	0.8816	0.9%	0.4079	0.32%	5.3	0.98%	3.16	0.56%

^a1pt/26.3hr (from 1 August 1868 to 31 December 2017). ^b1pt/17.9hr (from 1 August 1906 to 1 August 2006). ^c1pt/3hr (from 1 January 1868 to 31 December 2017). ^d1pt/1hr (from 1 January 1957 to 31 December 2014).

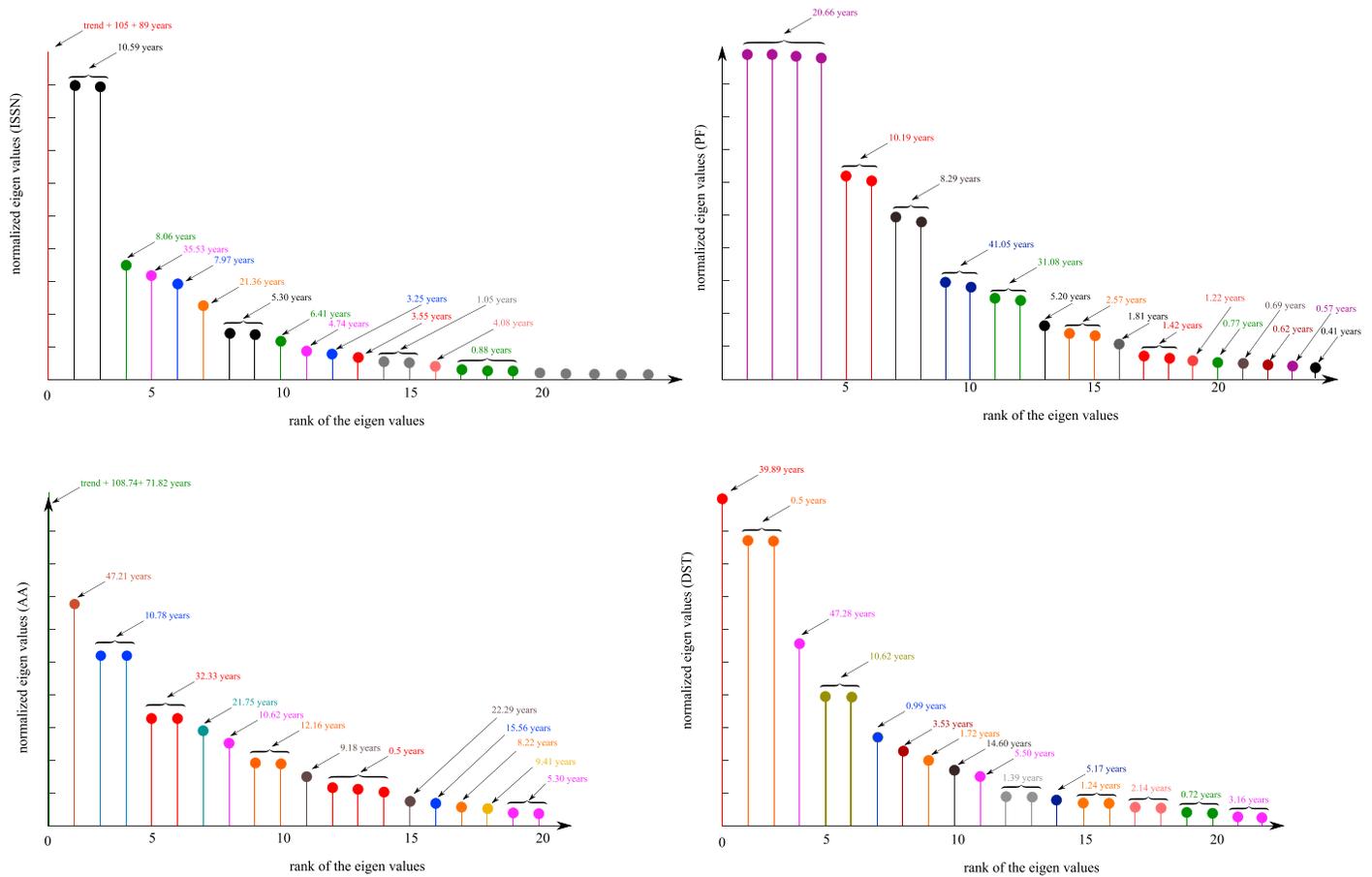


Figure 5. The SSA eigenvalues of the four series shown in the four previous figures. (top to bottom) ISSN, PF, aa, and Dst.

refer the reader to our previous analyses of some solar and terrestrial indices, with short (tutorial) explanations of the method (Le Mouél, Lopes, & Courtillot, 2019; Le Mouél, Lopes, Courtillot, & Gibert, 2019; Lopes et al., 2017). These papers also list some papers and books that are relevant to SSA. SSA allows one to separate and identify a trend and a number of pseudo-periodic oscillations, which are the main components of the series (the word trend is used in a loose sense; it encompasses periods longer than the time interval of data under study including a nonperiodic trend in the usual sense). Some of these oscillations had not been found previously (to our knowledge); they can be interpreted in relation to observed physical characteristics of solar-terrestrial relationships. Unveiling these oscillations should bring out new understanding of the nature and meaning of the aa and Dst indices.

3. SSA Analysis of aa and Dst and ISSN and PF: Results

Figure 3a represents the entire aa series over the available time span (1868–2017; 3-hourly values in the computations; monthly averages in the Figure), and Figure 3b represents its normalized Fourier spectrum. Several short period components appear on the left side of the graph, the “11-year” component being the most significant. Packets of energy with long periods of ~70 and 110 years are also important. Figure 4 provides a similar presentation of the Dst data. Table 1 lists the mean (pseudo-) periods of the SSA components of the ISSN, PF, aa, and Dst series, as a function of the rank (up to 15) of the corresponding eigenvalues, or components that are shown in Figure 5.

We illustrate the main components of aa (taken in the order of increasing rank of eigenvalues in Table 1, starting with the largest eigenvalue) and compare them with the components of the three other series. We first underline those components with periods that are shared by several indices (the half width of

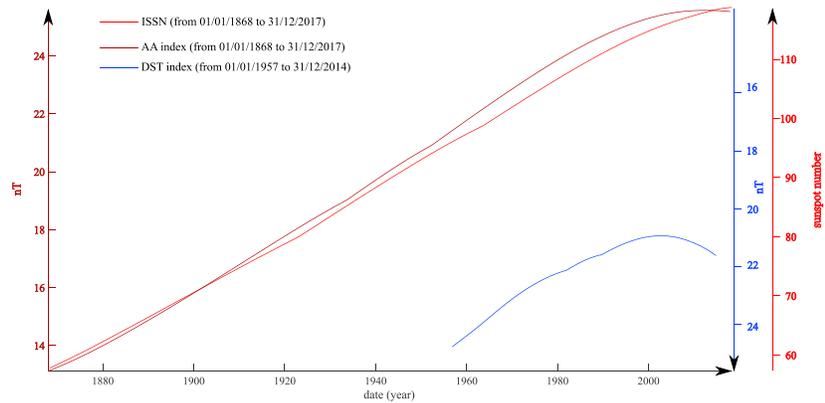


Figure 6. The SSA trends of the aa, Dst, and ISSN series.

spectral peaks at half maximum amplitude are used below as an estimate of the range of periods encompassed by a given SSA component; they are also used as an over-estimate of the uncertainties in peak spectral period).

Figure 6 represents the trends, that are the largest component of aa, ISSN, and Dst. The next SSA component for aa (rank 3) is at 47.21 ± 20 years (Table 1 and Figure 7). A similar component appears in PF at 41.05 ± 17 years (fourth rank) and Dst at ~ 47 years (third rank). It is not found in ISSN. The pseudo-periods of these components are of course long compared to the interval over which the data are available, and this results in a very small number of oscillations.

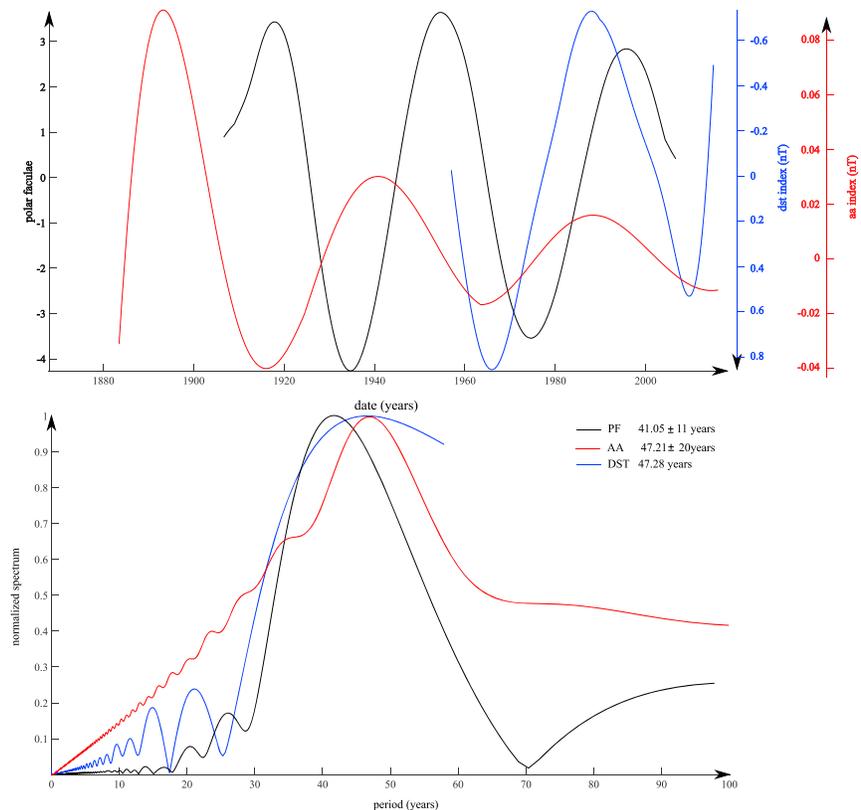


Figure 7. (top) The SSA components of the aa, Dst, and PF series near 43-year period (see text). (bottom) Their Fourier transforms.

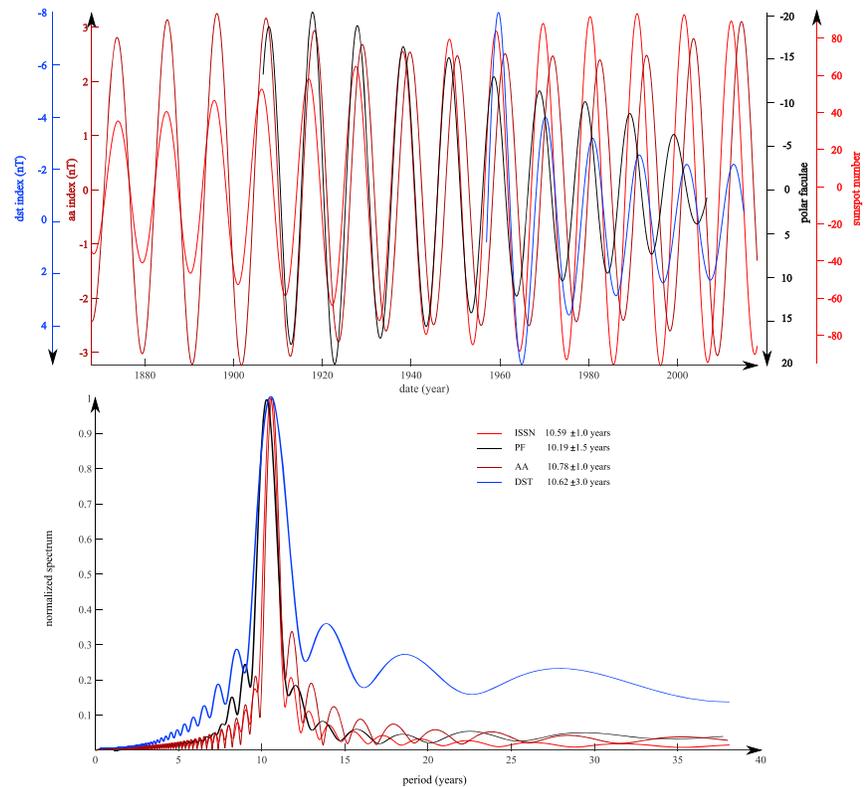


Figure 8. (top) The SSA components of the aa, Dst, ISSN, and PF series near 11-year period (see text). (bottom) Their Fourier transforms.

The 11-year component is found in all series at 10.59 ± 1.0 years for ISSN (rank 3), 10.19 ± 1.5 years for PF (second rank), 10.78 ± 1.0 years for aa (rank 4), and 10.62 ± 3.0 years for Dst (rank 4; Figure 8).

The following one is at 32.33 ± 5 years for aa (rank 5), 35.53 ± 5 years for ISSN (rank 5), and 31.08 ± 5 years for PF (rank 5), and it is not found in Dst (or it could correspond to the first eigenvalue at 39.89 years; Figure 9).

The next aa component is the 22-year “magnetic” cycle (Figure 10). It is found in all four series, 21.36 ± 1.05 years for ISSN (rank 7), 20.66 ± 1.52 years for PF (firstst rank), 21.75 ± 1.25 years for aa (sixth rank), and 20.88 ± 9.73 years for Dst (rank 19, not shown in the Table).

Finally, we note a 5.5-year component in all data series: 5.30 ± 0.30 years for ISSN (rank 8), 5.20 ± 0.30 years for PF (rank 6), 5.30 ± 0.30 years for aa (rank 15), and 5.50 ± 0.6 years for Dst (rank 9; Figure 11).

We next check which components in Table 1 have been left out of the description above. We have chosen to take as a threshold rank 15 of the SSA components, their sum comprising much of the energy in the original signals for ISSN and PF, less for aa and Dst (respectively 43.5%, 97.6%, 28.4%, and 15.6%). For aa and Dst, there is a significant amount of energy beyond rank 15. That energy at decreasing scales of time and space is the topic of another paper. For ISSN, two components are close to 8 years (ranks 4 and 6) and two around 5 and 6 years (ranks 9 and 10). For PF, five out of the six first components have been listed above: PF is almost completely reconstructed with only six components, amounting to almost 98% of the total variance. Component 3 of PF, at 8 years, is close to components 4 and 6 of ISSN. The following five are at 0.77 to 2.57 years. For aa, there are additional lines near 11 and 22 years that might be combined with the larger ones outlined above (components 7 to 9 at 10.62, 12.16, and 9.18 years, component 11 at 22.29 years) Interestingly, component 10 of aa is at precisely 6-month period, almost identical to the second component of Dst (Figure 12). In addition, for Dst, component 5 is at 1 year. Component 13 of ISSN is not far, at 1.05 year, but given our resolution this is significantly different from 1.00 year (Figure 13).

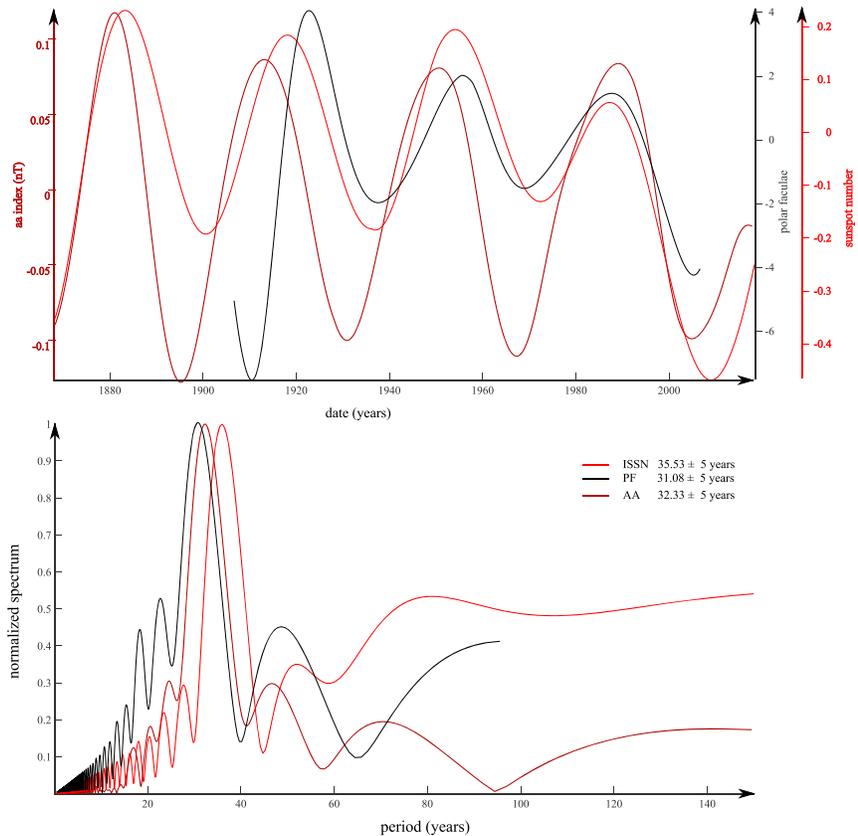


Figure 9. (top) The SSA components of the aa, ISSN, and PF series near 33-year period (see text). (bottom) Their Fourier transforms.

4. SSA Analysis of aa and Dst and ISSN and PF: Comparisons and Discussion

We now discuss further the components of aa and Dst found with SSA and the information gathered in Table 1. We compare our results with the relatively recent analysis of ISSN and aa by Prestes et al. (2006), who used multiple-taper method spectral analysis (1868–2001 annual and monthly data). With monthly data, these authors find the following (95% confidence level) periods for ISSN (133.0, 122.8, 17.7, 13.1, 8.7, 8.5, 8.3, 7.3, 5.6, 5.1, ... y) and aa (133.0, 63.8, 37.1, 17.5, 12.7, 8.7, 7.8, 7.4, 7.0, 6.0, ... y), in decreasing order of periods but without amplitudes. This can be compared with our SSA results for ISSN (105.2, 89.9, 10.6, 8.1, 35.5, 8.0, 21.4, 5.3, 6.4, 4.7, ... years) and aa (108.7, 71.8, 47.2, 10.8, 32.3, 21.7, 10.6, 12.2, 9.2, 0.5, ... years). The 21.4-year component corresponds to a single eigenvalue, not a pair, underlining that this component is far from perfect periodicity. Figure 3 of Prestes et al. (2006) displays the multiple-taper method spectra of ISSN (that they call R_z) and aa (that they write a_a). Comparison of their Figure with Figures 5–13 of the present paper shows that the SSA method provides a much more readable detection of components: for ISSN, after the long period trend, we obtain among other components the solar cycles at 10.6 and 21.4 years that are not seen among the list of Prestes et al. (2006). For aa, the first three components that form the trend are similar, but we find the solar cycle at 10.8 years (vs. 12.7) and we do find the 22-year cycle, plus an interesting component at 0.5 year. A further advantage of SSA is that it allows one to follow the evolution of the (pseudo-)period and amplitude modulation of each component (see below).

We call “trends” of aa and ISSN the sum of the two similar long-period components that appear in the spectra, at ~100 and ~80 years (first two eigenvalues; Table 1 and Figure 6); they may correspond to the ~90-year Gleissberg cycle of solar activity that does not appear clearly because of the insufficient length of the data record (Le Mouél et al., 2017). These two trends are almost identical; they increase regularly from 1868 to 1993–1994, ending with a flattening from 1993–1994 to the present. The total increase in amplitude for aa is 10 nT.

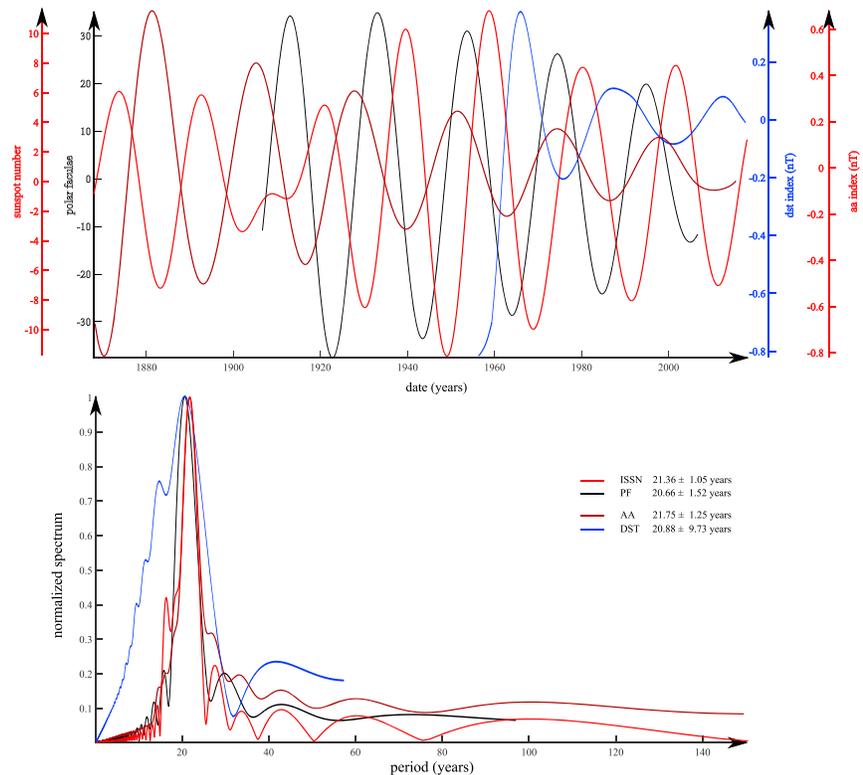


Figure 10. (top) The SSA components of the aa, Dst, ISSN, and PF series near 22-year period (see text). (bottom) Their Fourier transforms.

The most important next contribution to aa is a component at 47 years (that is also present in PF at 41 years and at 47 years with far smaller amplitude in Dst). It is not found in ISSN.

The largest component of aa is the 11-year component (Figure 8). It is shared by all four indices. Its amplitude for aa is on the order of 2.5 nT (the elongation is 5 nT, i.e., half of the trend). The 11-year components of aa and ISSN (Figure 8a) start being in phase and drift slowly, by about 3 years ($\pi/2$) in 150 years. Amplitude modulation with durations in excess of a century affect both ISSN and aa, but these modulations are not in phase and the relative amplitude for ISSN (numbers of sunspots increasing from 50 to 170) is much larger than that for aa (5 to 6 nT).

Livshits et al. (1979) have given evidence of an extended solar magnetic field and its variation with a 22-year period. Prestes et al. (2006) do not find it with annual or monthly data for the period 1868–2001. They find it only when annual averages from 1700 to 2000 are analyzed, and it is very weak. On the contrary, our SSA analysis finds a clear 22-year component and in addition a clear 5.5-year component in all four indices (Table 1). The 5.5-year component had not been found significant by Prestes et al. (2006).

The 22-year components of aa and ISSN (Figure 10a) are roughly in phase quadrature but suffer a significant phase jump around 1910. The ~5.5-year components (Figure 11a) remain in phase conjunction from beginning to end of the data interval, that is, for 150 years. Both increase in amplitude from 1868 to the late 1970s and then decrease slowly. The amplitudes of the 22- and 5.5-year components are about 1 nT (elongation is twice the amplitude).

The 22-, 11-, and 5.5-year components have been taken to be a series of harmonic terms (e.g., Prestes et al., 2006); also, for instance, components 6 and 7 of Dst at 3.53 and 1.72 years could be thought of as harmonics of the 22- or 11-year cycles ($\sim 22/6$, $\sim 22/12$). But such harmonic terms are not expected when using SSA, as the departures from exact periodicity are taken into account by the respective components: Their phases and amplitudes do not vary in unison, hence, cannot be harmonics of a fundamental period. We will call such components “pseudo-harmonics.”

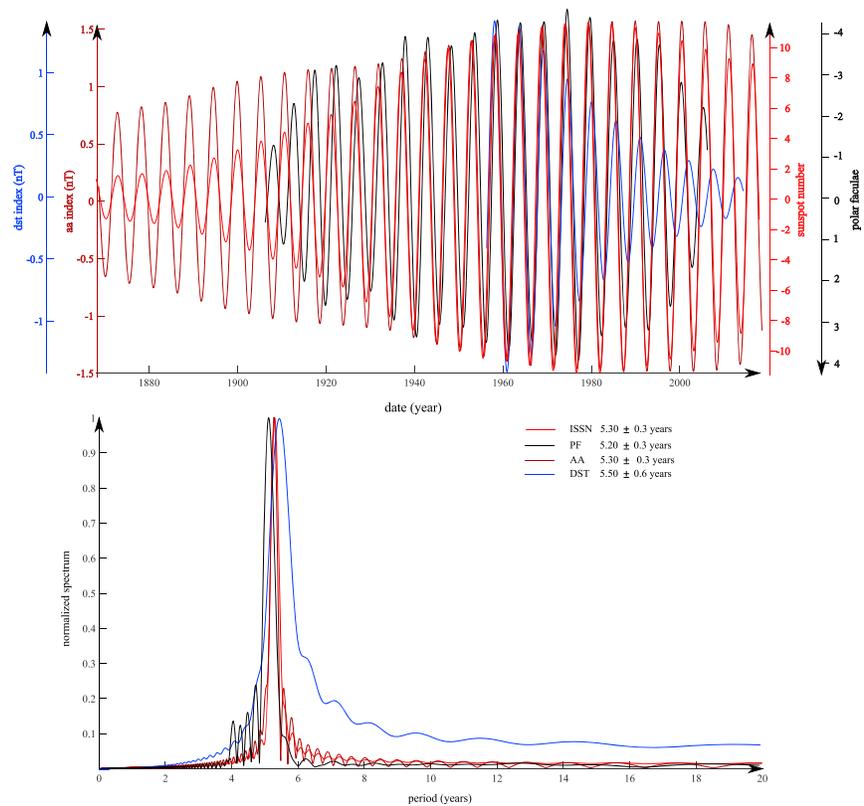


Figure 11. (top) The SSA components of the aa, Dst, ISSN, and PF series near 5.5-year period (see text). (bottom) Their Fourier transforms.

All three aa components at 22, 11, and 5.5 years (Figures 8, 10, and 11) display a long-term modulation on the order or longer than a century. The pseudo-harmonic 5.5-year component of aa (be it truly harmonic of the 11-year cycle or not) to our knowledge has seldom been mentioned in studies of aa, with the exception of Prestes et al. (2006), who consider it as a possible consequence of solar wind density variations; we have recently discovered it in a number of climatic indices (Le Mouél, Lopes, & Courtillot, 2019).

There is no doubt to us that the 22-, 11-, and 5.5-year components in aa and Dst, also prominent in ISSN and PF, have a solar origin; they are the only ones to be present and prominent in all four series we analyze in this paper. The order of importance of these various components is not the same in all series and is not expected to be: The (as yet) little known and probably complex processes by which the solar signals impact the magnetic indices may indeed be quite distinct.

For completeness, we note that Prestes et al. (2006) find a peak in aa near 4.3 years; we do not find this peak in the first 15 eigenvalues of the SSA of aa. But we agree with a component in ISSN near 4.7 years.

The aa index reflects sunspot number and solar wind parameters that have themselves solar cycle dependence. The aa index has been tied to solar wind speed and to the southward component of the interplanetary magnetic field (Crooker et al., 1977). Feynman and Crooker (1994) have used the trend in the aa index to demonstrate changes in solar wind magnetic field strength or velocity, or both, over the past century. Feynman (1982) distinguishes two separate equally strong periodic variations in 75 years of aa index data: the “traditional” 11-year sunspot cycle (that she calls the R component) and what she calls an I component, almost out of phase with R. The source of the R component would be short-lived solar events, whereas that of I would be long lived solar features such as coronal holes. The solar wind at Earth oscillates between the two. Feynman (1982) finds that these oscillations increase steadily from 1900 to 1960 and then start declining. The 11-year component of aa in Figure 8 (top) decreases from 1900 to 1980 and then increases up to the present.

Finally, we discuss the spectacular seasonal variations found in aa and Dst (Figures 12 and 13). The 1-year (365.52 ± 8.01 days) and 6-month (actually 182.67 ± 2.01 days) components in Dst (ranks 5 and 2) and the 6-

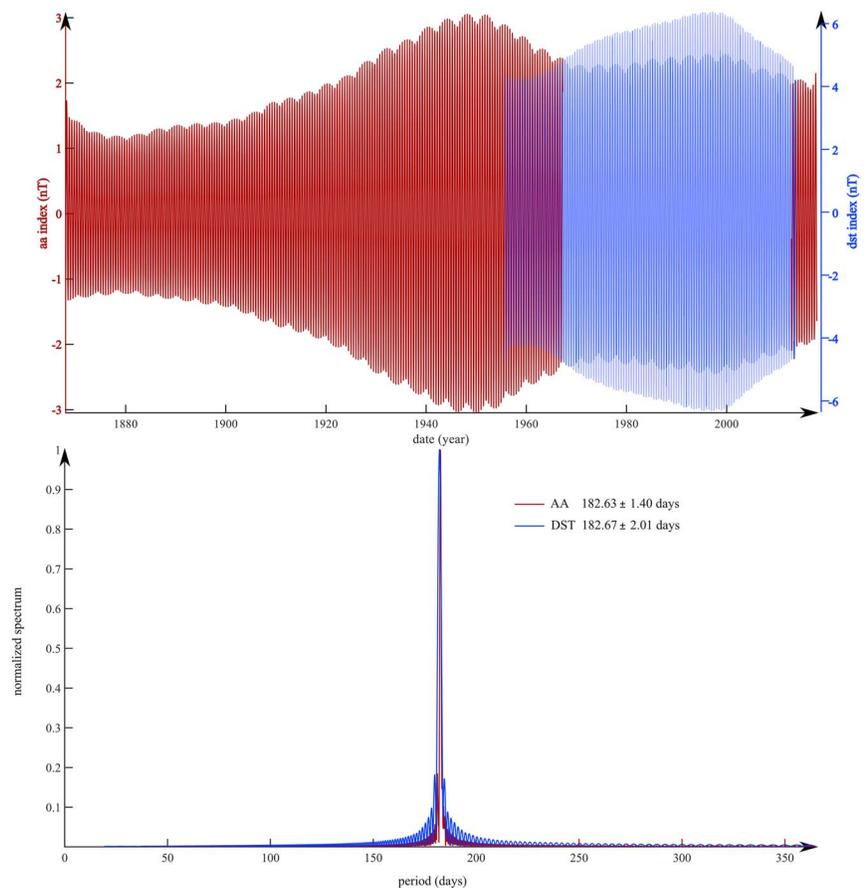


Figure 12. (top) The SSA components of the aa and Dst series at 0.5-year period (see text). (bottom) Their Fourier transforms.

month (actually 182.63 ± 1.40 days) component in aa (rank 10) are “pure,” almost Dirac-like, with precisely defined periods (Figures 12b and 13b). All have an elongation of 2 to 4 nT. These “seasonal” oscillations are linked to the revolution of Earth on its orbit around the Sun and are of course not found in the solar indices; they are terrestrial (or rather have an astronomical origin, due to the motion of the Earth’s rotation axis in the ecliptic plane), not solar in origin. The solar components have wider peak periods. Following Delouis and Mayaud (1975), we call the former “astronomical” (or “modulation” also “artificial”) periods and the latter “astrophysical” (or “excitation” also “true”) periods.

We note on Figures 12 and 13 that the envelope of the 0.5 and 1.0-year components of Dst are modulated in a similar fashion, with a fish-like shape and a maximum near 2000. And the envelope of the 0.5-year component of aa is bordered (modulated) by regular festoons with a period close to 3.6 years. This is a solar period (components 12 of ISSN and 6 of Dst), already mentioned long ago in the analysis of series of magnetic components from observatories (Courtillot & Le Mouél, 1976).

The annual and semiannual variations of geomagnetic activity were recognized early on by Cortie (1912) and Chapman and Bartels (1940). Mayaud (1980, Figure 54) was among the first to obtain a quantitative estimate of its annual variation, using a variant of the method of superimposed epochs over the time range 1957–1974. He considered that the annual variation was a permanent feature of the Dst index (Mayaud, 1978), as confirmed by our results above, not a consequence of magnetic storms but an artificial feature that could be suppressed by using a similar number of observatories in each hemisphere. Various explanations of the semiannual oscillation have been proposed over the years; quoting the first lines of a paper by Russell and McPherron (1973), these explanations “*can be divided roughly into two classes: the axial hypothesis, in which the heliographic latitude of the Earth plays a role, and the equinoctial hypothesis, in which the orientation of the Earth’s axis of rotation relative to the Earth-Sun line plays a role.*” Russell and McPherron (1973)

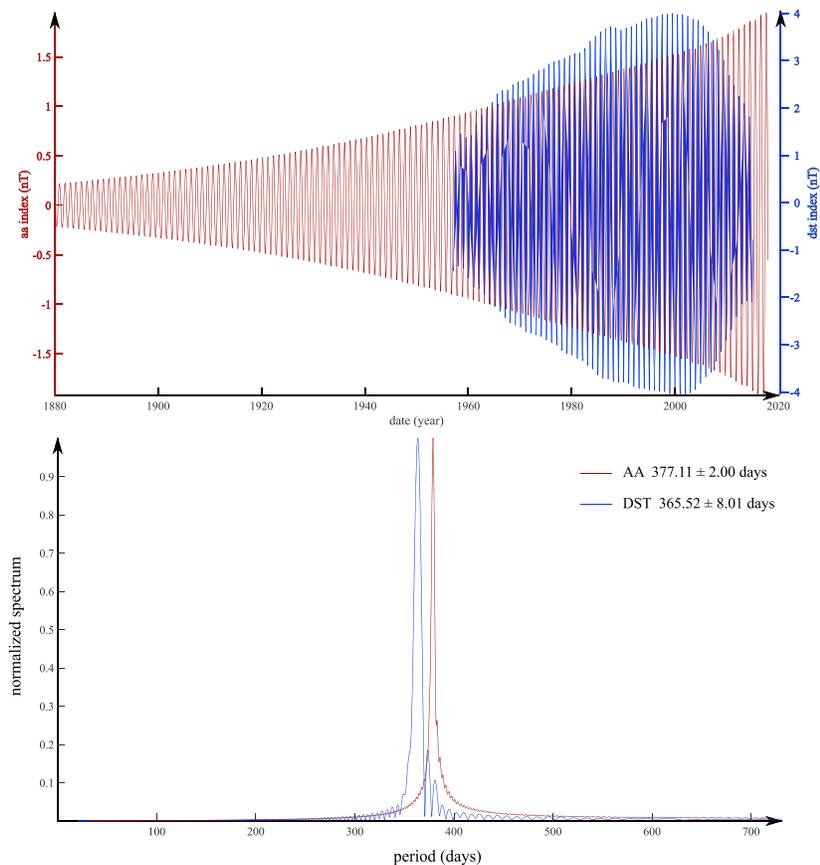


Figure 13. (top) The SSA components of the aa and ISSN series at 1-year period (see text). (bottom) Their Fourier transforms.

proposed as a third possibility that the semiannual variation of geomagnetic activity is caused by a variation in the effective component of the interplanetary field. Clua de Gonzalez et al. (1993) and Cliver et al. (2000) have shown that the three effects work together to act as modulators in the geomagnetic response to transient solar coronal mass ejections.

The base frequencies of the seasonal peaks are thus due to an astronomical mechanism. On the other hand, the envelopes of the seasonal lines represent a rather smooth, long-term variation, with modulated features that are revealed only by SSA. We attribute them to solar activity.

The above agrees with the extensive study by Malin and Isikara (1976), according to whom the 12- and 6-month variations in Dst would not be due to an average variation in the intensity of the ring current but to its variation with latitude. SSA extends these results to the present and complements them with the clear semi-annual component (rank 2, Table 1 and Figures 12a and 12b). It is therefore tempting to attribute the regular amplitude variations (modulation) that affect both components to genuine changes in the intensity of the ring current.

5. Conclusion

The aim of this study was to apply SSA in order to identify trends and quasi-periodic oscillations in the aa and Dst series of geomagnetic activity, that are monitors of solar-terrestrial interactions, affected by changes in solar activity, by travel through the interplanetary medium and impact on Earth with varying responses. aa is one of the best geophysical index series, initiated with the greatest care by P.N. Mayaud and still largely used nowadays.

The central results of the paper are encapsulated in Figure 5 that shows the SSA eigenvalues and therefore trends and oscillatory components of the four series in order of decreasing contribution and increasing rank.

The sunspot number ISSN is dominated by a trend (the Gleissberg cycle on an interval that is too short to display several waves), then a 10.6-year component, followed by a 35.5 and two ~8-year components, then the 21.4-year “magnetic” cycle and an interesting 5.3-year peak.

aa shows the same trend plus a ~47-year component, then 10.8, 32.3, and 21.8 years. There is a small but significant 6-month seasonal component.

The polar faculae PF number is dominated strongly by the 20.7-year period, followed by 10.2, 8.3, 41, and 31 years, then a 5.2 component.

Dst is dominated by a trend that is parallel to that of ISSN and aa but changes from a positive to a negative slope after the year 2000 (Figure 6). Then comes a strong 6-month seasonal component. Next are found a 47-year component, the 10.6-year component and a second seasonal line at 1 year.

The ~22-, ~11-, and ~5.5-year components are common to the four indices (except the 22-year line not found among the prominent Dst components). We call this cascade “pseudo-harmonics,” but we think that there is little doubt over the fact that these components are evidence of solar activity. The similarity of the spectra in Figures 8b (11 years), 9b (30 years), 10b (22 years), 11b (5.3 years), and 12b (6 months) is from good to remarkable. SSA has the power to represent components that vary both in instantaneous frequency and in amplitude. The evolution of the phase relationships of any two components over time can be studied in detail. An illustration is given by the remarkable phase coherency of the 5.3-year component in Figure 10 a. But the components are neither truly periodical nor exact multiples of each other, which is the reason why we call some of them pseudo-harmonics. These differences likely reflect the complex and different mechanisms that govern these indices of solar-terrestrial relationships.

Acknowledgments

We thank the two anonymous reviewers for their careful reading and useful suggestions on the original version of this paper. IGP contribution 4058. The data used in the paper are accessible at the following sites: ISSN (<http://www.sidc.be/silso/datafiles>), PF (<http://www.solar-dynamo.org/data.html>), aa (http://isgi.unistra.fr/data_download.php), and Dst (http://isgi.unistra.fr/data_download.php).

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