Geofísica Internacional (2004), Vol. 43, Num. 1, pp. 103-111

Reconstruction of the *aa* index on the basis of spectral characteristics

Echer, E., Rigozo, N. R., M. P. Souza Echer, L. E. A. Vieira and D. J. R. Nordemann
Instituto Nacional de Pesquisas Espaciais (INPE), São José dos Campos, Brazil

Received: March 31, 2002; accepted: June 19, 2003

RESUMEN

En el presente trabajo se hace un análisis espectral y una reconstrucción del índice geomagnético *aa,* usando los métodos de ondículas y de regresión iterativa (ARIST). La serie del promedio anual de *aa* (1868-1998) se descompuso en niveles de frecuencias. ARIST se aplicó a cada nivel para identificar las principales periodicidades y sus amplitudes y fases. Las frecuencias más relevantes al 95% de confianza fueron entre 2-5 años, entre 5-10 años, y alrededor de 11-12 años, 23 años, 31 años, 44 años, 100 años y 156 años. Para la tendencia a largo plazo se aplicó un ajuste lineal. Usando las frecuencias significativas, se calculó una suma de ondas sinusoidales y se añadió a la tendencia a largo plazo, con lo que se pudo recoinstruir el índice *aa*. Las series temporales reconstruidas y originales tienen un índice de correlación de r = 0.72 en el período 1868-1998. Se extendió la reconstrucción para el periodo 1800 – 2050 AD. La reconstrucción para 1800-1867 muestra valores bajos similares a los del período 1868-1920. Los valores para 2000-2050 muestran niveles de actividad geomagnética similares a los presentes, con un pequeño decremento en 2010-2025. La misma técnica fue aplicada al suavizamiento de 3 años del índice *aa* y la correlación entre la serie original y la reconstruida es de r = 0.91. Este mayor índice de correlación proviene del hecho de que se remueven las fluctuaciones de alta frecuencia; sin embargo, la tendencia a largo plazo es similar a la obtenida con las series anuales.

PALABRAS CLAVE: Índice *aa,* periodicidades, reconstrucción de *aa,* ondículas.

ABSTRACT

Spectral analysis and reconstruction of the geomagnetic activity *aa* index using the wavelet transform and an iterative regression method (ARIST) is presented. The *aa* annual average data (1868-1998) was decomposed in frequency levels using the best wavelet packet decomposition tree. ARIST was applied at each level to identify the main periodicities and amplitudes and phases. The most relevant frequencies at the 95% confidence level were found at periods between 2-5 years, between 5-10 years, and around 11-12 years, 23 years, 31 years, 44 years, 100 years and 156 years. The last level of wavelet decomposition is the long-term trend, and a linear fit was applied to this level. Using significant frequencies, a sum of sine waves was calculated and added to the long-term trend, to obtain a reconstructed *aa* index time series. The original and reconstructed *aa* time series have a correlation coefficient r = 0.72 in the period 1868-1998. The reconstruction was extended beyond the data interval, for the period 1800 – 2050 AD. The reconstructed past *aa* values (1800-1867) show low values, similar to the period 1868-1920. The forecasted values of *aa* for years 2000-2050 show geomagnetic activity levels similar to the present ones, and a small decrease in the period 2010-2025. The same technique was applied to the 3-year running average of the *aa* index and the correlation of this data with the reconstruction was higher (r = 0.91) because of the removal of high-frequency fluctuations. The long term trend of the reconstructed series is similar to the one obtained with *aa* annual averages.

KEY WORDS: *aa* index, wavelet transform, *aa* periodicities, reconstructed series.

INTRODUCTION

The solar modulation of geomagnetic activity and its corresponding effects on the Earth's atmosphere is a very well known fact. Also the 11-year solar cycle and the associated variability that it causes on the electromagnetic environment of Earth–the Geospace have largely been studied (Gorney, 1990; Kivelson and Russel, 1995; Gonzalez *et al.*, 1999).

The sunspot number has been largely used to infer about the long term variability of the solar activity. The longest time series of geomagnetic activity is the 3-hour antipodal activity index (*aa*), available since 1868 and which was defined by Mayaud (1971; 1972; 1973; 1980), to describe the characterization of the geomagnetic activity by using the K indices of two antipodal observatories. A planetary characterization may be reached because diurnal and annual variations in each hemisphere are cancelled using antipodal observatories. The *aa* index is the average of the 8 *aa* 3-hour indices of the day, similar to the Ap definition (Rostoker, 1972; Rangarajan, 1989; Menvielle and Berthelier, 1991) .

Nowadays records are available from the observatories of Melbourne in Australia and Greenwich in England. The slight changes that occurred in the sites of the antipodal geomagnetic observatories (Menvielle and Berthelier, 1991) have not affected the time series. The observatories locations were: Northern Hemisphere, Greenwich (1868-1925). Abinger (1926-1956) and Hartland (1957); Southern Hemisphere, Melbourne (1868-1919); Toolangui (1920-1979) and Canberra (1980). The invariant magnetic latitude of the antipodal observatories is about 50°.

Reconstruction of the *aa* index for a period near 500 years have been made using relations with the sunspot number (Kane, 1978; Silverman 1985). Calculations of *aa* index for specific periods, as the Maunder minimum, also have been made (Mendoza 1997; Cliver *et al.*, 1998a; 1998b). A reconstructed *aa* series for the period 1844-1880 was obtained by Nevanlinna and Kataja (1993) who have derived the *aa* series 1844-1880 using a correlation between hourly magnetic declination data at Helsinki and *aa* series.

In this work a spectral analysis using wavelet transform is made on *aa* annual averages (1868-1998). The *aa* data is broken down in frequency levels using the best wavelet packet decomposition tree and a regression model is applied using the most significant periodicities to obtain a reconstructed *aa* time series which was extended over the period 1800-2050. A similar technique was developed and used by Rigozo *et al*. (2001), in order to reconstruct the sunspot number series for a 1000 years period. A comparison with a smoothed series, the 3 year running average of the *aa* index, is also made in order to evaluate the influence of high frequencies in the reconstruction.

WAVELET ANALYSIS

The wavelet transform is a very powerful tool to analyze non-stationary signals and enables us to obtain expansions of a signal using time-localized functions – wavelets, that have good properties of localization in time and in frequency domain (Kumar and Foufola-Georgiou, 1997; Percival and Walden, 2000). The wavelet transform may be continuous or discrete.

The discrete wavelet transform may be used in multiresolution analysis, which is concerned with the study of signals or process represented at different resolutions and developing an efficient mechanism for going from one resolution to another (Percival and Walden, 2000). In this work the best wavelet packet decomposition tree was used to decompose the *aa* data in frequency levels. This method is a generalization of the wavelet decomposition and it offers a richer range of possibilities for signal analysis. In the wavelet decomposition analysis, the signal (S) is decomposed in an approximation (A) and in a detail (D). The detail contains the high-frequency part of the signal, whereas the approximation contains most of the characteristic frequencies of the signal. In the first step of the decomposition, $S = A_1 + D_1$. In a next step, the approximation itself is split in a second level approximation, $A_1 = A_2 + D_2$, and $S = A_2 + D_2 + D_1$. The most suitable decomposition of a given signal is selected on an entropy-based criterion and the process is repeated until this criterion is reached (Percival and Walden, 2000). In wavelet packet analysis, both details and approximations are split. Thus, in a first step $S = A_1 + D_1$. In a second step both approximation and detail are split, $A_1 = AA_2 + DA_2$ and $D_1 = AD_2 + DD_2$, and the signal is $S = AA_2 + DA_2 + AD_2 + DD_2$.

ITERATIVE REGRESSION ANALYSIS

It is well known from the classical spectral analysis that a quasi-stationary and quasi periodical time series could be represented by a sum of sine functions of *n* periods, expressed as

$$f(t) = \sum_{1}^{n} r_n sin\left(2\pi \frac{t}{T_n} + \phi_n\right), \qquad (1)$$

where r_n is the amplitude of the *n-th* frequency, T_n is the periodicity and ϕ_n is the phase.

In order to identify the main periodicities, its amplitudes and phase in each wavelet decomposition level, an iterative multiple regression model (Wolberg, 1967), labeled ARIST "Análise por Regressão Iterativa de Séries Temporais"- Iterative Regressive Analysis of Time Series (Rigozo and Nordemann, 1998) was used.

The ARIST method gives information on frequency, amplitude and phase as well as their standard deviation. In this work the ARIST was applied to each one of the wavelet decomposition levels and the most significant periods at 95% (amplitude higher than two times the standard deviation) were analyzed and used in the reconstruction of *aa*.

RESULTS AND DISCUSSION

The period of 1868-1998 of *aa* annual averages was used in this work. *aa* series presents some well know characteristics. Besides a cyclical variation associated to the 11-year solar cycle, the *aa* shows an increasing trend in both minima and maximum values of the cycle (Gorney, 1990). The level of the magnetic activity is much lower during minimums of low sunspot activity cycles than during minimums of high sunspot activity cycles. Whereas sunspot number returns to low values at each solar minimum, *aa* minima reflect the long-term level of solar activity revealed by cycle-averaged sunspot number. Other well known feature in the *aa* time-series is the dual peak structure (Gonzalez *et al.*, 1990; Gorney, 1990), showing a peak near sunspot cycle maximum and other in the descending phase. This second peak is caused by geomagnetic disturbances due to coronal hole fast streams, which are more frequent in this part of the solar cycle.

In Figure 1 the best wavelet packet decomposition tree for *aa* is shown. These are the decomposition levels for *aa* and they were chosen based on the entropy criterion. In this decomposition, 20 frequency levels were obtained.

As explained in the Wavelet analysis section, at a first step the signal is decomposed in an approximation (1,0) and a detail (1,1). At each node of the decomposition tree, the information to be gained by performing each split is quantified and based on entropy criterion, the decision to decompose or not the level is taken. In the second step, the approximation (1,0) was decomposed in a new approximation (2,0) and a detail (2,1), and these one were decomposed: (2,0) = (3,0) + (3,1) and (2,1) = (3,2) + (3,3), so (1,0) = (2,0) + (2,1) = (3,0) + (3,1) + (3,2) + (3, 3). This process is repeated until the last levels shown in Figure 1.

In Figures 2 and 3 the decomposition frequency levels are shown. The levels are shown in growing order of peri-

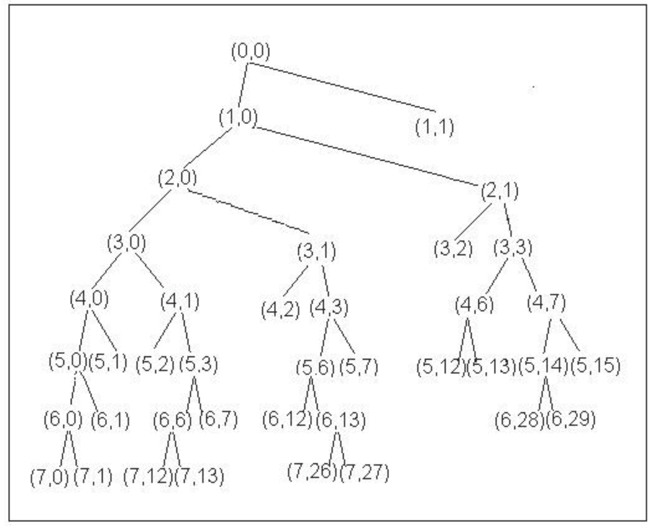

Fig. 1. Best wavelet packet decomposition tree for *aa* index annual averages (1868-1998).

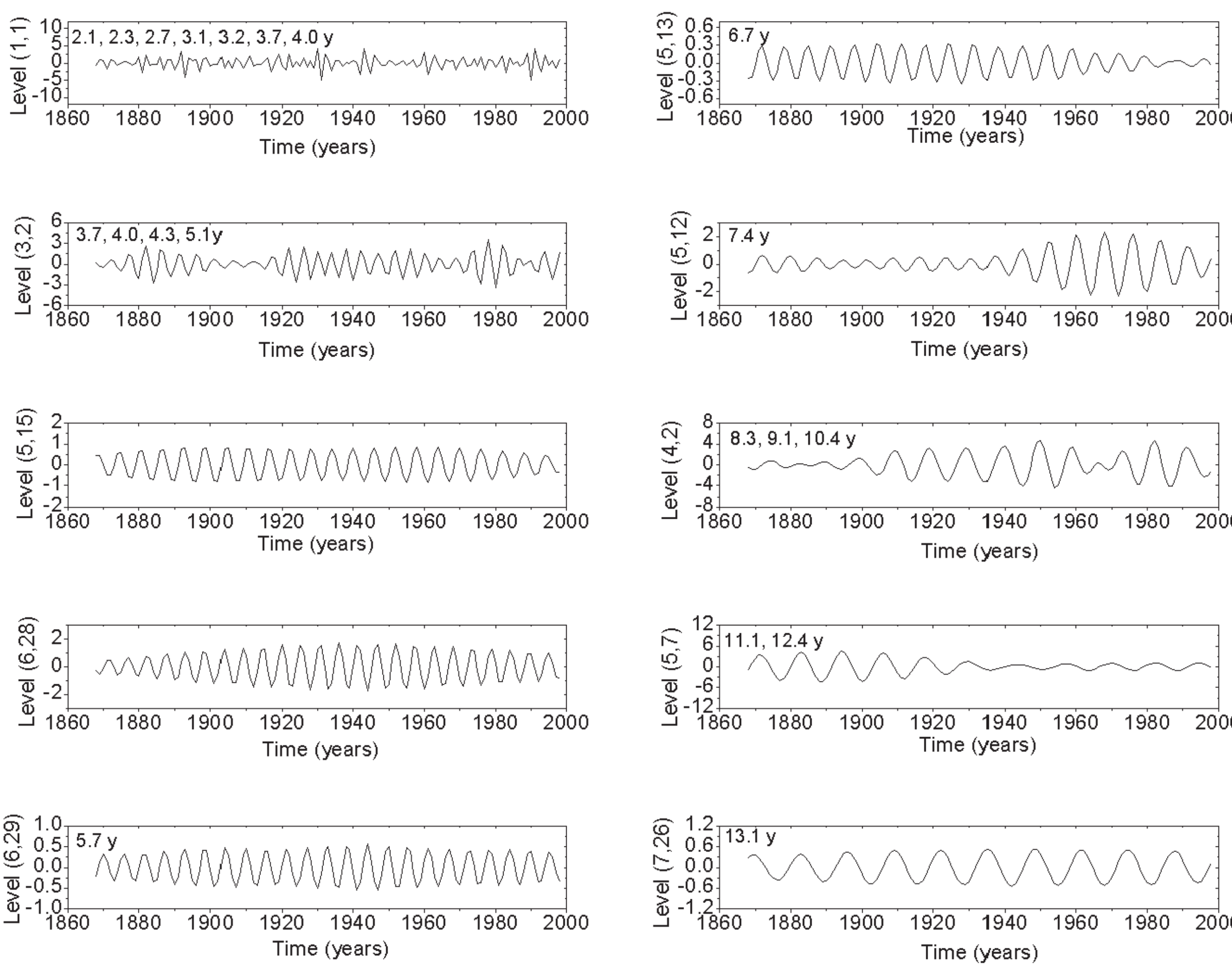

Fig. 2. Wavelet decomposition levels of *aa*. Levels (1,1), (3,2), (5,15), (6,28), (6,29), (5,13), (5,12), (4,2), (5,7) and (7,26).

ods. In Figure 2 the levels (1,1), (3,2), (5,15), (6,28), (6,29), (5,13), (5,12), (4,2), (5,7) and (7,26) are shown. In Figure 3 the levels (7,27), (6,12), (6,7), (7,13), (7,12), (5,2), (5,1), (6,1), (7,1) and (7,0) are shown.

After the determination of frequency levels, the ARIST method was applied to each one and the statistically significant periods (95%) were selected. These periodicities are shown in the upper part of each panel in Figures 2 and 3. For the last level, (7,0), the so-called scaling level, proportional to the average of the series (Percival and Walden, 2000), a linear fit was applied and the correlation coefficient of this fit was r = 0.99.

The 11-year related solar cycle signal has a set of periods between 8-14 years, with one at 11.10 years. It is also observed that there is a band of periodicities in the high frequency part of spectrum, between 2 to 5 years. Among them, a period near 4 years is observed, which has been found in several geomagnetic acitivity indices spectral analysis (Fraser-Smith, 1972; Delouis and Mayaud, 1975; Clúa de Gonzalez *et al.*, 1993; Rangarajan and Iyemori, 1997) and it is not present in the sunspot number (solar) spectrum (Clúa de Gonzalez *et al.*, 1993). This period is supposed to be caused by the dual-peak structure in the *aa* index (Clúa de Gonzalez *et al.*, 1993) and this dual-peak distribution could be caused by the fact that the distribution of intense magnetic storms has a separation of about 3-4 years (Gonzalez *et al*, 1990). An alternative explanation is that this 4-year periodicity could be caused by a similar periodicity in the high-speed streams associated with sector boundary passages (Rangarajan and Iyemori, 1997).

The solar magnetic cycle is also observed with a period of 24 years. The existence of this cycle has been questionable (Cliver *et al.*, 1996) and whereas it has been found in spectral analysis by some authors (Currie, 1973, Courtillot *et al.*, 1977), others have not been able to detect it (Fraser-

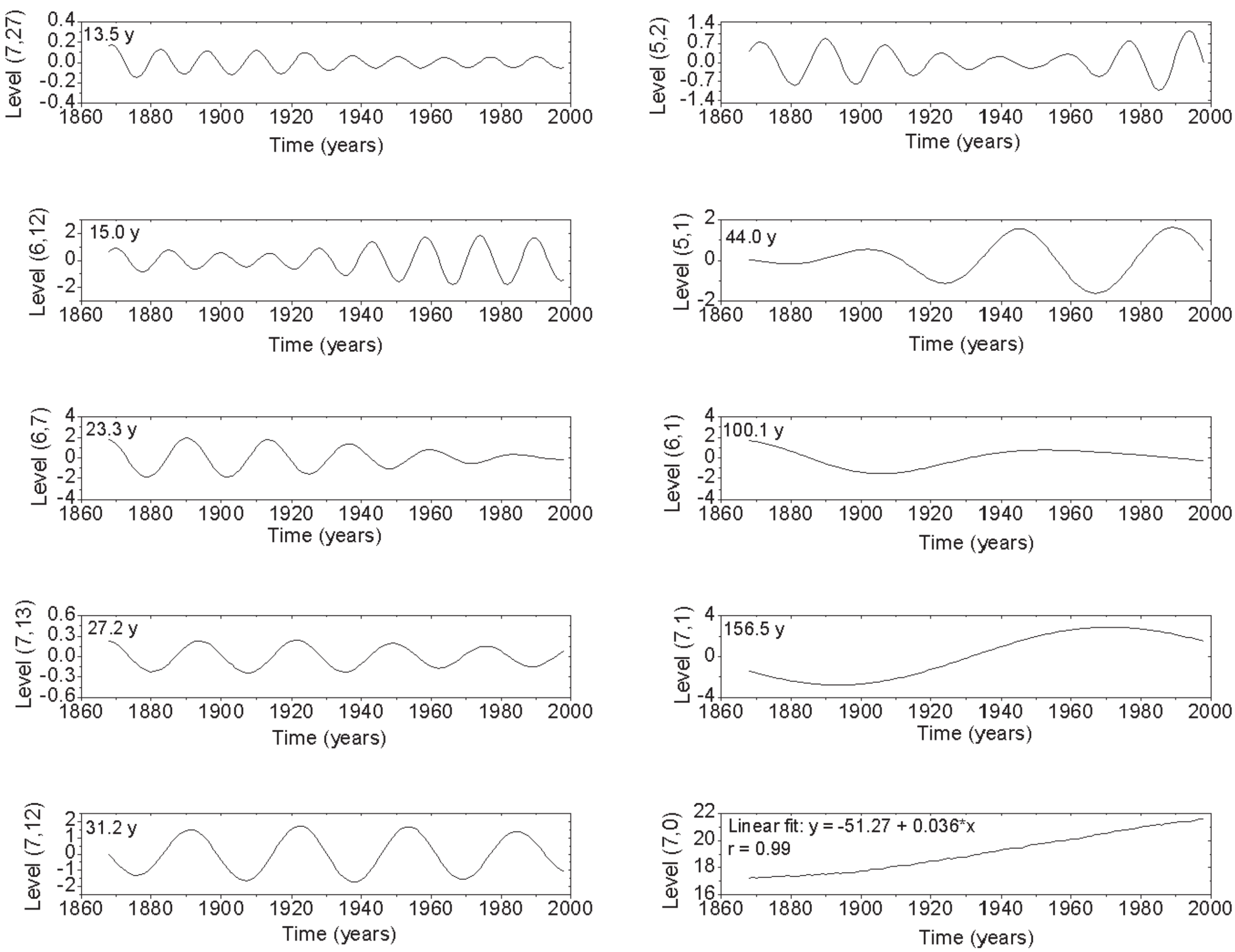

Fig. 3. Wavelet decomposition levels of *aa*. Levels (7,27), (6,12), (6,7), (7,13), (7,12), (5,2), (5,1), (6,1), (7,1) and (7,0).

Smith, 1972; Delouis and Mayaud, 1975; Clúa de Gonzalez *et al.*, 1993). Longer periods are observed around 31, 44 years, 100 and 156 years.

Periods near 30 years that were found in this work also have been found in other spectral analysis (Fraser-Smith, 1972; Delouis and Mayaud, 1975; Clúa de Gonzalez *et al.*, 1993; Rangarajan and Iyemori, 1997).

Longer periods were found in this work (100 and 156 years) because the wavelet filtering have isolate long-term trends and the ARIST method has the ability to detect sinusoidal variations even when a full period is not present (ARIST can fit a part of a sine wave signal).

The periods statistically significant shown in Figures 2 and 3 were used in Equation 1 to obtain the reconstructed *aa* time series. In Figure 4 the original (continuous line, period 1868 1998) and reconstructed (dotted line, period 1800-2050) *aa* index time series are shown in the upper panel. The correlation coefficient of both series (original and reconstructed) for 1868 1998 is r = 0.72, what indicates that the reconstruction explains about 50% of the series, and it indicates that the reconstruction describes reasonably the general behavior of *aa*. However, the observed disparities on several occasions could be expected on the basis that only 50% of the variance between the two series is explained by the linear fit.

In the lower panel the relative difference between the two series is shown, the dotted lines indicates the levels of ± 25% and the dashed line the levels of ± 50%. About 75% of the data points have a relative error lower than 25% and about 97% have a relative error lower than 50%, what is expected because of the correlation explain only 50% of the variance. In some ocassions high deviations are observed.

In Table 1 the statistics of both time series is presented, average, standard deviation and relative deviation (100* stan-

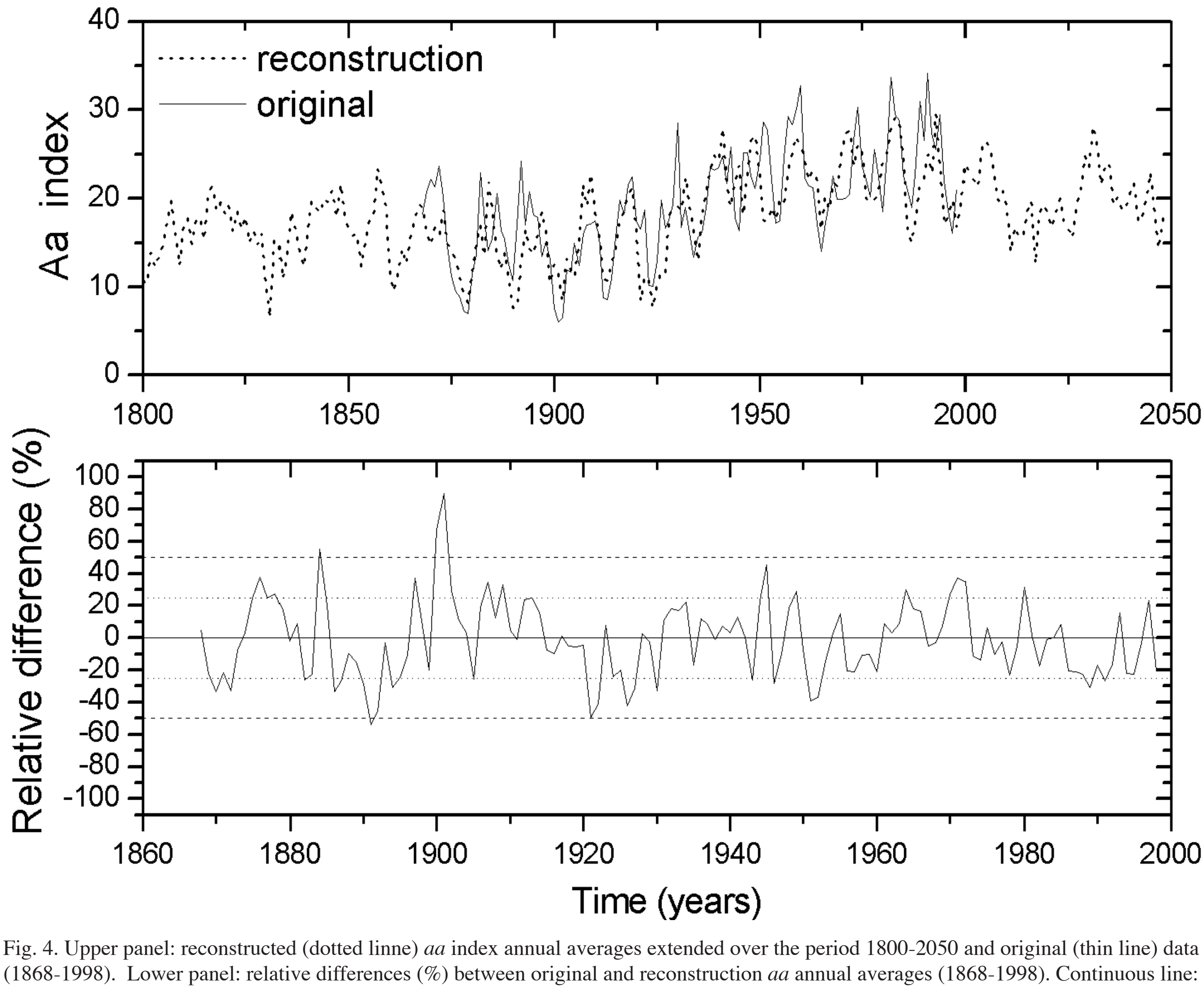

Fig. 4. Upper panel: reconstructed (dotted linne) *aa* index annual averages extended over the period 1800-2050 and original (thin line) data (1868-1998). Lower panel: relative differences (%) between original and reconstruction *aa* annual averages (1868-1998). Continuous line: 0%, dotted line: ± 25%, dashed line: ± 50%.

Table 1

Statistics of reconstructed and original *aa* index annual average time series

1868-1998	*aa* original	*aa* reconstructed
Mean	19.29 nT	18.32 nT
Standard deviation	6.08 nT	5.41 nT
(sd/mean)*100	31.51%	29.53%

dard deviation/average) for the whole period. It is seen that the average and standard deviation are similar, and the relative deviations are near 30%.

In the work of Rigozo *et al*. (2001), the reconstruction of the sunspot number series using a sum of sine waves resulted in a better correlation with original data than the one obtained in this work for *aa* series. Such results were obtained because the sunspot number series is more uniform, and a sum of sine waves could describe better it than the more irregular *aa* series. Feynman (1982) has shown that the *aa* index can be decomposed in two parts, one dependent only on solar activity/sunspot number and the other an excess over the observed linear trend. Rangarajan *et al*. (1998) have also shown that *aa* can be decomposed in a part dependent on sunspot number and that the residual is expressed by using 12 components. The smaller number of components needed for *aa* series dependent on sunspot number is consistent with the reconstruction of sunspot number with fewer components obtained by Rigozo *et al*. (2001).

It was observed by Rigozo *et al*. (2001) that this technique (wavelet + ARIST) gives good results in terms of long-term trends and averages for long periods. In some individual cases, however, a large deviation between original data and the reconstruction can be observed. As this sum of sine waves is data fit, it would be expected that some of data points could not be accurately described by the function. However, it seems that, for the objective to study the long term behavior of a time series, this technique could give significant and interesting results.

The reconstructed past *aa* values (1800-1867) have shown low values, similar to the period 1868-1920. The forecasted values of *aa* for years 2000-2050 show geomagnetic activity levels similar to the present ones, with a small decrease in the period 2010-2025.

Cliver *et al*. (1998b) analyzing recent *aa* data suggests that the long-term component of solar forcing will level off or decline during the solar cycle 23. It is observed in our reconstruction that *aa* levels in the future (2000-2050) are similar to the present ones, which is in agreement with the forecast of Cliver *et al*. (1998b). They forecast that geomagnetic minimum between cycles 23 and 24 (2007) will not exceed the value of 18.6 nT (1996 minimum) and 1987 minimum (19.0 nT). Our result forecast a minimum in the *aa* for 2008 of 19.7 nT.

RECONSTRUCTION USING A SMOOTHED *aa* SERIES

In order to verify if the reconstruction could be affected by biased annual *aa* values because of severe storms that sporadically could occur in a specific year, the same reconstruction technique was performed using the 3-year running average of the *aa* index. The best wavelet packet decomposition tree (not shown) was determined for this smoothed series similarly as for the *aa* index annual averages. The main difference between the two wavelet decomposition trees was that in the 3-year running average series the detail (1,1) is decomposed itself in sub-levels. Applying ARIST to these frequency levels, only periods higher than 3 year were found to be statistically significant (95%), as expected. The removal of these periods resulted in a correlation better than the one obtained with annual averages; the correlation coefficient between original and reconstructed 3-year running averages was $r = 0.91$ (80% of the variance is explained by this correlation against only 50% in the annual averages).

In Figure 5 the original (continuous line, period 1868-1998) and reconstructed (dotted line, period 1800-2050) 3-year running average of the *aa* index are shown in the upper panel. In the lower panel the relative difference between the two series is shown, the dotted lines indicates the levels of ± 25% and the dashed line the levels of ± 50%, as in Figure 4. Almost all data points have a relative error lower than 25% (only 4 points have deviations higher than 25%). In Table II the statistics of both time series is presented, average, standard deviation and relative deviation for the whole period. It is seen that the average and standard deviation are much more similar than the ones for annual averages (Table I). The relative deviation is about 28%, similar to the one of annual averages (30%).

Table 2

Statistics of reconstructed and original *aa* index 3-year running average time series

1868-1998	*aa* original	*aa* reconstructed
Mean	19.29 nT	19.09 nT
Standard deviation	5.46 nT	5.32 nT
(sd/mean)*100	28.30%	27.87%

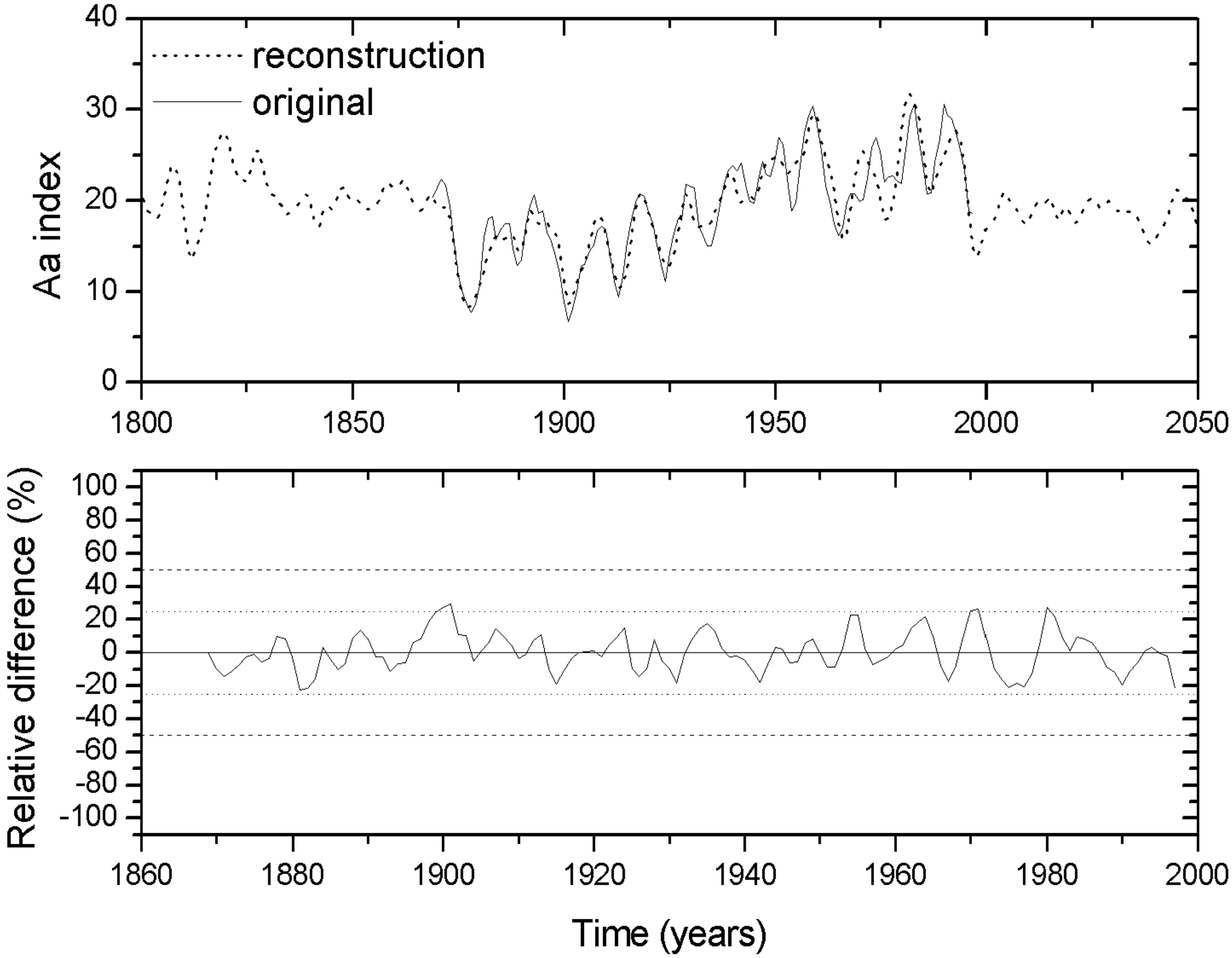

Fig. 5. Upper panel: reconstructed (dotted linne) *aa* index 3-year running averages extended over the period 1800-2050 and original (thin line) data (1868-1998). Lower panel: relative differences (%) between original and reconstruction *aa* 3-year running averages (1868 1998). Continuous line: 0%, dotted line: ± 25%, dashed line: ± 50%.

The general trend of both reconstructions is similar, both showing lower values until 1920-1930, an increase in geomagnetic activity from this period by around 2000 and a level-off and a slight decline for the period 2000-2050. A major difference is observed in the period 1800-1850, when the values of the 3-year running average reconstructed series are higher than the annual average reconstruction by about 30%, whereas in the remaining of the period the difference is of about 10%.

CONCLUSIONS

A spectral analysis of the *aa* index (1868-1998) was made in this work. The *aa* data was decomposed using the best wavelet packet decomposition tree in frequency levels. In every level the ARIST method was applied and the most significant periodicities were observed in the band 2-5 years, 8-14 years, and frequencies at 22, 33, 44, 100 and 156 years, besides a long-term trend. The reconstructed *aa* was then calculated, giving a correlation coefficient of $r = 0.72$ with original data. The reconstruction was calculated to the period 1800-2050. In the past reconstructed, 1800-1867, geomagnetic activity levels were low, similar to the period 1868-1920 (observed). The reconstructed 3-year running average of the *aa* index shows a better correlation with data ($r = 0.91$) because of the removal of high-frequency oscillations. The long-term trend of both reconstructions is similar, and the forecasted geomagnetic activity shows similar values to the present ones, which could imply that the long-term increase trend in the *aa* observed in the last century may be leveled off or declining.

ACKNOWLEDGEMENTS

Thanks to Fundação de Amparo a Pesquisa do Estado de São Paulo (FAPESP) for: doctorate fellowship (project number 98/04732-4); research support (project number 99/03625-2). Thanks to Conselho Nacional de Desenvolvimento de Científico e Tecnológico (CNPq), for doctorate fellowship (project number 140373/2000-4); productivity in research fellowship (project number 300031/94-7). Thanks to Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) for doctoral fellowship.

BIBLIOGRAPHY

CLIVER, E. W., V. BORIAKOFF and K. H. BOUNAR, 1998. The 22-year cycle of geomagnetic and solar wind activity. *J. Geophys. Res., 101,* 27091-27110.

CLIVER, E. W., V. BORIAKOFF and K. H. BOUNAR, 1998a. Geomagnetic activity and the solar wind during the Maunder Minimum. *Geophys. Res. Lett, 25,* 897-900.

CLIVER, E. W., V. BORIAKOFF and J. FEYNMAN, 1998b. Solar variability and climate change: Geomagnetic *aa* index and global surface temperature. *Geophys. Res. Lett., 25,* 1035-1038.

CLÚA DE GONZALEZ, A. L., W. D. GONZALEZ, S. L. G. DUTRA and B. T. TSURUTANI, 1993. Periodic variation in the geomagnetic activity: a study based on the Ap index. *J. Geophys. Res., 98,* 9215-9231.

COURTILLOT, V., J. L. LE MOUEL and P. N. MAYAUD, 1977. Maximum entropy spectral analysis of the geomagnetic activity index *aa* over a 107-year interval. *J. Geophys. Res., 82,* 2641.

CURRIE, R. G.,1973. Geomagnetic line spectra – 2 to 70 years, Astrophys. *Space Sci., 21,* 425 438.

DELOUIS, H. and P. N. MAYAUD, 1975. Spectral analysis of the geomagnetic activity index *aa* over a 103-year interval. *J. Geophys. Res., 80,* 4681-4688.

FEYNMAN, J., 1982. Geomagnetic and solar wind cycles, 1900-1975. *J. Geophys. Res., 87,* 6153-6162.

FRASER-SMITH, A. C., 1972. Spectrum of the geomagnetic activity index Ap. *J. Geophys. Res., 77,* 4209-4220.

GONZALEZ, W. D., A. L. C. GONZALEZ and B. T. TSURUTANI, 1990. Dual-peak cycle distribution of intense geomagnetic storms. *Planet. Space Sci., 38,* 181-187.

GONZALEZ, W. D., B. T. TSURUTANI and A. L. CLÚA DE GONZALEZ, 1999. Interplanetary origin of geomagnetic storms. *Space Science Reviews, 88,* 529-562.

GORNEY, D. J., 1990. Solar cycle effects on the near-Earth space environment. *Rev. Geophys., 28,* 315-336.

KANE, R. P., 1978. Predicted intensity of the solar maximum. *Nature, 274,* 139-140.

KIVELSON, M. G., and C. T. RUSSEL, 1995. Introduction to Space Physics, Cambridge University Press.

KUMAR, P. and E. FOUFOULA-GEORGIOU, 1997. Wavelet analysis for geophysical applications. *Rev. Geophys., 35,* 385-412.

MAYAUD, P. N., 1971. Une mesure planétaire d'activité magnétique basée sur deux observatoires antipodaux, *Ann. Geophys. 27,* 67.

MAYAUD, P. N., 1972. The *aa* indices: A 100-year series characterizing the magnetic activity. *J. Geophys. Res., 77,* 6870.

MAYAUD, P. N., 1973. A hundred year series of geomagnetic data, 1868-1967, indices *aa,* storm sudden commencements, IAGA Bull. 33, Int. Union of Geod. and Geophys., Publ. Off., Paris.

MAYAUD, P. N., 1980. Derivation, Meaning, and Use of Geomagnetic Indices, Geophysical monograph 22, American Geophysical Union.

MENDOZA, B., 1997. Geomagnetic activity and wind velocity during the Maunder minimum. *Ann. Geophysicae, 15,* 397-402.

MENVIELLE, M. and A. BERTHELIER, 1991. The K-derived planetary indices: description and availability. *Rev. Geophysics, 29,* 415-432.

NEVANLINNA, H. and E. KATAJA, 1993. An extension of the geomagnetic activity index series *aa* for two solar cycles (1844-1868). *Geophys. Res. Lett., 20,* 2703-2706.

PERCIVAL, D. B. and A. T. WALDEN, 2000. Wavelet Methods for Time Series Analysis, Cambridge University Press.

RANGARAJAN, G. K., 1989. Indices of Geomagnetic Activity. *In:* Jacobs, J. A., Geomagnetism V. 3, 323-384, Academic Press Limited.

RANGARAJAN, G. K. and T. IYEMORI, 1997. Time variations of geomagnetic activity indices Kp and Ap: an update. *Ann. Geophysicae, 15,* 1271-1290.

RANGARAJAN, G. K., B. D. KADAM and S. ALEX, 1998. Prediction of geomagnetic activity: a novel approach. *Revista Geofisica, 48,* 67-76.

RIGOZO, N. R. and D. J. R. NORDEMANN, 1998. Iterative regression analysis of periodicities in geophysical record time series. *Rev. Bras. Geofis., 16,* 151-158.

RIGOZO, N. R., E. ECHER, L. E. A. VIEIRA and D. J. R. NORDEMANN, 2001. Reconstruction of Wolf Sunspot Numbers on the Basis of Spectral Characteristics and Estimates of Associated Radio Flux and Solar Wind Parameters for the Last Millennium. *Solar Physics, 203,* 179-191.

ROSTOKER, G., 1972. Geomagnetic Indices. *Rev. Geophys. and Space Physics, 10,* 935-950.

SILVERMAN, S. M., 1986. Magnetic activity and solar wind velocity at and preceding solar minimum for the past 500 years. *J. Geophys. Res., 91,* 10157-10161.

WOLBERG, J. R., 1967. Prediction Analysis, D. Van Nostrand Company.

Echer, E., N. R. Rigozo, M. P. Souza Echer, L. E. Vieira and D. J. R. Nordemann

Instituto Nacional de Pesquisas Espaciais (INPE)
POB: 515 – CEP: 12201-970
São José dos Campos, Brazil
Fax: +55-12-3945 6810
Email: ezequiel@dge.inpe.br,
rodolfo@dge.inpe.br,
mariza@dge.inpe.br
eduardo@dge.inpe.br
nordeman@dge.inpe.br