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MULTIWAVELET ANALYSIS OF THREE-COMPONENT GEOMAGNETIC PULSATIONS DATA: APPLICATION TO SEARCH OF POLARIZATION OF HYDROMAGNETIC WAVES

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ABSTRACT

In this paper, the polarization parameters of geomagnetic pulsations recorded during a large geomagnetic storm on March 24, 1991 are calculated using the multiwavelet transform and the Singular Value Decomposition (SVD). Through the first right-singular vector and the singular values, obtained from SVD of the multiwavelet eigenspectral matrix we determined the polarization parameters of the hydromagnetic waves in the time-frequency domain. The results showed that this method is a powerful tool to detect pulsations events mixed to noise with high degree of polarization allowing determinate the polarization parameters continuously in both time and frequency. The fine continuous structure of time-frequency domain of spectral and polarization parameters is suitable to distinguish regular and irregular pulsations that have wide spectral band and short-lived time complex waveforms. The multiwavelets polarization method demonstrated have particular importance to localize polarized pulsations events that is associated to the coherent sources of MHD mode propagation waves in the magnetosphere, mailing during magnetic storms.

1. INTRODUCTION

The geomagnetic pulsations, also called as ULF waves, are generated by plasma instabilities in the Earth’s magnetosphere [1], have been studied by a wide variety of methods to determine their spectral and polarization characteristics [3,4,5,10]. The geomagnetic pulsations series can be have a complex time-frequency behavior containing multi-scale (multi-frequency) and short-lived waveforms in time. The traditional move-window of discrete Fourier transforms (DFT) has the same time-resolution for all frequencies that is an uncomfortable restriction for analysis of pulsations records, which are a composite of signals of varying durations and frequency contents [7]. The wavelet method is an appropriate technique to time-frequency analysis of signals that have short-lived transient components, with features at different scales or are nonstationary. In this paper, we adapt an algorithm based in multiwavelet spectral analysis proposed by Lilly and Park [2] and polarization analysis presented by Samson [3-5], to detect coherent signals mixed to noisy, and to estimate the polarization parameters of waves. The multiwavelets are a set of special functions derived from an optimization condition to have appropriated concentration in time and frequency domain. They are closely related to the prolate spheroidal functions [6] that are the foundation of the multitaper spectral method of Thomson [7]. We present results of the application of this method to analysis of a non-stationary geomagnetic pulsations time series obtained from a large geomagnetic storm in March 24, 1991.

2. MULTIWAVELETS POLARIZATION ANALYSIS

The approach used in this work incorporates concepts from diverse topics as wavelets transform [8], multitaper spectral and polarization analysis [9], multiwavelets spectral and polarization analysis [2] and polarization analysis in function of frequency [3-5]. The work of Slepian [8] and Thomson [7] introduced a new approach to finding finite time functions with their energy concentrated in a frequency band. These functions have been applied in a range of techniques commonly referred to as multitaper and multiwindow methods [9]. Recently, Lilly and Park [2] developed a generalization of this approach, as a wavelets function designed to concentrate energy within a frequency range defined by a center frequency f_c and a bandwidth $2f_w$. This wavelets are real discrete time series w_m with M samples and sampling rate Δt, designed to have optimal band-limiting properties. A given choice of frequency resolution associated to the time-bandwidth product $p_w = f_w M \Delta t$, and number-of-cycles associated to the time-bandcenter product $p_c = f_c M \Delta t$, describes a family of mutually-orthogonal "Slepian" wavelets that can be used for the cross-correlation of multi-component pulsation times series. Since this wavelets occur as even and odd pairs, with similar frequency localization and 90° out of phase, they can be combined into complex function $w^{(j)} = \left[w_e^{(j)} + i w_o^{(j+1)} \right] / \sqrt{2}$, where $w_e^{(j)}$ is the jth even wavelet and $w_o^{(j+1)}$ is the jth odd wavelet. The Slepian wavelets are mutually orthogonal, so that the transforms using different wavelets are statistically independent when evaluated at identical time-frequency points.

Lilly and Park [2] used an SVD and the Slepian multiwavelets to detect seismic waves in three-component seismograms. On the geomagnetic ground data, there are three-component with N grid-points that contribute to the multiwavelet transform matrix $\mathbf{M}(f_c, n\Delta t)$. The kjth element of this matrix represent the multiple wavelet transform of the kth complex Slepian wavelet with the jth data series $x^{(j)}(n\Delta t), n = 0,1,\ldots,N-1$, or multiwavelet transform at each point. The SVD of matrix $\mathbf{M}(f_c, n\Delta t)$ is $\mathbf{M} = \mathbf{U} \cdot \mathbf{D} \cdot \mathbf{V}^H$, where $\mathbf{U}$ is a $K \times K$ unitary matrix, $\mathbf{V}^H$ is a 3×3 matrix of mutually orthogonal rows, and $\mathbf{D}$ is a $K \times 3$ diagonal matrix. The superscript H denotes Hermitian conjugate. The first three diagonal elements of $\mathbf{D}$, denoted by $d^{(j)}, j = 1,2,3$ are the singular values of $\mathbf{M}$, with $d^{(1)} \geq d^{(2)} \geq d^{(3)} \geq 0$. The columns of $\mathbf{U}$ and $\mathbf{V}$ correspond to, respectively, eigenvectors $\hat{\mathbf{u}}^{(j)}$ of $\mathbf{M} \cdot \mathbf{M}^H$ and the three nontrivial eigenvectors $\hat{\mathbf{v}}^{(j)}$ of $\mathbf{M}^H \cdot \mathbf{M}$. The $\hat{\mathbf{u}}^{(j)}$ and $\hat{\mathbf{v}}^{(j)}$ are the left and right complex singular vectors of $\mathbf{M}$, respectively. The wavelet estimator of the time-varying spectral density matrix $\mathbf{S}(f,t)$ mentioned by Park et al. [9] is $\hat{\mathbf{S}}(f_c, t) = 2\mathbf{M}^H \cdot \mathbf{M}$, where K is the number of complex wavelets used. Therefore, the $\hat{\mathbf{v}}^{(j)}$ are the singular vectors of spectral density matrix $\hat{\mathbf{S}}$. The right-singular vector $\hat{\mathbf{v}}_1$ associated with the largest singular value is identified as the principal polarization or polarization vector, and the relative phases of its complex components determine the ellipticity and azimuth angles of the polarization of wave.

Samson [3-5] calculated the polarization parameters of ULF waves through the eigenvalues and eigenvectors of the spectral density matrix $\hat{\mathbf{S}}$. In our case, this is equivalent to find the singular values $d^{(j)}$ and the singular vectors $\hat{\mathbf{v}}^{(j)}$ of matrix $\mathbf{M}$

by SVD. A measure of degree of polarization $\beta(0 \le \beta \le 1)$ have been suggested for evaluating the amounts of polarization in multichannel data and it is calculated through singular values $d^{(j)}$ [3,4]. When the wave is unpolarized $\beta \to 0$ and when $\beta \to 1$ the wave is a pure state or purely polarized, which the polarization vector $\hat{\mathbf{v}}^{(j)}$ representing the state polarization of wave. The degree of polarization represents the ratio of polarized power to total power. The polarized power or purely polarized power of the waves is calculated through β and $d^{(j)}$[3]. The geometric interpretation of the complex components of polarization vector $\hat{\mathbf{v}}^{(j)}$ allow us to obtain the polarization parameters of the wave, such as: ellipticity ε and azimuth angle θ, and relative phase ϕ between components [9]. The ellipticity is defined as the ratio of the minor to major axis of the polarization ellipse, that can vary $-1 \le \varepsilon \le 1$. The polarization ellipse is linear when $\varepsilon \to 0$ and circularity when $\varepsilon \to \pm 1$. The sense of polarization is given by sign of ε and is right-handed or clockwise when ε is positive and left-handed or counter-clockwise when ε is negative, when looking into the propagating wave. In the case of ULF waves, the positive (negative) sign of corresponds to the left-handed (right handed) polarization, when viewed in the direction of the main field in the northern hemisphere [1,10]. Other important parameter in the investigation of ULF waves is the horizontal azimuth angle θ, that describes the orientation of the major axis of the polarization ellipse in the horizontal plane, and is defined as the angle between the major axes of the polarization ellipse and the geomagnetic north, counted positive (negative) from north toward east (north to west) [3-5,10].

3. GEOMAGNETIC PULSATIONS ANALYSIS

The multiwavelet polarization method was used to analysis of three-component magnetic pulsations time series recorded in a large magnetic storm that happened on March 24, 1991. This data were measured by a ground-based fluxgate magnetometer-system at geomagnetic station localized in Santa Inez, Brazil (geographic latitude $\phi = -3.60^{\circ}$, geographic longitude $\lambda = 314.61^{\circ}$, $dip = 2.07^{\circ}$). The Figs. 1a-b shows the band-pass 180-900 s (Pc5 band) filtered data in H (north-south) and D (east-west) components recorded at Santa Inez on March 24, 1991. Because of low power in the Z (vertical) component a simplified analysis of H and D components ($n = 2$) was done.

The two-component temporal series with 1440 points and sampling interval of 60 s, were submitted to multiwavelets polarization analysis. Our analysis uses three complex Slepian wavelets with $p_w = 2$ and $p_c = 10$. The results of the polarization parameters estimate at each point in the time-frequency plane are plotted in function of time and periodicity in the Figs.1c-d and Figs.2a-c. In this figures the abscissa is local time (LT=UT-3 hs) and ordinate is the periodicity in seconds. The analysis involves 40 spectral lines with periods since 180 up to 1200 s.

The Fig.2c shows clearly the existence of high polarized power density (PPD) regions simultaneous to high amplitude of pulsations that appear in the filtered H and D signals. There is an increase of PPD in hours between 00:00 and 03:00 LT, 04:00 and 06:00 LT; and between 16:00 and 18:00 LT. These wave packages are shown more located in the time with wide spectral band in periodicity centered around 600, 400, and 600 s, respectively. These events that have complex waveform variability are called of impulsive or irregular pulsation, which have high PPD, accompanied of degree of polarization above 70% (Fig.1c), in almost the whole spectral band. Close to 08:00 and 11:00 LT there is a very well defined event with more regular waveform, when the PPD is maximum in a narrow spectral band centered close to 600 s. This band is accompanied of degree of polarization above 70% in the whole spectral band (Fig. 1d, characterizing a regular pulsations event.

Reliable estimations of the ellipticity, azimuth angle may be obtained if the degree of polarization exceeds 70% accompanied of high PPD in the same spectral band [10]. The polarization parameters maps that appear in the Figs. 2a-c show regions with identical structures to high degree of polarization and high PPD regions. The four events mentioned above satisfy this approach and the Figs 2a-b show that this pulsations present small ellipticity and azimuth, with small significant variation during daytime. The ellipticity presents generally small values, showing absolute values smaller than 0.3, implies in predominantly linearity of polarization waves. The azimuth shows generally small values too, indicating that the major axes of polarization ellipse are mainly aligned in the north-south direction. The event between 08:00 to 11:00 LT it presents azimuth predominantly negative values up to -50°, indicating that the major axes of ellipse slightly inclined for the northwest quadrant. The relative phase between the components (Fig. 2c) shows predominantly larger values than -100° in the events above mentioned. However, a change of relative phase to larger positive values than

100° can be seen in the intermediary events between 04:00 to 06:00 LT and 08:00 to 11:00 LT.

6. CONCLUDING REMARKS

It can be seen that the wavelet analysis offers a fine-structure picture of pulsations waveform behavior in both time and periodicity, allowing distinguish the events of regular and irregular pulsations. Our analysis involving synthetic signals and geomagnetic pulsations during the magnetic storm, demonstrated that the multiwavelet polarization method of detects successfully the waves package with high degree of polarization being desirable to determine the progressive variation of ellipticity, azimuth and relative phase between components, exhibiting them continuously in the time-frequency domain. The results are comparable to those obtained from traditional methods, but the multiwavelets polarization analysis allows a superior control over the time and periodicity (frequency) resolution. The continuous multiwavelets analysis for polarizations parameters is useful to progressive study of MHD mode propagation waves in the magnetosphere, mailing to the irregular pulsations with complex waveforms.

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REFERENCES

[1] J. C. Samson, Geomagnetic pulsations and plasma waves in the Earth's magnetosphere. In: J. A Jacobs, Geomagnetism. London: Academic Press, 1991.

[2] J. M. Lilly, J. Park, Multiwavelets spectral and polarization analysis of seismic records. Geophysical Journal International,122 (1995) 1001-1021.

[3] J. C. Samson, Descriptions of the polarization states of vector process: applications to ULF magnetic field. Geophysical Journal Royal Astronomical Society, 34 (1973) 403-419.

[4] J. C. Samson, J. V. Olson, Some comments on the description of polarization states of waves. Geophysical Journal Royal Astronomical Society, 61 (1980) 115.

[5] J. C. Samson, Pure states, polarized waves, and principal components in the spectra of multiple, geophysical times-series. Geophysical Journal Royal Astronomical Society, 72 (1983) 647.

[6] D. Slepian, Prolate spheroidal wave functions, Fourier analysis, and uncertainty - V: The discrete case. Bell System Technical Journal, 57 (1978) 1371-1430.

[7] D. J. Thomson, Spectral estimations and harmonic analysis. Proc. IEEE, 70 (1982) 1055-1096.

[8] P. Kumar, E. Fouíoula-Georgiou, Wavelets analysis for geophysical applications. Review of Geophysics 35 (1997) 385-412.

[9] J. Park, F. L. V ernon, C. R. Lindberg, Frequency dependent polarization analysis of high-frequency seismograms. Journal of Geophysical Research, 92 (1987) 12664-12674.

[10] C.W. S. Ziesolleck, F. R. Fenrich, J. C. Samson, D. R. McDiarmid, Spatial characteristics of low-latitude Pc3-4 geomagnetic pulsations. Journal of Geophysical Research, 198 (1993) 197-207.

Figure Captions

Figure 1 – Multiwavelet polarization analysis of H (a) and D (b) pulsations signals obtained from Santa Inez on March 24, 1991. Graphics (c) and (d) represents the time-periodicity domain plot of polarized power density and degree of polarization, respectively.

Figure 2 – Time-periodicity domain plot of ellipticity (a), azimuth (b) and relative phase (c) obtained from multiwavelet polarization analysis of H and D signals showed in Fig.3.

Figures

Figure 1

Figure 2