STATISTICAL AND SPECTRAL TOOLS FOR ANALYSING OF DISTURBANCE OF GEOMAGNETIC FIELD

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ABSTRACT

In this paper, we performed the wavelet and statistical analysis for the geomagnetic data recorded in the Geomagnetic Surlari Observatory with acquisition periodicity of 0.5 seconds to 1 minute. We have selected several recording periods in the cases of solar quiet day variation, solar disturbance daily variation and geomagnetic storm periods.

For wavelet analysis, I used MATLAB and compared the answer for the used of different mother functions at different levels.

The rapid sampling rate allowed us to highlight micro pulsations and pulsations with periods of time between 2 seconds (minimum detection limit for a discreet signal with a sample interval of 0.5 seconds) and 10 minutes (in the case of Pc5 class pulsations and irregular pulsations from the class Pi3).

Also, we highlighted the continuous pulsations from classes Pc2, Pc3 and Pc4, as well as irregular pulsations from classes Pi1 and Pi2.

In order to identify the periodicities of more than one hour, to half-day and one day periods, we used a series of data for at least 4 days, sampled at 1 minute.

For studying the geomagnetic field morphology in the periods before geomagnetic perturbations, we have developed a series of programs to highlight the associated phenomena of geomagnetic sub-storms and storms.

Keywords: *disturbance of geomagnetic field, wavelet, spectral analysis, MATLAB*

INTRODUCTION

Traditional geomagnetic measurements in observatories lead to the knowledge of the geomagnetic field, which define its direction and the intensity of its elements after certain directions.

The geomagnetic elements are: 1) magnetic declination D, represented by the angle between projection on the horizontal of the field and the north direction, 2) magnetic inclination I, i.e. the angle between the total field direction and its projection on the horizontal plane and 3) horizontal component H, the projection of the total magnetic field F on the horizontal plane.

Also, can be used in the geomagnetic observatory records, the following changes: declination changes ΔD, variations of the horizontal and vertical component, ΔH and ΔZ.

Usually, are recording three orthogonal elements: North component (X), east component (Y) and vertical component downward (Z), that are performed by means of devices, based on magnetic induction, as so type fluxgate magnetic sensors.

These parameters vary depending on the location of the observation point on Earth. Reported to a local reference system, defined by the horizontal and the north direction, i.e. to the tri-rectangular axis system oriented in the directions north, east and vertical (downward), the geomagnetic field is determined without ambiguity, if are known three geomagnetic elements: either two angles and the total intensity (or the intensity of a component of it), or two components of the intensity and an angle, or the intensity of three components.

For measuring declination and inclination of the geomagnetic field in absolute terms, to establish the base level of permanent records, usually are used fluxgate magnetometers mounted on a nonmagnetic theodolite and for the absolute total magnetic field are used proton precession magnetometers [1], [2].

ANALYSIS METHODS OF GEOMAGNETIC FIELD

In many papers we present several applications, examples and results of the statistical and spectral methods of analysis of the geomagnetic data [3].

For this purpose, we used methods and algorithms as a numerical derivation in time, polynomial regression, correlation factor determination, spectral analysis and wavelet analysis. With these algorithms, we have been developed work's program sequences in MATLAB [4], [5], [6] and Auto Signal [7] to study the geomagnetic field morphology and to determine the spectrum of geomagnetic phenomena at different time intervals.

Through derivation on time, the removal of periodic components is achieved and geomagnetic disturbances are clearly highlighted.

Another way of processing the data we used was a spectral analysis of the signals. Through spectral analysis performed with Fast Fourier Transform, a temporal signal is decomposed into real and complex parts. This transform provides a complete spectre of the frequencies that make up the signal, but it does not keep any information as to when these occur.

The Fourier series is a linear combination of mono-frequential signals and describes the behavior of the original signal in time and frequency. It highlights the temporal evolution of the signal and its frequency content. If we apply direct Fourier transform to a signal is obtained the spectral function of the signal (spectral characteristic), which is a signal parameter. The spectral function is a complex quantity, which can be continuous or discrete, periodic or no periodic.

If the spectral function is discrete is called complex amplitude spectrum and characterization sizes in polar coordinates are called amplitude spectrum, respectively phase spectrum.

Even if the signal is periodic but the time window isn't chosen to be a multiple of the signal period (an integer number of periods), the spectral function obtained may be distorted. This may occur where signal acquisition isn't adapted to the signal periodicities or where periodicities of the signal purchased are not known.

If the time window is chosen correctly then the actual virtual sequence coincides with the infinite duration signal, otherwise the virtual signal is distorted compared the real signal. Using a time window for signal processing is equivalent to the filtering problem, but the goal is to mitigate potential discontinuities at the end of finite segment of the data evolution over time.

In order to achieve the best possible accuracy, the spectral window used (Fourier transform of the time window) must satisfy the following basic requirements:

• main lobe of the window should be very narrow;

• main lobe contains most of the window energy;

• the energy of the secondary lobes must be evenly distributed between them

Generally, these three requirements cannot be met by any window because the first two requirements are contradictory. From this point of view, we can say that there is no optimal window, each providing a compromise between the three requirements.

Bartlett temporal window provides a strong suppression of side lobes of the corresponding spectral window, however, increases the width of the main lobe and reduces its amplitude.

The Hamming time window provides a stronger suppression of the side lobes and minimizing the main lobe amplitude for the chosen frequency.

A large time window leads to a good resolution in frequency, but a low resolution in time domain (narrowband spectrogram) and a short time window determine a good location in time, but a poor frequency resolution (broadband spectrogram).

If the assessment of the power spectrum is based on direct application of Fourier transform followed by mediation, then we deal with the averaged periodogram. Mediation is usually done by dividing the signal into a variable number of segments, possibly overlapping, followed by Fourier transform calculation of all these segments (average for minute, hourly or daily of the geomagnetic signals).

Given the need for high-performance signal analysis, many variations of spectral analysis of this type have been developed, generally called periodograms. Thus, one of the most popular periodograms mediated assessment procedures is attributed to Welch, who is a modification of the original segmentation scheme, developed by Bartlett.[4]

Modern approaches of spectral analysis are designed to overcome some of the distortions produced by traditional methods and are very effective especially for short segments of analysis.

According to the Heisenberg uncertainty principle, is not possible to accurate and simultaneous localization in both the time domain and frequency domain.

Wavelet analysis preserves the information in the time domain and those in the frequency domain. A discussion about wavelets begins with Haar wavelet, the first and simplest. The Haar wavelet is discontinuous, and resembles a step function. It represents the same wavelet as Daubechies db1,that we used in our examples. The Daubechies wavelets *dbN*, where db is the “surname” of the wavelet and *N* is the order , are a family of orthogonal wavelets defining a discrete wavelet transform. The family of Daubechies wavelets have the property of linear phase, which is needed for signal and image reconstruction. By using two wavelets, one for decomposition and the other for reconstruction instead of the same single one, many properties are derived. Its are characterized by a maximal number of vanishing moments for some given support. With each wavelet type of this class, there is a scaling function (father wavelet) which generates an orthogonal multiresolution analysis.

Function *wt = cwt(x)* returns the continuous wavelet transform of *x*. The input, *x* is a real- or complex-valued vector with double-precision, or a single-variable sampled with equal equidistance, that must have at least four samples. The minimum and maximum scales are determined automatically based on the wavelet's energy spread in frequency and time. If *x* is real-valued (respectively, complex-valued) *wt* is a 2-D matrix (respectively, 3-D matrix) where each row (respectively, 2-D matrix) corresponds to one scale. The column size of *wt* is equal to the length of *x*.

In this paper we refer to methods of analysis of geomagnetic records and especially to the wavelet method for the analysis of disturbance of geomagnetic field. We also performed a wavelet analysis that gives us additional information on the relationship between frequency and time of occurrence. Based on complex analyses, where wavelet analyses are of particular importance, predictions of major geomagnetic disruptions can be made [8], [9], [10].

EXPERIMENTAL RESULTS

In our example, we used the data recorded at the Surlari Geomagnetic Observatory at a frequency of 2Hz to identify correlations occurring between the high-frequency oscillations of the geomagnetic field components over 4 days (2018, August 24, 00:00:00 to August 28, 00:00:00). We used in Fourier and wavelet analysis 691200 samples at 2 Hz sampling rates or 5760 samples at 0.0166 Hz sampling rates, where we can view the predominant frequencies for each point and can be a distinguished range of frequencies.

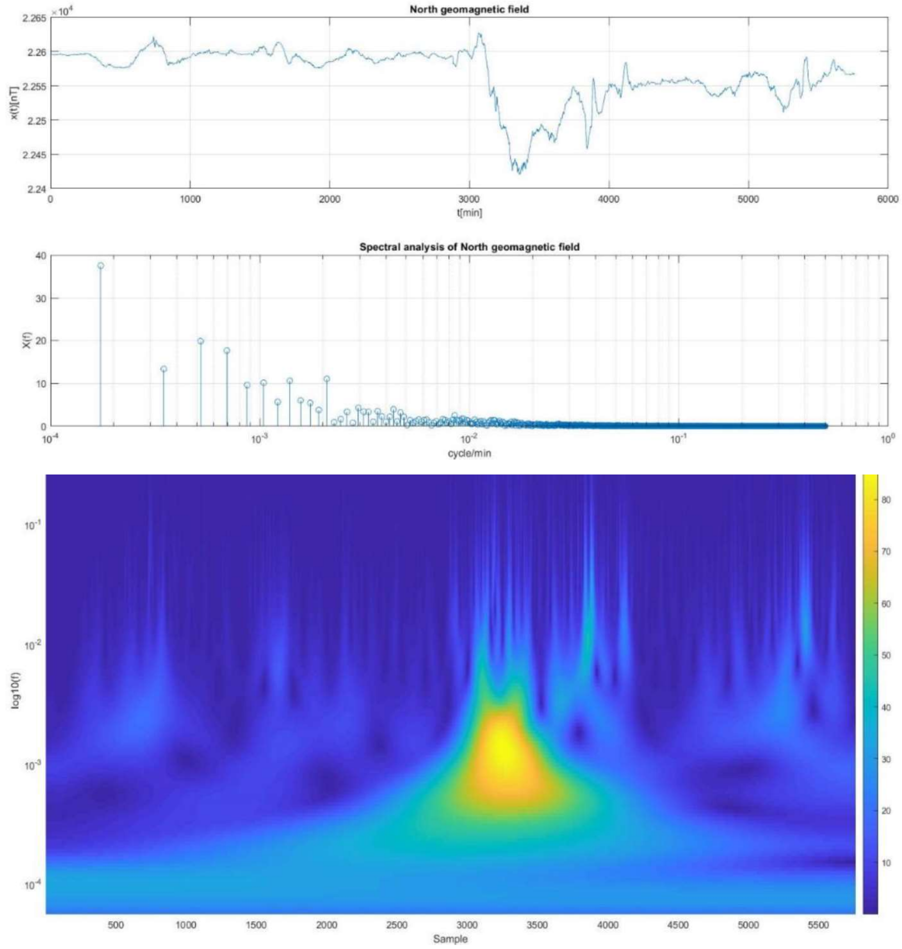

Fig.1 – Time series (up), spectral analysis (middle) and wavelet analysis (down) for North geomagnetic field, with sampling rates 0.0166 Hz (1-minute period).

The values on the scale determines the compression of wavelet. The lower scale are correlates better with high frequencies. Small scale coefficients of continuous wavelet transform CWT highlight the fine features of the input signal. Increasing the scale values of scale allow highlight low frequency content of the signal.

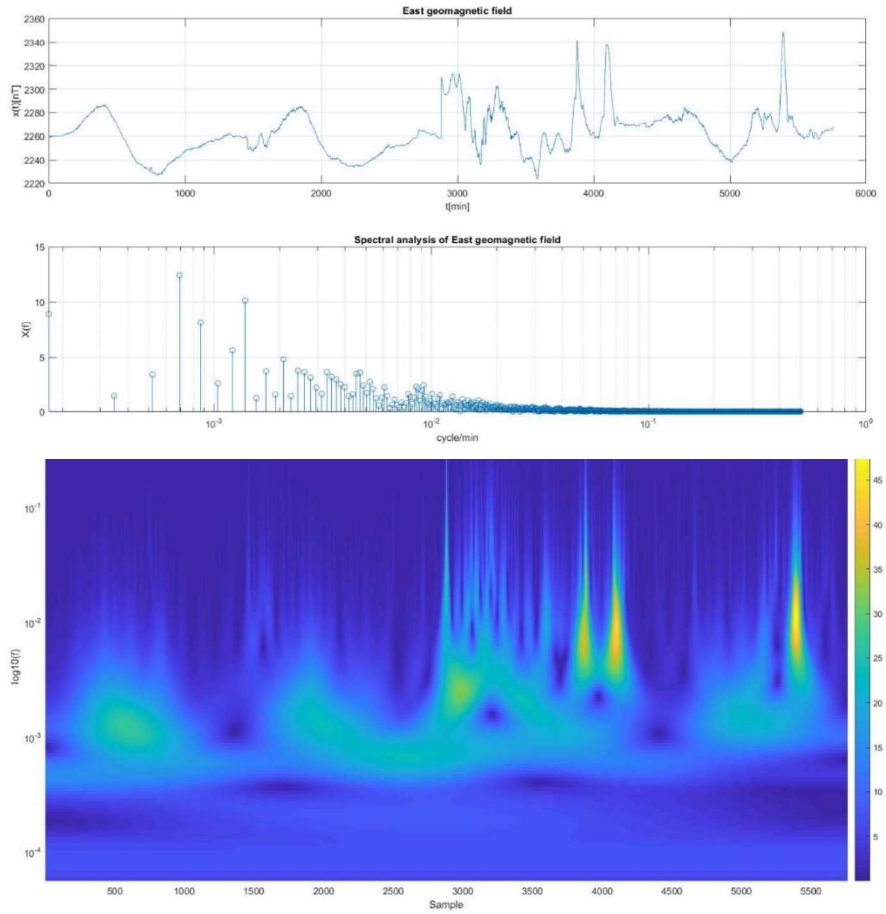

Fig.2 - Time series (up), spectral analysis (middle) and wavelet analysis (down) for East geomagnetic field, with sampling rates 0.0166 Hz (1minute period).

In fig. 1-4, we used for Fourier analysis the MATLAB code:

```
load table.txt; X1= table (:,1); X2= table (:,2); X3= table (:,3); N=length(X1); t=1:1:N; fe=1/N; x=X1'; Xt=fft(x); Xm=abs(Xt); X=Xm(1,1:N/2+1)/(N/2); f=[0:N/2]*fe; subplot(211); plot(t,x); grid; xlabel('t[min]'); ylabel('x(t)[ ]'); title(' '); subplot(212); stem(f,X); xlabel('f[o.5Hz]'); ylabel('X(f)'); grid; title('')
```

Also, for wavelet analysis we used function Daubechies db1, the same wavelet as Haar, with following code:

```
load table.txt; SX=table(:,1); signal = SX; lev   = 5; wname = 'db1'; nbcol = 64; [c,l] =wavedec(signal,lev,wname);len = length(signal); cfd = zeros(lev,len); for k = 1:lev; d = detcoef(c,l,k); d = d(:)'; d = d(ones(1,2^k),:); cfd(k,:) = wkeep1(d(:)',len); end

cfd =  cfd(:); I = find(abs(cfd)<sqrt(eps)); cfd(I) = zeros(size(I)); cfd   = reshape(cfd,lev,len); cfd = wcodemat(cfd,nbcol,'row'); h211 = subplot(2,1,1);
```

h211.XTick = []; plot(signal,'r'); title('Analyzed signal.'); ax = gca; ax.XLim = [1 length(signal)]; subplot(2,1,2); colormap(cool(128)); image(cfd); tics = 1:lev; labs = int2str(tics'); ax = gca; ax.YTickLabelMode = 'manual'; ax.YDir = 'normal'; ax.Box = 'On'; ax.YTick = tics; ax.YTickLabel = labs; title('Discrete Transform, absolute coefficients.'); ylabel('Level'); figure;[cfs,f] = cwt(signal,1,'waveletparameters',[3 3.1]); hp = pcolor(1:length(signal),f,abs(cfs)); hp.EdgeColor = 'none'; set(gca,'YScale','log'); xlabel('Sample'); ylabel('log10(f)');

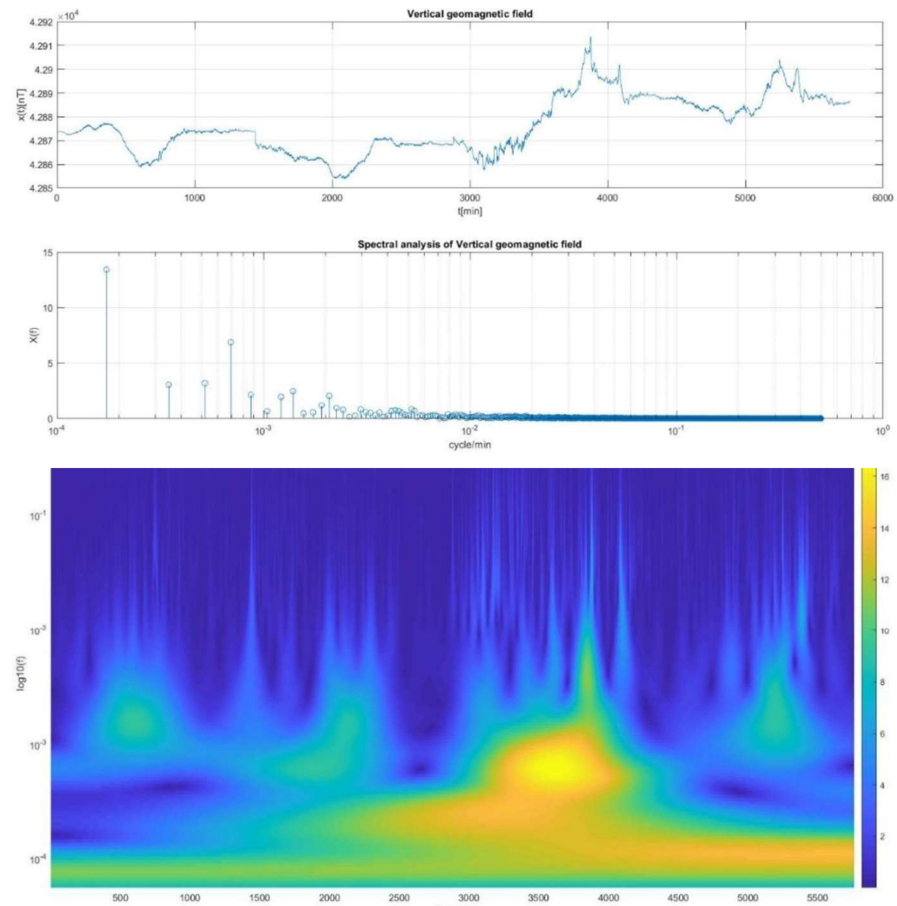

Fig.3 – Time series (up), spectral analysis (middle) and wavelet analysis (down) for vertical geomagnetic field, with sampling rates 0.0166 Hz (1 minute period).

While for the 4-day series we have 5760 samples (Figures 1-3), for the one-day time series we used the maximum sampling density (2Hz), which corresponds to 172800 samples (Figures 4). Here, in the graphs of 26 August, the elements of the geomagnetic storm can be more accurately identified.

Amplitude in the North direction had variations of up to 200 nT, in the East direction up to 100 nT and in the vertical direction up to 50 nT.

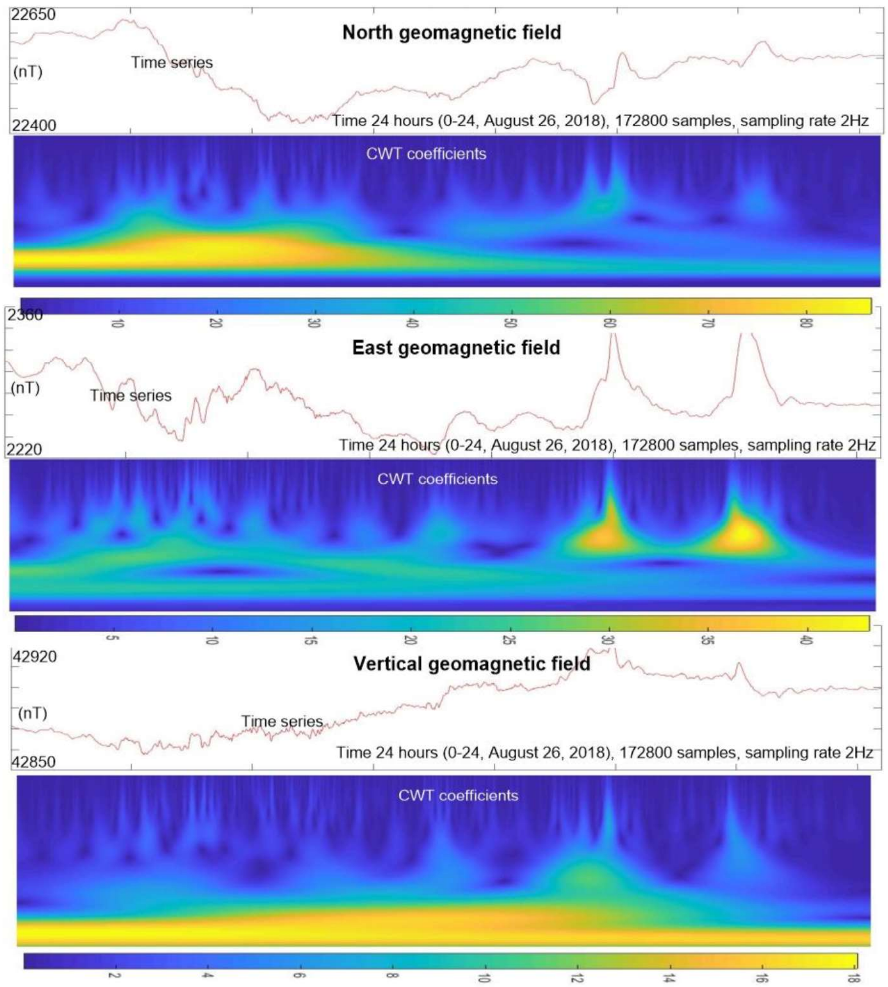

Fig.4 – Time series (up) and wavelet analysis (down) for three orthogonal elements North, East and vertical geomagnetic field, with sampling rates 2 Hz for August 26, 2018.

CONCLUSION

Geomagnetic field elements can be estimated with good accuracy for magnetically calm days. For agitated days, and even more so during magnetic storms, the variation of the declination parameter becomes significant. A geomagnetic storm is known to have different characteristics (amplitudes, gradient, geomagnetic coefficients) depending on the latitude at which it is measured. Thus, at the beginning of a geomagnetic storm, the data from the closest to ground (geomagnetic observation points) is needed on-line for the corrections of the guidance systems.

Geomagnetic storms are created after periods of high-speed solar wind and a southward directed solar wind magnetic field transferring energy from the solar wind into Earth's magnetosphere. Also, these storms are associated with solar coronal mass ejections.

Geomagnetic disturbances are the sum of disturbance produced by: solar corpuscular flux at the magnetopause, magnetospheric ring currents, magnetospheric tail current, ionospheric currents and induced ground currents.

In addition to calculating the geomagnetic activity tri-oral indices Kp, observatory records were subjected to a morphological analysis procedure resulting in the selection of the 10 quiet day variation, 10 disturbance daily variation and the geomagnetic phenomena of SFE and SSC type.

From these information's reported to the World Data Center (from each geomagnetic observatory from INTERMAGNET network) was selected the 5 quiet international days and 5 international disturbance days.

Because the wavelet coefficients are complex valued, the coefficients provide phase and amplitude information of the signal being analyzed. Analytic wavelets are well suited for studying how the frequency content in real world nonstationary signals evolves as a function of time been a good choice when doing time-frequency analysis with the CWT.

In our examples fig. 1-4, wavelet analysis shows predominant frequencies and amplitude for each moment.

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