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FRACTAL AND MULTI-FRACTAL ANALYSES OF THE GEOMAGNETIC FIELD VARIATIONS CAUSED BY THE EARTHQUAKE ON JANUARY 24, 2020 IN TURKEY

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ABSTRACT

Fractal and multi-fractal properties of the Earth's magnetic field time variations caused by the earthquake took place on January 24, 2020 in Turkey were investigated. Using Dynamical Fractal Analysis method proposed by the authors for both (D and H) horizontal components of geomagnetic field, the time dependences for the Hurst fractal dimension were obtained. With usage of the Wavelet Transform Module Maxima method and the Multi-Fractal Detrended Fluctuation Analysis method, the set of traditional and original multi-fractal numerical characteristics was estimated. Combining the fractal and multi-fractal analyses results with ones for the time-frequency structure, obtained the Continuous Wavelet Transform application, the set of disturbances caused by the earthquake was discovered. For these disturbances, all needed time-frequency, fractal and multifractal characteristics were estimated. The disturbances were shown to be fractal ultra-wideband processes with complex, non-stationary multi-fractal structure. Two promising candidates for the role of earthquake precursors were revealed. One possible earthquake precursor in both horizontal components of the geomagnetic field time variations seems to be detected. This precursor was shown to be registered 25.5 hours before the earthquake event. Being be found in time variations of the multi-fractal characteristics only for both horizontal components of the geomagnetic field, another possible earthquake precursor took place 0.5 hours before the earthquake event. The so-called transition of the multi-fractal process to the mono-fractal mode was detected. For both precursors, the time-frequency, fractal and multifractal characteristics were estimated.

Keywords: Fractal Ultra-Wideband Process, Fractal Analysis, Multi-Fractal Analysis, Geomagnetic Field Time Variations, Earthquake

1. INTRODUCTION

According the non-linear paradigm formulated in the late 1970s by prof. L. F. Chernogor, many processes in open, non-linear, dynamical systems, which caused by impact of a non-stationary, powerful source, are appeared to be short-time, non-linear, ultra-wideband (UWB) and fractal ones [1 – 3]. A powerful earthquake is namely such source, and the Earth – atmosphere – ionosphere – magnetosphere (EAIM) system is namely such system. All subsystems in the EAIM system strongly interact with each other and, therefore, the significant disturbances in the magnetosphere caused by the powerful earthquake impact can be found. Moreover, the corresponding perturbations in the EAIM system were appeared to be global. This fact is fully explained by the phenomenon of appearance of the large-scale and global perturbations in the EAIM system caused by a non-stationary, powerful source influence. Such phenomenon had been discovered in the former Soviet Union in the late 1980s by the scientific group led by prof. L. F. Chernogor [1 – 3].

Therefore, the geomagnetic field time variations caused by a powerful earthquake can be registered by the magnetometers very far from the source. These signals are expected to be both UWB and fractal ones. Thus, the theme of the paper seems to be actual, topical and interesting.

The purpose of this paper is to investigate the fractal and multi-fractal properties of these signals with usage of the fractal and multi-fractal analysis methods, which are able to research a non-stationary fractal structure of a signal.

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2. EARTHQUAKE EVENT AND EXPERIMENTAL DATA

An earthquake with a magnitude of 6.7 and a duration of 15 s occurred at 17:55:14 (hereafter universal time, UT) on January 24, 2020 near the Sivridge city, Elazig province, Turkey, where about 4 thousand people live. 1,547 people were injured by the earthquake, and 35 people died. The coordinates of the epicenter are as follows: 38.4° N. w., 39.1° east. d. The depth of the earthquake was 10 km [4].

Basing on data on the space weather state during the earthquake [4], it can be maintained that this day was magnetically quiet. This allows to hope that the cause of the studied variations of the Earth's electromagnetic field is really this earthquake, and therefore the detected effects can be associated with it. The experimental data were obtained with the unique magnetometer-fluxmeter placed on the Radiophysical Observatory of the V. N. Karazin Kharkiv National University (Grakovo, Kharkiv Region, Ukraine) [5].

A thorough analysis of the time-frequency structure of wave processes that occurred in the geomagnetic field during the powerful earthquake of January 24, 2020, was performed in [4]. Therefore, here we will focus specifically on the study of the fractal properties of these identified processes. In our research, the time variations of the geomagnetic field (horizontal D- and H-components) were analyzed as they occurred from 15:00 to 21:00 on the eve of the earthquake (January 23, 2020), on the day of the earthquake (January 24, 2020) and in the day after the earthquake (January 25, 2020).

3. FRACTAL AND MULTI-FRACTAL ANALYSIS METHODS

In our investigations, the fractal analysis is represented by the Dynamical Fractal Analysis (DynFA) [6] which includes the Hurst fractal dimension calculated in sliding window in time domain and the Continuous Wavelet Transform (CWT) [7].

The multi-fractal analysis is connected with usage of the Wavelet Transform Modulus Maxima (WTMM) [7] and the Multi-Fractal Detrended Fluctuation Analysis (MF DFA) [8]. Using these two methods, the set of the multi-fractal characteristics of a signal analyzed are estimated.

In addition to the traditional characteristics such as the minimal (α_{min}) and the maximal (α_{max}) values of the multi-fractal spectrum function $f(\alpha)$, it's width ($\Delta\alpha$) and the maximum location (α^*) known also as the 'Generalized Hurst Exponent', the three new ones were proposed. Let's consider them.

By the definition, the asymmetry coefficient of the multi-fractal spectrum function is given by the relation:

$$K_f = \log \frac{\alpha_{\max} - \alpha^*}{\alpha^* - \alpha_{\min}} \tag{1}$$

Practical experience suggests that real multi-fractal spectra are often appeared to be asymmetric. The new numerical characteristic given by the relation (1) allows to take this into account. If K_f=0, a multi-fractal spectrum is symmetric; if K_f>0, a multi-fractal spectrum maximum is shifted to the left; if K_f<0, it is shifted to the right. It is important that if a multi-fractal to a monofractal simplifies, K_f=0.

The second new multi-fractal characteristic introduced in the paper is called as 'the relative multi-fractal width'. By the definition, it is given by the relation:

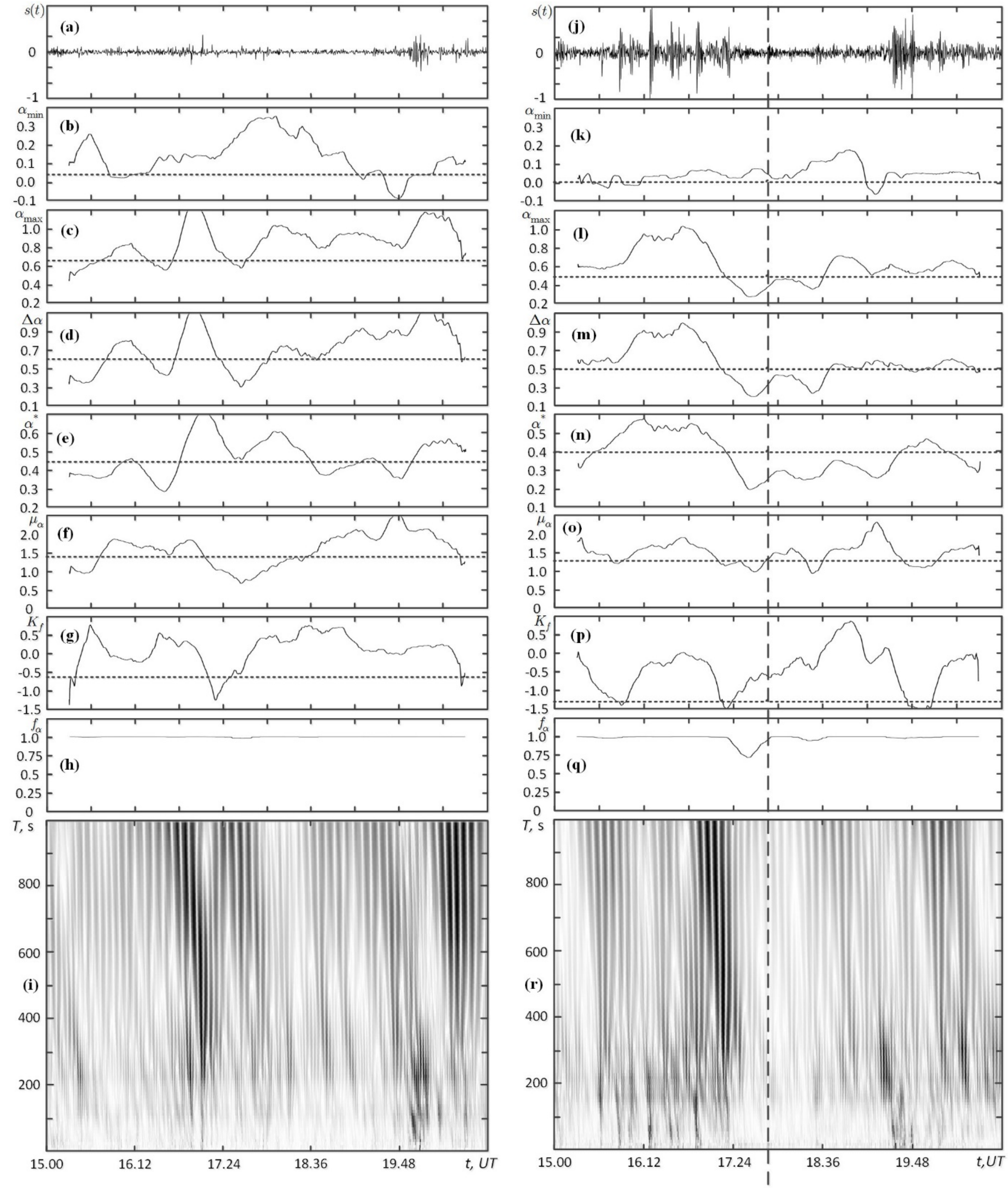

Figure. Results of multi-fractal analysis (MF DFA method) of time variations of the geomagnetic field on January 23, 2020 (D-component): (a) is the signal in time domain, (b) is $\alpha_{min}(t)$, (c) is $\alpha_{max}(t)$, (d) is $\Delta\alpha(t)$, (e) is $\alpha^*(t)$, (f) is $\mu_\alpha(t)$, (g) is $K_f(t)$, (h) is $f_\alpha(t)$, (i) is the CWT SDF; and on January 24, 2020 (H-component): (j) is the signal in time domain, (k) is $\alpha_{min}(t)$, (l) is $\alpha_{max}(t)$, (m) is $\Delta\alpha(t)$, (n) is $\alpha^*(t)$, (o) is $\mu_\alpha(t)$, (p) is $K_f(t)$, (q) is $f_\alpha(t)$, (r) is the CWT SDF. The CWT SDF was obtained with the fourth order Daubechie's wavelet usage. The vertical dashed line shows the moment of the earthquake. The horizontal dotted lines denote the corresponding values estimated with the WTMM method usage for the whole signal investigated.

$$\mu_\alpha = \frac{\Delta\alpha}{\alpha^*} \tag{2}$$

The relation (2) is an analogue of the relative bandwidth, which is used to describe, in particular, the UWB signals [9].

The third new multi-fractal characteristic is a multi-fractal support dimension, which is defined as a value of the multi-fractal spectrum function $f(\alpha)$ calculated for $\alpha=\alpha^*$, that is $f_\alpha=f(\alpha^*)$.

In our investigations, all estimations of the disturbance time-period parameters for signals analyzed were performed in the period range $T = 15\ldots1000$ s, as well as namely this period range had been used in [4].

4. ANALYSIS RESULTS

Using the DynFA as a fractal analysis method, we obtained such results. About half an hour before the earthquake, the Hurst dimension $D_H(t)$ began to increase from approximately 1.5 to 1.9. The maximum of the function $D_H(t)$ coincided with the beginning of the earthquake, after which it began to decrease. Its second maximum, slightly smaller in magnitude, was observed approximately 70 minutes after the beginning of the earthquake and is most likely associated with the aftershock. From a physical point of view, this means that the fractal process half an hour before the earthquake significantly changed its character: from almost purely random ($D_H(t)$=1.5) it became strongly anti-persistent ($D_H(t)$=1.9). It should also be noted that this happened almost synchronously for both components of the geomagnetic field. Instead, in order to find out whether the obtained effects are a regularity for large earthquakes, many more similar events should be investigated in the future.

The main information about time changes of the multi-fractal characteristics of the studied signals was provided by the MF DFA method. Being strongly limited by the approved paper volume, as the examples, we introduce the results of multi-fractal analysis of time variations of the geomagnetic field on January 23, 2020 (D-component) (Figure, a – i) and on January 24, 2020 (H-component) (Figure, j – r) only. On the graphs of time dependences of multi-fractal characteristics, the corresponding values of these characteristics, obtained by the WTMM method, are shown by horizontal dashed lines. This is quite convenient, because it demonstrates how the local value of the characteristic deviates from what is obtained immediately for a whole signal analyzed. The spectral density function (SDF) of the CWT (Figure, i, r) allows to show all peculiarities of the time-period structure of the signal analyzed.

Let's start with January 23, 2020, that is, the day before the earthquake. For the D-component of the geomagnetic field (Figure, a), two main disturbances were detected: the first from 16:30 to 18:00, the second from 19:30 to 21:00 (Figure, i). During the first of them (16:30 – 18:00 UT), an increase of the $\alpha_{min}(t)$ from approximately 0.1 to 0.3 (Figure, b), a sharp increase followed by a drop in the values of the $\alpha_{max}(t)$ (Figure, c), $\Delta\alpha(t)$ (Figure, d) and $\alpha^*(t)$ (Figure, e) in the ranges of 0.6 – 1.3, 0.4 – 1.2 and 0.3 – 0.7 respectively, an almost linear decrease of the $\mu_\alpha(t)$ (Figure, f) from 2.0 to 0.6, as well as the formation of a significant local minimum of the $K_f(t)$ (Figure, g) in the range from 0,5 to -1.4 were observed. The authors [4] associate this disturbance with the precursor of the earthquake, which appeared approximately 25.5 hours before the event itself. The second wave disturbance is associated with an increase in magnetic activity [4]. The following features of multi-fractal characteristics were revealed for it. An increase of the $\alpha_{min}(t)$ (Figure, b) approximately from -0,1 to 0.1, a sharp increase followed by a drop in the values of $\alpha_{max}(t)$ (Figure, c), $\Delta\alpha(t)$ (Figure, d) and $\alpha^*(t)$ in the ranges of 0.8 – 1.2, 0.6 – 1.2, and 0.35 – 0.55, respectively, an almost linear decrease of the $\mu_\alpha(t)$ (Figure, f) from 2.5 to 1.2 were obtained. For the H-component of the geomagnetic field, all multi-fractal characteristics slightly fluctuated near their average values for the entire six-hour period.

On the day of the earthquake (January 24, 2020), for the D-component of the geomagnetic field for disturbances observed from 19:10 to 20:25 and associated with the magnetic effect of the earthquake, the changes of the $\alpha_{min}(t)$ in the range from 0.0 to 0,2, the increasing of the $\alpha_{max}(t)$ from 0.6 to 1.0, of the $\Delta\alpha(t)$ from 0.5 to 0.9 and of the $\alpha^*(t)$ from 0.3 to 0.55 were registered. In the same period of time, for the H-component (Figure, j), the insignificant variations of the $\alpha_{min}(t)$ (Figure, k), $\alpha_{max}(t)$ (Figure, l) and $\Delta\alpha(t)$ (Figure, m), the formation of a time maximum of the $\alpha^*(t)$ (Figure, n) in the range of 0.25 – 0.45, as well as a time minimum of the $K_f(t)$ (Figure, p) in the range of 0.0 to -1.5 were detected.

But the most interesting thing, in our opinion, on the day of the earthquake in the behavior of the multifractal characteristics was that about half an hour before the earthquake itself, "falls" in the function $f_\alpha(t)$ (Figure, q) appear in the registrations of both components. Such "falls" were not found anywhere else on any of the analyzed days. For the D-component of the geomagnetic field, these "falls" were accompanied by the formation of the $\alpha_{min}(t)$ maximum in the range from 0.05 to 0.25, minimums of the $\alpha_{max}(t)$ from 0.3 to 0.6, $\Delta\alpha(t)$ from 0.2 to 0.55), $K_f(t)$ from 0.0 to -1.3 and $\mu_\alpha(t)$ from 0.5 to 1.6, a decrease of the $\alpha^*(t)$ from 0.5 to 0.25. For the H-component, the minimums of the $\alpha_{max}(t)$ (Figure, l) from 0.3 to 0.5, $\Delta\alpha(t)$ (Figure, m) from 0.2 to 0.5), $\alpha^*(t)$ (Figure, n) from 0.2 to 0.4, $K_f(t)$ (Figure, p) from -0.5 to -1.5 and $\mu_\alpha(t)$ (Figure, o) from 0.5 to 1.6 were found. In addition, as shown by the CWT SDF (Figure, r), in the half hour before the earthquake, the activity in the period band T = 15…1000 s generally became very small.

5. DISCUSSION

Both considered disturbances, detected on January 23, 2020, are quite similar in nature. In both cases, a wave perturbation appeared in the form of the UWB process, which can be considered non-fractal. As it was found during our investigations of the large model signal set, the appearance of a non-fractal component on the background of a fractal signal leads to a significant increase of the $\alpha_{max}(t)$, $\Delta\alpha(t)$ and $\alpha^*(t)$. In addition, in many cases, these values may even go beyond the limits of fractality ($0<\alpha<1$). This was observed here for the first two functions. If the function $\alpha_{min}(t)$ also does not change, then this is a normal reaction of the fractal signal to the appearance of an additive non-fractal component. But in both cases, a slight increasing of the $\alpha_{min}(t)$ were appeared to be detected. That is, we can make an assumption that the parameters of the fractal component of the signal have also changed somewhat, and this gives grounds to say about the presence of not just the UWB process, but the fractal UWB (FUWB) process.

Now let's return to the "falls" in the function $f_\alpha(t)$. From a physical point of view, the obtained results mean that half an hour before the earthquake, in the absence of actual disturbances, there was a significant change in the fractal properties of the time variations of both components of the geomagnetic field. The typical multi-fractal behavior ($\Delta\alpha$=0.5, α^*=0.4) changes sharply to almost monofractal ($\Delta\alpha$=0.2, α^*=0.2) one, which is clearly shown by the drop in the multifractal support dimension $f_\alpha(t)$ relative to the traditional unit level. Therefore, before the earthquake itself, the multifractal nature of the variations of both components of the geomagnetic field changed to a monofractal, moreover, strongly anti-persistent (fractal dimension D=2- α^* is equal to 1.8). suddenly, only future studies of geomagnetic field time variations caused by the powerful earthquakes will be able to answer the question of whether the obtained feature can be considered as a "marker" of a future earthquake and can be used for the earthquake prediction.

It is worth emphasizing that the results of the multi-fractal analysis coincide very well with the results of the monofractal analysis. A significant addition to the monofractal analysis result is the fact that the growth of the $D_H(t)$ (and, accordingly, the decrease of the $\alpha^*(t)$) was accompanied by the transition of the multi-fractal process to the monofractal regime. It is also important that this process was more significant for the first maximum of the $D_H(t)$ than for the second one: although the narrowing of the multi-fractal spectrum is well observed in both cases, the decrease of the function $f_\alpha(t)$ in the second case is less noticeable. The last means that the degree of "monofractalization" of the multi-fractal process in the second case was appeared to be smaller.

6. CONCLUSIONS

Using fractal and multi-fractal analysis methods, fractal and multi-fractal properties of the Earth's magnetic field time variations caused by the earthquake took place on January 24, 2020 in Turkey were investigated. The set of fractal and multi-fractal characteristics was estimated.

The UWB processes found in the complex time-period structure of disturbances were shown to be the FUWB ones.

Peculiarities of time dynamics of fractal and multi-fractal characteristics, which may be associated with precursors of earthquakes, have been revealed. It was found that before the earthquake itself, the multi-fractal nature of the variations of both components of the geomagnetic field changed to a monofractal, moreover, strongly anti-persistent one, which is clearly shown by the drop in the of the multifractal support dimension. It is possible that this transition can be used as a "marker" of a nearby earthquake, but studies of other earthquakes are needed to confirm or disprove this.

In both components of the geomagnetic field, another, less pronounced transition to the monofractal regime was detected. It occurred already after the beginning of the earthquake and was possibly associated with the aftershock. The fact that the degree of "monofractalization" of the multi-fractal process in the second case was smaller can be explained by the lower power of the aftershock compared to the first shock.

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