MULTI-FRACTAL ANALYSIS OF THE EARTH'S ELECTROMAGNETIC FIELD TIME VARIATIONS CAUSED BY THE POWERFUL GEOSPACE STORM OCCURRED ON SEPTEMBER 7-8, 2017

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The results of multi-fractal analysis of time variations of the Earth's electromagnetic field caused by the powerful geospace storm occurred on September 7-8, 2017 were considered. To obtain the most detailed results, the multi-fractal detrended fluctuation analysis, the Hurst exponent in sliding time domain window and the continuous wavelet transform were simultaneously applied. The set of numerical characteristics, which describe the peculiarities of the Earth's electromagnetic field time variations, was estimated.

PACS: 94.30.Lr, 94.80.+g, 05.45.−a, 05.45.Tp

INTRODUCTION

The problems of the on-line monitoring of the geospace state and of the predicting the influence of the geospace on the functioning of human civilization are one of the most important problems facing international scientific community today. To solve these problems, the adequate geospace models are needed. But successful creation of such models was found to be not so simple and so fast as long as, one side, all components of geospace (for example, the atmosphere, the ionosphere, the magnetosphere) are appeared to be simultaneously the members of the more complex systems (namely, the Earth – atmosphere – ionosphere – magnetosphere (EAIM) system and the Sun – interplanetary space – magnetosphere – ionosphere – atmosphere – Earth (SISMIAE) system) and, other side, the EAIM and the SISMIAE systems are open, non-linear and dynamical ones. According the non-linear paradigm had been formulated by prof. L. F. Chernogor in the 1970th, the processes in such systems are appeared to be very complex and diverse, in particular, short-time, non-linear, ultra-wideband and fractal [1 - 3]. The complexity of interactions in the open, non-linear and dynamical systems can be explained by the system paradigm had been created prof. L.F. Chernogor in the 1980th [1 - 3].

Moreover, as it had been discovered by the scientific group headed by prof. L.F. Chernogor in 1980th, the disturbances in geospace caused by the powerful, non-stationary, local source of energy release are found to be large-scale and even global. This amazing phenomenon was explained by the trigger effect appearance [1 - 3].

As far as the magnetosphere is a part of EAIM and SISMIAE systems, the geospace storm is a powerful, non-stationary, local source of energy release, the Earth's electromagnetic field time variations may have fractal structure. Its detail investigations are able to give us a lot of information about complex processes in geospace. Thus, the theme of the paper seems to be actual and modern.

The purpose of the paper is to research the multi-fractal properties of the Earth's electromagnetic time variations caused by the geospace storm occurred September 7-8, 2017.

1. MAGNETIC STORM OCCURRED ON SEPTEMBER 7-8, 2017

A geospace storm is a synergistically interacting complex of the magnetic, atmospheric, ionospheric and electrical storms. The geospace storms are usually caused by the powerful, non-stationary processes at the Sun accompanied by the significant increasing of the solar wind and the coronal mass ejections [4].

In this paper we analyze the experimental registrations of the Earth's electromagnetic field (two orthogonal components) caused by the powerful geospace storm occurred on September 7-8, 2017. These registrations 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].

It is necessary to point that the magnetic storm analyzed was appeared to be the twentieth in power of the storm for the entire time of observations of the Earth's magnetic field and the first – for 2017 [6]. If on September 7 the Ap-index reached the value of 36 only, then on September 8 it reached the value of 106. At the same time the Kp-index had the value 8- between 21:00 UT and 24:00 UT on September 7, the value 8 between 00:00 UT and 03:00 UT the value 8+ between 12:00 UT and 15:00 UT on September 8.

2. ANALYSIS METHODS

To describe the fractal properties of the time variations analyzed, the multi-fractal detrended fluctuation analysis (MF DFA), the Hurst exponent in sliding time domain window and the continuous wavelet transform (CWT) were simultaneously applied (see Figs. 1and 2).

MF DFA allows to estimate the multi-fractal spectrum parameters in sliding window in time domain [7]. These are the minimal ($\alpha_{\min}$) and the maximal ($\alpha_{\max}$) values of the multi-fractal spectrum $f(\alpha)$, it's width ($\Delta\alpha = \alpha_{\max} - \alpha_{\min}$) and the maximum location (α^*) known also as the 'Generalized Hurst Exponent'. Due to sliding time domain window usage, they obtain a time dependency.

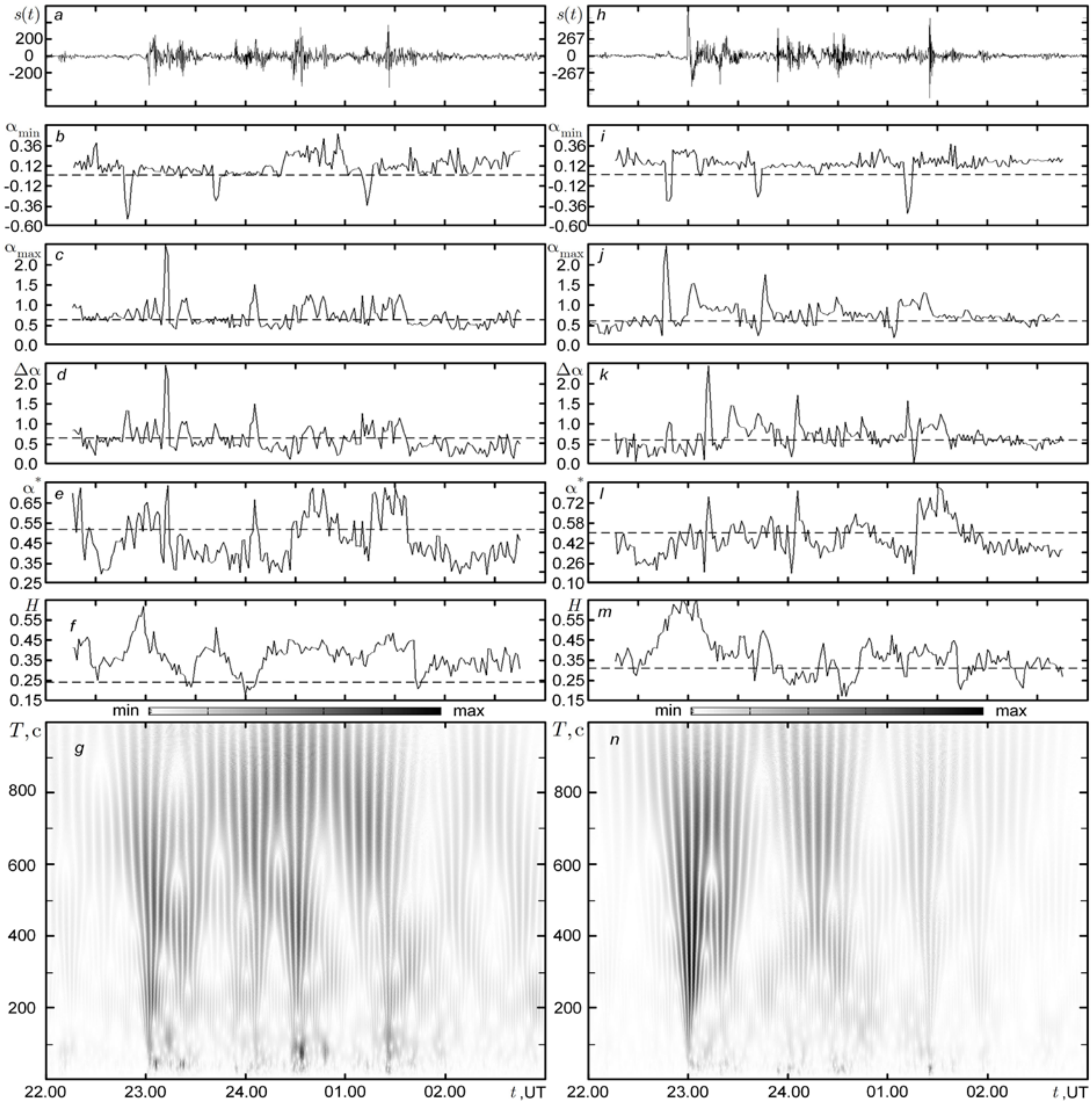

Fig. 1. The results of multi-fractal analysis of Earth's electromagnetic field time variations caused by the powerful geospace storm occurred from 22:00 UT to 03:00 UT on September 7-8, 2017 for both the field components: 1) D-component: a – the signal in time domain, b – the $\alpha_{\min}(t)$ dependence, c – the $\alpha_{\max}(t)$ dependence, d – the $\Delta\alpha(t)$ dependence, e– the $\alpha^*(t)$ dependence, f – the $H(t)$ dependence, g – the CWT SDF of the signal; 2) H-component: h – the signal in time domain, i – the $\alpha_{\min}(t)$ dependence, j – the $\alpha_{\max}(t)$ dependence, k – the $\Delta\alpha(t)$ dependence, l– the $\alpha^*(t)$ dependence, m – the $H(t)$ dependence, n – the CWT SDF of the signal; CWT SDF calculations were performed with usage of the Morlet wavelet

As far as each value listed above was estimated in the window with given width (in this case it is one tenth of the signal length), this value is assigned to the position of the window center in time domain. To compare with the results of the generalized Hurst exponent estimations, the Hurst exponent in sliding time domain window $H(t)$ was calculated. The window length was the same as for MF DFA.

To describe the time-frequency structure of the time variations investigated, the CWT [8] was used. It was represented by the CWT spectral density function (SDF) module calculated with the Morlet wavelet usage.

The analysis methods listed above were applied to the investigations of two signal registrations (D- and H-components), a duration of five hours each. Such time bounds were chosen as long as they contain the most valuable magnetic field disturbances. The estimations the disturbance time-period parameters were performed in the period band T = 15…1000 s.

3. ANALYSIS RESULTS

For D-component of the Earth's electromagnetic field from 22:00 UT on September 7 to 03:00 UT on September 8, four groups of disturbances were detected.

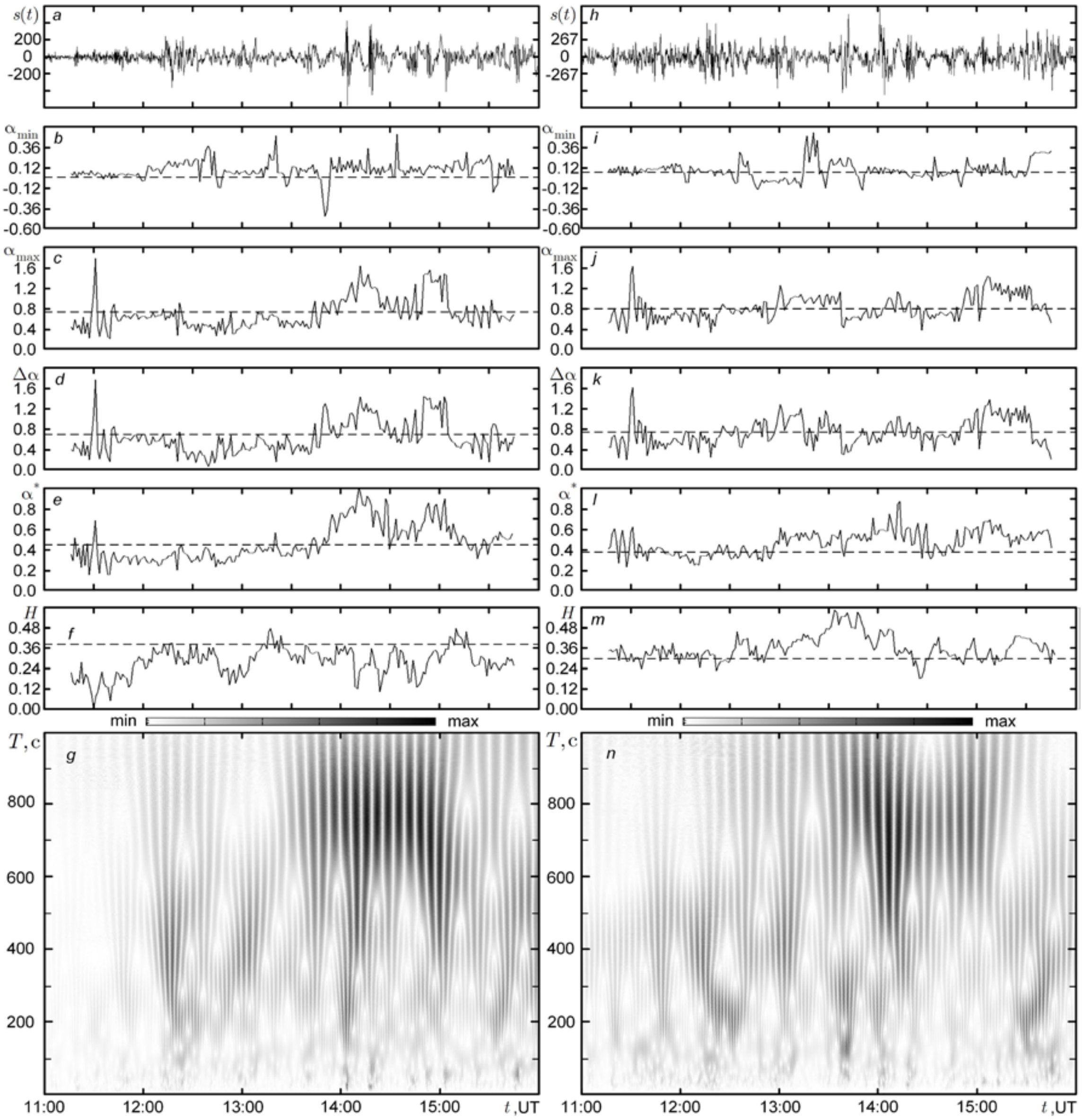

Fig. 2. The same as on the Fig. 1 for the Earth's electromagnetic field time variations occurred from 11:00 UT to 16:00 UT on September 8, 2017

The first group (23:00 – 23.33 UT) has the duration τ = 33 min, the period band T = 15…850 s, α_{min} = 0.0…0.1, α_{max} = 0.5…2.5, $\Delta\alpha$ = 0.5…2.5, α^* = 0.30…0.75, H = 0.25…0.65 and contains one ultra-short (US) ultra-wideband (UWB) process with τ = 5 min, T = 100…750 s, the relative bandwidth μ = 1.5. The second group (23:54 – 00.17 UT) has τ = 23 min, T = 250…800 s, α_{min} = 0.0…0.1, α_{max} = 0.5…1.5, $\Delta\alpha$ = 0.5…1.5, α^* = 0.30…0.65, H = 0.25…0.45 and contains one US UWB process with τ = 8 min, T = 400…750 s, μ = 0.6. The third group (00:27 – 00.52 UT) has τ = 25 min, T = 15…1000 s, α_{min} = 0.1…0.4, α_{max} = 0.5…1.2, $\Delta\alpha$ = 0.3…0.9, α^* = 0.50…0.70, H = 0.35…0.45 and contains two US UWB processes with τ = 3 min, T = 20…120 s, μ = 1.4 and τ = 8 min, T = 200…800 s, μ = 1.2 correspondently. The fourth group (01:12 – 01.45 UT) has τ = 33 min, T = 15…1000 s, α_{min} = -0.4…0.4, α_{max} = 0.5…1.2, $\Delta\alpha$ = 0.2…1.0, α^* = 0.35…0.75, H = 0.25…0.45 and contains one US UWB process with τ = 2 min, T = 60…130 s, μ = 0.7.

For H-component of the Earth's electromagnetic field from 22:00 UT on September 7 to 03:00 UT on September 8, four groups of disturbances were detected too. The first group (23:00 – 23.33 UT) has the duration τ = 33 min, the period band T = 15…1000 s, α_{min} = 0.0…0.3, α_{max} = 0.5…1.5, $\Delta\alpha$ = 0.5…1.5, α^* = 0.15…0.75, H = 0.35…0.65 and contains one US UWB process with τ = 8 min, T = 15…750 s, μ = 1.9. The second group (23:54 – 00.22 UT) has τ = 28 min, T = 200…1000 s, α_{min} = 0.0…0.1, α_{max} = 0.4…1.0, $\Delta\alpha$ = 0.2…1.0, α^* = 0.30…0.75, H = 0.25…0.65 and contains one US UWB process with τ = 10 min, T = 250…800 s, μ = 1.0. The third group (00:27 – 00.52 UT) has τ = 25 min, T = 15…700 s, α_{min} = 0.1…0.3, α_{max} = 0.5…1.1, $\Delta\alpha$ = 0.5…1.0, α^* = 0.40…0.60, H = 0.15…0.45 and contains one US UWB process with τ = 8 min, T = 200…700 s, μ = 1.1. The fourth group (01:12 – 01.45 UT) has τ = 33 min, T = 15…750 s, α_{min} = -0.4…0.4, α_{max} = 0.5…1.1, $\Delta\alpha$ = 0.0…1.5, α^* = 0.20…0.75, H = 0.20…0.45 and contains one US UWB process with τ = 40 s, T = 15…50 s, μ = 1.1.

For D-component of the Earth's electromagnetic field from 11:00 UT to 16:00 UT on September 8, four groups of disturbances were detected. The first group (12:06 – 12.34 UT) has the duration τ = 28 min, the period band T = 15…820 s and contains one UWB process with changing mean frequency (ChMF) with τ = 10 min, T = 120…700 s, μ = 1.4, the dynamical relative bandwidth μ_d = 0.8…0.5, the decreasing mean period T_0 = 400…190 s, α_{min} = 0.0…0.1, α_{max} = 0.5…2.5, $\Delta\alpha$ = 0.5…2.5, α^* = 0.30…0.75, H = 0.25…0.65. The second group (12:47 – 13.12 UT) has τ = 25 min, T = 170…700 s, α_{min} = 0.0…0.1, α_{max} = 0.4…0.7, $\Delta\alpha$ = 0.2…0.7, α^* = 0.25…0.40, H = 0.15…0.35 and contains one US UWB process with τ = 12 min, T = 200…600 s, μ = 1.0. The third group (13:28 – 15.10 UT) has τ = 100 min, T = 15…1000 s, α_{min} = -0.4…0.4, α_{max} = 0.4…1.6, $\Delta\alpha$ = 0.2…1.4, α^* = 0.3…1.0, H = 0.10…0.45 and contains two ChMF UWB processes with τ = 20 min, T = 250…1000 s, μ = 1.2, μ_d = 0.7…0.6, T_0 = 775…325 s. The fourth group (15:22 – 16.00 UT) has τ = 38 min, T = 15…900 s, α_{min} = -0.1…0.2, α_{max} = 0.4…0.8, $\Delta\alpha$ = 0.2…0.8, α^* = 0.3…0.6, H = 0.20…0.35 and contains one US UWB process with τ = 2 min, T = 15…90 s, μ = 1.4.

For the corresponding H-component, three groups of disturbances were detected. The first group (11:40 – 13.12 UT) has the duration τ = 92 min, the period band T = 15…800 s, α_{min} = -0.1…0.3, α_{max} = 0.4…1.2, $\Delta\alpha$ = 0.2…1.2, α^* = 0.25…0.60, H = 0.25…0.45 and contains one ChMF UWB process with τ = 35 min, T = 60…550 s, μ = 1.6, μ_d = 0.6…1.2, T_0 = 340…325 s. The second group (13:32 – 14:35 UT) has τ = 63 min, T = 15…1000 s, α_{min} = -0.1…0.1, α_{max} = 0.4…1.1, $\Delta\alpha$ = 0.4…1.0, α^* = 0.35…0.85, H = 0.20…0.60 and contains one ChMF UWB process with τ = 35 min, T = 120…1000 s, μ = 1.6, μ_d = 0.9…0.7, T_0 = 700…190 s. The third group (14:40 – 16.00 UT) has τ = 80 min, T = 15…1000 s, α_{min} = -0.1…0.2, α_{max} = 0.6…1.3, $\Delta\alpha$ = 0.2…1.3, α^* = 0.40…0.65, H = 0.25…0.45 and contains one US UWB process with τ = 35 min, T = 400…1000 s, μ = 0.9.

CONCLUSIONS

The Earth's electromagnetic field time variations caused by the powerful geospace storm occurred on September 7-8, 2017 were shown to be multi-fractal and ultra-wideband.

Using MF DFA and Hurst exponent in sliding time domain window, the set of fractal and multi-fractal characteristics of the variations investigated was estimated.

Using CWT SDF, the time-period characteristics of the variations investigated in period band T = 15…1000 s were calculated.

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Article received 04.06.2018

МУЛЬТИФРАКТАЛЬНЫЙ АНАЛИЗ ВРЕМЕННЫХ ВАРИАЦИЙ ЭЛЕКТРОМАГНИТНОГО ПОЛЯ ЗЕМЛИ, ВЫЗВАННЫХ МОЩНОЙ ГЕОКОСМИЧЕСКОЙ БУРЕЙ 7-8 СЕНТЯБРЯ 2017 г.

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Рассмотрены результаты мультифрактального анализа временных вариаций электромагнитного поля Земли, вызванных мощной геомагнитной бурей, произошедшей 7-8 сентября 2017 г. Для получения наиболее подробных результатов одновременно применены мультифрактальный анализ флуктуаций без тренда, показатель Херста, вычисляемый в скользящем окне во временной области, и непрерывное вейвлет-преобразование. Оценено множество числовых характеристик, которые описывают особенности временных вариаций магнитного поля Земли.

МУЛЬТИФРАКТАЛЬНИЙ АНАЛІЗ ЧАСОВИХ ВАРІАЦІЙ ЕЛЕКТРОМАГНІТНОГО ПОЛЯ ЗЕМЛІ, ВИКЛИКАНИХ ПОТУЖНОЮ ГЕОКОСМІЧНОЮ БУРЕЮ 7-8 ВЕРЕСНЯ 2017 р.

Л.Ф. Черногор, К.П. Гармаш, О.В. Лазоренко, А.А. Онищенко

Розглянуто результати мультифрактального аналізу часових варіацій електромагнітного поля Землі, викликаних потужною геомагнітною бурею, що відбулася 7-8 вересня 2017 р. Для отримання найбільш докладних результатів одночасно застосовано мультифрактальний аналіз флуктуацій без тренда, показник Херста, який обчислюється в ковзаючому вікні в часовій області, та безперервне вейвлет-перетворення. Оцінено безліч числових характеристик, які описують особливості часових варіацій магнітного поля Землі.