IRSTI 37.15.29 https://doi.org/10.26577/JPEOS.2022.v24.i1.i4

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APPLICATION OF DYNAMIC METHODS IN RADIO ASTRONOMY DATA PROCESSING

Abstract. The paper investigates oscillatory processes in solar flares based on observational data obtained by a 12-meter radio telescope at a frequency f=3 GHz belonging to the Ionosphere Institute of the Kazakhstan Republic. The results of a brief review of methods for processing non-stationary time series suggest that the requirement of adaptability is also important. It is shown that this possibility is provided by the method proposed by Norden Huang. For clarity, the method of implementing EMD (Empirical Mode Decomposition) - the method of decomposing signals into functions (modes) will be considered using the example of a digital signal array x(t). In order to obtain more realistic results, the type of series was determined using fractal analysis. It is shown that at this stage, for the reliability of obtaining CPP, it is necessary to carry out visual control and compare the results obtained by different methods. The paper shows that one of the important conditions is to add to the simulation the presence of quasi-periodic pulsations in the process to explain the physics of the phenomenon of flare events occurring on the Sun. Accordingly, an understanding of the specific mechanisms responsible for the appearance of checkpoints, in combination with their observed parameters, makes it possible to diagnose flare regions and can significantly improve flare prediction.

Keywords: Space weather, solar radio emissions, solar flares, quasi-periodic pulsations, fractal analysis, empirical method of signal decomposition into modes.

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ПРИМЕНЕНИЕ ДИНАМИЧЕСКИХ МЕТОДОВ В ОБРАБОТКЕ РАДИОАСТРОНОМИЧЕСКИХ ДАННЫХ

Аннотация: В работе исследуются колебательные процессы в солнечных вспышках по данным наблюдений, полученных с помощью 12-метрового радиотелескопа на частоте f=3 ГГц, принадлежащего Институту ионосферы Республики Казахстан. Результаты краткого обзора методов обработки нестационарных временных рядов позволяют сделать вывод о важности требования адаптивности. Показано, что такую возможность обеспечивает метод, предложенный Норденом Хуангом. Для наглядности метод реализации EMD (Empirical Mode Decomposition) - метод разложения сигналов на функции (моды) будет рассмотрен на примере массива цифровых сигналов x(t). Для получения более реалистичных результатов тип ряда определялся с помощью фрактального анализа. Показано, что на данном этапе для достоверности получения КПП необходимо проводить визуальный контроль и сравнивать результаты, полученные разными методами. В работе показано, что одним из важных условий является добавление к моделированию наличия квазипериодических пульсаций в процессе объяснения физики явления вспышечных событий, происходящих на Солнце. Соответственно, понимание конкретных механизмов, ответственных за появление контрольных точек, в сочетании с их наблюдаемыми параметрами позволяет диагностировать вспышечные регионы и может значительно улучшить прогноз вспышек.

Ключевые слова: космическая погода, солнечное радиоизлучение, солнечные вспышки, квазипериодические пульсации, фрактальный анализ, эмпирический метод разложения сигналов на моды.

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Радиоастрономия деректерді өңдеуде динамикалық әдістерді қолдану

Аннотация: Жұмыс Қазақстан Республикасының Ионосфера Институтына тиесілі f=3 ГГц жиіліктегі 12 метрлік радиотелескоппен алынған бақылау деректері негізінде күн алауындағы тербелмелі процестерді зерттейді. Тұрақты емес уақытша қатарларды өңдеу әдістерін қысқаша шолу нәтижелері бейімделу талабының да маңызды екенін көрсетеді. Бұл мүмкіндік Норден Хуан ұсынған әдіспен қамтамасыз етілгені көрсетілген. Түсінікті болу үшін EMD (Эмпирикалық режимнің декомпозициясы) жүзеге асыру әдісі - сигналдарды функцияларға (режимдерге) ыдырату әдісі x(t) цифрлық сигнал массивінің мысалында қарастырылатын болады. Неғұрлым шынайы нәтижелерді алу үшін қатарлардың түрі фракталдық талдау арқылы анықталды. Көрсетілгендей, бұл кезеңде КПП алу сенімділігі үшін визуалды бақылауды жүзеге асыру және әртүрлі әдістермен алынған нәтижелерді салыстыру қажет. Жұмыста маңызды шарттардың бірі ретінде Күнде болып жатқан алау құбылыстары құбылысының физикасын түсіндіру процесінде квазипериодты пульсациялардың болуын модельдеуге қосу болып табылады. Тиісінше, бақылау-өткізу пункттерінің пайда болуына жауап беретін нақты механизмдерді түсіну олардың байқалатын параметрлерімен үйлестіре отырып, алау аймақтарын диагностикалауға мүмкіндік береді және алауды болжауды айтарлықтай жақсартуға мүмкіндік береді.

Түйін сөздер: ғарыштық ауа райы, күн радиосәулеленуі, күн жарқырауы, квазипериодтық пульсация, фракталдық талдау, сигналдарды режимдерге бөлудің эмпирикалық әдісі.

Introduction

It should be noted that although facts about the quasi-periodicity of pulsations arising in flare processes on the Sun were discovered 50 years ago, this issue has retained its relevance to this day.

Observations of the Sun provide answers to numerous questions related to solar-terrestrial relationships. The physical processes occurring on the Sun are of great interest for understanding and predicting the interaction of solar plasma with the atmosphere and the Earth's magnetic field. This turn is essential for understanding the earth's climate and space weather. The observable Universe is a plasma, so its study is of great interest for modern physics [1].

On the Sun, in addition to such relatively constant processes as thermal radiation, there is also a sporadic impulsive energy release in flares and coronal mass ejections. The duration of these processes is from several seconds to several hours, and the released energy reaches erg. Solar flares occur in the solar atmosphere, mainly in active regions, but sometimes also between them [2].

For a long time, the classical Fourier method and its various modifications have been used for mathematical processing of time series composed of data from objects of various origins, and the results obtained in most cases contradict each other. The main reason for this is that the time series that we use to determine the time of solar flares in centimeter wavelengths is non-linear and non-stationary [6-8].

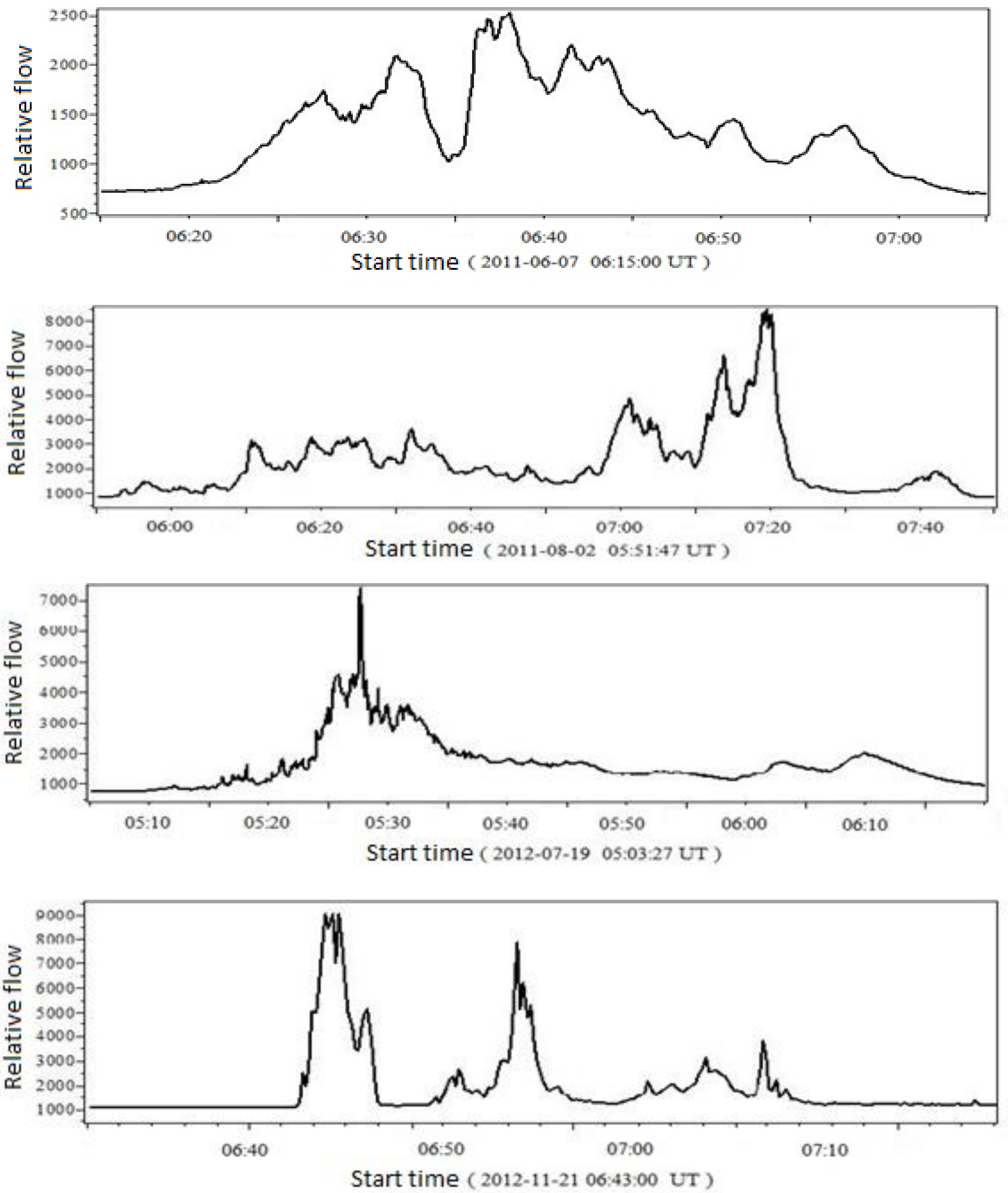
Increasing the sensitivity and resolution of instruments, improving methods for analyzing observational data, and advancing the development of theoretical modeling of physical processes occurring in flares have led both to an understanding of the causes leading to checkpoint.

In the modern era, to eliminate these shortcomings, which consist in the mathematical processing of time series composed of complex signals in practice, in 1995 in the United States, the method “Empirical Decomposition Method (EMD)” by Norden Huang was proposed to study vortex waves [3,4]. The main reason for the wide application of this method in various fields of science and technology is that it is adaptive (i.e., determining the basic function based on the time series under study). We also developed a software package that modified this method based on Huang's algorithm and split the input signal into modes using solar flare time series.

Despite the importance and intensive research, there is still no complete understanding of the physical processes leading to pulsed energy release.

Experimental data and its processing

As observational material, we used 7-isolated solar bursts observed in 2011÷15. on the RT-12 radio telescope in Ionosphere Institute of Kazakhstan Republic.



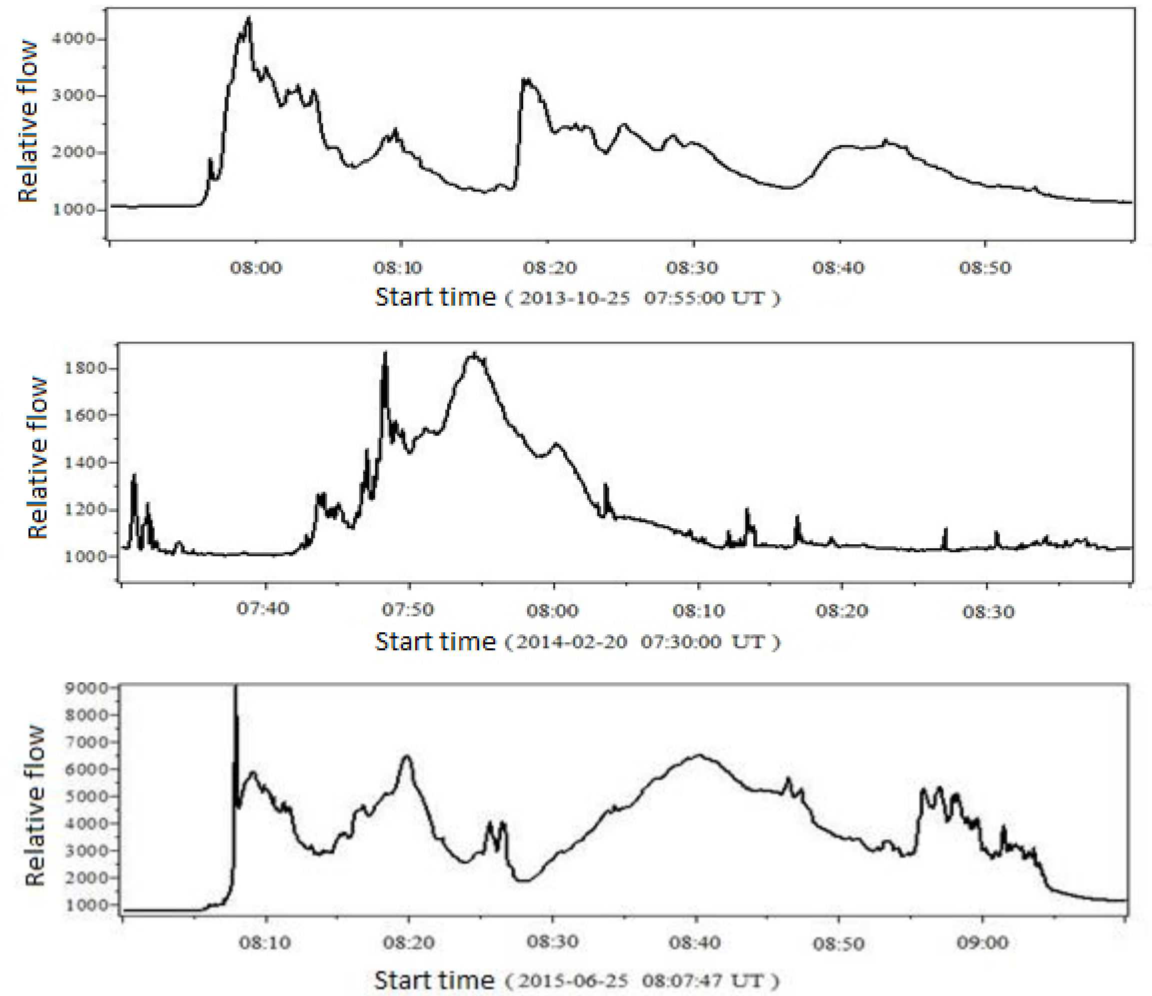


Figure 1 – Time profiles: 7-solar flares observed in 2011÷15 on RT-12 with a CPP in the microwave range λ=10.7 cm in Ionosphere Institute of Kazakhstan Republic.

It can be seen from these figures that repeated pulsations of radiation fluxes are observed in solar flares, which change according to a harmonic law. However, it is obvious that when observing solar flares, it is impossible to meet exactly harmonic signals. Instrumental errors, instrumental noise, the influence of the Earth's ionosphere and troposphere, the different nature of phenomena on the Sun, and others lead to the fact that we are dealing with such deviations from the harmonic signal. All of the above deviations make the observed signal not periodic, but quasi-periodic [2].

Results of processing and its discussion

Firstly, for greater accuracy of the results obtained on the basis of studying the time series that we compose during flares, we calculate the exponent $\mathbf{H_t}$ - Herest and the degree $\boldsymbol{D_t}$ - of the fractal dimension of each order. It also allows us to determine the type of these series when we examine them.

Table 1. The tables show the estimates of the Herest exponent and the degree of the Fractal dimension

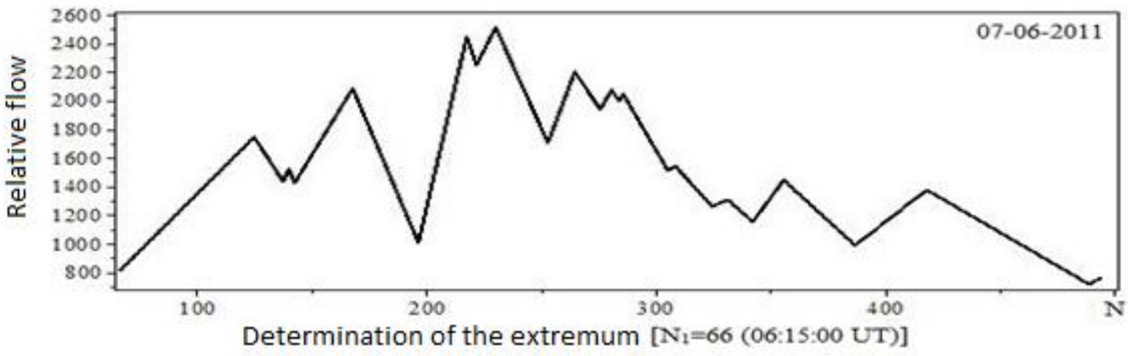
Date (at the time of events)	Hurst exponent H_t	Fractal dimension D_t
07.06.2011 (06:15:00 – 07:08:43 UT)	0.805	1.194
02.08.2011 (05:51:47 – 06:49:00 UT)	0.776	1.223
19.07.2012 (05:03:27 – 06:23:19 UT)	0.775	1.224
21.11.2012 (06:43:00 – 07:16:00 UT)	0.718	1.281
25.10.2013 (07:55:00 – 09:09:15 UT)	0.799	1.200
20.02.2014 (07:30:00 – 08:28:55 UT)	0.799	1.200
25.06.2015 (08:07:47 – 10:58:19 UT)	0.774	1.225

Based on this table, it can be seen that is the $\mathbf{H_t}$ **-** Herest exponent and $\boldsymbol{D_t}$ **-** degree of the Fractal dimension, respectively equal to $0.5 < \mathbf{H_t} \leq 1$ and $1 < \boldsymbol{D_t} < 1.5$. These estimates obtained show that, chaoticity is replaced by smoother chaoticity during solar flares. More precisely, chaoticity turns into non-stationary quasi-periodic beats [9].

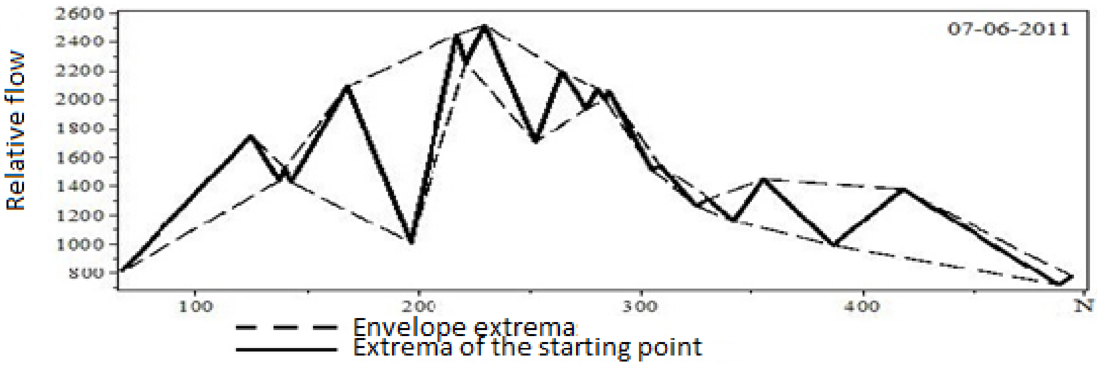
After defining the type of time series, we use the Empirical Mode Decomposition (EMD) method. The mode decomposition of signals is based on the assumption that any data consists of various internal fluctuations. Each oscillation, linear and non-linear, is a modal function that has maxima, minima, and zero crossings. We applied this efficient algorithm to a solar flare that occurred on 07.06.2011.

In the general case, for a given signal x(t), an efficient empirical mode decomposition algorithm consists of the following steps [4,5]:

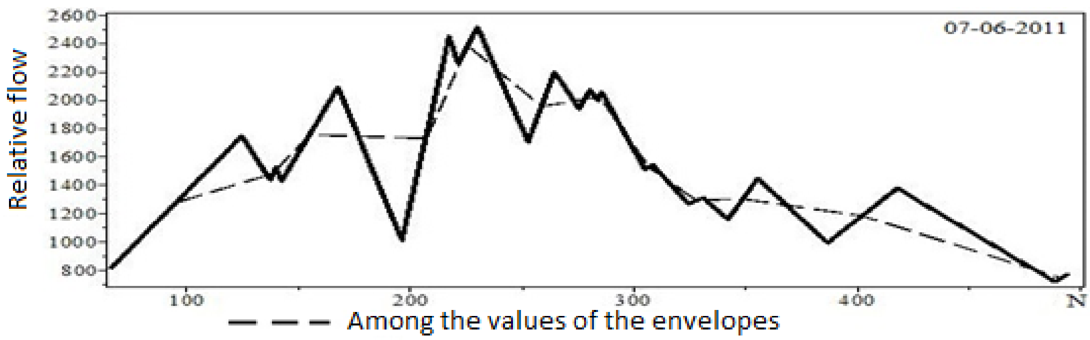
Step 1. Determination of all extrema of the original signal x(t).



Step 2. Finding the upper $B_{\max}$ (t) and lower $B_{\min}$ (t) envelopes for all local extrema, respectively.



Step 3. Calculation of the average value of the obtained envelopes $m_1(t)=[B_{\max}(t)+B_{\min}(t)]/2$.



Step 4. Separation of the difference $h_1(t) = [x(t) - m_1(t)]$. If $h_1(t)$ does not satisfy two conditions: the number of extreme points and the number of zero crossings must either be equal or differ by a maximum of one; at any point, the average values of the envelopes must be equal to zero, then $h_1(t)$ is used as the initial signal to repeat steps **1-3** until the function $h_{1k}(t) = h_{1(k-1)}(t) - m_{1k}(t)$ satisfies the specified condition. In this case, the function $c_1(t) = h_{1k}(t)$ will be the first components of the EM signal x(t).

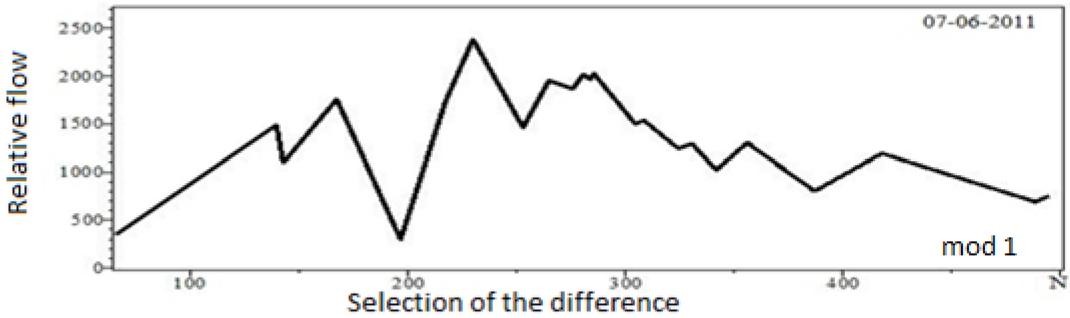
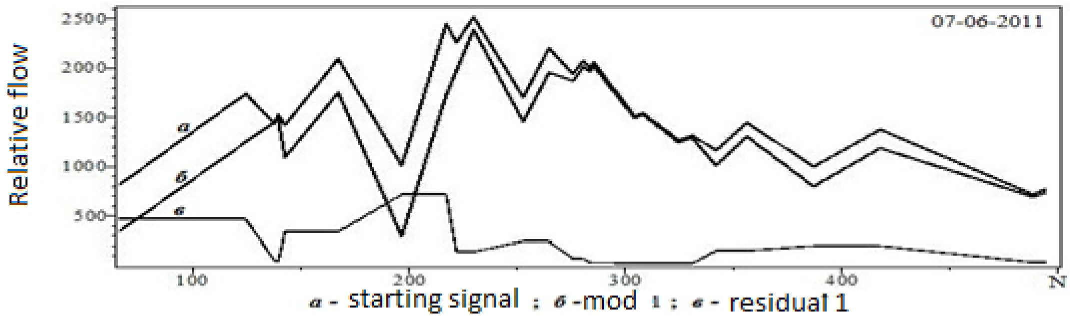


Figure 2 – An efficient algorithm of empirical mode decomposition (EMD) is applied to real signals to the solar flare that occurred on 06.07.2011.

Step 5. Subtracting the function $c_1(t)$ from x(t), we get

$$x(t) - c_1(t) = r_1(t) \quad (1)$$



Function $r_1(t)$ - used further to perform steps **1-4**. As a result, the function $c_2(t)$ will be obtained, which will be the second component of the EM signal x(t).

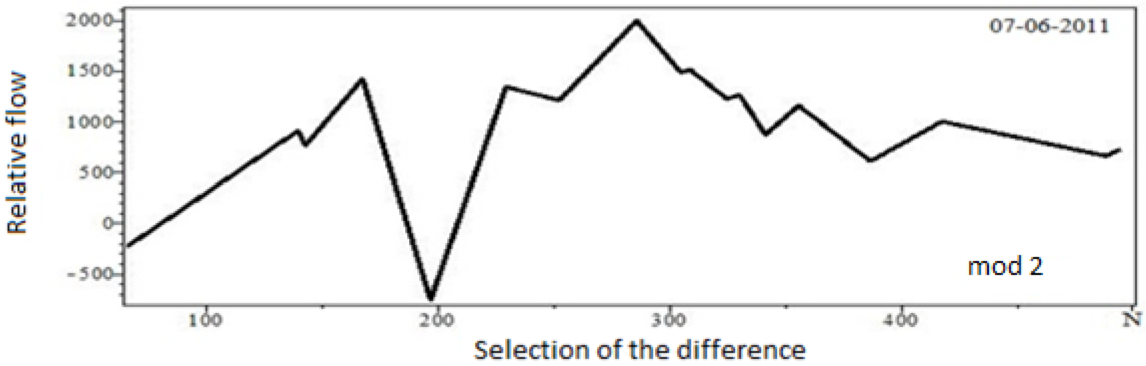
Repeating this operation, you can get n - EM components x(t) :

$$\begin{aligned} r_1 - c_2(t) &= r_2 \\ &\text{- - - - - - - - -} \\ r_{n-1} - c_n(t) &= r_n \end{aligned} \quad (2)$$

Summing up equations (1) and (2), we can obtain the expansion of x(t) in the form:

$$x(t) = \sum_{i=1}^{n} c_i(t) + r_n \quad (3)$$

where is the remainder r_n, which can be a trend or a constant value.



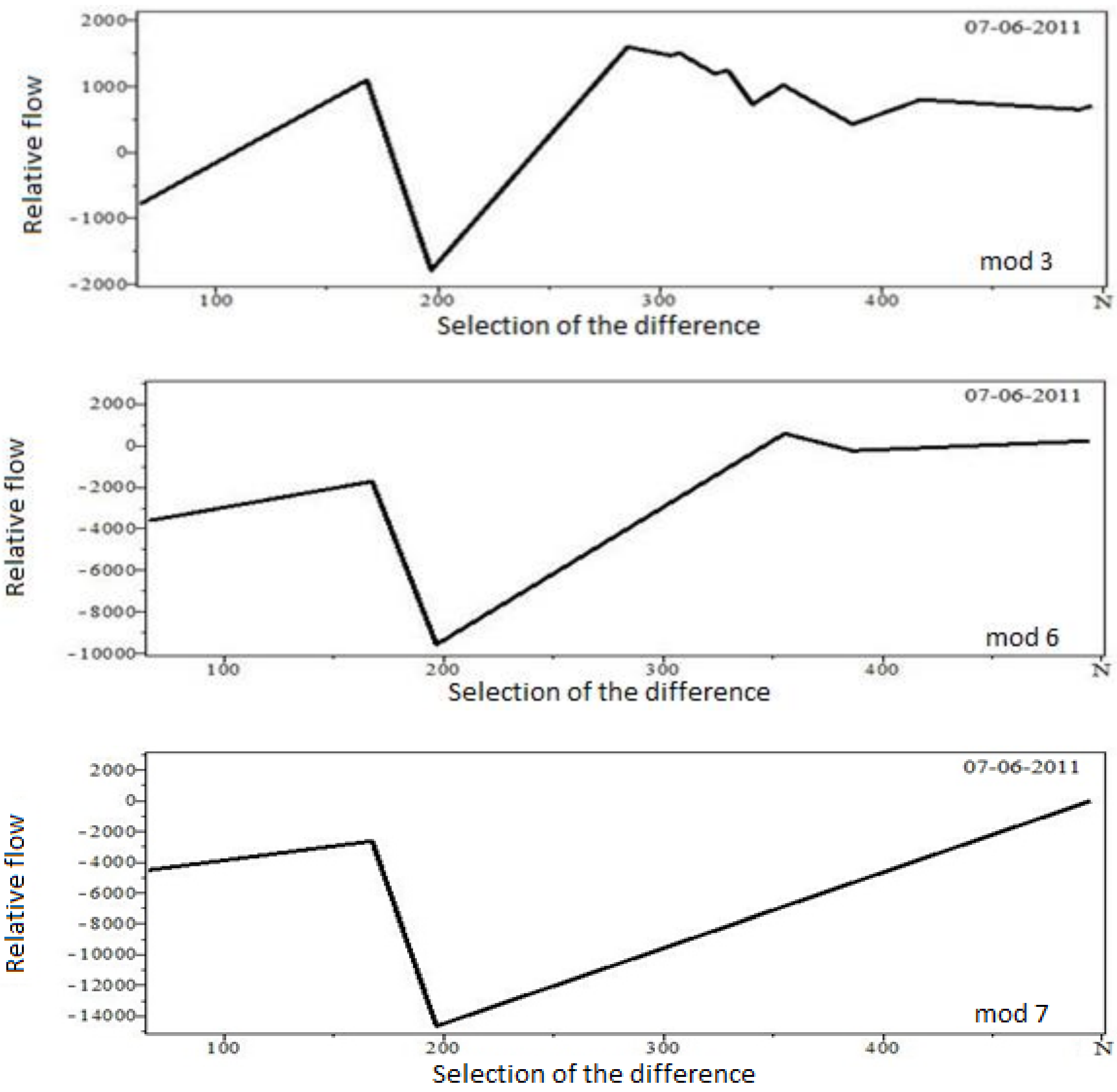


Figure 3 – Implementation of EMD (Empirical Mode Decomposition) - the method of signal decomposition into functions showed that 5-7 iterations are enough to perform high-quality screening of mode functions.

Conclusion

The combined application of methods in solar flares to fractal studies and the separation of empirical modes in radio emission in the centimeter range λ = 10.7 cm made it possible to draw the following conclusions:

1. Non-stationary quasi-periodic pulsations are observed in all phases of solar flares.
2. The observed non-stationarity of quasi-periodic oscillations parameters in the ignition region depends on the dynamics of physical processes independent of each other and the geometric dimensions of the ignition region.
3. In the time-intensity profiles of solar flares, non-stationary quasi-periodic beats with a duration of 20 ÷ 350 seconds were found as a result of their division into modes.
4. Determining the period of ignition pulses and estimating the amplitudes of their modes are additional indicators for predicting events and diagnosing space weather.

Thus, one of the important conditions is to add to the simulation the presence of quasi-periodic pulsations in the process in order to explain the physics of the phenomenon of flare events occurring on the Sun. Understanding the specific mechanisms responsible for the appearance of checkpoints, in combination with their observed parameters, makes it possible to diagnose flare regions and can significantly improve flare prediction.

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Принято в печать 15.05.2022