Astronomical Journal of Azerbaijan, 2023, Vol. 18, No. 1

)

STUDY OF SOLAR FLARES IN CENTIMETER RANGE BY DYNAMICAL METHODS

S. Sh. Huseynov [a], ***Sh. Sh. Huseynov*** [a*]

[a] *N.Tusi Shamakhy Astrophysical Observatory of Azerbaijan National Academy of Sciences, Shamakhy, Azerbaijan*

The article 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 quasi-periodic pulsations (QPPs), it is necessary to carry out visual control and compare the results obtained by different methods

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

1. 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

)AJAz:2023_1_54.pdf

* E-mail: shirin.guseyn@gmail.com

http://doi.org/10.59849/2078-4163.2023.1.54

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 10^{33}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 we use for solar flares at centimeter wavelengths are 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 QPPs.

In order to overcome these shortcomings, which consists of the practical mathematical processing of time series consisting of complex signals, in 1995, "Empirical Decomposition Method (EMD)" was proposed by Norden Huang in the United States [3, 4], to study hurricane waves. 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. The purpose of the proposed work is the application of dynamic methods for the analysis of non-stationary signals. The found periods of solar flare pulses and the estimation of their modes amplitudes are additional indicators for predicting events and diagnosing space weather.

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

2. EXPERIMENTAL DATA

As observational material, we used 7-isolated solar bursts observed in 2011-2015 on the RT-12 radio telescope in Ionosphere Institute of Kazakhstan Republic. Figure 1(a,b,c,d,e,f,j) shows the time profiles of flare events at f=3 GHz for the indicated years. Discretization step $\Delta t = 5$ sec.

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

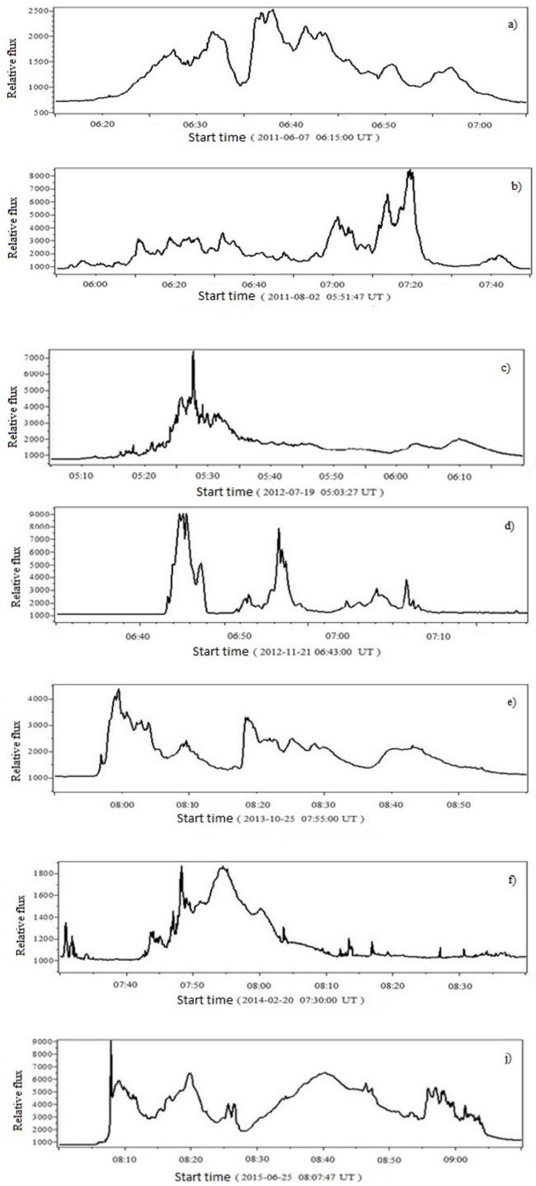


Fig. 1. Time profiles: 7-solar flares observed in 2011-2015 on RT-12 with a QPPs in the microwave range $\lambda = 10.7$ cm in Ionosphere Institute of Kazakhstan Republic.

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].

The 7 flare events studied by us showed that the existing quasi-periodic pulsations can be conditionally divided into 4 types:

1. Those with stable mean periods in the range 20–40 sec. (7 events),
2. Those with spectral drift to shorter periods, during the rise phase of a burst (4 events),
3. Those with drift to longer periods, during the decay phase (5 events),
4. In the rise phase, quasi-periodic pulsations with a period of 20-60 sec. (4 events).

This result indicates that oscillations are an intrinsic feature of flaring energy release. Thus, our understanding of solar flares cannot be complete without revealing the physical mechanisms responsible for the generation of the periodicity.

3. 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 H_t- Herest and the degree D_t - of the fractal dimension of each order. It also allows us to determine the type of these series when we examine them. The H_t-Herest exponent determines the type of events being analyzed, D_t -fractal dimension shows the degree of randomness. The table 1 show the duration of the 7 flare events we considered, the types of time series, and the quantitative estimate of randomness.

Based on this table, it can be seen that is the H_t - Herest exponent and D_t - degree of the fractal dimension, respectively equal to $0.5 < H_t \leq 1$ and $1 < D_t < 1.5$. These estimates obtained show that, chaoticity is replaced by smoother chaoticity during solar flares. More precisely, chaoticity turns into non-stationary quasi-periodic beats. The rules for calculating estimates of the Herest exponent and the degree of fractal dimension were fully described in [9].

After defining the type of time series, we use the Empirical Mode Decomposition (EMD) method. It should be noted that the decomposition in the EDM starts from the highest frequency mode contained in the signal x(t), so each subsequent EM contains oscillations of a lower frequency than the previous one. This decomposition is based on the following assumptions: the signal x(t) has at least two extremes (one minimum and one maximum). The characteristic time scale is determined by the time interval between two consecutive extrema. We applied this efficient algorithm to a solar flare that occurred on 07.06.2011 (fig.1a).

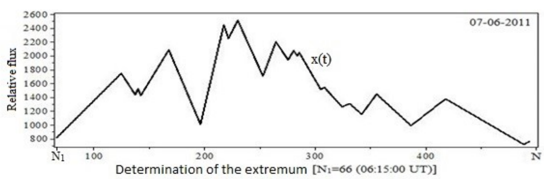
In the general case, for a given signal x(t), an efficient empirical mode decomposition algorithm consists of the following steps [4, 5]:

To obtain the second mode, we take the function $c_1(t)$ as an input signal and repeat 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).

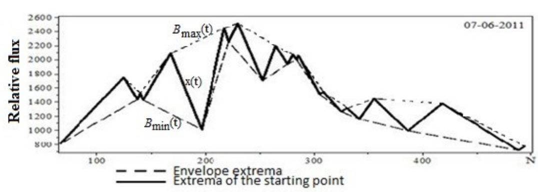
Table 1. The estimates of the Herest exponent and the degree of the fractal dimension.

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

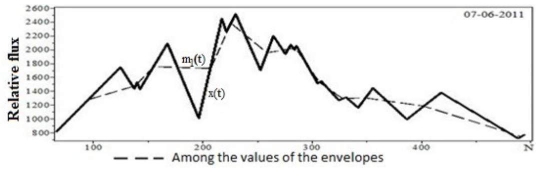
Step 1. Determination of all extrema of the original signal x(t). Point $N_1 = 66$ corresponds to the beginning of the flare in the observational material, which coincides with 06:15:00 UT. Here the sampling step is $\Delta N = 1$, which corresponds in time to $\Delta t = 5$ seconds.



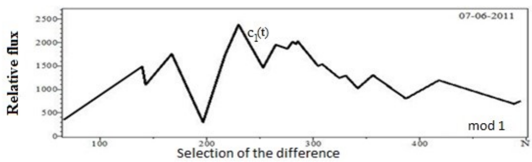
Step 2. Finding the upper B_{max} (t) and lower B_{min} (t) envelopes for all local extrema, respectively.



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

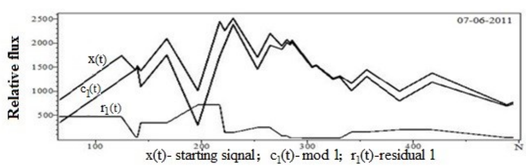


Step 4. Separation of the difference $h_1(t) = [x(t) - m_1(t)]$. If $h_1(t)$ does not satisfy two conditions: the number of extreme points and the number of zero crossings must either be equal or differ by a maximum of one; at any point, the average values of the envelopes must be equal to zero, then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



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

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



By repeating this operation, it is possible to obtain n-number of EM components in the signal x(t):

$$\mathrm{r_1 - c_2(t) = r_2}$$

$$- \cdots - \cdots$$

$$\mathrm{r_{n-1} - c_n(t) = r_n} \quad (2)$$

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

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

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

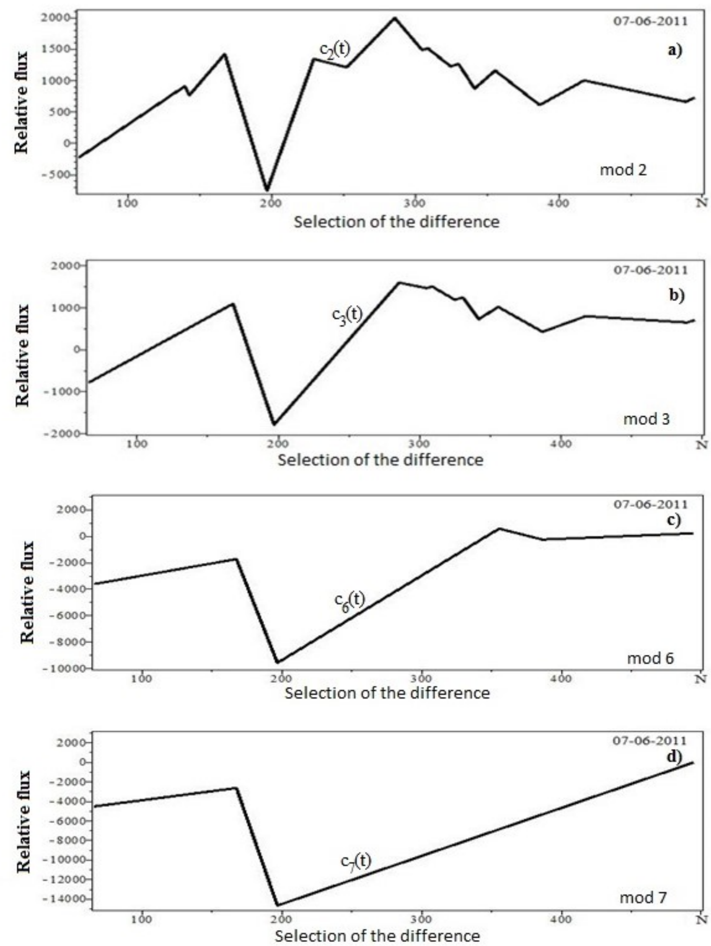


Fig. 2. TDecomposition of the signal x(t).

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 (fig.2d). It should be noted that, in the case when the residual r_n becomes a monotonic function, from which it is no longer possible to extract the EM, then the sifting process ends.

4. 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 $\lambda = 10.7$ 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 $20 \div 350$ 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.

REFERENCES

1. Zheleznyakov V.V., 1964, Radio emission from the Sun and planets. Publishing house M.: “Nauka” , 560.

2. Kupriyanova E.G., Kolotkov D.Yu., Nakaryakov V.M. and Kaufman A.S., 2020, Quasi-periodic pulsations in solar and stellar flares. Review, Solar-Terrestrial Physics, V.**6**, No.1, 3-29.

3. Huang N.E., Shen Z., Long S.R., Wu M.C. [et al]., 1998, The empirical mode decomposition method and the Hilbert spectrum for non-stationary time series analysis, Proceedings of R. Soc. London, Ser. A, **454**, pp. 903-995.

4. Huang N.E., Wu Z., 2008, A review on Hilbert-Huang transform: Method and its applications to geophysical studies. Rev. Geophys. Vol **46**, iss 2, id. RG2006. DOI: 10.1029/2007RG000228

5. Kan Sh.Ch., Mikulovich A.V., Mikulovich V.I., 2010, Analysis of non-stationary signals based on the Hilbert-Huang transform. COMPUTER SCIENCE, April-June, No.2, 25-35.

6. Davydov V.A., Davydov A.V., 2010, Control of the empirical mode decomposition of signals in the analysis and processing of geophysical data. Karotazhnik., No.5, 98-114.

7. Dolgal A.S., Khristenko L.A., 2017, Application of empirical mode decomposition in processing geophysical data. Bulletin of the Tomsk Polytechnic University. Engineering of Georesources, Vol. **328**, No.1, 100-108.

8. Guseinov Sh.Sh., Guseinov S.Sh., 2019, Modern problems modeling the time series of the solar radioradiation. TRANSACTIONS of ANAS, Physics and Astronomy, Vol. **39**, No.5, 196-200.

9. Guseinov Sh.Sh., Somsikov V.M., Guseinov S.Sh., Andreev A.B., Kapytin V.I., 2020, Modeling the structure of non-stationary and short time series of solar radio emission based on fractal analysis. Journal of Problems of the Evolution of Open Systems (Journal of PEOS), Almaty, Vol. **1**, 21-26.