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The study of time series of monthly averaged values of $F_{10.7}$ from 1950 to 2010

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Abstract. Prior to 1947, the activity of the Sun was assessed by the relative numbers of sunspots (W). The 10.7 cm radio emission (frequency of 2.8 GHz) for observations of the variability of radiation of chromosphere and the lower corona ($F_{10.7}$) became used from 1947. For the $F_{10,7}$ are available more detailed observational archive data, so this activity index more often than the other indices is used in the prediction and monitoring of the solar activity. We have made the analysis of time series of $F_{10.7}$ with the use of different mother wavelets: Daubechies 10, Symlet 8, Meyer, Gauss 8 and Morlet. Wavelet spectrum allows us not only to identify cycles, but analyze their change in time. Each wavelet has its own characteristic features, so sometimes with the help of different wavelets it can be better identify and highlight the different properties of the analyzed signal. We intended to choose the mother wavelet, which is more fully gives information about the analyzed index $F_{10.7}$. We have received, that all these wavelets show similar values to the maximums of the cyclic activity. However, we can see the difference when using different wavelets. There are also a number of periods, which, perhaps, are the harmonics of main period. The mean value of 11-year cycle is about 10.2 years. All the above examples show that the best results we get when using wavelets Morley, Gauss (real-valued) and multiparameter family of wavelets Morley and Gauss (complex-valued).

Keywords: Solar cycle: observations, solar activity indices, wavelet spectrum;

Introduction

The nature of solar activity is very complex. It has become of great practical and societal importance to predict solar activity and space climate. There are some important global indices of solar activity which allow us to monitor the situation on the sun and to build various forecasts. We have studied these indices and their mutual correlation during the solar cycles 21 - 23 in Bruevich and Yakunina (2011). The high degree of correlation of the 10.7 cm flux with all global indices suggests some dependence upon common plasma parameters and that their sources are spatially close. Another strong correspondence is between 10.7 cm flux and full-disc X-ray flux. When activity is high, they are well-correlated; however, when activity is low, the X-rays are too weak to be detected, while some 10.7 cm emission in excess of the "Quiet Sun Level" is always present (Kruger 1979). Our study of the connection between 10.7 cm flux and full-disc X-ray flux Bruevich and Yakunina (2011) also confirm the conclusions of Kruger (1979).

Thus we have enhanced 10.7 cm radiation when the temperature, density and magnetic fields are enhanced. So $F_{10.7}$ is a good measure of general solar activity.

10.7 - cm solar radio flux activity index

The solar radio microwave flux at wavelengths 10.7 cm $F_{10.7}$ has the long running series of observations started in 1947 in Ottawa, Canada and maintained to this day. This radio emission comes from high part of the chromosphere and low part of the corona.

At the present time the 10.7 - cm solar radio flux is measured at the Dominion Radio Astrophysical observatory in Penticton, British Columbia by the Solar Radio Monitoring Programme. $F_{10.7}$ is a useful proxy for the combination of chromospheric, transition region, and coronal solar EUV emissions modulated by bright solar active regions whose energies at the Earth are deposited in the thermosphere. The data we used in our paper were published in Solar-Geophysical Data Reports (2009) and National Geophysical Data Center. Solar Data Service (2013).

According to Tapping and DeTracey (1990) the 10.7 - cm emission from the whole solar disc can be separated on the basis of characteristic time-scales into 3 components: (i) transient events associated with flare and similar activity having duration less than an hour; (ii) slow variation in intensity over hours to years, following the evolution of active regions in cyclic solar activity designated as S-component; (iii) a minimum level below which the intensity never falls - the "Quiet Sun Level". The excellent correlation of S-component at 10.7 cm wavelength with full-disc flux in Ca II and Mg II was discussed by Donnelly et al. (1983). The 10.7 cm flux resembles the integrated fluxes in UV and EUV well enough to be used as their proxy (Chapman and Neupert, 1974; Donnelly et al., 1983; Nicolet and Bossy, 1985; Lean, 1990).

$F_{10.7}$ radio flux has two different sources: thermal bremsstrahlung (due to electrons radiating when changing direction by being deflected by other charged participles - free-free radiation) and gyro-radiation (due to electrons radiating when changing direction by gyrating around magnetic fields lines). The (iii) a minimum level component (when SSN is equal to zero as it was at the minimum of the cycle 24 and local magnetic fields are negligible) is defined by free-free source. When the local magnetic fields become strong enough at the beginning of the rise phase of solar cycle and solar spots appear the gyro-radiation source of $F_{10.7}$ radio flux begins to prevail over free-free so (i) and (ii) components begin to grow strongly. The S-component comprises the integrated emission from all sources on solar disc. It contains contribution from free-free and gyroresonance processes, and perhaps some non-thermal emission Gaizauscas and Tapping (1998).

The history of wavelets is not very old, at most 15 to 20 years. There are lots of successes for the community to share.

Fourier techniques were liberated by the appearance of windowed Fourier methods that operate locally on a time-frequency approach.

The wavelets bring their own strong benefits to that environment: a local outlook, a multiscaled outlook, cooperation between scales, and a time-scale analysis. They demonstrate that sines and cosines are not the only useful functions and that other bases made of weird functions serve to look at new signals, as strange as most fractals or some transient signals.

The choice of wavelet is dictated by the signal or image characteristics and the nature of the signal application. If you understand the properties of the analysis and synthesis wavelet, you can choose a wavelet that is optimized for your application.

We tried to choose the wavelet most useful for the analysis of observational data of different indices of solar activity. In this paper we analyzed the different mother wavelets for the study of $F_{10.7}$ data (as a measure of general solar activity).

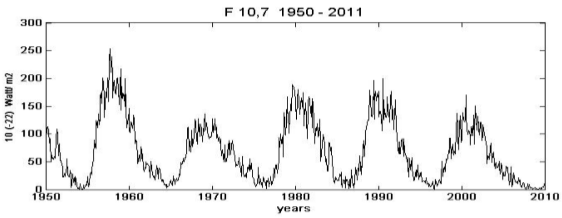

Figure 1: The time series of monthly average of $F_{10.7}$ from 1950 to 2010. According to National Geophysical Data Center of Solar and Terrestrial Physics data.

Modern methods of spectral analysis, in particular wavelet analysis, allow us to successfully carry out the processing of data of observations of the solar activity on different time scales Morozova et al. (1999).

In this paper we have made the analysis of time series of $F_{10.7}$ with the use of different mother wavelets: Daubechies 10, Simlet 8, Meyer, Gauss 8 and Morlet (real and complex). It's known that Fourier analysis consists of breaking up a signal into sine waves of various frequencies. Similarly, wavelet analysis is the breaking up of a signal into shifted and scaled versions of the original (or mother) wavelet.

The wavelets bring their own strong benefits to that environment: a local outlook, a multiscaled outlook, cooperation between scales, and a time-scale analysis. They demonstrate that sines and cosines are not the only useful functions and that other bases made of weird functions serve to look at new foreign signals, as strange as most fractals or some transient signals. The wavelets are the localized functions constructed with help of one so-called mother wavelet $\psi(t)$ by shift operation on argument (b) :

$$\psi_{ab}(t) = (1/\sqrt{|a|}) \cdot \psi((t-b)/a)$$

and scale change (a):

$$\psi((t-b)/a)$$

The wavelet time-scale spectrum C(a,b) is the two-arguments function 'a' is measured in reversed-frequency units 'b' is measured in time units:

$$C(a,b) = (1/\sqrt{|a|}) \int_{-\infty}^{\infty} s(t) \cdot \psi((t-b)/a) dt$$

The choice of mother wavelet for our $F_{10.7}$ study

Wavelet analysis is successfully applied for the processing of time series of astronomical observations. In Vityazev (2001) it has been analyzed the possibility of using of various mother wavelets for a set of astronomical applications. The choice of wavelet is dictated by the signal or image characteristics and the nature of the application. If you understand the properties of the analysis and synthesis wavelet, you can choose a wavelet that is optimized for your application. Wavelet families vary in terms of several important properties. Examples include:

support of the wavelet in time and frequency and rate of decay;

symmetry or antisymmetry of the wavelet. The accompanying perfect reconstruction filters have linear phase;

number of vanishing moments. Wavelets with increasing numbers of vanishing moments result in sparse representations for a large class of signals and images;

regularity of the wavelet. Smoother wavelets provide sharper frequency resolution. Additionally, iterative algorithms for wavelet construction converge faster.

Morlet wavelet

The Morlet wavelet is suitable for continuous analysis. The Morlet wavelet – is the plane wave, modulated by Gaussian function:

$$\psi((t) = \frac{1}{\sqrt[4]{\pi}} e^{-\frac{t^2}{a^2}} e^{i2\pi t}$$

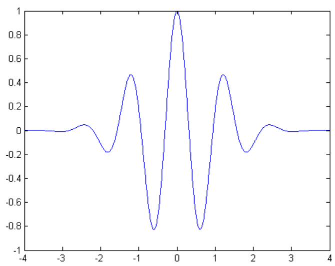

Figure 2a: The Morley wavelet function ψ .

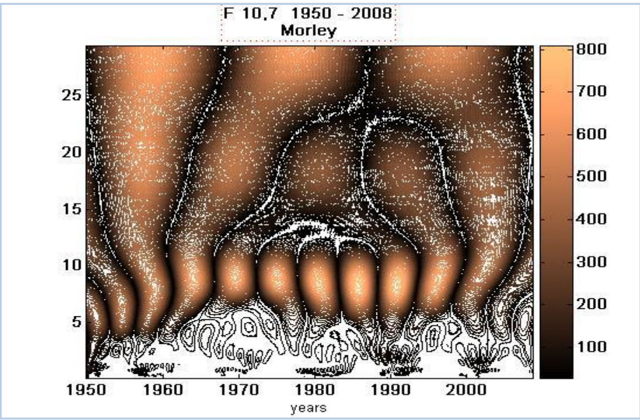

Figure 2b: Analysis of time series of monthly averaged $F_{10.7}$ with the use of Morlet mother wavelet.

At Figure 2b we see the results of the wavelet analysis of time series of monthly averaged F10.7. Plane XY corresponds to the time-frequency plane (a, b): a - Y (Cyclicity, years), b - X- (Time, years). The C(a,b) coefficients characterizing the probability amplitude of regular cyclic component localization exactly at the point (a, b), are laid along the Z axis. At Figure 2b we see the projection of C(a,b) to (a, b) or (X, Y) plane. This projection on the plane (a, b) with isolines allows to trace the changes of the coefficients on various scales in time and reveal a picture of local extremum of these surfaces. It is the so-called skeleton of the structure of the analyzed process. In Vityazev (2001) for processing of time series of astronomical observations the preference is given to the Morley mother wavelet. The interpretation of Morley-wavelet images is similar to the interpretation of the results of Fourier analysis of data sets. We can also note that the configuration of Morley wavelet is very compact in frequency, which allows us the most accurately (compared with other wavelets) to determine the localization of instantaneous frequency of observed signal. We can see the main 11-yr cycle of activity. The most probable value of this cyclicity is about 10 years. We also can see a set of quassi-biennial cycles inside of every 11-yr cycle which duration vary from 3 to 2.5 year.

Daubechies wavelet

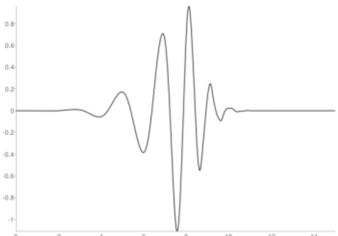

Figure 3a: The Daubechies 10 wavelet function ψ.

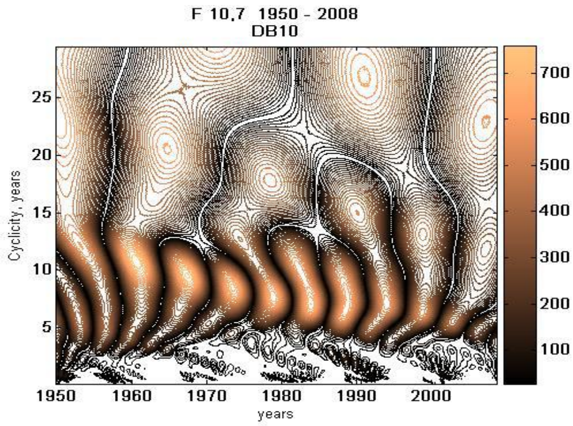

Figure 3b: Analysis of time series of $F_{10.7}$ with the use of Daubechies 10 mother wavelet.

At Figure 3 we demonstrate the analysis of radio emission $F_{10.7}$ with the help of Daubechies 8 mother wavelet. This study of time series of $F_{10.7}$ shows that the previous cycles affect the subsequent cycles. This is connected with peculiarity of this wavelet, its wider coverage of the sample studied observations. But such a wide filter leads to more blurred values which determine the maximum probability of the determination of duration of the cycle.

Simlet wavelet

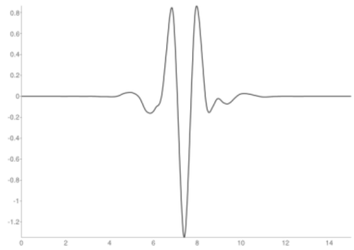

Figure 4a: The Simlet 8 wavelet function ψ.

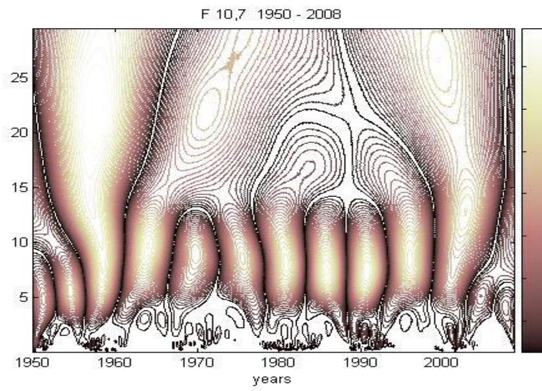

Figure 4b: Analysis of time series of $F_{10.7}$ with the use of Simlet 8 mother wavelet.

At Figure 4 we demonstrate the analysis of radio emission $F_{10.7}$ with the help of Simlet 8 mother wavelet. We see that time-frequency parameters in this case have much more blurred contours around the maximums. Thus, errors in determining the most probable values of the cycle's duration are increased compared with the study of a given series of observations using the wavelet Morley.

Meyer wavelet

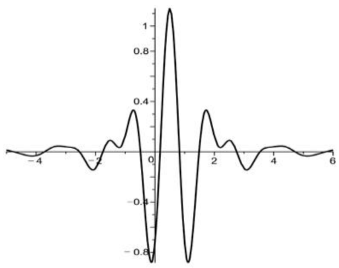

Figure 5a: The Meyer wavelet function ψ.

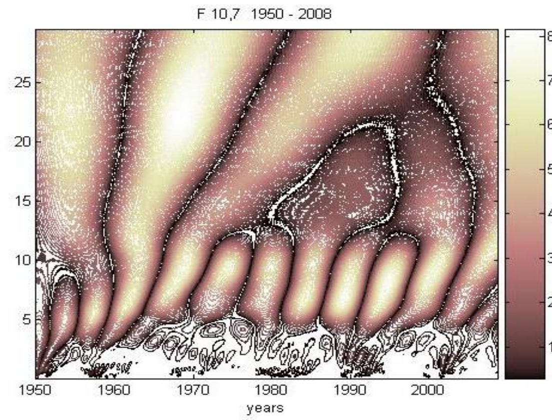

Figure 5b: Analysis of time series of $F_{10.7}$ with the use of Meyer mother wavelet.

At Figure 5 we demonstrate the analysis of radio emission $F_{10.7}$ with the help of Meyer mother wavelet. We also see that time-frequency parameters in this case are not as good as in the case of Morley wavelet. Thus, errors in cycle's duration determination are increased compared with the study of a given series of observations using the wavelet Morley.

Gaussian wavelet

The results of processing observation series using the Gaussian wavelet are very similar to the results of processing with the Morley wavelet. We also can see along with a basic 11-yr cycle of activity the quassi-biennial cyclicity.

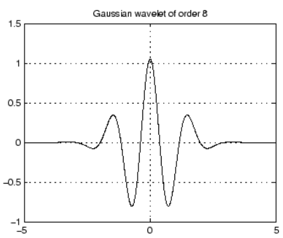

Figure 6a: The Gaussian 8 wavelet function ψ .

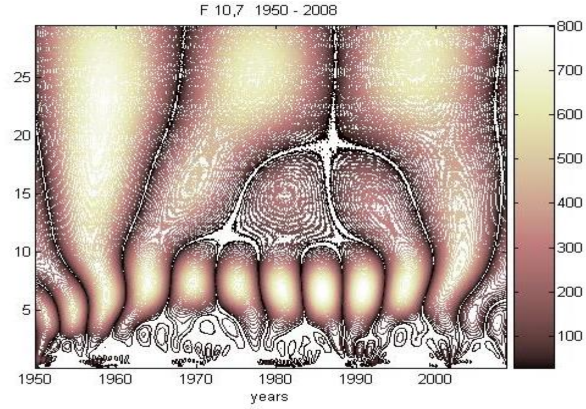

Figure 6b: Analysis of time series of $F_{10.7}$ with the use of Gauss 8 mother wavelet.

At Figure 6 we demonstrate the analysis of radio emission $F_{10.7}$ with the help of Gaussian mother wavelet. We see that time-frequency parameters in this case are practically coinciding with the characteristics obtained with the use of the mother wavelet Morley. Errors in determination of the most probable values of duration of the cycles are not more than in case when we use the Morley wavelet. The differences between these wavelet studies we see in small details, more concerning quassi-biennial cycles.

Complex Morlet wavelet

A complex Morlet wavelet is defined by:

$$\psi((x) = \frac{1}{\sqrt{\pi f_b}} e^{2i\pi f_c x} e^{-\frac{x^2}{f^b}}$$

Depending on two parameters: f_b is a bandwidth parameter and f_c is a wavelet center frequency.

At Figure 6 we show the analysis of time series of monthly averaged $F_{10.7}$ (1974 – 2010 years) with help a complex Morlet wavelet. In this case, there are two additional parameters that can be varied in accordance with the objectives set tasks and, as in the case of Fourier analysis, we get the array of coefficients which give us information not only about the frequency-temporal distribution of the amplitude and about the frequency-temporal distribution of the phase of the signal. The parameters of the mother wavelet Complex-valued Morlet 1.5-1 best describe the 11-year cycle to the detriment of cycles less pronounced and irregular. It is also seen that the magnitude of the 23rd cycle of activity for more than 12 years (this value we do not get with use of real-valued wavelet Morlet as a result analysis).

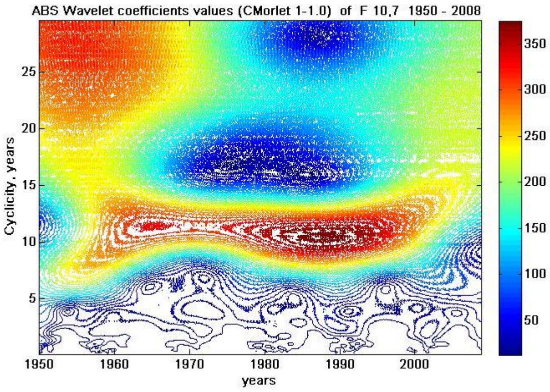

Figure 7: The time series of $F_{10.7}$ (1975 – 2010 yr) and analysis of the F10.7 data with the use of complex Morlet 1-1.0 wavelet.

At Figure 7 we show the analysis of time series of monthly averaged $F_{10.7}$ (1974 – 2010 years) with help a complex Morlet 1-1.0 wavelet. We can see that in this analysis the main cycle (11-year) is dominated and other cycles with lower amplitudes are suppressed.

Summary and conclusion

Wavelet spectrum allows us not only to identify cycles, but analyze their change in time.

Each wavelet has its own characteristic features, so sometimes with the help of different wavelets it can be better identify and highlight the different properties of the analyzed signal.

We intended to choose the mother wavelet, which is more fully gives information about the analyzed solar index $F_{10.7}$. These are Morley and Gauss real-valued and Morley complex-valued wavelets. With these wavelets we can study the solar cyclicity evolution of the most accurate form in every moment of time. We can see also a number of periods, which, perhaps, are the harmonics of main period. The complex-valued Morley and Gauss wavelet analysis gives us the additional information about signal phase evolution. Note than the Daubechies 10 wavelet-analysis (more wide filter window) allows us to analyze the influence of the previous cycle to the next. The Mexican hat wavelet inhibits the main cyclicity and allows us to analyze the cyclicity of second- order.

The analysis with all mother wavelet shows that the mean value of 11-year cycle is about 10.2 years during the period 1950 - 2000. The complex-valued Morley wavelet analyzes shows the more long duration of 11-yr cyclicity for the cycle 23 – about 12 yr.

Acknowledgments

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