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INTERFEROMETRIC OBSERVATIONS OF THE QUIET SUN AT DECAMETER WAVELENGTHS UNDER STRONG RADIO FREQUENCY INTERFERENCE

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ABSTRACT. Studies of the quiet Sun radio emission were carried out in a wide range of wavelengths from extremely short up to decameter ones. At the longest wavelengths, the measurements of angular sizes of the solar corona were previously carried out using the UTR-2 radio telescope in the scanning mode. We have developed a simple interferometric technique for measuring the angular diameter of an extended radio source. It uses a set of interferometers formed from the antenna sections of the north-south and east-west arms of the UTR-2 radio telescope to measure the size of the quiet Sun in the equatorial and polar directions. The first interferometric observations with this approach were carried out using the receivers and software of the URAN interferometers back in 2014. That study allowed us to determine equatorial and polar solar sizes at the fixed frequencies of 20 and 25 MHz. To expand the frequency range of the studies in the following observations, we used broadband digital DSPZ receivers in the correlation mode. However, in the daytime, broadband observations are complicated by radio frequency interference of various types, which often significantly exceed the level of wanted signals. To limit the effect of RFI, software has been developed that automatically detects and mitigates narrowband and impulse interference in a recorded signal. The paper describes the methods of RFI mitigation and criteria for the degree of signal clearing, which are used in this software. We also present the measurement results of the angular parameters of the quiet Sun radio emission, which were obtained by the interferometric method in the frequency range of 10 – 30 MHz. The observations were carried out during the minimum of solar activity in 2018 – 2020.

Keywords: quiet Sun, interferometer, decameter range, interferences.

АНОТАЦІЯ. Дослідження радіовипромінювання спокійного Сонця проводилися в широкому діапазоні довжин хвиль від гранично коротких до декаметрових. На найбільших довжинах хвиль вимірювання кутових розмірів сонячної корони за допомогою радіотелескопа УТР-2 раніше проводилися в режимі сканування. Ми розробили просту інтерферометричну методику для вимірювання кутового діаметра протяжного радіоджерела. В ній використовується низка інтерферометрів, сформованих із секцій північно-південної та східно-західної антени радіотелескопа UTR-2 для вимірювання розміру спокійного Сонця в полярному та екваторіальному напрямках. Перші інтерферометричні спостереження з таким підходом були проведені за допомогою приймачів і програмного забезпечення інтерферометрів УРАН ще в 2014 році. Ці дослідження дозволили визначити екваторіальні та полярні розміри Сонця на фіксованих частотах 20 і 25 МГц. Для розширення частотного діапазону досліджень у наступних спостереженнях використовувалися широкосмугові цифрові приймачі DSPZ у кореляційному режимі. Однак у денний час широкосмугові спостереження ускладнені радіочастотними завадами різного типу, які часто значно перевищують рівень корисних сигналів. Щоб обмежити вплив радіочастотних завад, було розроблено програмне забезпечення, яке автоматично виявляє та видаляє вузькосмугові та імпульсні завади в зареєстрованих сигналах. У статті описано методи боротьби з такими завадами та критерії ступеня очищення сигналу, які використовуються в цьому програмному забезпеченні. Ми також наводимо результати вимірювань кутових параметрів радіовипромінювання спокійного Сонця, отримані інтерферометричним методом в діапазоні частот 10 – 30 МГц. Спостереження проводилися під час мінімуму сонячної активності в 2018 – 2020 роках

Ключові слова: спокійне Сонце, інтерферометр, декаметровий діапазон, інтерференція.

1. Introduction

Radio emission of the quiet Sun has been studied since the 1940s in a wide range of wavelengths from millimeters to meters. Individual observations were also made at frequencies close to the decameter range. Thus, in 1971, observations were made using the Arecibo radio telescope (Aubier et al, 1971) and the flux density, equatorial diameter, and brightness temperature of the quiet Sun at the frequencies of 29.3 and 36.9 MHz were obtained. Later, at close frequencies, studies were performed with the Clark

Lake (Erickson et al, 1977), UTR-2 (Abranin et al, 1986), and Gauribidanur (Sastry, 1994) radio telescopes. It was found that the parameters of the quiet Sun change depending on the period of solar activity. Most of these studies, including those with UTR-2, used scanning radio heliographs (Stanislavsky et al, 2013). As it is known, when an object is scanned by a beam, the output signal is a convolution of the brightness distribution of the observed radio source and the telescope beam pattern. The true size of the object is easily determined by the width of the response if the angular dimensions of the source significantly exceed the width of the beam. With their close dimensions, antenna smoothing leads to an increase in the width of the response compared to the real size and must be taken into account. So, for example, the width of the beam pattern of the UTR-2 radio telescope at the frequency of 25 MHz is 25' and is close to the angular diameter of the quiet Sun at this frequency. In addition, measurements by the scanning method are complicated by the fact that the beam patterns of array antennas used in low-frequency radio astronomy have a significant level of side lobes. furthermore, correlation-type radiometers, which are used on UTR-2 to eliminate the influence of the galactic background, have sign-changing side lobes, the two-dimensional picture of which is quite complex and changes noticeably depending on the orientation of the telescope beam. All this makes it much more difficult to take into account the effect of antenna smoothing when determining the true size of the source.

Alternatively, an interferometric method is used to measure the angular size of radio sources. The north-south and east-west antenna arrays of the UTR-2 radio telescope consist of several identical sections spaced at a distance of 225 m, which can be used to create some interferometers with baselines of up to 1575 m in the north-south direction and up to 675 meters in the east-west. This structure of the radio telescope and the identical parameters of its sections made it possible to develop a simple interferometric technique (Shepelev, 2015) for studying the angular structure of extended sources, such as solar radiation. This technique was used in observations of the quiet Sun conducted in 2014 (Melnik et al, 2018). In this study, we used receivers of the URAN interferometers (Rashkovsky et al, 2012) with a bandwidth of 250 kHz operated at fixed frequencies in the decameter range. Note that these receivers have an effective algorithm for suppressing narrowband interference at the signal recording stage. This algorithm made it possible to carry out observations during the daytime in conditions of a large amount of radio frequency interference. In these observations, the flux density, size, and brightness temperature of the quiet Sun were measured at 20 and 25 MHz. It was also shown that the dependence of the normalized visibility function on the length of the interferometer baseline (Fig. 1) is in good agreement with the calculation for a source with a Gaussian brightness distribution according to the well-known expression:

$$\gamma_n = \exp\left(-\left(\frac{\pi\theta L}{2\sqrt{\ln(2)}\lambda}\right)^2\right), \tag{1}$$

where L is the length of the interferometer baseline, θ is the angular diameter of the source at half brightness, and λ is the wavelength.

In this case, by measuring the visibility function on two arbitrary baselines, one can determine the angular size using the formula

$$\theta = \frac{2\lambda\sqrt{\ln(2)}}{\pi}\sqrt{\frac{\ln(\gamma_1/\gamma_2)}{\left(L_2^2 - L_1^2\right)}}, \tag{2}$$

where L_1 and L_2 are the lengths of the interferometer baselines, γ_1, and γ_2 are the visibilities measured on these baselines.

Observations were conducted at two frequencies and showed that it is necessary to expand the frequency range of observation for a more accurate determination of the model of the solar corona and to determine how parameters of the quiet Sun depend on the wavelength.

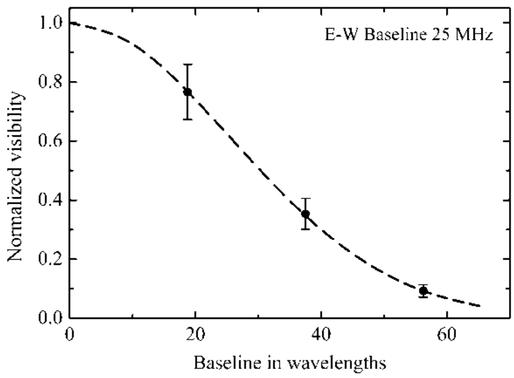

Figure 1: Normalized visibility of the quiet Sun in the east-west direction at 25 MHz and calculated dependency for radio source with Gaussian brightness distribution

2. Broadband observations

The UTR-2 radio telescope is equipped with broadband digital spectral polarimeters DSPZ (Zakharenko et al., 2016) capable of recording signals in the range from 8 to 33 MHz which can be used for interferometric study according technique described. These receivers have two inputs and form at their output a complex dynamic cross-spectrum that is the dependence of covariance of two input signals on frequency and time. Two receivers connected to outputs of the sections of the arrays of the UTR-2 radio telescope form two interferometers with different baselines and allow measuring the angular size of the quiet Sun according to expression (2) in the entire frequency range. To demonstrate the possibility of such a study in a wide frequency range we observed the Sun during the week of April 2015 (Shepelev et al, 2017).

This experiment showed that the main problem with broadband observations during the daytime is the large amount of radio frequency interference, especially in the long-wave part of the range. This problem is aggravated by the use of individual sections of UTR-2 as interferometer antennas, which have a wider beam than that of the entire telescope. In addition, the radiation of the quiet Sun is quite weak at decameter waves and does not have frequ-

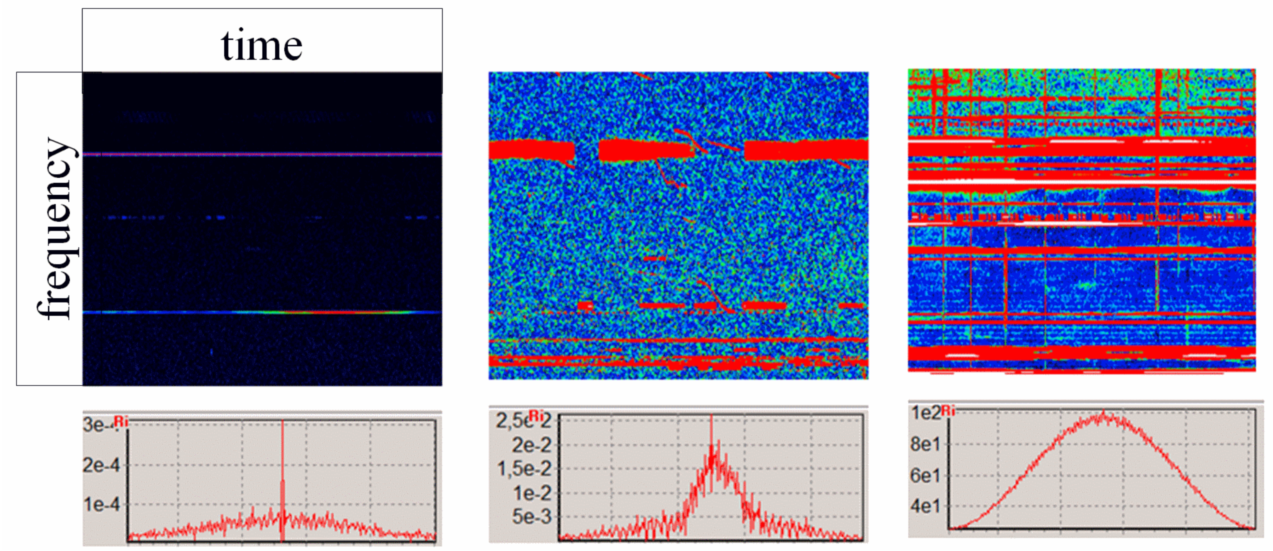

Figure 2: Interference in decameter range

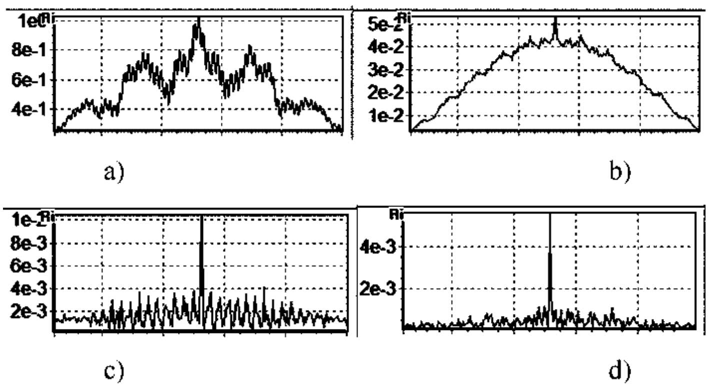

Figure 3: Correlation functions of the "dirty" signal (a) and after two (b), three (c), and four (d) cleaning iterations

ency-time features that make it possible to distinguish it from the interference background.

The broadband DSPZ receivers cannot mitigate interference during observations, which is inherent in URAN receivers, but they have a high dynamic range, which eliminates signal distortion, so interference can be removed at the signal processing stage. To solve these problems, software was developed that allows:

- select a frequency-time frame of the registered with DSPZ correlation dynamic spectrum (cross-spectrum) with a width of up to ΔF = 1 Mhz in frequency and several minutes in time;
- carry out automatic cleaning of this area from narrowband and pulse interference;
- perform coherent integration of the signal in the selected frame;
- calculate the visibility functions and the size of the radiation source;
- visualize processing and results.

The dependence of the module of the visibility function on the differential delay of the input signals of the interferometer (correlation function) serves as an indicator of the presence of interference and a criterion for cleaning the signal since it is significantly different for a wide-band signal of a radio source and narrow-band interference. As is known, the spectrum of the signal at the output of the interferometer and its correlation function are related by a pair of Fourier transforms.

The width of the main lobe $\Delta\tau$ of the correlation function of the useful signal is determined by the width of the spectral window ΔF so that $\Delta\tau \sim 1/\Delta F$. With the selected frame band of 1 MHz, the correlation function has a delta shape with the width $\Delta\tau \sim 1\mu s$. Interference has much narrower spectra, and therefore broader correlation functions. Hence, an obvious way to determine the contribution of radio frequency interference to the signal power of the observed source is the analysis of the entire form of the correlation function. However, with a high level of interference and their large quantity, it is quite difficult to separate the contribution of the signal and interference. In some cases, the interference contribution significantly exceeds the level of the useful signal. Figure 2 shows screenshots of the processing software: dynamic spectra and corresponding averaged correlation functions for three different cases. The upper row shows frames of dynamic spectra with a width of 1 MHz (vertically) and one minute (horizontally). The bottom row is the correlation function of the signal and interference sum.

Here, the interference level increases from left to right, and the correlation function changes accordingly from a simple situation where the signal contribution can be easily determined to a case where the signal is difficult to detect. It is obvious that preliminary cleaning of the dynamic spectrum is necessary. One of the most effective filtering methods, which was used in the URAN receivers, operates according to the following algorithm:

– signal spectrum modules in frequency channels are integrated in a few seconds to increase sensitivity;
– statistical characteristics of the sequence of signal levels in spectrum channels are calculated;
– channels with signal level that exceeds the value of the average level by more than 4 σ (σ is a standard deviation) are considered to be affected by interference and are removed;
– this procedure is cyclically repeated a given number of times.

It was found that in most cases two to four iterations are enough to significantly improve the shape of the correlation function, which is an indicator of the correctness of processing. The goal is to bring it closer to the delta function characteristic of a "pure" signal. Figure 3 demonstrates screenshots of the software, which show the correlation functions of the signal with interference before and after several iterations of the described processing. Note that the level of the correlation function in Fig. 3a is more than two orders of magnitude higher than the level of the "purified" signal in Fig. 3d.

Short pulse interferences that significantly affect the signal level during time averaging can also be removed using a similar algorithm.

New interferometric observations of the quiet Sun and their processing using this software were carried out in the summer of 2018-2020 during the minimum solar activity. Four DSPZ receivers were used to form pairs of interferometers in each direction from the NS and EW antenna sections. Interferometer baselines were 225 and 450 m or 225 and 675 m at different times. The full receiver frequency recording range of 8–32 MHz was used, but a limited range of 10–30 MHz was used for processing. The most reliable data were obtained at frequencies from 15 to 30 MHz, except frequencies close to 27 MHz, where powerful broadband interference is observed. An example of the dependence of the angular size of the quiet Sun on the operational frequency obtained in observations with strong interference, which demonstrates the capabilities of the software, is shown in Fig. 4.

3. Conclusion

Radio astronomy observations of the quiet Sun at decameter wavelengths with interferometers and broadband DSPZ radio receivers showed a significant influence of radio frequency interference on the data quality.

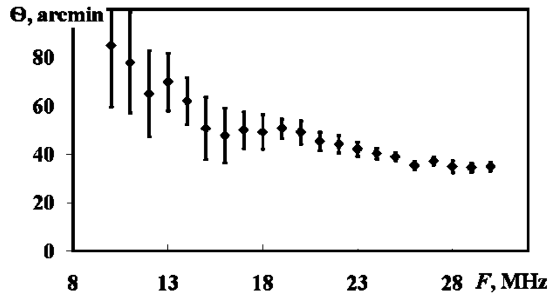

Figure 4: Polar diameter of the quiet Sun as a function of frequency

The software has been developed for the mitigation of narrowband and pulsed interference of various origin.

The use of the cleaning algorithms during data processing made it possible to determine the parameters of the studied radio sources of continuum radio emission under conditions of strong radio frequency interference, which significantly exceeded the level of useful signals

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