PROCEEDINGS OF SCIENCE

Detection of absorption in the decimeter radio emission of solar corona

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The results of new observations of the radio emission of the solar corona in the range of 1–3 GHz with the RATAN-600 are presented. Observations in this range are characterized by a presence of strong industrial interference from mobile communications, GPS, microwave ovens, aircraft radars, etc. At the same time, problems related to the conversion of magnetic energy into flare energy, coronal heating, the role of narrow-band phenomena, and quasi-periodic pulsations in the solar corona remain topical. Change in the concept of receiving spectral equipment for the RATAN-600 radio telescope has become an urgency. Thus, work is now underway on the creation of a series of new generation spectral complexes covering the entire operating range of RATAN-600 from 1 GHz to 40 GHz. In this article, we present the results of the first series of observations with the Panoramic Analyzer of Spectrum in the range of 1–3 GHz (PAS 1–3 GHz) for studies of low-contrast coronal structures. This equipment has fine spectral resolution (more than 8000 channels/GHz), a wide frequency range (more than an octave), high time resolution (up to 8 ms/spectrum), and a wide dynamic range (about 90 dB). A multi-object observation mode becomes available for various objects, from powerful flare phenomena to faint structures down to the radio granulation level. A high-speed pipeline for receiving, digitizing, and processing information has been developed and implemented in order to separate useful signals and interference in real time. These features, together with the capabilities of the RATAN-600 in terms of effective area and wide frequency coverage, made it possible to observe weak coronal structures in the 1–3 GHz range. As a result, new properties of the coronal plasma were discovered. One of the first results of these observations was the registration of narrow-band absorption in the frequency band 1520–1630 MHz, near the OH absorption line (1612–1720 MHz). Possible ways of explaining the nature of such absorption in the solar corona are discussed.

The Multifaceted Universe: Theory and Observations - 2022 (MUTO2022)
23-27 May 2022
SAO RAS, Nizhny Arkhyz, Russia

[*] Speaker

PoS(MUTO2022)005

1. Introduction

The physics of the solar corona has undergone major changes in recent years due to the emergence of several powerful instruments, such as DKIST with a ViSP polarimeter with an aperture of 4.0 m (USA FIRS) [1, 2], Hinode [3], AIA SDO [4], RHESSI [5], and others. New objects, jets, plumes, coronal rain, various modes of loop oscillations, etc. were detected [6]. A new scentific direction has appeared in the search for recombination lines H, OH, H_2, CO, CN, etc. [7, 8] in different ranges. The radio emission of the solar corona in the range of 1-3 GHz should reflect the phenomena associated with the process of reconnection of magnetic lines in the corona, which, according to the Parker model, is the main one and occurs in structures of various scales, down to nanoflares. However, observational possibilities in this range are severely limited due to a large amount of industrial interference (mobile communications, GPS, microwave appliances, aircraft radars, etc.). On the other hand, some observational data [9, 10] indicate the presence of a fine structure (microbursts, spikes) for the study of which an adequate radio astronomical technique is necessary. In this paper, we propose a new concept of spectroradiometry for use on the RATAN-600 large instrument, consider its possibilities and the first results of its application for the analysis of radio emission from the solar corona.

2. Technical aspect of the new concept of radio spectroscopy

RATAN-600 has its own history of observing weak structures. These are the chromospheric grid first observed in 1975, the so-called “radiogranulations” with amplitudes of 10^{-4} solar flux unit (s.f.u.) [11], the detection of microbursts with an amplitude of less than 10^{-3} s.f.u. [12]. Weak absorptions near powerful spots and weak changes in the sign of circular polarization have been detected; search is underway for cyclotron lines and H recombination lines [8], [13]. Microwave radio astronomy studies of the Sun at RATAN-600 in the multi-octave wavelength range (from 1.7 cm to 30 cm now and from 0.3 cm to 30 cm in the future) provide instant information about the active processes in a wide range of altitudes (from the chromosphere, transition layer and corona) in individual objects on the disk. At the same time, the frequency range of 1–3 GHz remained beyond the scope of research until recently due to the presence of powerful interference, the absence of large instruments, and the requirements for the regularity of observations. In recent years, such an opportunity has appeared due to the creation of large antenna arrays in China [14] and in Irkutsk [15], but this range is still under development. We are now starting observations on a new experimental basis. What makes these observations different is not only an unprecedented high frequency resolution in a wide frequency range and a high dynamic range, but also data processing methods that give the possibility to implement multi-object observation modes, i.e. a weak signal can be distinguished against the background of a strong signal using the Principal Components method, which is widely used in Big Data technologies [16]. Important features of the tools for such research are:

- Wide frequency range 1-3 GHz and simultaneous measurements on all frequencies.
- High spectral resolution up to 0.1 MHz over the entire frequency range,

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- Spatial resolution that allows one to select an active region of about 1.2-3.5 arc minutes at all frequencies.
- Solid coverage of the spatial frequency plane (one-dimensional resolution in the horizontal plane is applied to obtain a response from narrow frequency discontinuities).
- Possibility to study the dynamic behavior of the reconnection process.
- Flux sensitivity ranges from 10^{-3} s.f.u. to 10^{5} s.f.u., which ensures the registration of both weak micro- (or nano-) bursts and strong bursts associated with powerful events. The assessment was done according to the following formula and is practically confirmed by real data:

$$\Delta F = \frac{2kT_{\rm sys}}{A_{u,v}(f)S\sqrt{n\Delta F \tau N}}.$$

Here

ΔF is the sensitivity of the radio telescope in terms of radiation flux, s.f.u.,

$A_{u,v}(f)$ is the transmission of the spatial frequency filter,

$k = 1.38 \cdot 10^{-23}$ W·m^2/Hz is the Boltzmann constant,

$T_{\rm sys} = T_{\rm a} + T_{\rm s} + T_{\rm rad}$ is temperature of the system, comprising antenna, source and radiometer temperatures,

S is the effective antenna area of RATAN-600 which is 500–1000 m^2,

τN are the reading constant ($\tau = 10^{-3}$ s – 1 s) and the number of accumulation intervals N, whose product in the tracking mode amounts to 10^3 s,

$n\Delta f$ is the number of frequency channels (around 10^4/GHz with a bandwidth of 0.1 MHz),

$\Delta f/f = 10^{-4} - 10^{-5}$ is the relative frequency resolution, with absolute resolution $\Delta f = 60 - 120$ kHz,

$D = 90$ dB is the dynamic range.

3. Conducting spectral observations of the solar corona

Here we consider the observation of the solar corona on March 27, 2022. For observations, we used the Southern Sector with the Periscope antenna system of the RATAN-600 radio telescope [20], scanning the Sun disk with a knife-shaped beam in one dimension.

The results of observations obtained on March 27, 2022 in the range of 1060–2620 MHz with a horizontal spatial resolution of 1.1–3.3′ and a vertical spatial resolution of 1.2–3.5° are shown in Fig. 1, 2. Fig. 1 shows the spectrum of received radiation *vs.* time. Fig. 2 is composite and consists of parts *a*, *b* and *c*, which show a series of scans superimposed on the SDO HMI magnetic map of the Sun. On that day, solar activity was moderate, there were several active regions on the Sun: NOAA 12978 (on the limb) and NOAA 12974, 12975, and 12976 (in the center of the disk).

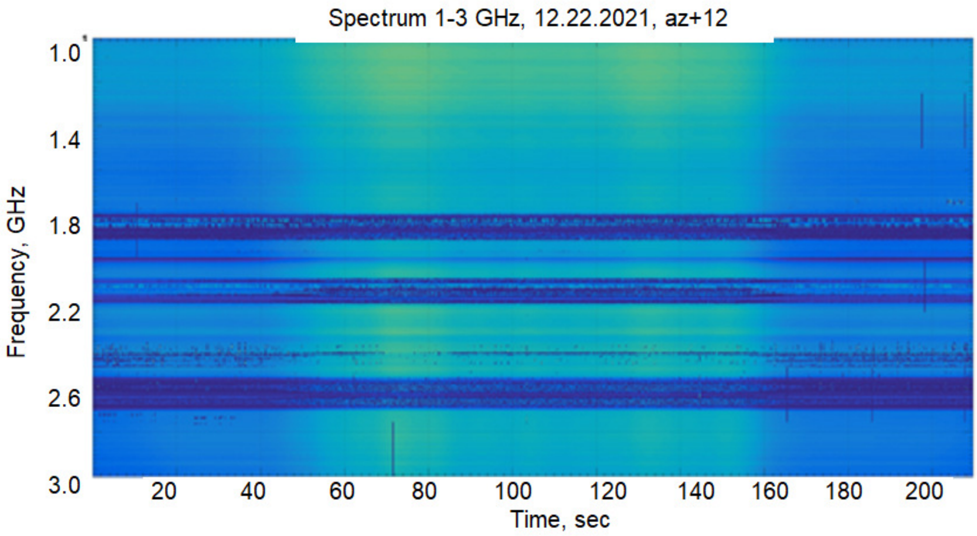


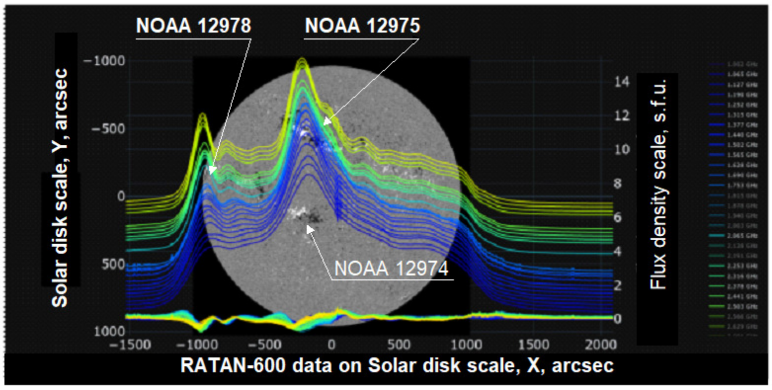
Figure 1: Spectrum of the sky at all receiving frequencies. The stripes mark the frequency regions associated with interference from mobile communications.

4. Observations of low-contrast formations using the spectral complex PAS 1-3

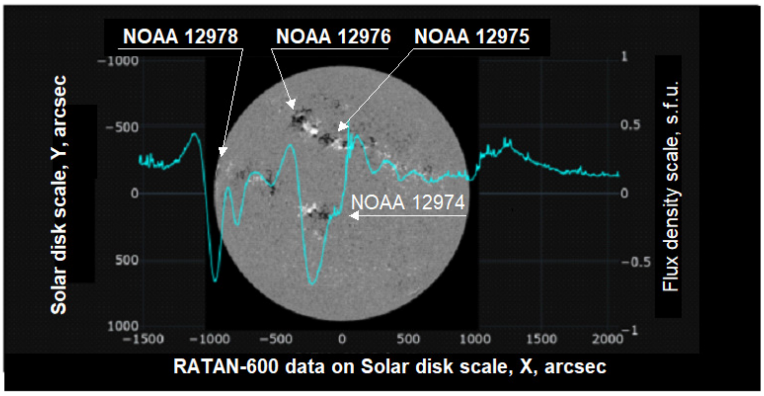
Registration of weak active formations on the bright disk of the Sun is an important observational task for all wavelength ranges, which is associated with the main problem of heating the solar corona. The main difficulty lies in the fact that the registration of such processes takes place against the background of a powerful signal from the quiet Sun, which makes it difficult to observe weak sources. In the radio range, the picture is the same, but the radio radiation quantum has a lower energy and can carry information about important weak processes. Since the sensitivity in the radio range is quite high, there is a possibility for the development of methods for isolating weak signals against the background of strong ones. The large collecting surface of the RATAN-600 radio telescope in the Southern Sector with the Periscope mode is about 600–1000 m^2, which makes it valuable for recording weak radiation and absorption signals. A distinctive characteristic of the new concept is the combination of high frequency resolution $\Delta f/f \sim 10^{-5}$, simultaneous coverage of the entire spectral range of 1-3 GHz, high sensitivity (up to 10^{-3} s.f.u.), high temporal resolution (up to 8 ms), and high dynamic range (up to 90 dB) [17]. As a development, there is a mode of azimuthal observations [18], which is necessary for studying the temporal properties of coronal structures. Additionally, the use of high frequency and time resolutions makes it possible to develop methods for eliminating interference [19] and to implement a multi-object observation mode, i.e. observation of weak objects against the background of powerful structures. The methods of multivariate statistics based on factor analysis look very promising, in particular, the selection and sorting of principal components [16].

5. Processing of spectral data by the Principal component method

Large arrays of spectral data require new approaches for their processing. In the new spectral complex, the maximum number of channels in the 1-3 GHz band is 8192 channels/GHz (i.e. 16384 *a*



b



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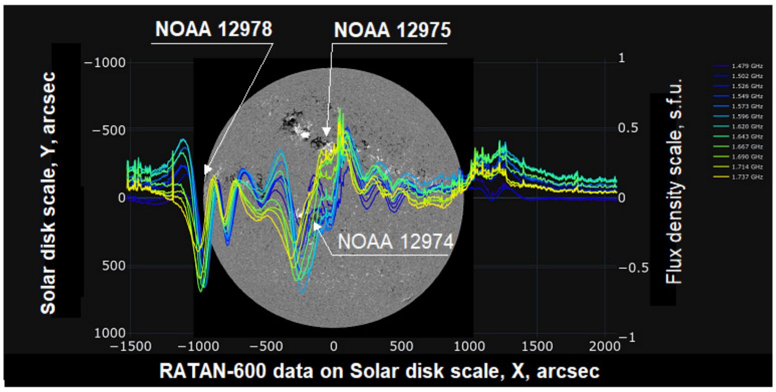

Figure 2: *a* — Set of scans of the emission intensity at different frequencies superimposed for comparison on the HMI SDO photosphere magnetic map. Above all the ARs, characteristic brightening is visible. A plot of weak signals after the removal (by the method of principal components) of strong signal components associated with the signal of the quiet Sun and AR is shown in the bottom part of the image. *b* — Record at 1620 MHz. The plot clearly shows structures with significant absorption (about 1 s.f.u.) for NOAA 12978 (on the limb) and above NOAA 12974, 12975, 12976. *c* — Collection of records in the 1060–2620 MHz range, in which absorptions were registered (see also Fig. 3). The figure implies that the sensitivity of the method for measuring weak signals is about 0.01–0.005 s.f.u. in accordance with the theoretical assessment.

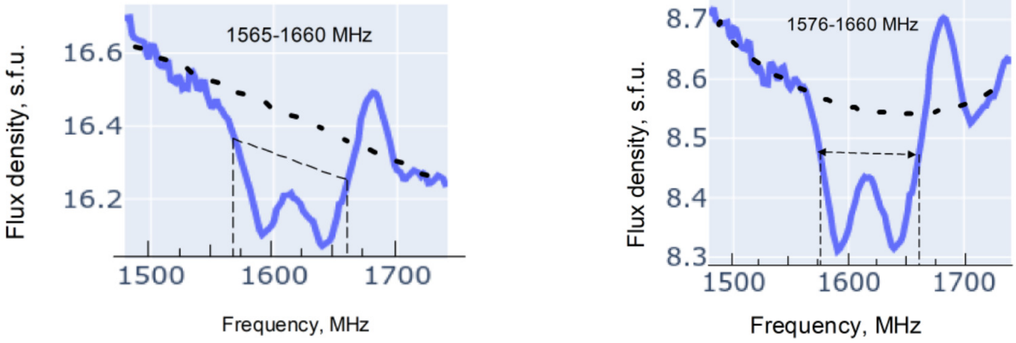

Figure 3: Part of the absorption spectrum in the range 1500–1700 MHz. Left: absorption in the 1565–1660 MHz range above the NOAA 1298 active region (on the limb). Right: absorption in the 1576–1660 MHz range above the NOAA 12974, 12975, and 12976 active regions (in the center of the disk).

channels in intensity and the same number in polarization). The usual duration of one scan of the solar disk is 150 seconds, which at a time resolution of 0.0084 seconds/spectrum gives $150 \times 119 = 17850$ readings. Thus, we have a matrix of 16392×17850 samples. To process and analyze the RATAN-600 multiwavelength data, we used the principal component method, which has long been used in chemometrics [21]. This method is based on a multivariate statistical dimensionality reduction technique used to study relationships between values of scale variables. In the total data array of the Sun, there are signals of different amplitudes, different frequency covariance relationships, which are difficult to distinguish against the background of a powerful signal from a quiet or active Sun. The applied method is implemented as a product of matrices, representing the data space as a sum of mutually orthogonal proper subspaces, excluding cross-correlation of data. To do this, in the data space, the direction of the maximum change in the amplitudes is determined, and a new coordinate system with the minimum dimension values is selected. Thus, the data of the 1st Principal Component is formed. Sequentially, each successive principal component maximizes the residual variation (scatter of data around the previous component) on a new orthogonal basis, and so on. As a result of this definition, the components turn out to be uncorrelated, forming a field of spectral Principal components. These components are sorted by their contribution to the total energy, large-scale structures are represented by a small number of first principal components. The remaining principal components give us the hidden variables we are looking for, given the desired signal-to-noise ratio. When applied to solar radio data, the following are sequentially distinguished: (i) slowly varying radio component and the quiet Sun, (ii) rapidly varying component (bursts), (iii) interfering components, and (iv) Gaussian noise components. With a high spectral resolution, this makes it possible to identify processes in a selected spectral range or in individual regions of the Sun and determine their multicomponent structure [22]. In addition, at this stage the final cleaning of interference is performed. For the preliminary interference cleaning we use a method based on the statistical estimation of the fourth moment of the distribution of signal power values (kurtosis) [19], which makes it possible to distinguish between signals of natural and artificial origin [22]. Such preliminary cleaning makes it possible to effectively carry out further data processing, principal component analysis (PCA) and parallel 3-dimensional factor analysis (PARAFAC) [21].

6. Analysis of observations

The observations made with high radio flux sensitivity, high dynamic range, and high frequency resolution indicate the presence of a fine spectral structure in the corona in the atmosphere above the sunspots. The presence of flare impulsive formations in the corona is often recorded in observations with small instruments. However, here the weak stable spectral inhomogeneities are studied below 0.01 s.f.u. Spectral observations on March 27, 2022 reveal stable absorption regions (with a maximum up to 0.6 s.f.u.) on the eastern limb above NOAA 12978 (see Fig. 2, *a*). The recorded height profile indicates the existence of absorption at a height of 30 Mm, above which there is heated plasma at a height of 40 Mm (with a maximum of up to 0.3 s.f.u.). The other three active regions were located in the center of the disk, NOAA 12974, 12975, and 12976, whose radiation fell into the knife-shaped beam pattern of the RATAN-600. It is characteristic that the total absorption above these regions is recorded in the same frequency range 1565–1660 MHz. Thus, we can summarize the main observational facts.

1. Absorption is stable in certain active regions.
2. The regions in which extinctions were noted were flare-active.
3. The absorption frequency range is generally stable.
4. The absorption value is within 0.2–0.6 s.f.u.
5. The absorption maximum tends to coincide with the tail of the sunspot group.

The main question is what the nature of the recorded absorption is. Two versions are provisionally considered. First, the absorption can be associated with processes occurring in the active area. Second, it can be related to the system of the absorption lines of hydroxyl radical.

7. Possible interpretation of the effect of absorption in the active region in the decimeter range

It can be assumed that the flaring in active regions is a long process, where powerful flares alternate with continuous generation at a lower level. As a result of the continuous moderate effect of magnetic reconnection at the loop vertices of a relatively stable active region, accelerated particles (mainly electrons) are generated, which fly out from the heated region in all directions. In this case, electrons flying down the magnetic field lines pass through plasma layers of different temperatures. In the tail part of the magnetic structure of the active region, magnetic traps can form, in which the temperature is lowered due to a decrease in heat transfer and condensation of hot electrons occurs (such as coronal rain), the density of which increases with time, hence the optical depth rises, and the opacity in these places becomes visible in absorption. It is also possible that cold plasma in traps is the basis for the generation of molecular processes such as the O_2 molecule, or H_2, or CH, etc. Perhaps taking into account Zeeman and Stark effects will clarify the situation [7, 24, 26]. Small-scale condensates with similar temperatures and, possibly, densities (about 10^3–10^4 K, 10^{10}–10^{12} cm^{-3}) can form in coronal loops and appear in observations as the phenomenon of “coronal rain”, which can be observed, for example, in H_α above the limb [27].

The physical mechanism responsible for condensation (a sharp cooling of the plasma accompanied by a sharp increase in density) is most likely a thermal instability that occurs when the balance between heating and cooling of the coronal plasma is disturbed. This scenario requires numerical simulations performed under certain assumptions about the parameters of the heating process, the nature of which remains unknown. Thus, coronal rain is a kind of "hidden" cold and dense matter that exists in compact structures in the corona.

8. Conclusions

The work is devoted to the first results of observations with a new high-resolution spectral complex in a wide frequency range on the RATAN-600 radio telescope. The high sensitivity of the method for measuring weak signals was confirmed, which is about 0.01–0.005 s.f.u. in a wide frequency range. Several new effects were noticed: stable absorption in the 1560–1665 MHz range, uneven thermal distribution in detailed temperature spectra, the effect of absorption on the limb at heights of 15–30 Mm and the brightening above it at a height of 40 Mm were measured. A preliminary interpretation is proposed, which needs further elaboration.

Acknowledgements

Observations with the SAO RAS telescopes are supported by the Ministry of Science and Higher Education of the Russian Federation. The renovation of telescope equipment is currently provided within the national project "Science and Universities".

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