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REVIEWS

Study of the solar atmosphere based on the spectral and polarization observations on the RATAN-600. Achievements and prospects

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Abstract. The current state of solar physics study with the radio telescope RATAN–600 is reviewed. The main parameters of the radio telescope and possibilities of their improving for future observations are described. The role of solar investigations with the RATAN–600 in the world's solar physics is defined.

Key words: sun: atmosphere – telescopes: RATAN-600

1. Introduction

The largest in Russia, and in a number of parameters in the world, the radio telescope RATAN–600 has been used for more than 20 years (since 1974) as a radio astronomy instrument (Parijskij et al., 1981; Korol'kov et al., 1989; Parijskij, 1993). The parameters of the telescope turned out to be unique for a study of the Sun. For reflector-type telescopes, RATAN–600 has a very high resolution, up to 5 arcseconds at the high frequency edge of the working wavelength range, at 8 mm. The design range of the radio telescope extends towards the long wavelengths up to 30 cm. Thus, the telescope covers 5.5 octaves in frequency, which is unique in world practice. This was achieved at a sacrifice in other important parameters, namely, the absence of the tracking mode, which is especially vital for rapidly variable sources (the Sun). By the present time, one observation per 24 hours in the transit mode has been the basic condition of observations. Another demerit of the instrument is the impossibility of two–dimensional mapping.

Experience of operation over two decades has shown that the shortcomings mentioned can be eliminated, the working range can be extended towards both the short and long waves. Temporary analysis of radio emission can be extended from a few hours to the tracking mode with a resolution as high as fraction of a millisecond. There is also a possibility of increasing the spatial resolution.

The objective of the paper is to report the results of solar radio radiation study that have already been obtained with the radio telescope RATAN–600, to show its position among other radio telescopes of the world and to describe fundamental present-day problems of solar physics which can be solved with it.

2. Physics of the Sun and scientific progress

All multiformity of various structures observed in the solar atmosphere, as well as the solar activity for the last few decades have been associated with the magnetic fields of the Sun. Investigations (both experimental and theoretical) of these features are the basic ones in the study of solar physics in the middle of the XXth century. Solar physics was often a convenient "testing ground" for the development of methods of plasma physics, and the study of behaviour of plasma of the corona was treated as a possible source of ideas for solving the problem of thermonuclear reaction control.

Meanwhile, over the last two decades there conceived an idea that the reason of structurization is not only in the magnetic fields, but also in the nonlinearity of the basic equations that describe the behaviour of plasma (clearly defined structures are observed in the Earth's stratosphere as well, where magnetic fields are not so significant). It does not mean at all that the solar atmosphere physics can be studied without measuring and analysing the magnetic fields, but this implies the necessity of application of an essentially non-linear theory (and numerical experiments) in solution of appropriate problems, in particular, in study of instabilities which may be responsible for the origin of structures.

In this connection the Sun offers a unique possibility of detailed study of plasma structures of cosmic scale with cosmic life times, but yet amenable to our detailed study and with a wide scale of temporal variation – from milliseconds to hundreds of years. It seems to us that it is this fundamental problem of modern science that the major interest of mankind in physics of solar phenomena will be connected with. Below we describe the contribution made by investigations with the RATAN–600 to the study of various solar structures and possible prospects in this direction.

At the same time the interest to the problems of solar physics, as a part of problems of solar-stellar physics, is being growing.

At last, the applied aspects of the study of solar activity, which is accompanied by hard electromagnetic radiation, ejection of plasma and cosmic rays will remain an important stimulus in investigation of the Sun. It may be expected that a number of research programmes will be focused on the search for ways of transition from empirical to physically grounded methods of prediction of geoeffective actions of the Sun.

3. Results of solar observations with the RATAN-600 (1975-1996)

Observations of the Sun with the radio telescope were initiated on November 3, 1974, and the most important results were obtained owing to the unique combination of the following characteristics of the instrument:

- detailed coverage of the range 0.8-32 cm (as many as 12 wavelength bands until 1991 and over 45 wavelengths at present);
- good sensitivity for measurements of circular polarization of radiation (of the order of 1-1.5 % for the whole Sun and less than 0.1 % for point sources);
- possibility of making long series of daily observations (monitoring and target-oriented programmes);
- moderately high spatial resolutions ($5''$ in one coordinate in the short-wave part of the working range at 8 mm).

This allows us to do the diagnostics of plasma physical parameters in a wide class of plasma structures of the solar corona and chromosphere (Table 1). As follows from the table the investigation of the Sun on the RATAN-600 embraces a wide range of its atmosphere: from radio emission of the chromosphere network (radio granulation), various structures in active regions to outer structures of the solar atmosphere (solar wind).

The spectral and polarization studies of the Sun at the radiotelescope formed the basis for development of radio astronomy techniques to measure magnetic fields in different coronal structures. The following methods were developed:

- method for measurement of strong (up to 2000 G) magnetic fields in the corona above the spots based on the gyroresonance mechanism of radiation at the first three harmonics of gyrofrequency (Akhmedov et al., 1982; 1987);
- method for measurement of weak magnetic fields in the low-contrast structures (of flocculus type, Bogod et al., 1980), coronal loops (Korzhavin et al., 1994), prominences (Bogod and Gel'freikh, 1978) and filaments (Korzhavin et al., 1994);
- magnetic field measurement method at elevations of 100-200 thousand km using the circular polarization effect (often repeated) of sign inversion (Gel'freikh et al., 1987; Bogod et al., 1993);
- method of magnetic field measurement of the large-scale sector structure of the Sun from the Faraday effect. In the past few years increasing attention has been given to the development of techniques for investigation of the three-dimensional structure of solar formations;
- method of angular and spectral radio tomography (Bogod et al., 1994; 1996) using azimuthal and spectral observations with the RATAN-600.

4. The solar corona structure

4.1. Radio characteristics of the quiescent Sun

Multifrequency observations of the Sun with a high spatial resolution make it possible to get information on radio characteristics of the quiescent Sun, such as spectral dependence of the radio radius, spectrum of brightness temperatures, distribution of radio brightness from the centre towards the limb. It is only on the RATAN-600 that all the characteristics can actually be obtained simultaneously during one observation.

The data obtained with the radiotelescope are consistent with those obtained with large VLA, WSRT, OVRO telescopes and with the X-ray data. The data are evidence of inhomogeneous structure of the quiescent atmosphere and that different small-scale structures, such as chromospheric network, spicules and macrospicules, coronal loops, minor bipolar structures, X-ray points, etc., need to be taken into account (Borovik et al., 1972; 1990; 1993).

Table 1: *Results of the Sun observations obtained with the RATAN-600 (1975-1996)*

Object	Results	Physics problem
	Quiescent Sun	
Brightness distribution on the limb	Uniform limb, stability in the cycle	Nature of radio source at elevations (7-30)·10^3 km, models
Radio granulation	Sizes, $T_B(\lambda)$, $gradT$, H_{rad}, optical identification	Atmosphere models
Prominences	$T_B(\lambda)$, $gradT$, H_{rad}, N_e	Models
	Regions with low T_B	
Coronal holes	ΔT_B, spectra (2–30) cm	Atmosphere models, relation with cycle
Filaments	Sizes, identification	Models, geophysical effects, predictions
Filament cavities	Sizes, identification	Mechanisms, models
	Active regions	
Spot sources	$T_B(\lambda)$, $gradT, H_{rad}$, $gradH$, structure	Inhomogeneous models
Flocculi, faculae	$T_B(\lambda)$, $gradT, H_{rad}$, N_e, structure	Atmosphere models, relation with cycle
Loops, condensations	$T_B(\lambda)$, $gradT, H_{rad}$, N_e, elevations	Models
Peculiar sources	Detection, $T_B(\lambda)$, non-thermal spectrum	Mechanisms, plasma turbulence, particle acceleration
Decimetre halo	Non-thermal spectrum, structurelessness	
	Magnetic fields	
Thermal bremsstrahlung	H estimates in flocculi, loops, prominences	Adequate atmosphere models
Cyclotron radiation	$H_{rad}, gradH, H_{rad}/H_{opt}$	Spot magnetosphere
Polarization inversion	Detection, $T_B(\lambda)$, non-thermal spectrum	Three-dimensional magnetic field structure
Faraday effect	H in corona during a cycle	
	Bursts	
MM-sources in corona	Identification at cm wavelengths, I and V spectra	Atmosphere models, relation with cycle
Slow bursts	Spectra, polarization, generation mechanisms	Models, geophysical effects, prediction
Pulse bursts	Multicomponent structure of ordinary bursts	Mechanisms, models

4.2. Radio granulation

In the first years of solar observations the RATAN-600 was mainly operated as a combination of the Northern sector of the circular antenna and the Feed as a non-symmetric parabolic cylinder (Parijskij et al., 1972). In that case it turned out important to realize high two-dimensional resolution, which can be attained at high angles of observation (in summer it is $12'' \times 72''$ at 2 cm). Different procedures to compensate for the strong signal of the quiescent Sun and to isolate the small-scale structure (called radio granulation) were developed. This allowed us to detect radio granulation at several wavelengths of the centimeter range, to reveal correlation with the K CaII line granulation, to determine characteristic sizes ($30'' - 50''$), to establish the mechanism of radiation (thermal bremsstrahlung), to estimate the magnetic field (< 3 G in an area of $24'' \times 2\rlap{.}'4$) and the life time of such radio granules $6^h < t < 24^h$ (Bogod, 1978). The results obtained are used in a number of modern models of the solar atmosphere structure (Gel'freikh et al., 1987).

4.3. Radio emission of floccules, loops and condensations

The high sensitivity of the RATAN-600 enabled observations of floccules, coronal loops and condensations in a wide wavelength range, which is difficult to do with other instruments. It was managed for the first time to make magnetic field estimates in such structures. Their radiation is quite satisfactory described by the thermal bremsstrahlung mechanism when the fields are weak (a few tens of gauss). Measurement of polarized radio emission at several wavelengths is the basis of the method (Bogod et al., 1992).

The method of magnetic field estimation in loops at great (100-200 thousand km) heights in the corona is of importance. This technique is based on the effect of inversion of the sign of circular polarization of emission from spot sources, when the radiation traverses the regions of quasilateral magnetic fields (Gel'freikh et al., 1987).

4.4. Prominences and filaments

The first observations of prominences at the radiotelescope (Bogod and Gel'freikh, 1978) were compared with the observations in the CaII line, which gave the first estimate of their maximum magnetic field and emission measure. This work stimulated later extensive investigation of prominences at other instruments.

4.5. Coronal holes

For the first time comprehensive studies of coronal holes in a wide wavelength range were carried out (Borovik et al., 1990; 1992; 1993). During the solar cycle the contrast of coronal holes (CH) was found to increase in the periods of minimum solar activity. The effect of changing radio radius of CHs at sunrise and sunset can be used for prediction of geoeffective events.

4.6. Active regions on the Sun

Due to the complex structure and a great variety of processes occurring in the active regions on the Sun, they attract much attention in investigations with the RATAN-600. Based on long-term observations (including observations at LPR), detailed classification of the sources that compose the structure of active regions was made, their observational characteristics, such as intensity and polarization spectra, sizes, heights, magnetic field strengths were studied. The radio data were compared with the optical and X-ray data.

Fig. 1 shows the generalized structure of the active region. It includes:

- sources located above the spot umbra (spot sources);
- flocculus radio brightenings, which surround spots and their penumbras;
- coronal loops and condensations;
- sources located above the magnetic field neutral line and at the places with a magnetic field of delta configuration ("peculiar sources");
- wide structureless formation with a maximum of radiation in the decimeter range (decimeter halo).

4.7. Spot sources

Radiation of spot sources has been established to be well described within the frames of thermal magnetic bremsstrahlung mechanism at the first three harmonics of gyrofrequency. This made it possible to develop a method of magnetic field measurement at the level of chromosphere – corona transition layer, which is based on spectral and polarization observations (Akhmedov et al., 1982). A comparison of the coronal magnetic fields measured by the radio astronomy technique with the fields on the photosphere shows that $H_{rad}/H_{opt} = 0.8$ in a wide range of magnetic field values. As subsequent observations showed H_{rad}/H_{opt} may serve as an index of the magnetosphere state and suggests excess currents in the corona (for large values) and possible turbulization of plasma in the corona (for smaller values).

4.8. Peculiar sources

These unusual sources were first detected with the RATAN-600 in cooperative (VLA, USA) observations in June 1992.

They generally appear with emergence of a new magnetic flux on the photosphere and in the periods of powerful flare (proton) activity. Their basic parameters are as follows: range 2-4 cm, stable radiation for 3-5 days, size and elevation about 10000 km, degree of circular polarization 10-30 %, high brightness temperatures 10^7 K. A characteristic distinction of the flux spectra is a high spectral index, n=10, at 3-4 cm. Such spectrum features are similar to those of gyrosynchrotron radiation of hot electrons ($T = 10^7 - 10^8$K) with a Maxwell distribution in velocity in moderate magnetic fields, which may be considered as a possible version of interpretation (Akhmedov et al., 1984; 1986; 1987; Vatrushin et al., 1993; Korzhavin et al., 1989; 1994; Sych et al., 1993).

Based on a lot of data it can be stated that peculiar sources define the sites with constant powerful energy release, possibly, in the form of current layers accompanied by heating the corona to 10^8 K, or these are a variety of long-lived bursts of the type of slow rise and fall.

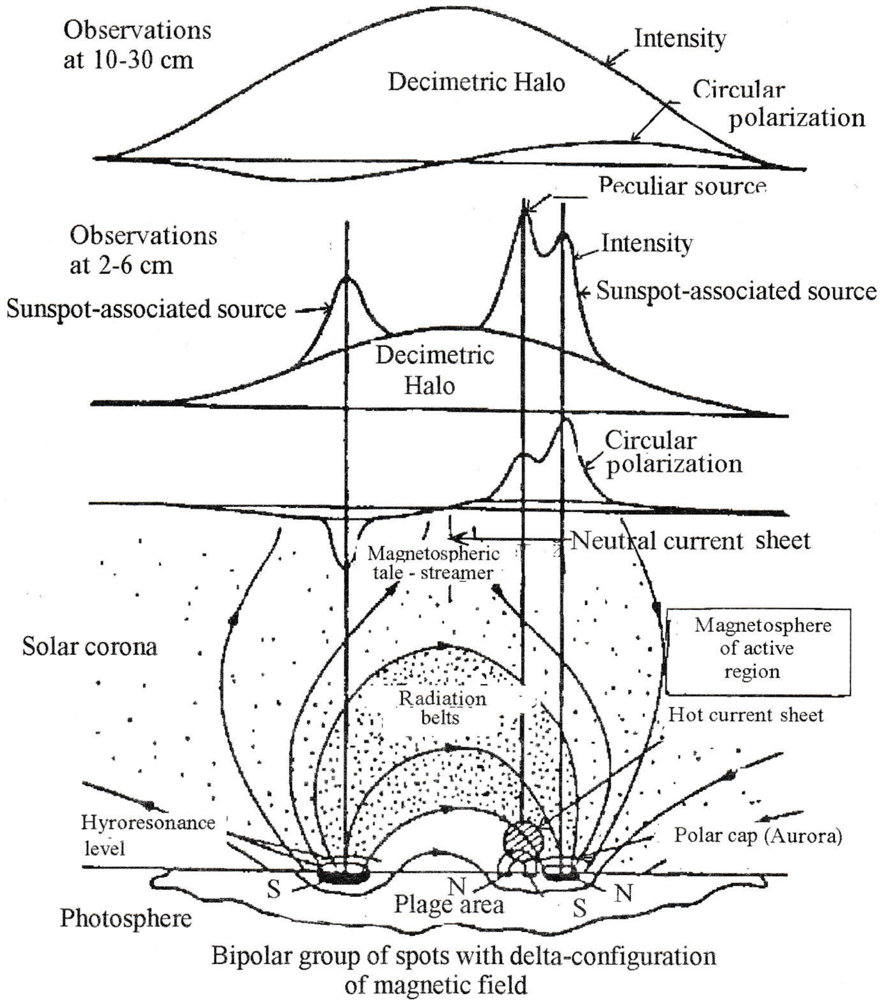

Figure 1: *The generalized structure of the active region and its magnetosphere depicted on the basis of the set of observational data. At the top are shown the scans in intensity I and circular polarization V for the centimeter and decimeter wavelengths. In the radio ranges are recorded the thermal emission of the spot sources above the spot umbras, the non-thermal emission of peculiar sources above the hot current layers, the non-thermal emission of the halo in the decimetre range above the whole active region and the thermal emission above the flocculi.*

4.9. Decimeter halo

This weak wide diffuse structure was also detected with the RATAN-600 (Akhmedov et al., 1986; 1987). It covers the whole active region and is likely to be a fundamental element of its structure. The halo is present nearly in every (weak or strong) active region. It can be found even in active regions composed entirely of plages. The maximum of the halo flux spectrum is observed at the decimeter range, at 20-30 cm waves and is shifted shortward to 8-15 cm for strong active regions. The behaviour of the well-known index of solar activity at 10.7 cm, which is well correlated with the Wolf numbers in optics, is, apparently, due to the existence of such a halo.

The gyrosynchrotron emission of subrelativistic electrons with a power distribution in energy held in magnetospheres may be the most likely mechanism of halo radiation (see, for instance, Korzhavin et al., 1992). The drop of the spectrum towards the long-wavelength edge is due to the scattering of the emitted radiation on the waves of plasma turbulence excited by the same population of electrons.

On the whole one may speak of the halo as of extended continuous processes in the radiation belts of magnetospheres of active regions (Lang et al., 1993), which are accompanied by acceleration of particles.

Both the peculiar sources and the decimeter halo represent new-type objects, and their observational characteristics are not described by the thermal mechanism.

4.10. Active regions and noise storms

A comparison of spectra of solar active regions from high spatial resolution observations made on the RATAN-600 (S component) in the microwave range with the flare component of the VLA observations revealed (contrary to the present-day knowledge) the existence of a powerful and prolonged noise storm precisely in the region of the weak decaying active region (with strong ARs on the disk). The data obtained suggest the "decimeter halo"-type component of active regions to be directly related to long-lived sources of noise storms. This is a decisive corroboration of the fact that such a halo contains non-thermal particles even if it is not associated with relatively simple magnetic configuration in the photosphere (Bogod et al., 1995).

On the other hand, it was found that in active regions with noise storms the polarized microwave radiation of spot sources undergoes repeated (often narrow-band) inversions of the sign as it traverses the complex magnetic structure of the active region. Such phenomenon can be explained by the presence of a spatially narrow structure of the type of current sheets, the theory of which is commonly used in solar flare models. Further investigation will prove the validity of this interpretation and possibility of localization of theoretically predicted current layers in the upper layers of the solar atmosphere (Bogod et al., 1996).

4.11. The conception of the active region magnetosphere

The above mentioned data of observations with a high spatial resolution, and with a detailed spectral-and-polarization analysis of the structure of coronal magnetic fields and localization of regions that release thermal and non-thermal energy led to development of the concept of MAGNETOSPHERE of the active region by analogy with the magnetospheres of the Earth, planets and some stars.

At the photosphere level magnetic fields and their variations are caused by subphotospheric motions (currents) of plasma. Investigation of magnetic field in the corona is quite amenable to radio astronomy techniques with a hight spatial resolution. The decimeter halo radiation is supposed to be due to accelerated electrons captured by magnetic loops, and may be an analogue of the Earth's radiation belts.

5. Radio astronomy and physics of the Sun in XXI century

It is apparent the further development of solar physics must be based on observational programmes in which the selected objects of the solar plasma structure is analyzed concurrently in all possible wavelength ranges with the use of the most advanced facilities and observational techniques (Figs. 2 and 3).

The radio astronomy techniques prove to be capable of solving problems that practically can not be resolved by other means of ground-based and space astronomy. Among these are measurements of magnetic fields in the corona of the Sun and upper chromosphere, diagnostics of plasma turbulence, electron fluxes through the corona. In a number of cases the radio astronomy methods of measuring the local electron density, temperature, emission measure, diagnostics of electron acceleration turn out to be the most efficient, although these parameters can also be measured from observations in other ranges – primarily in the X-rays (from satellites). It should be noted that the radio astronomy method has still been young in the study of plasma structures in the solar atmosphere. A radio spectrum covers a wide multioctave wavelength range, therefore a great variety of objects can be observed applying different methods of analysis. In the radio range we can study radiation of the upper layers of solar atmosphere: from the upper layers of chromosphere (at short millimetre wavelengths) to the regions responsible for generation of solar wind (metre range). This atmosphere range is characterized by large differences in physical parameters of plasma.

- The brightness temperatures vary from 10^4 K to $10^{12} - 10^{15}$ K.
- The magnetic field varies from a few gausses (total magnetic field of the Sun) to a few thousand gausses (4000 G has been recorded).
- The plasma densities in the solar atmosphere vary between 10^6 cm^{-3} and 10^{12} cm^{-3}.

Studying of multiparameter plasma is impossible with one instrument only, and important results are generally obtained in observations with a number of radioastronomical instruments, optical devices and space-borne facilities involved. On the face of it, the very different instruments exist in the world to meet the requirements of radio astronomy, however under closer scrutiny it is evident the potentialities of radio astronomy are far from being fully realized. Two-dimensional images of space objects in the widest spectral range (image spectroscopy) are likely to become the principal gain of information. However this approach at radio wavelengths with an angular resolution of $1'' - 10''$ (reached in optical and X-ray ranges) is yet far from being realized. For such an ex-

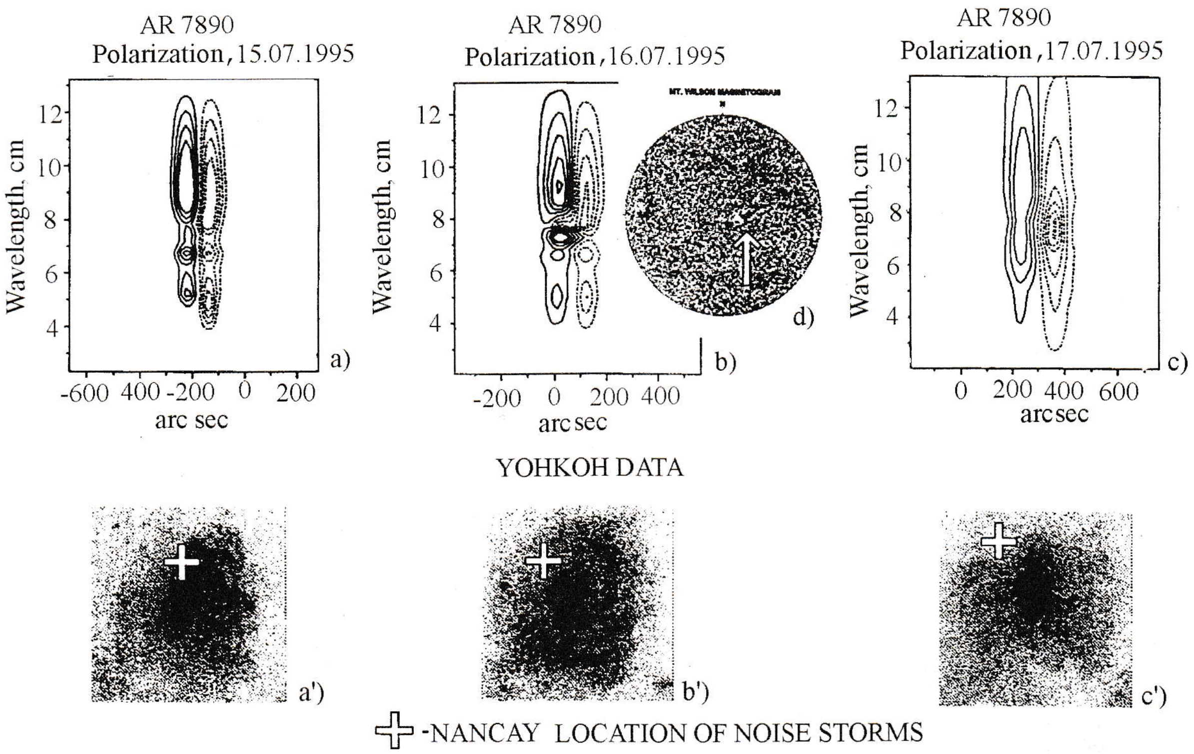

Figure 2: *Observations of the active region AR 7890 in different ranges of the electro-magnetic spectrum. a), b), c) — the spectra of scans in polarization for three days of observations, d) — the map of the magnetic fields (obtained at Mt. Wilson). a'), b'), c') — the two-dimensional images of the active region from the soft X-ray YOHKOH data. The crosses indicate the localization of the noise storms from observations with the heliograph of Nancay (France). Correlation is seen between the unusual effects in X-ray and radio ranges.*

tended and variable object as the Sun the problem is complicated by the fact that it is necessary to obtain simultaneously a wide field of view (about 3000″) with a high temporal resolution (milliseconds).

In accordance with the above discussed concept, observations must be conducted in all ranges of solar radio emission. Here we are concerning with the microwave range since we have a wealth of experience of investigation at the RATAN-600. As compare with such telescopes as the VLA and WSRT, this radio telescope has a lower spatial resolution, however it allows more complete spectral measurements in the range 0.8–30 cm. Besides, owing to the design of the telescope, long series of investigations of the Sun turned out possible without serious interference for other observing programmes. In solar observations this merit of the RATAN-600 is of importance.

Attention is attracted by the remarkable variety of solar atmosphere structures, which proved to be accessible to observations with the radiotelescope, as well as by the diversity of diagnostics methods of solar plasma, especially coronal magnetic fields, developed on its basis. The data are given in Table 1. The observational results of coronal magnetic fields above the spots and the detection of the long-living local sites of non-thermal energy release in the corona of active regions deserve a particular attention. These problems could not be resolved without a detailed spectral analysis in the radio range in combination with accurate polarization measurements which are practically lacking at other large telescopes.

6. Development of the RATAN-600 for solar studies

Radio diagnostics of solar plasma is greatly dependent on the telescope parameters such as completeness of spectrum analysis, accuracy of polarization measurements, spatial resolution, dynamic range, possibility of long-term observations (during the day and daily during the year). Being at a disadvantage in resolution as compared to the VLA and WSRT, RATAN-600 made it possible to have more complete spectrum analysis and more accurate polarization measurements as well as an essentially larger amount of observations. This allowed effective measurements of coronal magnetic fields and diagnostics (and localization) of extended non-thermal processes in the magnetosphere of the active region on the Sun. At the same time new important results in physics of

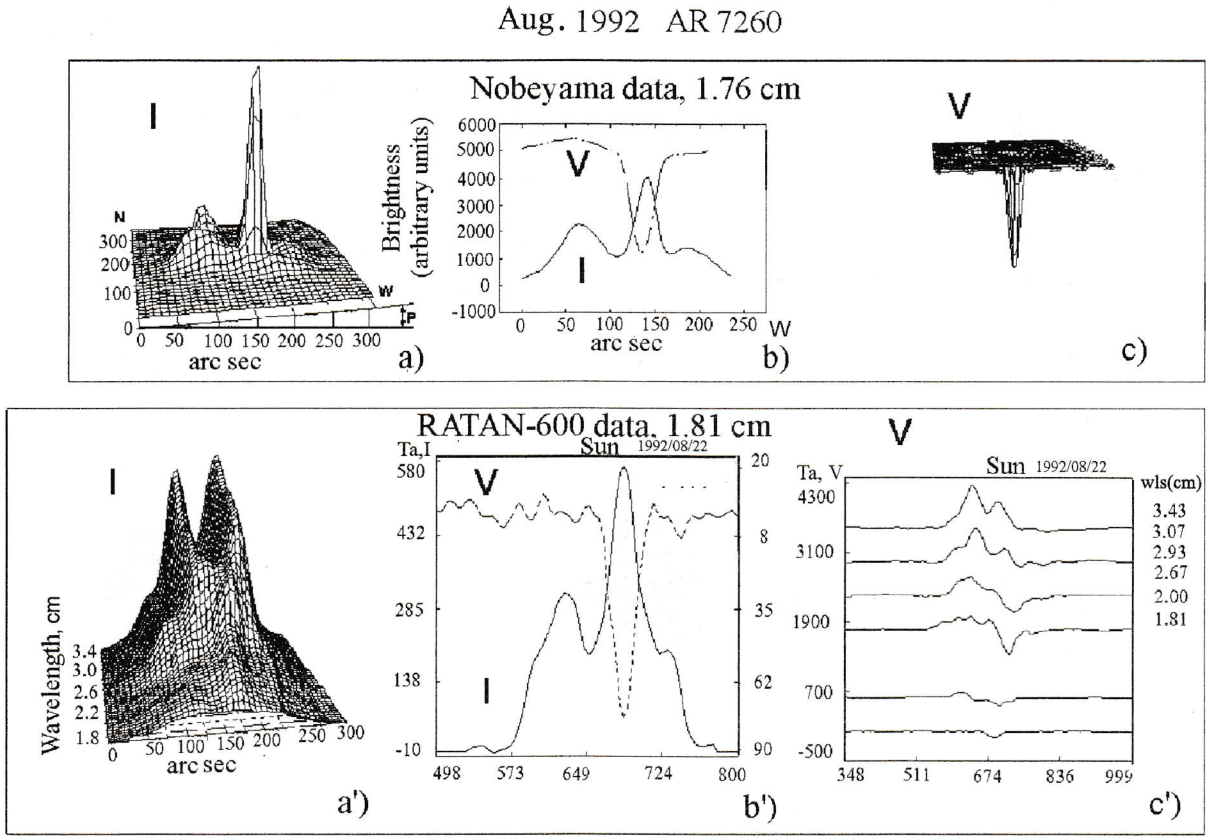

Figure 3: *An example of joint observations of the Sun with the Nobeyama heliograph (Japan) and RATAN-600 at several wavelengths in the centimeter range. a) — the two-dimensional intensity map at 1.7 cm (Nobeyama), b) — the same convoluted with the knife beam pattern of the RATAN-600, c) — the two-dimensional circular polarization map, a') — the multiwave spectrum of the RATAN-600 scans, b') — the RATAN-600 observations at 1.81 cm, c') — the scans at seven wavelengths in polarized radiation. It is seen how two-dimensional and spectral data obtained with the two instruments complement each other.*

the Sun, which could not be obtained at the RATAN-600 because of insufficient resolution, were obtained with the aperture synthesis antennae. It should be noted, however, that for 20 years of solar investigations with the RATAN-600 its antenna parameters were not used to full advantage. Observations were basically carried out with an aperture of 260 × 5 m, while it can be brought up to 600 × 400 m. Two-dimensional mapping of the Sun was not actually made, although effective multifrequency heliography with instantaneous mapping of the entire solar disk was possible. A very limited amount of observations was used for the study of dynamics of sources.

6.1. Spectral investigations

For spectral investigations with the RATAN-600, a panoramic spectral analyzer (PSA) has been designed and is being developed to enable coverage of the whole frequency range of the antenna (0.8-30 cm) (Fig. 4) and beyond its limit (to 5 mm towards the short-wave side and to 50-100 cm on the long-wave side). This analyzer ensures concurrent analysis of the spectrum of the whole range with a band of 5 % frequency resolution and is unique in radioastronomical studies of the Sun (Bogod et al., 1988; 1993).

The device resolves the problem of fast simultaneous recording for all the channels, and now the recording is as fast as 1 ms. This is vital for the tasks on localization and bursts analysis at the initial stage (spike-type processes) in a wide wavelength range and for determination of structural, temporal and frequency relations.

This kind of investigations carried out by a unified technique provide a bulk of new data for major studies of solar physics and solar-terrestrial relations.

6.2. Study of temporal characteristics of solar structures

The importance of study of dynamical properties of individual solar structures, acquisition of multioctave spectra of intensity and circular polarization can not be overestimated for such a variable object as the

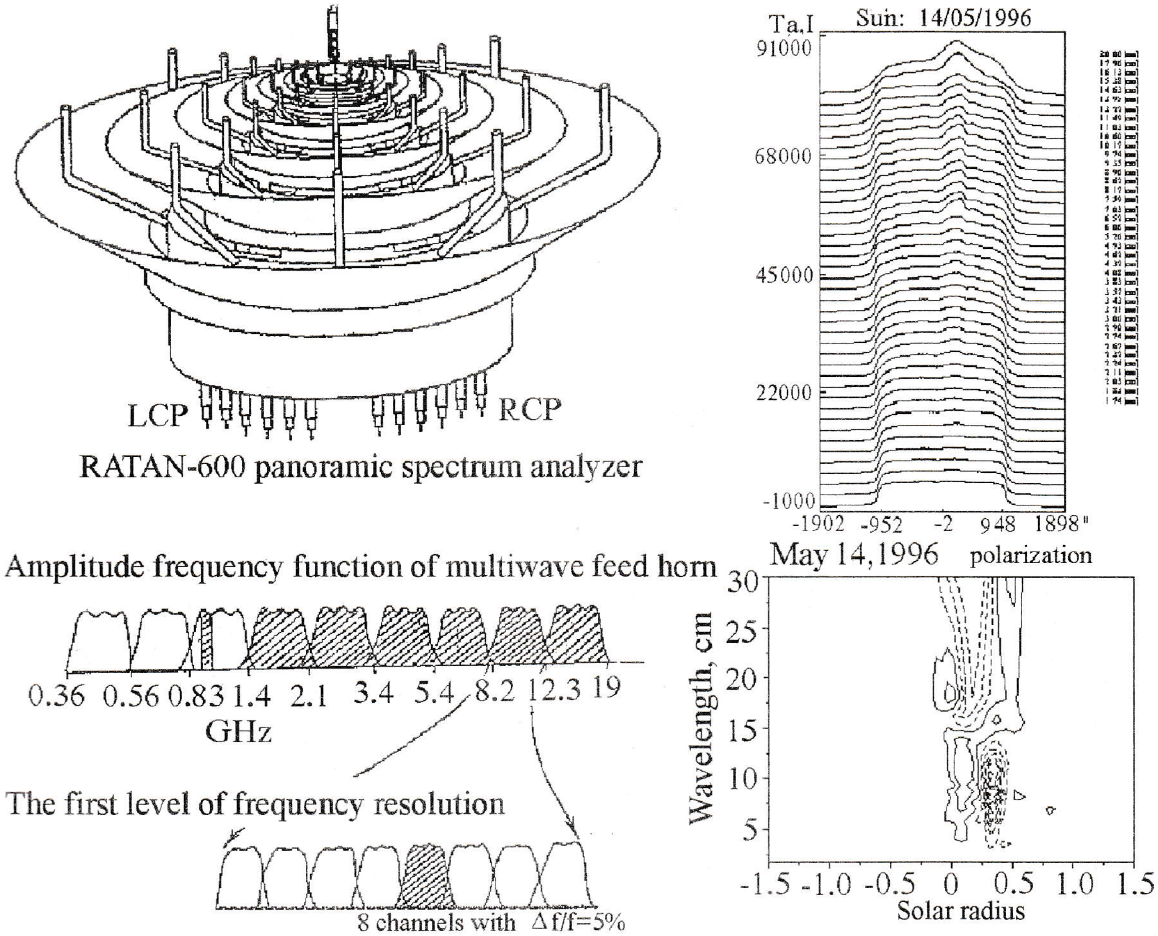

Figure 4: *The input multiwave feed for the frequency range from 0.83 GHz to 18 GHz. The multioctave range is broken up into seven subranges, each being divided into eight channels with a frequency resolution of 5%. At the top (right) is an example of observations of the Sun at 39 wavelengths (the wavelength increases upword from the short wavelength, 1.74 cm, to the long wavelength, 30.0 cm) in intensity, at the bottom right is the circularly polarized radiation within the same wavelength range of a weak active region at the centre of the Sun (enlarged scale).*

atmosphere of the Sun.

Two regimes (tested casually) of frequent (with an interval of 5-15 min) observations of the Sun during 4 hours are possible. One of them involves the movement of the South sector secondary mirror with the periscope on the circular rails, and simultaneous moving of the main reflector and the periscope. Under this condition the beam of the telescope is knife-edge, which is often convenient for observations of all objects on the Sun. The beam turn angle in the azimuth reaches $\pm 8°$ and can be used for two-dimensional mapping of stable objects.

Another mode was proposed by Golubchina and Golubchin (1989), in which the secondary mirror is positioned at the centre of the telescope, while the different parts of the main reflector is being pointed on the Sun in turn during diurnal rotation of the Earth. Under this regime extended (6-8 hours) observations with short breaks are possible. This is occasionally utilized to perform the tasks that do not require high spatial resolution (the resolution here is three times as low as that of the full sector of the radio telescope).

We are pinning our hopes on observations with the South sector and periscope, which will be working in the Schmidt telescope mode. The source tracking time in this mode of observations may reach 1-2 hours.

And finally, it is naturally that on completion of the instrument automation project, extended (4 hours) observations will get regular and open a new page in study of dynamics characteristics of solar structures by means of the RATAN-600.

6.3. RATAN-600 as a multirange radio heliograph for instantaneous mapping

The research work on the development of mapping techniques on the RATAN-600 performed for a number of years (Gel'freikh and Opeikina, 1992; Bogod

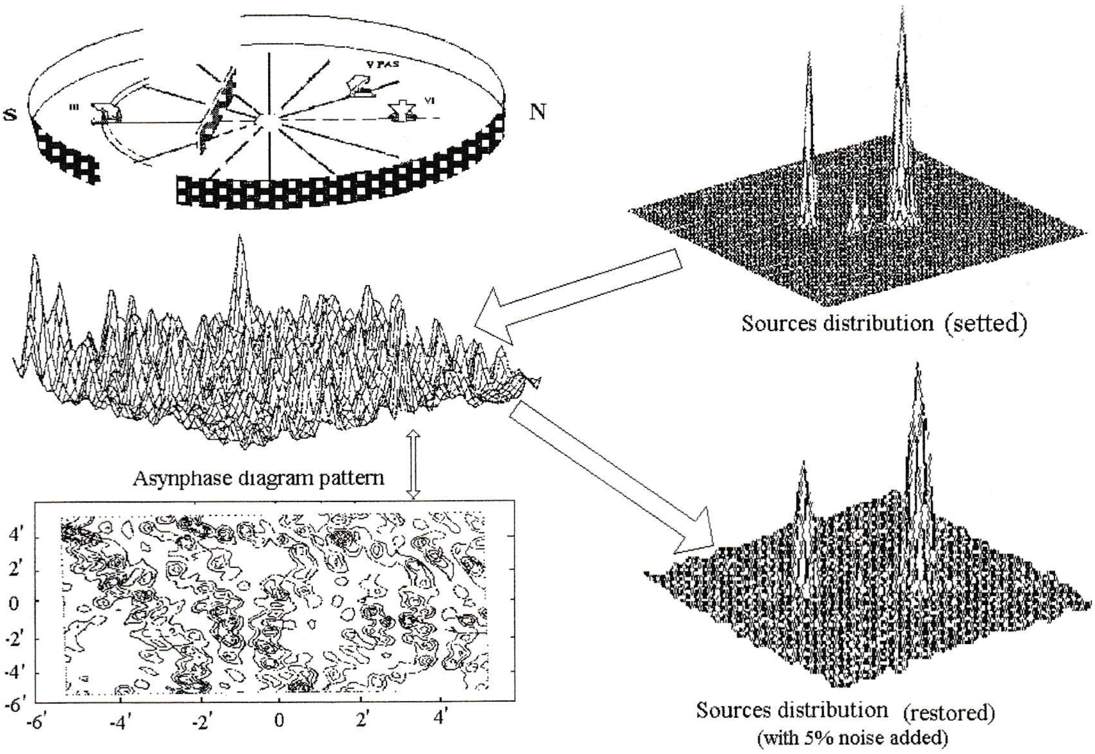

Figure 5: *RATAN-600 in the heliograph mode.*

and Grebinsky, 1996) resulted in creation of a project of a radio heliograph with the parameters superior to those of the existing instruments. The idea of the new-type heliograph consists in using non-coherent illumination of the antenna aperture whose beam pattern comprises a few hundred lobes comparable in power with sizes of order λ/D, where λ is the wavelength and $D = 600$ m is the size of the mirror. The lobes are distributed in space in a random but known positions. This permits the combination of a high angular resolution and a wide field of view of the order of the solar diameter ($0.5 - 1^\circ$ in cm range) to be realized. The Sun image is obtained as a result of its moving across the multilobe frequency-dependent beam pattern with a correlation interval of 1-5 MHz. (Fig.5).

The spectrum analyzer of the 256-512 channels raises the sensitivity, thus making faint objects accessible to the instrument, and increases the rate of mapping for bright sources (radio bursts) to 1 ms (for observation of spikes which are the most direct evidence of particle acceleration in active regions).

For the first time multifrequency high-speed radio mapping with a field of view $> 30' \times 30'$ turns possible, which cannot be done with other instruments of the world. Fig.6 shows a comparison of the radio heliograph parameters in axes: angular resolution–frequency with other instruments of the world used or to be used in solar observations. Its parameters in millimeter range are seen to be fair for adequate comparison of the radio, optical and X-ray ranges.

6.4. Techniques of the corona three-dimensional structure study

Spectral and polarization measurements of the Sun can be used for the development of the projection and emission tomography methods for the purpose of reconstruction of the three-dimensional structure of solar sources (Bogod et al., 1994; Bogod and Grebinsky, 1996). From their projections under the conditions of solar corona this will make it possible to study the spatial distribution of the emission measure and the character of inhomogeneities of structural elements from the radio emission in the centimeter and decimeter ranges. The three-dimensional modelling of the quiescent Sun regions, coronal holes and magnetospheres of active regions above the spots will result in the refinement of the physical mechanisms responsible for the corona heating and for the cyclic events of solar activity.

Three directions of tomographic investigations are being developed on the RATAN-600.

1. Emission tomography. Observations of the one and the same object at several wavelengths allows the

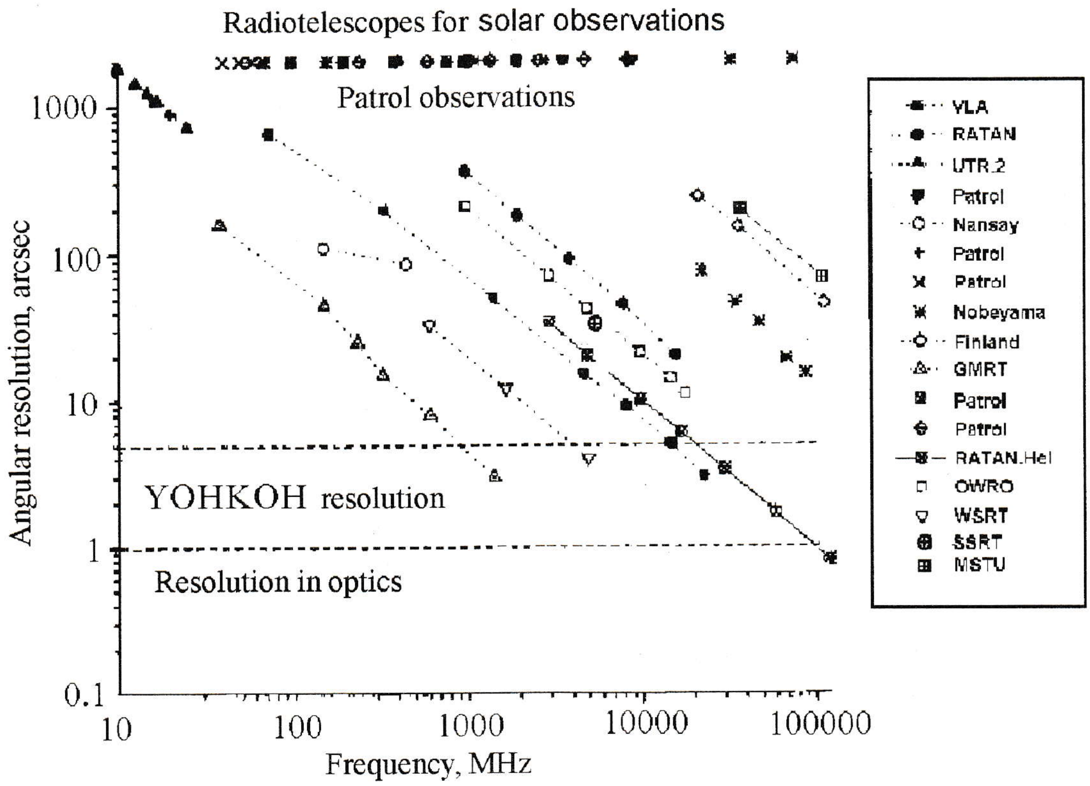

Figure 6: *Comparison of the radio heliograph parameters with the parameters of other instruments of the world (used or to be used in solar observations) in the spatial resolution — frequency axes. It can be seen that in the millimetre range observations with the RATAN-600 are comparable in spatial resolution with optical and space-borne observations, which makes adequate comparison of ranges.*

contribution made by different layers to the radiation to be separated and the temperature and density of each layer to be determined.

2. Projection tomography. Observations of one and the same object at different angles enables acquisition of data on its three-dimensional structure.

3. Solar spectroscopy. Correlating two images of an object at different angles one can find its height from the relative shift of its projection with the use of the proper rotation of the Sun.

7. Conclusion

We believe that solar radio astronomy and the radio telescope RATAN-600, in particular, hold much promise for studies of solar physics. With a sufficient financial support, not only Russian but also worldwide astrophysics will have a unique instrument capable of promoting the study of structurization of solar plasma as part of general physics. This advance will turn out possible provided that solar observations are conducted within the frames of international projects. Attention should be paid to the fact that such an approach requires target-oriented funding for establishment of communication with other observatories and for the facilities of fast processing of observational data as well as for their astrophysical interpretation and making them available to the users. These measures, when put together, with sufficient funding and manpower resources will ensure effective research in the field of solar physics for a number of decades.

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