Observations of the sun with the RATAN-600 radio telescope—preliminary results

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Some results are reported of the first test observations of solar radio emission with the RATAN-600 radio telescope. The antenna parameters, instrumentation, and observing techniques are described briefly. Various classes of objects that can be investigated with the RATAN-600 are outlined.

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1. INTRODUCTION

Since July 1974, several series of centimeter-range observations of the sun (λ = 2–13 cm) have been made with the north section of the RATAN-600, the radio telescope of the Special Astrophysical Observatory near Zelenchukskaya in the Caucasus.[1–3] The aim of these observations has been to ascertain the capabilities of the radio telescope as an instrument for solar research, and to develop observing and data reduction techniques. This one instrument combines high resolving power (up to 12"), large effective area ($\approx$1000 m^2), and wide-band (Δf = 1000 MHz), high-sensitivity receivers. Together with its ability to measure spectroscopic and polarization parameters, it significantly extends the class of accessible objects compared to those investigated with the large Pulkovo radio telescope,[4,5] and those observed with multielement solar interferometers.[6–8]

In the past few years, however, several surveys of the sun have been made in the centimeter range yielding fundamentally new results. The largest modern radio telescopes have been employed for this purpose, such as the three-element interferometer of the U.S. National Radio Astronomy Observatory, the 100-m fully steerable paraboloid at Bonn, and the Nançay system. Observations with these instruments have shown that an improvement in the resolving power along with an increase in the radio sensitivity will permit essentially new objects to be detected on the sun, including small areas with 5-min brightness fluctuations[9] and irregularities in the brightness distribution over the quiet sun.[10,11]

We offer in this paper a brief description of the main classes of objects that have been found during the early trial period of the RATAN-600. The design specifications of the radio telescope and the availability of a special instrumental complex have enabled regular studies of the sun to be carried on concurrently with other programs in which the RATAN-600 is engaged. This opportunity has been a most valuable one for so variable an object as the sun.

2. INSTRUMENTATION

The observations reported here have been made with all or part of the surface of the northern section of the antenna, which comprises 225 reflecting elements forming a 90° circular arc. For observations during the summer months the characteristic size of the antenna aperture was 408 × 75 m, and for winter observations, 310 × 18 m, determining the size of the main lobe at the half-power level (12" × 1'.2 at λ = 2 cm in the summer). The radiometers were mounted on a feed with a secondary reflector having the shape of an asymmetric parabolic cylinder. Most of the observations of the sun utilized a complex of medium-sensitivity radiometers, comprising five receivers operating at wavelengths λ_1 = 2.0 cm, λ_2 = 2.3 cm, λ_3 = 2.7 cm, λ_4 = 3.2 cm, and λ_5 = 4.0 cm. These are of standard design[12] using solid-state elements (the principal components are a solid-state local oscillator, a low-noise diode mixer with a Schottky barrier, and a wide-band transistorized i.f. amplifier) with high stability (about 1% per hour) and high operational reliability.

Table 1 gives the chief radiometer parameters. The wide-band transistorized amplifiers (600 MHz) and low noise temperatures of the receivers ensure high radiometer sensitivity to a flux density of (1–3)$\cdot 10^{-26}$ W$\cdot$m$^{-2}\cdot$Hz^{-1} for sources on the solar disk. The radiometer modulation channels permit measurement of the Stokes parameters V and I, and afford compensation of the measured signals over a wide range of level. Horn input antennas were placed on the same focal line no more than 2.5 λ_i from the focus. Each source crossed the beam successively at different wavelengths.

TABLE 1

λ, cm	T_n, °K	Δf, MHz	ΔT_{rms}, °K	λ, cm	T_n, °K	Δf, MHz	ΔT_{rms}, °K
2.0	1500	600	0.20	3.2	1500	600	0.19
2.3	1350	600	0.12	4.0	1200	600	0.10
2.7	1200	600	0.12				

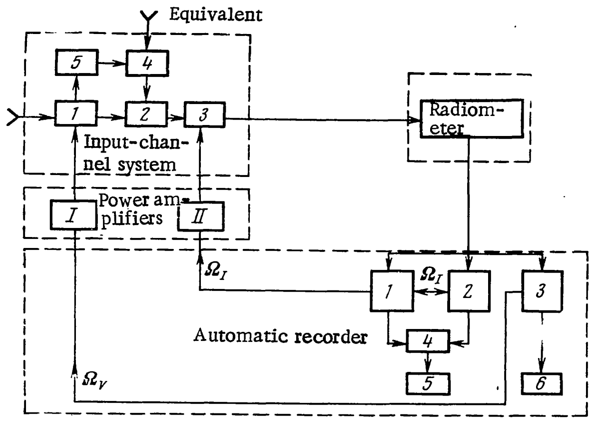

Fig. 1. Block diagram of a radiometer operating in the double-compensation mode. Input-channel system: 1) modulator of the parameter V; 2) T-junction; 3) modulator of the parameter I; 4) compensation attenuator; 5) noise generator. Automatic recording system: 1-3) low-frequency analog channels; 4) subtracting device; 5, 6) recording devices.

The recording system utilizes a UAR-6 automatic recorder, which provides tracings in six of 10 possible channels. The choice of channels depended on the problem at hand. Tracings were made on a type KSP-4 unit with a time constant $\tau = 0.4$ sec. A thermal load corrected for antenna noise level served for calibration.

3. OBSERVATIONS OF LOW-CONTRAST FEATURES

Since the observations were made near the phase of minimum solar activity, many of them were conducted at times when no bright, well-defined local sources were present on the sun. Tracings of the sun at ordinary scale exhibited an essentially smooth curve, with no utilization of the high radiometer sensitivity. Several techniques were applied to enhance the contrast of the radio image: 1) close scanning; 2) simple compensation (the quasi-null method); 3) double compensation; 4) 10-bit digital readout and recording on magnetic tape.

In the close-scan mode, modulation was achieved by switching two horns separated at the antenna focus by a distance close to the width of a narrow section of the focal spot. The resultant pattern has two narrow maxima, positive and negative; the side-lobe background is largely suppressed. Integration of the tracing recovers the ordinary curve. With observations of this type, sources in the central part of the disk can be studied by integrating from an arbitrary point with cutoff of a large part of the quiet-sun signal. A "cleanup" technique is employed to restore the image.

Simple compensation involves the ordinary quasi-null recording method in which the main part of the quiet-sun signal is compensated by a constant noise signal injected into an equivalent channel. The level of compensation is specified in advance and taken nearly equal to the signal of the quite sun. Recording begins at low amplification with the noise generator turned on. When the sun enters the beam and the compensation signal is no more than 5% of the sun level, the gain is increased by a factor of 10 or 20, so that low-contrast features at the center of the disk can be discerned. Further increase of the gain in this method is restricted by the large-scale variations due to the sphericity of the sun.

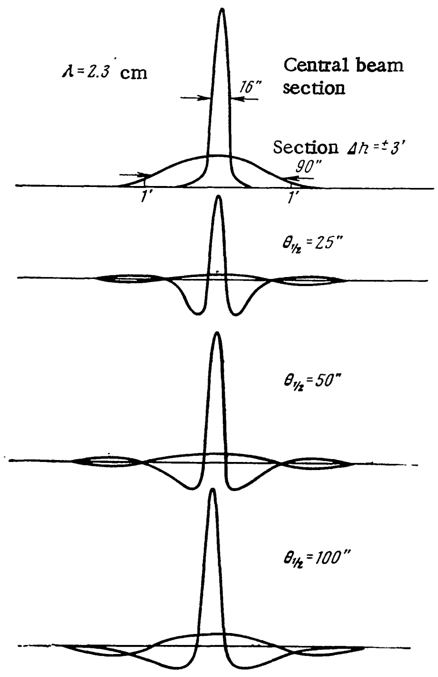

Fig. 2. Choice of averaging interval for "cleanup" of the beam pattern. Top, antenna beam computed for altitude h = 70°; lower curves, beam after "stationarization" with different Gaussian weighting functions along two sections: across the center and at $\Delta h = \pm 3'$.

An application of the double-compensation technique (Fig. 1 shows a block diagram of a radiometer in this mode) permits the radiometer gain to be increased several times over the preceding method, eliminating the large-scale variations and thereby ensuring that weak signals will be recorded not only at the center of the disk, but to some extent on the sides.

The principle of this method is as follows. The first main compensation is achieved by introducing a noise signal into the equivalent channel. The second auxiliary compensation is made at low frequency by using two recording channels operating in opposition but with intergration constants differing by tens of times; the signal in the channel with large τ_1 is subtracted from the signal in the channel with small τ_2. One shortcoming of this method is that the averaging "lags," since the averaged record is shifted by τ_1 sec relative to the record with small τ_2. As a result, the method works poorly at the limb of the sun, where the signal varies sharply and nonmonotonically.

In addition to applying the methods of compensation by a noise signal at the radiometer input, we have tested a method of recording small-scale sources with a 10-bit digital readout followed by storage on magnetic tape, with the aid of an Elektronika K-200 computer. This method is indispensable for studying the limb of the solar disk, where other techniques fail to work satisfactorily. It does have the disadvantage of an incomplete utilization of the sensitivity of the receiving system (a 10°K recording threshold), but an increase in the number of bits to 13 removes this defect.

4. DISCRIMINATION OF NARROW SOURCES

In order more clearly to discriminate low-contrast, narrow features on the solar surface, we have applied a

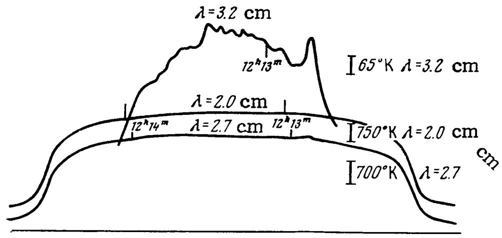

Fig. 3. Sample tracings of the sun, obtained June 12, 1975. Large-scale tracing at 3.2-cm wavelength; small-scale at 2.0 and 2.7 cm.

special technique for processing the tracings by "stationarizing" the curves. A computer routine averages a curve with a Gaussian weighting function, and the result is then subtracted from the original curve. The Gaussian is taken to be several times as wide as the core of the beam pattern so that narrow sources will be "smeared out," while broad ones will experience little change. After this reduction has been applied, only narrow sources will remain in the curve (Fig. 2).

The properties of the RATAN-600 beam do not permit us on a single tracing to distinguish a broad source at the center of the beam from a narrow one displaced in altitude. However, the halfwidth of horizontal sections of the beam is preserved within the central core and increases rapidly with distance from the center. As a consequence, broad sources disappear in the "stationarized" curve and

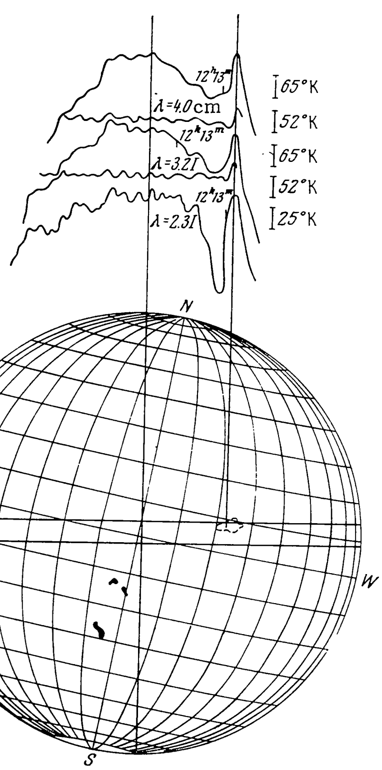

Fig. 4. Top, sample tracings of the sun, obtained June 12, 1975. Large-scale tracing at 2.3 cm is recorded in the double-compensation mode; tracings at 3.2 and 4.0 cm are recorded in the simple-compensation mode and processed by the "cleanup" technique. The map of the sun for June 12 is taken from the bulletin Solnechnye Dannye. A plage is apparent in the scan strip, shown for λ = 3.2 cm.

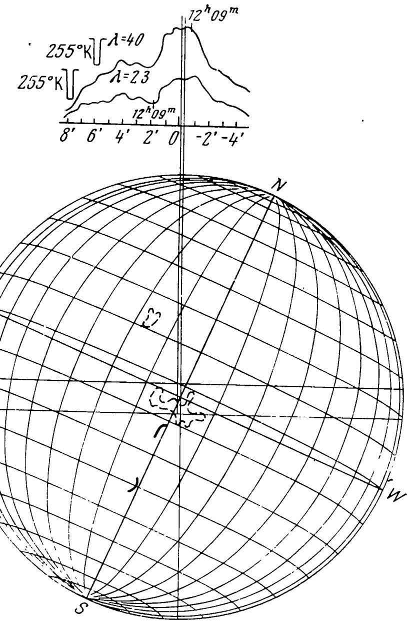

Fig. 5. Sample tracing of a plage on May 16, 1975, with the map of the sun given in Solnechnye Dannye. The scan strip for λ = 4.0 cm is indicated.

only narrow sources remain, confined to a narrow band about 2'.2 wide at λ = 2.3 cm, if h = 45°. Thus the procedure we have described represents a means of "cleaning up" the image. It has some disadvantage in excluding broad sources from the observations and in introducing negative side lobes into the pattern.

5. RADIO GRANULATION

Large-scale tracings distinctly reveal irregularities in the brightness distribution over the quiet sun. At the limit of accuracy of the recording device (such as an automatic pen) these irregularities can be discerned even if the scale of the tracing is small (Fig. 3), and they are recorded in both the equatorial and the polar regions of the sun. These features, which we shall call "radio granules," probably are a manifestation of the chromospheric network.[13] We have determined the main parameters of the radio granules by means of the recording and reduction techniques described in Secs. 3 and 4;

A comparison of tracings at wavelengths of 2-4 cm (Fig. 4) shows practically 100% agreement in the positions of the radio granules as well as a proportionality of their flux at these wavelengths. This circumstance represents a persuasive demonstration that the features observed do belong to the sun, since the tracings at different wavelengths are shifted in time by up to 15 sec. The 15-sec interval also serves as a lower estimate on the lifetime of the granules.

On the other hand, a comparison of records obtained on successive days shows substantial changes in the structure of the granulation. A more accurate measurement of the granule lifetime and the character of the variations will require further research.

The number of granules on the solar disk can be estimated by assuming that they are distributed uniformly over the disk. Such a calculation yields an estimate of

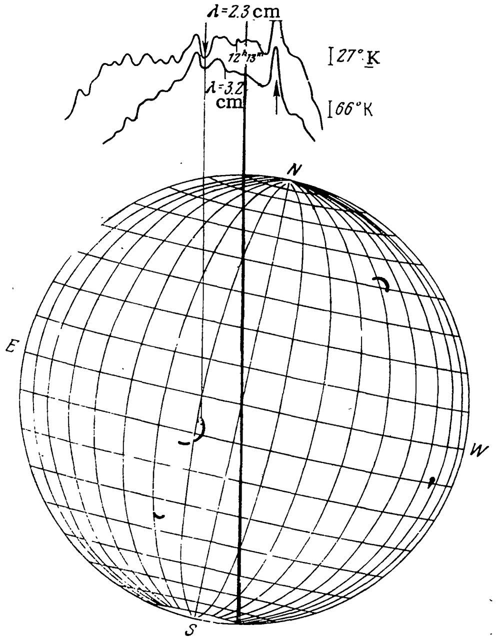

Fig. 6. Sample large-scale tracing of the sun, obtained June 11, 1975. The downward arrow marks a filament; the upward arrow, a local source not reported by the optical service in the June 11 map. The scan strip is indicated for the shortest wavelength, λ = 3.2 cm, in accord with the halfwidth of the vertical pattern. A comparison of these diagrams demonstrates the high sensitivity of the RATAN-600 to weak manifestations of activity.

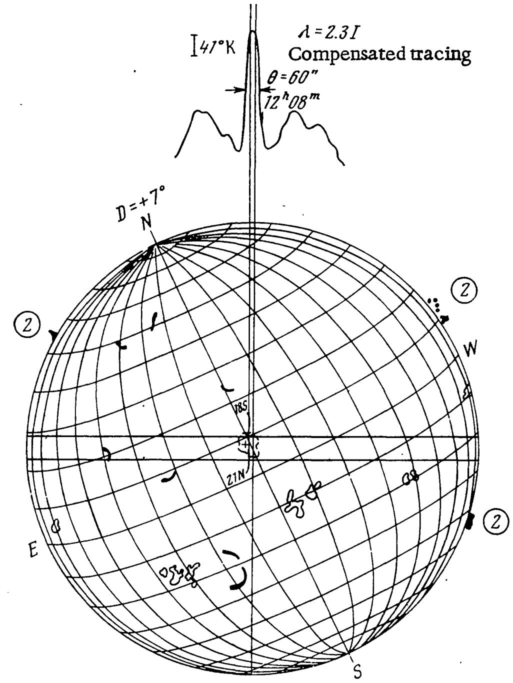

Fig. 7. Sample tracing of a spot (pore), obtained September 18, 1975, with the map of the sun given in Solnechnye Dannye. The scan strip for λ = 2.3 cm is indicated.

the order of several thousand granules over the whole disk at λ = 2.3 cm.

The amplitude of the antenna-temperature fluctuations is ≈ 30°K, corresponding to a flux density of 100 Jy, or a few thousandths of one percent of the total flux density of the sun. In some cases surface areas are encountered where the amplitude of the antenna-temperature fluctuations is ≈4-5°K.

The mean distance between sources on the 2.3-cm tracing is about twice the beam halfwidth. Thus their size is ≈10" or less, and the fluctuations in brightness temperature amount to about 3000°K, on the average (assuming circularly symmetric sources).

Several observations apparently relating to the same phenomenon of "radio granulation" have been described in the literature. These include observations at short millimeter wavelengths[14] with the RT-25 antenna at the Gor'kii Radiophysics Institute, with one-dimensional resolution up to 10"; observations with the 100-m Bonn telescope,[15] having resolution up to 50" in both coordinates; observations of a transit of Mercury across the solar disk[16] at 8-mm wavelength, and possibly observations of quasiperiodic fluctuations carried out by Lang[9] with the NRAO interferometer. On the whole these results are consistent with one another and with our new RATAN-600 observations. Because of the high resolving power and large effective surface area of the antenna, our observations permit individual details in the structure to be localized, which is necessary if they are to be identified with optical and x-ray imagery.

6. PLAGES AND OTHER WEAK SOURCES

In a number of cases the simple- and double-compensation tracings distinctly reveal sources of enhanced emission with amplitudes 10 or more times the level of the radio granules. These sources are fairly stable and can be followed in the tracings for several successive days. The typical tracing shown in Fig. 5 represents the case of a wide source (≈ 3') associated with a plage of comparable size. In Fig. 6 the source is comparatively narrow (≈1'), and has parameters similar to those of a source identified with a very small spot group (Fig. 7). However, according to the reports in Solnechnye Dannye there were no spots or pores on the solar disk on the date in question or the adjacent dates. Only on June 12 (see Fig. 4) did a weak plage of approximately the same size (≈1') appear at this site. It is worth noting that on June 11, optical observations made 3 h before the radio observations showed no solar activity in this region. The radio observations demonstrate the very high sensitivity of the antenna to weak manifestations of solar activity, and in particular to the emersion of magnetic fields in the corona. The low polarization of the objects (≲5%) makes a synchrotron contribution to their radiation unlikely, however. Probably we are dealing with a condensation of comparatively hot material, not necessarily coronal, in a region of magnetic field with a strength of several hundred gauss.

7. OBSERVATIONS OF FILAMENTS

In addition to isolated bright sources, a number of tracings show clearly identifiable dark regions. As in other cases reported in the literature,[15] these regions correspond to dark filaments recorded in the Hα line (Fig. 6).

8. OBSERVATIONS OF SPOTS

Spot groups are rather scarce in the series of

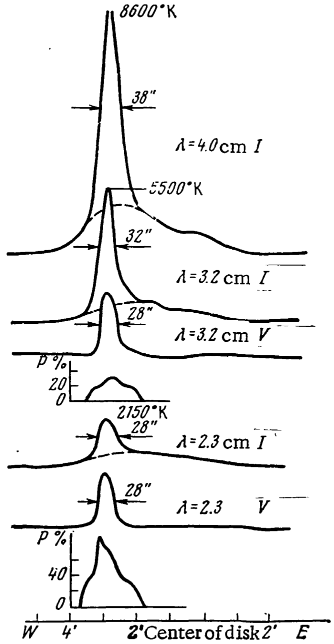

Fig. 8. Sample tracing of spot group No. 51, obtained July 1, 1975.

RATAN-600 observations of the sun. One example is provided by the local source of spot group No. 51 on July 1, 1975 (Fig. 8). The intensity tracing shows a distinct source with a diameter of ≈30" (approximately equal to the leading main spot of the group in the photosphere). The spectrum of this source falls off sharply toward shorter wavelengths. The broad source, whose size is comparable to that of the whole group, has a considerably flatter spectrum. Tailed pores appear weakly in the tracings. The polarization curves show only a narrow source, and at 2.3 cm the source appears to be ≈ 10% polarized. (Instrumental polarization has been removed from these observations by a numerical procedure.) From synchrotron-radiation theory one can estimate the strength of the spot magnetic field emerging into the corona. It is found to be H = 1500 gauss, with the field at the photospheric level equal to 3000 gauss, according to Solnechnye Dannye.

9. LIMB OF DISK AND TRANSITION LAYER

We have not undertaken a detailed analysis of the tracings for the limb of the disk. However, a brightening is noticeable even visually (see, for example, Fig. 3) at all wavelengths from 2 to 4 cm. It is to be hoped that observations at several wavelengths with the high resolution afforded by the RATAN-600 will permit a new step to be taken toward the development of models of the transition layer, which is so important for solar physics.

10. CORONA AND SOLAR WIND

These early trial observations have already shown that at wavelengths greater than 4 cm, coronal radiation can be observed beyond the solar limb out to distances of order $R_\odot$ or more. The radio observations will complement the information gathered with ultraviolet and x-ray telescopes in space. Incidentally, observations of the solar atmosphere (the solar wind) at distances of several solar radii from the center of the sun could be made by recording "occultations" of discrete sources at centimeter wavelengths. Such observations can be conducted successfully with the high-sensitivity instrumentation provided for this radio telescope.

11. CONCLUDING REMARKS

The radio observations of the sun with the RATAN-600 radio telescope have provided information for a wide gamut of phenomena, ranging from supergranules to the solar wind. Bursts of radio emission, however, represent one matter that remains outside the capability of the radio telescope. This capability can be achieved only after work has been completed on the complex automation of the RATAN-600. As mentioned above, we have described in this paper only the types of objects whose observation has proved feasible with the RATAN-600 telescope. By making observations with a resolving power of about 10" in one coordinate in conjunction with the relatively high resolution of ≈1' in the second coordinate, using techniques of recording that permit the measurement of low-contrast features, one can investigate a whole variety of new classes of objects, and refine the parameters of such familiar radio sources as plage areas and dark filaments. To obtain a fuller spatial, spectroscopic, and scaled picture of the radio emission of the sun, we need, on the one hand, more systematic and complete observations with the RATAN-600, while on the other, more comprehensive use should be made of data in the optical, far-ultraviolet, and x-ray ranges.

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