**On Detecting the Fourth Gyrofrequency Harmonic in Microwave Emission Spectra above Sunspots**

Spectral polarization observations of radio sources above sunspots are regularly carried out with the RATAN-600 radio telescope (RATAN is a Russian acronym for the Radio Astronomical Telescope of the Academy of Sciences). The in-depth studies of the spectra reveal new effects. In this paper, we analyze the manifestation of radio emission of the fourth gyrofrequency harmonic in microwave spectra obtained with 1-percent frequency resolution in a range of 3–18 GHz. Registration of the extraordinary mode in the short-wavelength range of the spectrum is compared to the model calculations of the second-to-fifth gyrofrequency harmonics against a background of the thermal bremsstrahlung emission of flocculi, surrounding the spot structure of an active region. The brightening of the extraordinary mode in the short-wavelength spectral range and the kinks in the intensity spectra of emission are analyzed. The interpretation of the RATAN-600 observational data with probable diagnostics of the emission of the fourth gyrofrequency harmonic is considered as examples.

# I

The microwave emission spectra of active regions (ARs) above sunspots are an important instrument to study coronal magnetic fields. Space observatories completely survey the structure of photospheric magnetic fields on the near and far sides of the Sun. The current technology has achieved impressive progress in designing high-resolution magnetographs [1, 2]. However, it is a challenge to study the structure and magnitude of the coronal magnetic field, since the high temperature of plasma makes it difficult to apply optical spectroscopy methods. The use of large radio telescopes with a spatial resolution less than the size of an AR allows information about coronal magnetic fields to be obtained from observations of the radio sources above sunspots directly on the disk. At present, coronal magnetometry is an urgent problem of solar physics [3]. Measurements of coronal magnetic fields with the use of radio data were repeatedly discussed in the literature (e.g., [4–9]).

The results of numerous model calculations showed that the emission of radio sources above sunspots is mainly determined by the thermal cyclotron mechanism at the second and third gyrofrequency harmonics and the thermal free-free emission [10, 11].

The essence of radio astronomy methods for measuring the magnetic field in solar sources is based on the fact that the radio emission generated in the presence of a magnetic field is circularly polarized and the sign and degree of polarization depend on the emission mechanism, temperature, and plasma density at the place, from which the radiation originated and propagated. If the emission mechanism is identified, polarization measurements of the radio emission provide an opportunity to determine the magnetic field strength (e.g., [12, 13]).

The authors of [5] were the first to show how the magnitudes of coronal magnetic fields can be estimated from the polarized emission spectra of radio sources above sunspots with the use of the cyclotron mechanism on the second and third gyrofrequency harmonics. Polarization observations carried out at five wavelengths in a range of 2−4 cm at the RATAN-600 radio telescope were considered (RATAN is a Russian acronym for the Radio Astronomical Telescope of the Academy of Sciences). The main inference from statistical measurements was that the magnetic field above a sunspot at the chromosphere-to-corona boundary is only 20−30% lower than its magnitudes in the photosphere. As was ascertained from observations at different radio telescopes, the emission on the second and third gyrofrequency harmonics can be reliably detected [9, 14–18].

Spectral and polarimetric observations of all ARs on the solar disk are carried out at the RATAN-600 radio telescope every day [19]. At present, the equipment characteristics of this instrument have been significantly improved [20]. Now, the polarization spectrum (1%) of the radio emission can immediately be analyzed in detail in the entire microwave frequency range. Based on this analysis, certain progress has been achieved in developing methods to detect the altitude structure of magnetic fields above sunspots in the chromosphere-to-corona transition zone [21–25].

In this paper, we discuss the detailed microwave spectra of ARs for the right- and left-hand circular polarizations with a 1-percent frequency resolution in a wide range of frequencies, corresponding to emissions of the ordinary and extraordinary modes on low gyrofrequency harmonics. The contribution of harmonics to the total emission forms the spectrum shape according to both emission modes. Since some spectra exhibit extraordinary mode brightenings in the short-wavelength spectral range and kinks when passing to longer wavelengths, it is of interest to study whether the emission of the fourth gyrofrequency harmonic may appear. The model calculations and interpretation of the observational data suggest that the emission of the fourth gyrofrequency harmonic is directly detected.

# 1. MEASUREMENT TECHNIQUE

We consider multi-wavelength polarization observations at the RATAN-600 radio telescope performed with the one-dimensional spatial resolution that is higher than or equal to the sizes of the studied radio sources above spots [26]. The RATAN-600 regular observations cover a frequency range of 1 to 18 GHz with the 1-percent frequency resolution in the simultaneous-recording operation mode at all 112 frequencies. Figure 1 presents an example of the registered multi-wavelength scan of the solar disk. The observations are carried out every day by the Southern Sector antenna system with a periscope [20], and the horizontal and vertical sizes of the diagram, the half power beam width (HPBW) are determined by interrelations HPBW*h* = 8.5 × λ and HPBW*v* = 7.5 × λ, where HPBW*h*, HPBW*v*, and λ are expressed in angular seconds, angular minutes, and centimeters, respectively.

Thus, at wavelengths longer than 4 cm, the emission of radio sources within the entire solar disk is detected in RATAN-600 scans. To register simultaneously the spectra for both circular polarizations, a wideband feed [20] with a single center for the entire frequency range of 0.7−3 and 3−18 GHz is used. Due to high spectral resolution of the solar reception system, which can simultaneously register the right- and left-hand circular polarizations with 15-arcsec spatial resolution at 1.7 cm, the spatial and frequency features in the plasma emission of active and quiet regions on the Sun can be identified at a level of the upper chromosphere and lower corona.

In Fig. 1, the whole multi-frequency spectrum is registered in the course of one observation with a onedimensional diagram of the radio telescope, which yields simultaneous data on intensity *I = I*(*R*) *+ I*(*L*) and circular polarization *I = I*(*R*) *− I*(*L*) of all radio sources on the solar disk. The analyzed region, NOAA 11312, from which a significant polarization signal of cyclotron emission was registered, was in the center of the solar disk. Independent information about the *I*(*R*) and *I*(*L*) spectra are also available (see Fig. 2), which makes it possible to determine the type of emission wave (o- or e-mode) from comparison to the photospheric magnetogram for each radio source.

Figure 2 shows how cyclotron radio source NOAA 11312 was isolated. The positions of radio sources NOAA 11315 and 11312 are identified with the positions of sunspots in the MDI/SDO magnetogram, and the enlarged image of the NOAA 11312 scans in both modes is shown in the center. The bright emission of a narrow source of the e-mode indicates its cyclotron nature, while the bremsstrahlung (free-free) emission of the e-mode is less intense and exhibits no distinct structure. The absence of polarization in sources NOAA 11313 and 11315 suggests that there is no cyclotron emission at a short wavelength.

As is seen in Fig. 2, the emission of the active radioemission component, containing radio sources above spots, flocculi and filaments, radio granulation structure, etc., occurs against a background of a strong signal of the quiet Sun. To register all structures correctly, a large dynamical range and a high sensitivity to the emission flux are required. For RATAN-600, these parameters in the 100-MHz frequency band of the channel are currently larger than 60 dB from the inherent noise level and about 0.01 s.f.u., respectively.

The topics on determining the level of the quiet Sun form a special issue. In the analysis of narrow and bright individual ARs, the contribution of inaccuracies to the determined level of the quiet Sun is small; however, in the studies of wide structures like wide flocculi and halos [27], minor inaccuracies in determining this level may substantially skew the result. Consequently, in every individual case, additional information, such as photospheric magnetograms, maps of calcium flocculi, etc., is required for correction.

At short wavelengths (from 1.5 to 2.5 cm, depending on the magnitude of the photospheric magnetic field), the radio emission intensity of sources decreases to the quiet-Sun level. It is rather difficult to isolate weak radio sources against a background of a strong signal of the quiet Sun. In this case, we used a unified technique for a large number of simultaneously registered channels, which is rather efficient for isolating the large-scale signal of the quiet Sun. In this procedure, the monotonic wavelength dependence of the antenna temperature of Sun *T*a(λ) measured in the disk center was taken into account. The residual value for antenna temperature did not exceed the value of the frequency resolution that is approximately 2%.

2. CHARACTERISTICS OF THE NOAA 11312

# SPECTRUM OBSERVED IN THE SHORT-WAVELENGTH CENTIMETER RANGE

In Fig. 2, the NOAA 11312 radio source is isolated at the 1.9-cm wavelength in two emission modes (e and o-modes) corresponding to right- and left-hand polarizations. At this wavelength, only the cyclotron emission of the e-mode is registered, while the emission of the o-mode is bremsstrahlung (free-free). This is also indicated by a wide size of the o-mode source. Figure 3 shows how the intensity and the polarization of radiation sharply rise with increasing the wavelength from 1.90 to 2.33 cm at 15 frequencies. In Fig. 4, the individual spectra of the e- and o-modes are presented. The emission spectrum of the e-mode is more intense, begins to rise at frequencies below 16 GHz, and exhibits a kink at 13.5 GHz. The emission spectrum of the o-mode is less intense than that of the e-mode, and it grows starting from the lower frequency (approximately 12 GHz). According to accepted theoretical understandings, the emission level of the o-mode is lower than that of the e-mode. It is interesting to analyze the kink observed in the spectrum near a 13-GHz frequency (see Fig. 4). Many spectra of both modes for different ARs (see Section 4) suggest that this kink exists. The model calculations described in Section 3 confirm the presence of this kink in the total emission spectra of the fourth and third gyrofrequency harmonics.

Let us estimate the possibility to measure the maximum magnitude of the coronal magnetic field on harmonics of radio emission with the use of a technique [11], which is based on the assumption that the polarized emission of a source above a spot is detected at the low-corona level. In this technique, the steep slope of spectrum *V* in a range of short centimeter wavelengths is linearly extrapolated to the axis of minimum emission, i.e., to the free-free level. Distinct from [5], we consider here substantially more wavelengths, independent spectra of the right- and left-hand circular polarizations, and the information on Stokes parameters *I* and *V*. Moreover, the use of this potential allows the coronal magnetic field for each mode to be independently determined. It is known that rotational motion of nonrelativistic electrons in the plasma’s magnetic field results in the gyromagnetic emission at frequency *fB* = ω*B* 2π = 2.8 ×106*B*, where ω*B* = *eB mc* is the angular cyclotronic frequency determined by the magnetic field magnitude. The gyromagnetic emission occurs in the main frequency and its harmonics *s* = *f fB* .

The cyclotron emission of microwave spot sources on the Sun is efficient on low gyrofrequency harmonics, of which only the second and third harmonics create the conditions for preferential radiation. The magnitude of magnetic field *B* is connected with the harmonic number by the following simple interrelations depending on the frequency [11]:

*B*(ν = 2ν*B*) = 180 × *f*, *B*(ν = 3ν*B*) = 120 × *f*, and *B*(ν = 4ν*B*) = 180 × *f*, where *f* is expressed in GHz.

In the zone, where the gradient of the kinetic temperature of electrons is high, cyclotron emission is characterized by a high degree of polarization, reaching values close to 100%. This is caused by the fact that the extraordinary wave is generated in the transitionzone layers that are higher and, consequently, hotter. The emission is generated in the gyroresonance layer, the spatial thickness of which is Δ =*l LB* v*T* , where *c LB* is the scale length of the magnetic field and v*T* is the thermal velocity of electrons [11].

Figure 5 illustrates how the spectra presented in Fig. 4 can be explained. If the spectra of both modes are considered under the aspect of gyrolevels that gradually emerge to the corona with increasing the wavelength, the upper third and fourth gyrolevels are the first to enter the corona. For the fourth gyrolevel, the optical thickness may become detectable (0.1−1.0) even at angles of deflection from the meridian, reaching approximately 10° (see the results of calculations in Section 3). Since the optical thickness of higher-order levels is rather small, they are not considered here. In the right part of Fig. 5, we present the situation, where the fourth gyrolevel has reached the region of coronal temperatures, while the third and second gyrolevels are still under chromospheric temperatures and do not influence the total emission of the radio source. In the center of Fig. 5 (for a wavelength longer than that in the right plot), there is a case, where the third gyrolevel penetrates the corona. This moment corresponds to the beginning of a sharp rise in the emission spectra of the e-mode at frequencies lower than 14 GHz (see Fig. 4), which explains the kink in the e-mode spectrum. Thus, in the frequency range between 12 and 17 GHz, only the extraordinary mode emits. In the left part of Fig. 5, the second gyrolevel reaches the region of coronal temperatures. Consequently, the emission of the ordinary mode starts to grow; and the cyclotron emission of the o-mode grows at frequencies smaller than 13 GHz (see Fig. 4). Further, in the range of longer wavelengths (lower frequencies), the intensity of the emission of the radio source above a sunspot is governed by the joint influence of both modes and all listed harmonics, while the contribution of the fourth harmonic to the emission is rather small as compared to those of the second and third.

# 3. SIMULATIONS OF THE CORONAL EMISSION SPECTRUM ABOVE A SUNSPOT

As was shown in [10, 11], the strong microwave emission above sunspots is explained by cyclotron emission on low gyrofrequency harmonics, while the main contribution is made by the optically thick second gyrofrequency harmonic in the ordinary mode and the third gyrofrequency harmonic in the extraordinary mode. It is difficult to detect the emission on higher harmonics in observations, since their contribution is small. The ratio of the contributions of gyrofrequency harmonics depends on the electron concentration, temperature, magnetic field, and angle between the magnetic field lines and radiation propagation direction, rather than only the wavelength and emission mode [11]. The contributions of harmonics substantially vary in dependence on the conditions in the solar corona. Below, we model the manifestation of the fourth gyrofrequency harmonics of the radio emission in the microwave spectra. The cyclotron and bremsstrahlung emission of a source above a sunspot is calculated, and the dipole model is used for the distribution of the magnetic field over the sunspot.

The altitude distribution of the kinetic temperature and the electron concentration was calculated with Selhorst’s model of an AR [28]. The coefficients of gyroresonance and thermal bremsstrahlung absorption were determined by complete formulas [11]. The brightness temperature of emission *T*b was calculated by integrating the radiative transfer equation along the line of sight from the corona altitudes to the photosphere through gyroresonance layers (from the first layer to the fifth) of the sunspot source.

The results of calculations of the brightness temperature and optical thickness for the extraordinary mode along the sunspot diameter are presented in Fig. 6. The magnetic field is modeled by a dipole immersed 2 ⋅ 109 cm underneath the photosphere, and the magnitude of the photospheric field on the dipole axis is 2500 G. To avoid radiation along force lines, the sunspot is moved 10° eastward of the disk center, in which the transparency window is maximum.

In Fig. 6, the contributions of the third and fourth harmonics (3s and 4s) and the thermal bremsstrahlung emission to the total emission (shown by a darker curve) of the sunspot source at three frequencies are shown; at the highest one, 14.2 GHz, the optical thickness of the fourth harmonic is approximately 0.01−0.1. This quantity is sufficient to increase the brightness temperature to 3 ⋅ 105 K, which exceeds the bremsstrahlung emission level; the third harmonic has not reached corona altitudes, while the fifth one has already reached them, but its optical thickness is insignificant; and they both (the third and fifth) do not exceed the bremsstrahlung emission level. At lower frequencies, the main contribution is transferred to the third harmonic (as is seen in Fig. 6, this occurs approximately at 12 GHz). Gradually, while the frequency is decreasing, all gyroresonance layers of the second-to-fifth harmonics go to the corona (see the lower example for the 8-GHz frequency); the main emission is generated on the third harmonic, and the second harmonic emits in the sunspot center along the magnetic field lines. The fourth harmonic remains semitransparent and contributes mostly on the spot periphery.

Thus, at frequencies between 18 and 12 GHz, the bremsstrahlung emission is replaced by the dominant gyroresonance one, while the gyrolevels rise to the hot layers of the upper transition zone. For the extraordinary mode, the relative contribution of the fourth harmonic is largest, when the fourth gyrolevel is in the hot layer, while the third one is still at a low temperature. The fourth harmonic remains optically thin in the entire considered range, from 6 to18 GHz.

The calculated emission spectrum for the same model is shown on the left of Fig. 7 (the calculated region is 40000 × 40000 km2 in area). The characteristic kink in the model spectrum near frequencies at 14−15 GHz, which is similar to that observed in the RATAN-600 spectra of ARs, is seen. As the simulations have shown, this effect is caused by the replacement of the efficient harmonic. When the magnitude of the modeled magnetic field decreases, the kink in the spectrum moves toward long frequencies; when the magnetic field becomes stronger, the kink moves toward short frequencies (see Fig. 8).

Considering the fourth harmonic improves the technique to determine the magnetic field based on the third harmonic [5] and offers a new possibility to check the magnetic field magnitude determined from the fourth harmonic. The coronal magnetic field can be estimated with the known technique [5], which uses the supposition on detecting the polarized emission of a source above a sunspot at the level of the lower corona. According to this technique, the steep slope of the spectrum in a range of short centimeter wavelengths is linearly extrapolated to the axis point of the minimum emission, i.e., the free-free level. As distinct from [5], we consider here substantially more wavelengths and the independent spectra of the right- and left-hand circular polarizations. We can more accurately determine the magnetic field magnitude from the spectrum observed in more detail.

The gyroresonance levels in the magnetic field of the sunspot source emits at different altitudes. The detailed spectra of the polarized emission contain information about the plasma parameters at these altitudes, which makes it easier to study comprehensively the magnetic structure along altitudes and the atmosphere above a sunspot (under the corresponding diagnostic modeling [29]) in the poorly investigated upper transition zone and, particularly, to analyze the high temperature gradient.

We analyzed the manifestation of the radio emission of the fourth gyrofrequency harmonic in the microwave spectra obtained with the 1-percent frequency resolution in the range from 3 to 18 GHz.

The detection of the extraordinary mode in the short-wavelength range of the spectrum is compared to the models of the emission of the second-to-fourth gyrofrequency harmonics against a background of the thermal bremsstrahlung emission of flocculi surrounding the sunspot system of an AR.

The characteristic kink in the high-frequency range of the growth in spectra of ARs observed with the RATAN-600 telescope has been explained: as the simulations showed, this effect is related to replacing the efficient harmonic.

The interpretation of the RATAN-600 observational data was illustrated by detecting the emission of the fourth gyrofrequency harmonic as the brightening of the extraordinary mode in the high-frequency spectral range.