Incoherent Scatter Radar directional pattern using radio astronomical observations

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ABSTRACT

The Irkutsk Incoherent Scatter (IS) radar is a unique facility in Russia, designed for geophysical and radio-probing investigations of the upper atmosphere. The range of problems tackled using the radar is quite extensive. Having a high potential and investigative capability, the radar represents an extremely sophisticated engineering facility. A maximum possible knowledge of all performance data of this instrument is necessary for conducting accurate measurements of space environment parameters and for scientific experiments. Of particular interest in this regard is the radar's antenna system. The spatial distribution of the radiation power (directional pattern) of the antenna system is as yet imperfectly understood. Because of the complexity and the unconventional nature of the antenna design, a mathematical simulation and calculation of the directional pattern involves a highly cumbersome task, and the reliability of such calculations is low. The overall worldwide practice shows that the most powerful tool for obtaining the directional pattern characteristics is to measure the variations of the noise power level when various cosmic radio sources traverse the beam. The advancement of digital technology in the present state of the art makes it possible to record large amounts of information needed to construct an accurate spatial distribution of the power received and radiated by the antenna. Results, thus obtained, are useful for correctly selecting the IS radar operation modes

Keywords: Incoherent scattering, radio astronomic methods, directional pattern.

1. STATEMENT OF THE PROBLEM

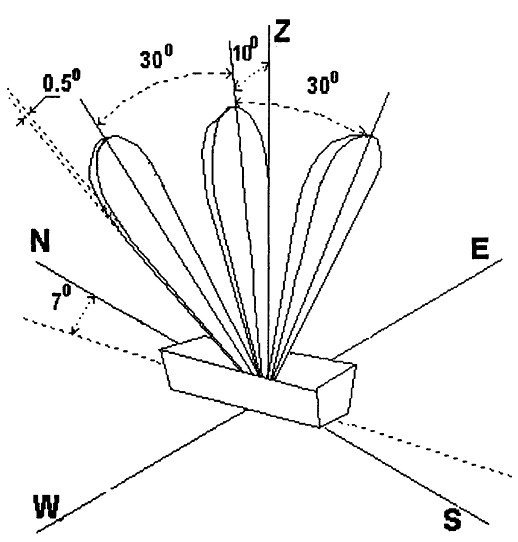

Fig. 1. Orientation of the IS-radar's antenna

Fig. 1 schematically represents the IS radar beam which, according to the ratings, has the following properties:

- beam width along the aperture's major axis from 0.5 level no more than 30';
- beam width along the aperture's minor axis from 0.5 level no more than 10°;
- sidelobe level not higher than 10-11 Db;
- gain of about 5000;
- the scanning is performed in the plane passing through the radar's major axis and normal to the horn aperture plane in the ±30° sector by varying the carrier frequency in the range 154-162 MHz.

The beam is generated by the linear array of slot radiators. The system of slot radiators is fed by the electromagnetic field of the traveling (surface) wave propagating above the retarding ribbed structure with pronounced dispersion properties. The required beam in the elevation plane is generated by means of the sectoral horn separated by a metal partition into two equal parts, each of which is connected with its receiving and transmitting channels. The northern end of the antenna's major axis is rotated with

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Eighth International Symposium on Atmospheric and Ocean Optics,
Gelii A. Zherebtsov, Gennaddi G. Matvienko Victor A. Banakh, Vladimir V. Koshelev, Editors,
Proceedings of SPIE Vol. 4678 (2002) © 2002 SPIE · 0277-786X/02/$15.00

respect to the N-S direction through 7° to the West, and the normal to the horn aperture plane is tilted by 10° from the zenith westwards.

It was necessary to calibrate the IS radar antenna against some object whose coordinates would be well known. The area of the sky covering the radar antenna scanning sector, includes three radio sources: Crab Nebula, "Cygnus A", and Cassiopeia. By selecting a particular source, we can obtain a set of time-dependencies (sections) of the noise signal power at the passage of this signal through the radar beam at different frequencies (inclination angles). On the basis of these experimental data, the following objectives can be formulated:

-to specify the dependence of the beam inclination angle on the carrier frequency;
-to construct the dependence of the spatial (from the azimuth and elevation in the antenna's coordinate system) power distribution for the frequency selected.

2. EXPERIMENT

The experiment on the "Cygnus A" radio source observation was conducted on April 4, 2000. As of the time of observation, the coordinates of the source were: right ascension α = 19.99143 hours, and declination δ = 40.7377°. The measurements were made in the mode of cyclic scanning in the frequency range 156-157.6094 MHz with steps of about 0.075 MHz, and the noise accumulation time at each of the frequencies was one second. Such a selection of the mode made it possible to measure the beam parameters in the radar antenna scanning sector with good time resolution. The dependencies of the received power on the frequency and time are plotted in Fig. 2.

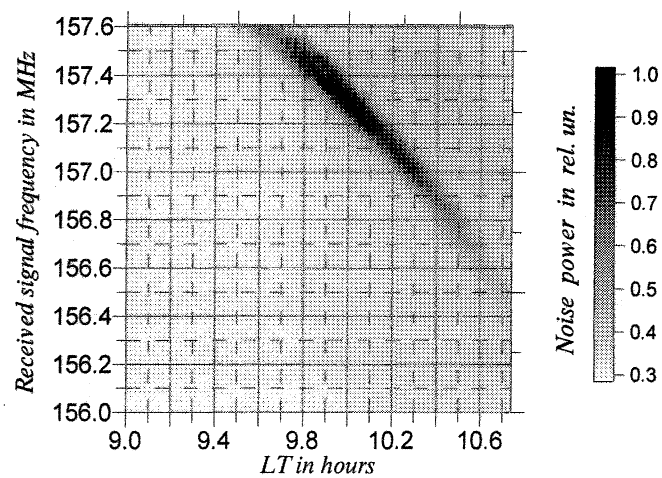

Figure 2. Experimental dependencies of the noise power received at different frequencies during the passage of the "Cygnus" radio source through the radar beam.

3. SIMULATION

3.1. Specification of the dependence of the beam inclination angle on the carrier frequency

From experiment we know only the temporary changing a noise power level on different frequencies at which the radio source observation was carried out. For determining the beam in space, we should know the relation relating the carrier signal frequency f to the angle ε of beam deviation from a normal to the horn aperture plane. In the general form, the angle of deviation of the beam axis from a normal to the radar antenna aperture (equation of beam scanning) is determined from the relation:

$$\sin(\varepsilon) = \gamma - \frac{\lambda}{d}; \tag{1}$$

where γ is the wave retardation coefficient in the ribbed structure; λ is the wavelength of the radiated signal in a free space; and d is the distance between the radiating slots. The quantity of the retardation coefficient γ is related to the slowing-wave antenna parameters by the relation:

$$\gamma = k_{str} \cdot \chi(f), \tag{2}$$

where $\chi(f)$ is the wave retardation coefficient for an infinite ribbed structure [1].

$$\chi(f) = \sqrt{1 + \left(\frac{a}{a+b}\right)^2 tg^2 kh} \qquad k = \frac{2\pi f}{c} \tag{3}$$

where c is the velocity of light in a free space, a is the distance between the walls of the retarding structure (a = 136 mm), b is the thickness of the ribs (b = 14 mm), h is the height of the ribs (h = 384 mm), and k_{str} is the coefficient taking into account the finite length of the structure and its value lays in an interval (k_{str} = 0.7-0.8) [1].

The angle of deviation of the beam from a normal ε depends strongly on k_{str}, and depends nonlinearly as a function of frequency. In a problem of refinement of frequency dependence of the DP inclination angle we shall imply just determination of the k_{str} parameter for each frequencies. To determine the dependence of k_{str} on the frequency f, we choose the "supporting points" which shown in the Table:

Table. The "support points" values.

№	f, MHz	ε, deg
1	154	0
2	162	30
3	157.3594	10.335

Where the first two frequencies (extreme frequencies of range of scanning) are taken from radar certificate, and the frequency 157.3594 MHz corresponds to a maximum of a signal received from a radio source, ε_3 - computational angle of inclination of DP center from a normal to intersect with maximum of the Cygnus-A signal power.

Assuming that k_{str} has a quadratic dependence on frequency, f, i.e.:

$$k_{str} = g_1 f^2 + g_2 f + g_3, \tag{4}$$

where g_i stands for some constant coefficients, and i is the "supporting point" number, we obtain the following system of equations:

$$\begin{cases} \sin(\varepsilon_1) = (g_1 f_1^2 + g_2 f_1 + g_3)\chi(f_1) + \dfrac{\lambda_1}{d} \\ \sin(\varepsilon_2) = (g_1 f_2^2 + g_2 f_2 + g_3)\chi(f_2) + \dfrac{\lambda_2}{d} \\ \sin(\varepsilon_3) = (g_1 f_3^2 + g_2 f_3 + g_3)\chi(f_3) + \dfrac{\lambda_3}{d} \end{cases} \tag{5}$$

where $\chi(f)$ are determined for each frequency in accordance with the expression (3). Hence the values of the constant coefficients: g_1 = 0.00022574274, g_2 = -0.07431684982, and g_3 = 6.83939309295, and the value of the coefficient k_{str} can be determined in accordance with (4) for any frequency f. After that, from the value of γ obtained from equation (2), we determine, in accordance with (1), the angle of beam deviation ε. Thus we have constructed the frequency-dependence of the beam inclination angle. Fig. 3 presents the dependence of the angle ε on the frequency f.

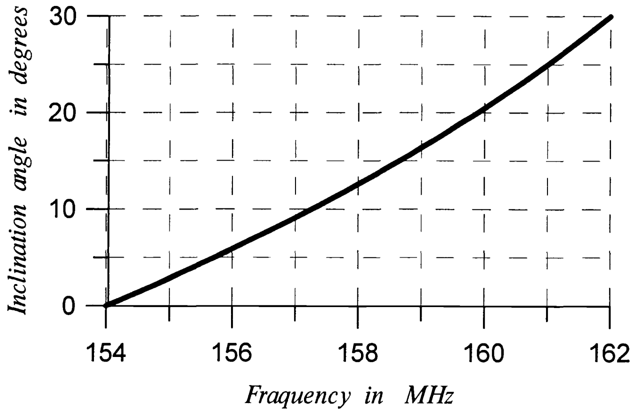

Figure 3. Frequency-dependence of the DP inclination angle.

3.2. Constructing the dependence of the spatial (in azimuth and elevation in the antenna coordinate system) power distribution for the frequency selected.

Let's assume that on close frequencies the shape of DP practically does not vary. Consequently, by recalculating the tracks of "Cygnus" from different frequencies to a single frequency having an absolute maximum for the accumulated noise power, we obtain a number of beam sections, from which we reconstruct its spatial portrayal.

We now determine the "Cygnus" coordinates in the antenna coordinate system (CS) for each of the frequencies. Let the WE direction correspond to the abscissa axis (the eastward directed axis x), let the NS direction correspond to the axis of ordinates (northward directed axis y), and let the Z-axis z be directed toward the zenith. All transformations will be carried out for a sphere of unit radius $R = 1$ (i.e. "Cygnus' is located on this sphere). It is convenient to transform known spatial polar coordinates of the Cygnus-A to orthogonal CS:

$$\begin{cases} x = \cos(h)\sin(Az) \\ y = \cos(h)\cos(Az)\text{'} \\ z = \sin(h) \end{cases} \tag{6}$$

where Az and h are the azimuth and height of the source, respectively, which are calculated from the following relations:

$$tg(Az) = \frac{\cos(\delta)\sin(t)}{\sin(\varphi)\cos(\delta)\cos(t) - \cos(\varphi)\sin(\delta)}; \tag{7}$$

$$\cos(h) = \frac{\cos(\delta)\sin(t)}{\sin(Az)}; \tag{8}$$

where φ is the latitude of the site of observation, and t and δ are the hour angle and the declination of the radio source, respectively [2].

To pass to the coordinate system connected with the radar antenna (i.e. the Z-axis is perpendicular to the horn aperture plane, and the axis of ordinates is directed along the antenna's major axis), we shall perform the following transformations:

-we let the beam rotate about the axis z through $a = 7°$ in a westward direction (i.e. the positive direction of the axis of ordinates coincides with the antenna axis).

$$\begin{cases} x1 = x\cos(a) + y\sin(a) \\ y1 = y\cos(a) - x\sin(a) \\ z1 = z \end{cases} \tag{9}$$

-we let the beam rotate about the axis $y1$ through $b = 10°$ in a westward direction (the Z-axis is perpendicular to the horn aperture plane).

$$\begin{cases} x2 = x1\cos(b) + z1\sin(b) \\ z2 = z1\cos(b) - x1\sin(b) \\ y2 = y1 \end{cases} \tag{10}$$

-we pass into the beam connected with some frequency; to do so, we let the antenna beam rotate through an angle ε about the axis $x2$ (ε being the angle (depends on the frequency f, see problem 1) of deviation of the beam from a normal to the horn aperture plane).

$$\begin{cases} y3 = y2\cos(\varepsilon) + z2\sin(\varepsilon) \\ z3 = z2\cos(\varepsilon) - y2\sin(\varepsilon) \\ x3 = x2 \end{cases} \tag{11}$$

To calculate the power received in a given direction, we use the angles: $x^0 3$ (plane $X3OZ3$), and y^0 (plane $Y3OZ3$).

$$x^0 3 = \arcsin(x3/R); \qquad y^0 3 = \arcsin(y3/R); \tag{12}$$

The angles $x^0 3$ and $y^0 3$ determine the section by the Cygnus ephemeris of the antenna beam for each of frequencies f (angle ε) selected in experiment. Then we can transform this obtained set of sectional views for different frequencies to one selected frequency and to reconstruct the form volumetric DP by interpolating it. The spatial distribution of power received by the IS-radar antenna in the antenna CS for frequency 157.3594 MHz is shown in the Fig. 4.

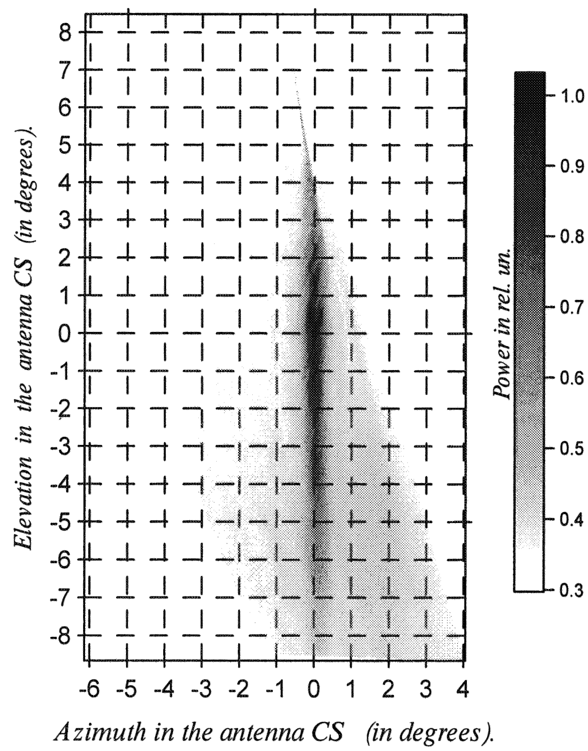

Figure 4. Directional pattern of the ISTP SB RAS IS radar, reconstructed using observations of the "Cygnus-A" radio source.

This work was done with support of the Russian Foundation for Basic Research within programs № 00-15-96710 and № 00-05-72026.

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