Results of the Radio Optical Modeling and Application of the New Radio Holography Method of the RATAN-600 Radio Telescope Surface Diagnosis

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***Abstract* — We describe a new radio holography method of the RATAN-600 radio telescope antenna diagnosis and adjustment, using the radial movement of the reference panel. We present the results of geometric optical ray tracing of the "South + Flat" antenna system in the autocollimation mode and radio optical modeling of the hologram recording and field reconstruction procedure, taking noise into account. Estimates for necessary isolation and acceptable spatial separation between transmitting and receiving feeds, geometrical tolerances, and requirements to the reference panel motion control are discussed. The experimental results of the method application to the diagnosis of radial errors in the positioning of panels of the RATAN-600 main mirror are reported.**

***Index Terms* — Antenna measurements, electromagnetic modeling, holography, radio astronomy, telescopes.**

I. Introduction

Radio holography (RH) methods of the antenna surface diagnosis for the RATAN-600 radio telescope have been developed successfully during 1980-90s [1]. In [2]-[4] an approach is considered that does not require any special phase stabilized measurement equipment, using a standard radio astronomy receiver instead.

Application of the RH methods requires a great care when conducting the experiments. When in an autocollimation mode, these requirements include (1) precision motion control of the reference panel and the carriage with transmitting and receiving feeds mounted on it; (2) high stability of the radiation source used for the hologram recording; (3) good isolation between transmitting and receiving feeds; (4) precision placement of the feeds on the focal line of the antenna system, and their proper orientation; (5) accurate orientation of the secondary mirror; and so on. In [4], the problem of movement precision of the reference panel is considered. The requirements to a source of the monochrome coherent radiation are discussed in [2], [3]. Characteristics of the RH signal receiver in general must be the same as those required from any receiver that can be used for a standard autocollimation antenna adjustment [5], though using a high sensitive and stable radio astronomy receiver enhance the signal to noise ratio (SNR) of the measurement procedure, provided that the dynamic range of the receiver is large enough (not less than 25-30 dB). Taking into account that a quasi-monochrome radiation source is necessary for RH measurements, a narrow band receiver allows for optimal reception and increases the SNR. The receiver sensitivity is proportional to $\Delta f^{-1/2}$ and a monochrome signal level at the output of the receiver is proportional to Δf^{-1}, hence the gain due to narrowing of the reception bandwidth is $\Delta f^{1/2}$. The influence of the surface layer atmospheric turbulence and the background caused by random scattering on the measured antenna and the environment require a separate detailed consideration.

II. Brief Description of the Method. Requirements to the Isolation Between Transmitting and Receiving Feeds

The essence of the proposed RH method is as follows. A signal from a strong space source or a geostationary satellite passing through the beam of the measured antenna or from a sine wave generator in an autocollimation mode reflected from the antenna surface is modulated by an external reference signal caused by reflection from a single antenna element (panel) moving in a radial direction (Fig. 1). Recording an interferogram in the vicinity of the focal point of the antenna system, subtracting an unmodulated power component and taking a Fourier transform, one gets [4]:

$$F[H(x)] \simeq E(\xi) * E_0^*(-\xi) * \delta(\xi + \xi_0 + c) + E^*(-\xi) * E_0(\xi) * \delta(\xi - \xi_0 - c), \quad (1)$$

where $E(\xi)$ and $E_0(\xi)$ are complex fields in the measured aperture and on the surface of the reference element. Variables ξ_0 and ξ correspond to the reference element and a current point in the aperture, respectively; $\xi = \sin\varphi$, where φ is an angular coordinate of a point in the aperture; c characterizes a slope of the phase shift due to the reference panel movement, $*$ denotes a convolution.

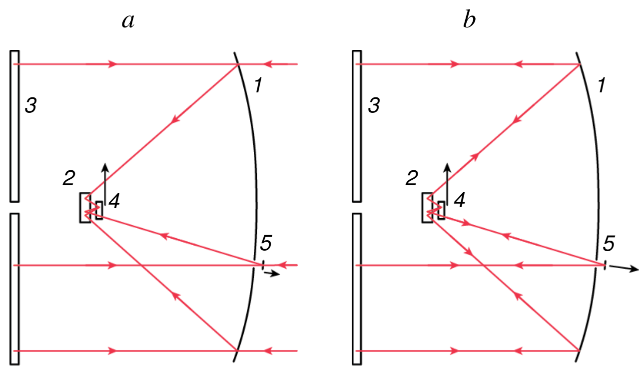

Fig. 1. Recording a hologram in the "South + Flat" antenna system of the RATAN-600 radio telescope; *a*—with a celestial source; *b*—in the autocollimation mode. *1*—main mirror; *2*—secondary mirror; *3*—flat reflector (periscope); *4*—carriage with TX and RX feeds mounted; *5*—reference panel

This method of the RH antenna measurements is suitable for any ground based or space radio telescope with an active surface. When measuring this way a surface of a fully steerable reflector radio telescope, it is convenient to record a hologram as an array of $2N \times 2N$ points, accumulating a signal from a space source at each point and shifting the reference panel by 120° in phase upon transition from row to row and from column to column [4].

In the autocollimation mode, good isolation between transmitting and receiving feeds is necessary, because the reference signal is weak with respect to the signal reflected by the rest of antenna. Power at the receiver input caused by reflection from the *i*-th panel is [5], [6]:

$$P_i = P_0 \left[\frac{\int_{\varphi_i - \Delta\varphi_i/2}^{\varphi_i + \Delta\varphi_i/2} K(\varphi)\eta(\varphi)F(\varphi)^2 d\varphi}{\int_0^{2\pi} F^2(\varphi) d\varphi} \right]^2 \cong P_0 \left[\frac{K_i \eta F(\varphi_i)^2 \Delta\varphi_i}{\Delta\varphi_{\mathrm{eff}}} \right]^2 \cong P_0 \left[\frac{K_i \eta F(\varphi_i)^2}{\chi N} \right]^2,$$

where P_0 is a full power radiated by the transmitter, $F(\varphi)^2$ is a normalized power beam pattern of the primary feed (here we assume that the transmitting and receiving feeds are identical), φ_i is an angular coordinate of the *i*-th panel, $\Delta\varphi_i$ is an angular size of the panel, $K(\varphi)$ is a vertical panel size utilization factor, K_i is a surface utilization factor of the *i*-th panel, η is an optical system efficiency accounting for losses due to spillover, random scattering, absorption, etc., $\chi = \Delta\varphi_{\mathrm{eff}} / (N\Delta\varphi)$, $\Delta\varphi_{\mathrm{eff}}$ is an effective width of the primary feed beam pattern, N is a number of panels in the measured sector of the antenna. In the ideal antenna system without random scattering $K_i\eta \to 1$ and χ usually is a little more than 0.5. However, an efficiency of the RATAN-600 “South + Flat” antenna system in autocollimation mode at $\lambda = 8$ mm is not better than 10 dB [5] because of adjustment imperfections, system focusing errors, and random scattering loss, all contributing several times as the radiation passes through the antenna system. That is, a power returned by antenna as a whole $P_{\mathrm{ant}} \le 0.1P_0$; due to this fact the power ratio of the reference to the signal from the rest of antenna may be several times greater than a theoretical value, providing an additional justification for the choice of $\lambda = 8$–10 mm for the RH antenna measurements.

RMS error of the RH measurements $\Delta\varepsilon$ is inversely proportional to the SNR at the hologram maximum, provided the reference signal level is high enough; usually the latter has the same amount as far sidelobes of the antenna system focal spot do. One should minimize another factors affecting the accuracy of measurements. In an ordinary holography, $\Delta\varepsilon = \lambda N / (4\pi \cdot \mathrm{SNR})$, where N is a number of points in the restored field [7]. In the phase retrieval methods there is no interference with a reference signal, thus their accuracy is $\mathrm{SNR}^{1/2}$ times more sensitive to noise: $\Delta\varepsilon \sim \lambda N / \mathrm{SNR}^{1/2}$ [8]. In our case, for $N = 100$ $\Delta\varepsilon = \lambda / 100$ when SNR = 796. The above expression for $\Delta\varepsilon$ accounts for both the receiver sensitivity and the effective antenna area including the antenna efficiency and the aperture illumination factor, as $\mathrm{SNR} = T_a / \sigma = S_f S_{\mathrm{eff}} / (2k\sigma)$, where S_{eff}, m^2 is an antenna effective area; T_a, K is a source antenna temperature; σ, K is a receiver sensitivity; S_f, $\mathrm{W \cdot m^{-2} \cdot Hz^{-1}}$ is a source radiation flux spectral density per unit area, $k = 1.38 \cdot 10^{-23}$ $\mathrm{J \cdot K^{-1}}$ is the Boltzmann constant.

Another factors affecting the accuracy of the autocollimation adjustment are the non-uniform phase distribution within the main lobe of the feed beam pattern and the influence of the surface layer atmospheric turbulence. E.g. if either transmitting or receiving feed has non-constant phase distribution with RMS = 7.2° there is no means to achieve the measurement accuracy better than $\lambda / 50$. In [9], the phase error due to the atmospheric turbulence was estimated as 0.03–0.3 mm depending on time of day, season and weather conditions.

Considering noise as fluctuations of the receiver output signal caused by both the receiver noise and cross-talk from the transmitter, we can estimate the necessary fluctuation sensitivity of the receiver ΔP_{r} and an acceptable level of the transmitter cross-talk P_{ct}:

$$P_{\mathrm{ct}} \cong \Delta P_{\mathrm{r}} \cong \frac{P_0}{\mathrm{SNR}} \left[\frac{2F(\varphi_i)^2}{N} \right]^2.$$

For $N = 167$, $\mathrm{SNR} = 1000$ (30 dB), and the illumination level $F(\varphi_i)^2 = 0.1$ at the edge of the measured antenna $P_{\mathrm{ct}} / P_0 \cong \Delta P_{\mathrm{r}} / P_0 = 1.4 \cdot 10^{-9}$. A design of both receiver and transmitter with a ratio of sensitivity to transmitted power of 10^{-9} does not pose any difficulties, but the consideration regarding the cross-talk implies near 90 dB isolation between the receiver and the transmitter.

There are three essential ways to achieve the necessary isolation level and suppress the unwanted signal as well as the random scattered background radiation [6].

1) Compensation method, using a single feed for both transmission and reception and a ferrite circulator at the receiver input. The unwanted signal entering the receiver through the circulator is suppressed by a portion of the transmitter signal which is added into the receiving path in opposite phase.

2) Gating method with a pulsed signal, also using a single feed for both transmission and reception and a ferrite circulator at the receiver input. The unwanted signal is cut off by means of range gating.

3) Spatial separation of the receiver and the transmitter, using two independent feeds for transmission and reception.

In the first two methods the internal cross-talk signal going from the transmitter into the receiving path is suppressed, as well as the external random scattered background from the measured antenna and the environment. In our approach the third method is used, providing good isolation between the transmitter and the receiver (more than 50 dB for 2-3 cm spacing between feeds) but more sensitive to the external background. The random scattered background not related to the adjustment errors of the antenna elements is caused mainly by diffuse reflection from the matt antenna surface. However, it is modulated by the scattering from gaps between the antenna panels, which are periodically spaced. Usually the background level is not higher than –30-40 dB relative to the useful signal, but the signal from the peripheral panels may be sufficiently weaker, as we have seen before. In order to compensate the background scattered by the main mirror of the telescope, several panels can be adjusted so that the signal they reflect and the background are in opposite phase at the position of the receiving feed.

The greater is the spatial separation between the feeds, the better is the isolation between the transmitter and the receiver. In the same time, this separation should not induce any unwanted effects such as optical aberrations in the antenna system. The possibility of a reliable measurement of a given panel position implies that the power contribution from that panel must be greater than the scattered background level. Power contribution of a single panel is of order $F(\varphi_i)^2/N^2$; obviously this value becomes very low for peripheral panels if the measured sector of the antenna is large enough. This leads to significant difficulties in autocollimation adjustment of such panels in their azimuthal and elevation coordinates. When measuring the radial coordinate, the adjustment is performed in the interference mode, when additive quantities are electric fields rather than their intensities, thus a single panel contribution is inverse proportional to N rather than N^2, and SNR is much higher. However, signal from peripheral panels usually cannot be registered reliably because of the surface layer atmospheric turbulence. The same considerations are valid for the contribution of the reference panel moving during the RH antenna adjustment, which is also inverse proportional to N and amounts to a few percent of the total magnitude of the RH signal only if $N \lesssim 100$. This is the usual limit for the number of elements in the antenna under measurements. In principle, one could overcome this limit using feeds with a flat-top beam pattern. This would amplify peripheral panels contribution by an order of magnitude and increase the number of simultaneously measured panels up to the whole sector size (167 panels for the "South + Flat" antenna system)—in particular, due to the possibility of using a peripheral panel as a reference, which is the best option in the case of a wide-angle optical system.

III. Autocollimation Radio Optics Model and the Results of its Application

Modeling of the antenna system allows us to determine an acceptable spatial separation between the feeds, establish the requirements to the accuracy of their placement and orientation, as well as to the secondary mirror positional and orientation tolerances. Fig. 2 presents the coordinate system used in calculations and the ray tracing results in the form of focal spots, i.e. diagrams of intersection of traced rays with the focal plane.

Radio modeling includes the calculation of the lengths of optical paths (hence field phases) from the transmitting feed to the aperture through the antenna system and the computation of field in the focal plane using the Fourier transform. In this way one can obtain either a modeled focal

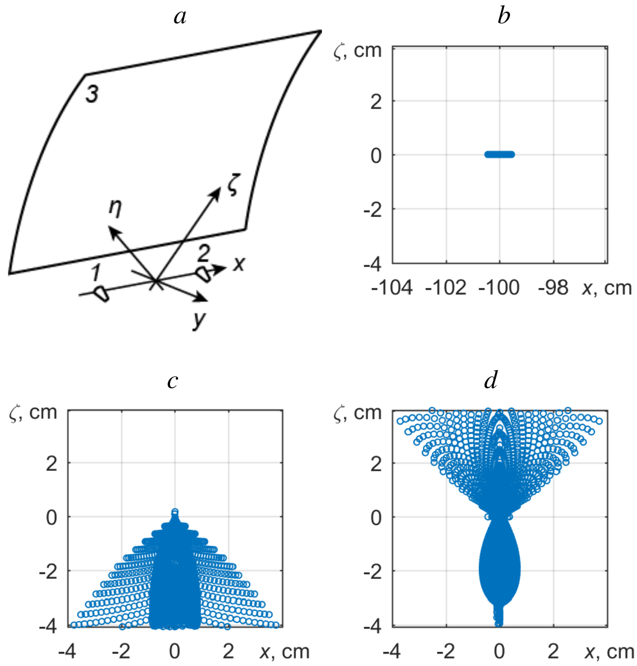

Fig. 2. *a*—coordinate system used in ray tracing calculations; η is parallel to the feed axes, ζ is in the plane of feed aperture; *1*, *2*—feeds, *3*—secondary mirror; focal spots: *b*—TX feed offset $\Delta x = 100$ cm; *c*—TX feed offset $\Delta\zeta = 0.1$ cm; *d*—TX feed offset $\Delta\eta = 0.1$ cm; the number of rays is 55×80

spot or a hologram. A hologram differs from a focal spot in that the reference panel is moving during the measurement, providing a linear phase shift which allows for separation of conjugated "images" of the field in the aperture from each other and the field autocorrelation part in a resulting hologram (cf. eq. (1)). Adding a certain amount of noise to the model, one can estimate the accuracy of the experimental reconstruction of the field amplitude and phase distributions in the aperture. Model holograms for two distinct spacing between feeds are shown in Fig. 3.

The modeling revealed that uneven movement of the reference panel can dramatically impair the quality of reconstruction of field in the aperture. E.g. the phase retrieval is practically impossible if the coefficient of variation (i.e. ratio of the standard deviation to the mean) of the reference panel speed is 1.5% of its mean value. The modeling suggests that the coefficient of variation of the reference panel speed must not exceed 0.5% in order to achieve reasonable results.

An alternative way to increase the accuracy of measurements is in discrete repositioning of both the receiving feed and the reference panel, when the precision positioning matters, rather than the speed control. In this approach, a step of the phase shift due to the reference panel movement can be e.g. 120°, which gives a discrete sequence of phase shifts 0°, 120°, 240°, ... and the reference panel position can change cyclically. This method is suitable not only for the RATAN-600 antenna measurements, but for any ground based or space reflector antenna with an active surface [9].

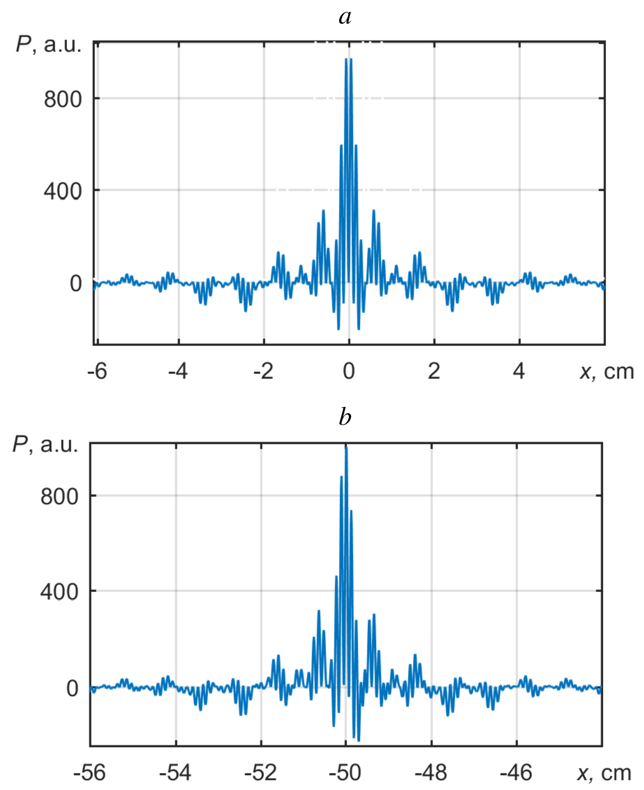

Fig. 3. Modeled holograms: *a*—feed spacing Δx = 0; *b*—feed spacing Δx = 100 cm

IV. Results of the Radio Holography Antenna Measurements

In order to stabilize the speed of the reference panel movement its power circuit with relay control and a magnetic starter was replaced by a variable frequency drive (VFD). This allowed to maintain the unevenness of the reference panel movement below 0.5% and increase its speed several times, which lead to 2-to-3 times decrease in measurement time and improved the repeatability of the field reconstruction. In Fig. 4 the results are given of the reconstruction of amplitude and phase in the aperture for two consecutive measurements taken within an hour using a standard power circuit of the reference panel and three measurements using a VFD driving the reference panel at a double speed. The measure of the reconstruction repeatability was the mutual correlation coefficient of the restored amplitude and phase distributions $R_{1,2}$. A gap in the center of the amplitude distribution is caused by shading the center elements of antenna by the secondary mirror.

It is seen from Fig. 4 that increasing the speed and excluding its instability lead to increase in $R_{1,2}$ from 0.8 to 0.97. High repeatability of the field restoration, and also reliable reconstruction of the radial coordinates of the panels which were slightly offset from their standard positions in order to verify the measurement procedure, allow us to proceed with a next step that will be the fine adjustment of the panels position based on the RH data.

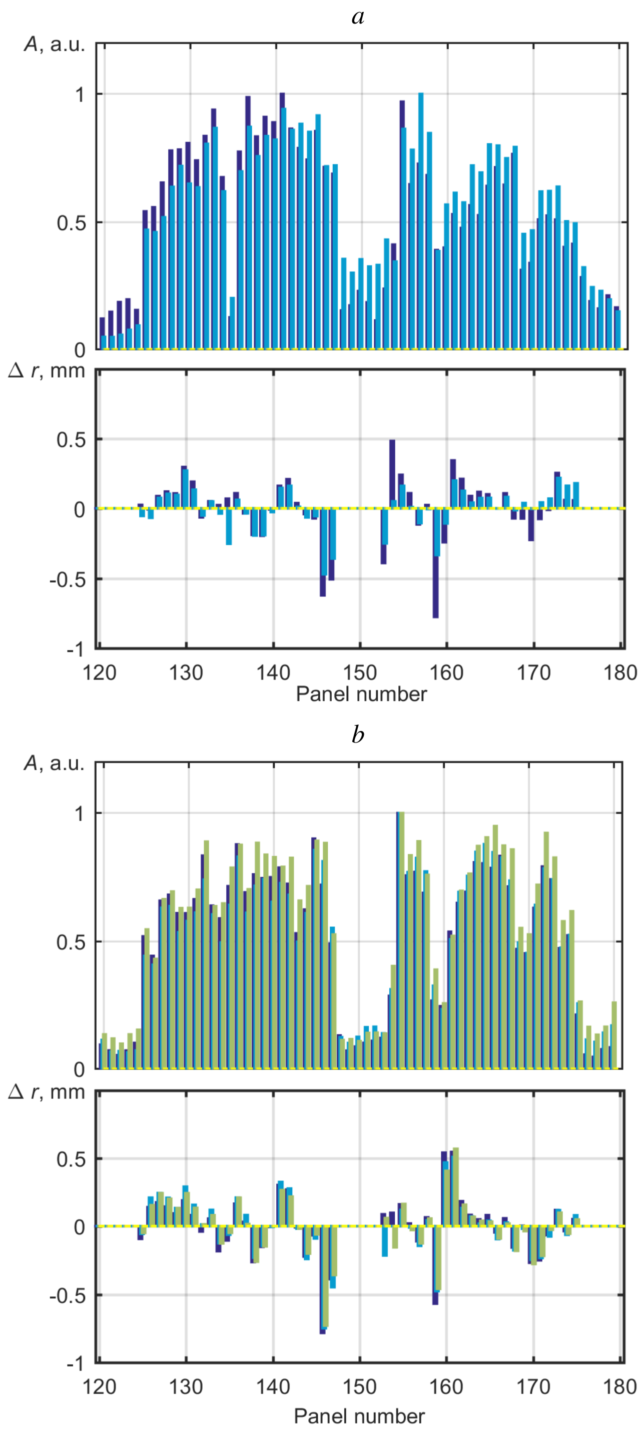

Fig. 4. Reconstruction of amplitude distribution in the aperture *A* and deviation of the positions of the main mirror panels from the ideal parabola in the radial direction Δr: *a*—two records made using the standard power circuit of the reference panel; panel 135 was turned 5° around its elevation axis; correlation between phase distributions within the aperture $R_{1,2} = 0.836$; *b*—three records made with the VFD, correlation between phase distributions within the aperture $R_{1,2} = 0.960$, $R_{2,3} = 0.972$, $R_{1,3} = 0.967$

V. Conclusion

Our report presents the results of the radio optical modeling of the new RH method intended for the diagnosis and adjustment of the RATAN-600 radio telescope “South +

Flat" antenna system. The feed positional and orientation tolerances, acceptable spacing between feeds, as well as the requirements to the transmitting and receiving paths are considered.

The increase in spacing between feeds provides better isolation between transmitting and receiving paths, and also lower the level of the background caused by random scattering on the environment and the antenna itself. Among the requirements to the feed installation accuracy the most critical are that related to the positional tolerances of the displacement of feeds from the focal line in the plane of their apertures $\Delta\zeta$ and along their axes $\Delta\eta$, which must not exceed ±1 mm. The spacing between feeds along the focal line Δx may be any within 1 m. In order to record a symmetric hologram, it is desirable to place the transmitting and the receiving feed at the same distance from the middle of the feed carriage. At least the mount of the transmitting feed must be fine adjustable in η and ζ coordinates. As both the modeling and the experiment have shown, provided the radiation source is coherent, high precision of the reference panel movement and short recording time are the key factors of the high repeatability and accuracy of the proposed method.

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