Development of Methods for Autocollimation Adjustment and Efficiency Monitoring of the RATAN-600 Antenna System

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Abstract. The autocollimation (AC) is the most popular method of the antenna adjustment and measurements on the RATAN-600 radio telescope because of the similarity of the characteristics of the radio telescope in the autocollimation and operating modes and the easy transition of the antenna from the adjustment state to the operating state. The requirements for autocollimation adjustment equipment, features of the autocollimation methods for antenna adjustment and monitoring of the radio telescope antenna efficiency are considered. The results of the autocollimation method employment for the RATAN-600 antenna adjustment and monitoring of its efficiency in automatic mode, as well as monitoring the surface quality of mirrors comprising the AC scheme by means of modern laser geodesy, are presented.

Keywords: telescopes; techniques: radar astronomy

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The AC method is widely used in optics for tilt measurements and alignment components of optical systems. The AC method for a variable profile antenna (VPA) adjustment was proposed at the end of the 1960s on the BPR (Khodjamukhamedov et al. 1970) and is still the most popular technique for antenna adjustment and measurements on the RATAN-600 radio telescope due to similarity of the antenna characteristics in AC and operating mode and the ease of repositioning the VPA from the adjustment configuration to the operating one. In Khaikin & Verkhodanov (1993), a comparison of the measured two-dimensional AC focal spot with the simulated one was used to assess the antenna efficiency of a radio telescope. Khaikin et al. (2014) describe a new generation two-frequency complex operating at the wavelengths 8 mm and 18.8 mm and a procedure of its application for the AC adjustment. Its introduction on the RATAN-600 led to giving up the long-term practice of the antenna AC adjustment in a semi-automatic mode. In Khaikin & Bursov (2016), an algorithm is proposed and the results of AC adjustment and measurement of the efficiency (contribution) of panels in an automatic (unmanned) operation mode are presented. In Khaikin et al. (2019), the results of optical modeling of an AC scheme for radio-holographic alignment of the main mirror are presented. In this work, we continue the development of the AC adjustment technique and evaluation of the efficiency of the RATAN-600 antenna system (AS).

To separate the transmitted and received signal in the transceiving AC complex, time gating, compensation, or spatial separation are used. The first and second methods use a single horn with a transmitter and a receiver connected through a circulator. To suppress the parasitic signal penetrating into the receiver through the circulator, as well as stray external background, the first method use the pulse modulation of the transmitter and gating of the receiver; in the second method, the parasitic signal in the receiver is suppressed by a portion of the transmitter signal reflected in antiphase from the compensator installed between the horn and the circulator. In the third method, the decoupling of the receiver and transmitter is achieved by the spatial separation of the transmitting and receiving horns.

A characteristic feature of the AC method of adjustment a multi-element wide-angle antenna is the low power reflected from one panel with respect to the reflected signal from the entire antenna. The situation aggravates for peripheral panels because of the illumination taper. Furthermore, Khaikin et al. (2009) showed that due to suboptimal shape of the secondary mirror (SM) the total energy loss for AS “South+Flat” (AS “S+F”) amounts to 10-15%, while the fraction of incompletely illuminated panels reaches 20-30%.

Estimate the requirement for the isolation of the transceiver channels for the AC alignment. Assuming the noise of the receiver to be the fluctuations of receiver’s output signal caused both by its intrinsic noise and by the unsuppressed parasitic signal of the transmitter, the required fluctuation sensitivity of the receiver $\Delta P_{\rm rec}$ and the permissible level of the spurious signal of the transmitter in the receiver $P_{\rm par}$ can be found as $P_{\rm par} \cong \Delta P_{\rm rec} \cong (P_0/M) \cdot \big(F^2(\Phi_i)/N\big)^2$, where P_0 is full power radiated by the source, N is the number of panels, Φ_i is the coordinate of the center of the i-th panel, $F^2(\Phi_i)$ is the normalized directivity pattern of the primary feed, M is the practically achievable S/N ratio at the receiver output (Khodjamukhamedov et al. 1970; Khaikin et al. 2014). For $N = 225$, $M = 200$, $F^2(\Phi_i) = 0.1$ at the farthest elements of the antenna, we have $P_{\rm par}/P_0 \approx \Delta P_{\rm rec}/P_0 = 1 \cdot 10^{-9}$. Let us take into account the scattering losses in a non-ideal antenna system. In the AC mode the mirror surface error doubles. The typical AC efficiency of the RATAN-600 sector at a wave-

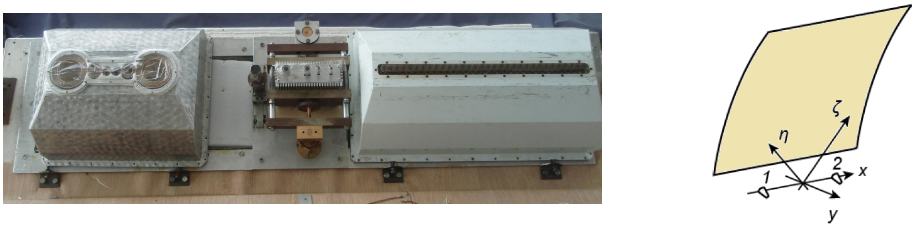

Fig. 1. New generation AC adjustment complex installed in the center of the movable carriage of the feed cabin No. 2 (left), coordinate system near focus (right)

length of 8 mm is less than 6-10 dB, i. e. the power returned from the sector is $P_{\rm ant} = (0.25 \ldots 0.1)P_0$, and the required dynamic range (DR) of the receiver is $P_{\rm ant}/P_{\rm rec} = (0.25 \ldots 0.1)P_0/(10^{-9}P_0) = (2.5 \ldots 1.0) \cdot 10^8$, i. e. more than 80 dB, which is very difficult to realize. Hence, the adjustment is usually performed with the entire antenna retracted, by successive engaging a few panels being adjusted relative to one reference panel. So the DR of the receiver can be significantly reduced, but the required decoupling of the receiver and transmitter remains the same ($\geq$ 80 dB), which poses a technically difficult problem if the time gating or compensation is used, and is much easier to achieve with the spatial separation.

A new generation two-frequency AC adjustment complex with spatial separation of channels installed in the center of movable feed carriage is shown in Fig. 1. Optical modeling in Khaikin et al. (2019) showed that the tightest tolerances ($\leq$ 1 mm) for the AC horns position in the vicinity of focus of the SM are required along the ζ and η axes. In the AC method, the surface quality and the azimuthal turn of the SM are subject of increased requirements, as SM contributes twice and can introduce noticeable systematic errors in the alignment results. For AS "S+F", the quality of the geodetic alignment of the flat reflector (FR) is also critical. To assess the surface quality of the FR and SM, modern laser geodesy was used (Khaikin et al. 2013), showing the possibility of a significant improvement in the surface condition of SMs and FR, which would significantly increase the accuracy of AC adjustment of the main mirror.

During adjustment the positions of the panels in three coordinates are sought, which give a maximum of the AC signal relative to the reference panel. The final adjustment is performed at a wavelength of 8 mm, a wavelength 18.8 mm can be used for preliminary alignment of the antenna and when significant correction is needed, in order to eliminate and ambiguity of $\lambda/2$ in the Northern sector and $\lambda/4$ at the AS "S+F", where operation at 18.8 mm is more convenient.

When the spatial separation between channels is used, the phase centers of the primary feeds should be placed in two foci F_1 and F_2 of the elliptic main mirror. However, as the distance F_1F_2 is small with respect to the mean antenna radius R_0, the ellipse does not differ much from the circle with the center at halfway between the foci. This difference is equal to $10^{-3}R_0F_1F_2\cos\varphi_0$ and for $F_1F_2 < 100$ mm does not exceed 0.06 mm at the edge of the sector ($\varphi_0 = 45°$), which does not lead to any significant systematic error in the profile of the adjusted antenna for observations at a wavelength of 8 mm. The possibility of spacing between horns up to 100 mm in the AC mode at the Northern sector is not in doubt; however, it can cause cubic aberrations in AS “S+F”. Optical simulation in Khaikin et al. (2019) showed that even larger spacing of horns on the feed carriage does not affect the autocollimation focusing at AS “S+F”, though to avoid the cubic aberration of the focal spot and the corresponding additional phase shift at the edges of the aperture horn spacing should not exceed 2-3 wavelengths, i. e. 25-60 mm for the wavelengths 8-20 mm.

Even more significant systematic phase errors occur at the edge of the sector if the feed is offset longitudinally relative to the center of the original circle with a radius of 288,000 mm. In this case, for the i-th panel, azimuthal and radial corrections to the panel initial positions are $\Delta\alpha_i = \arcsin(\sin\varphi_i/[R_0/d-1])$, $\Delta r_i = d\,(1-\cos\varphi_i+\sin\varphi_i\tan[\Delta\alpha_i/2])$, where φ_i is the angle between the antenna axis and the direction to the i-th panel, d is the longitudinal displacement from the center of the original circle. As follows from these expressions, the radial correction vanishes on the axis and becomes close to $0.3d$ in the direction $\varphi_i = 45°$, i.e. with a longitudinal focus shift of 3 mm, the resulting correction of radial positions is close to 1 mm. Therefore, before starting the AC adjustment, the longitudinal position of the SM must be determined with great care.

To assess the quality of the antenna before and after alignment, it was proposed in Khaikin & Bursov (2016) to perform automatic monitoring of the efficiency (contribution) of the panels placing them in turn at known positions (AC-zeros). In the algorithm for automatic measurement of contributions of the panels, all the panels of the sector except for the reference one are first retracted to a certain position in elevation; then they are guided in turn to AC-zeros in elevation, which allow for evaluation both the power contribution of the given panel and its phasing with the reference one. Another way of monitoring of the antenna system efficiency is in measuring two-dimensional AC focal point before and after antenna adjustment (Lebedev et al. 2019). The report presents the results of applying the AC method for adjustment, measuring the efficiency of panels and measuring the two-dimensional focal spots of the AS “S+F” in automatic mode, as well as monitoring the surface quality of SM and FR comprising the AC system using modern laser geodesy.

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