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A RESEARCH OF DIFFERENT DEFORMATIONS INFLUENCE ON ROT-54/2.6 RADIO TELESCOPE ANTENNA

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Abstract: A telescope is never perfect because of mechanical, gravity, temperature and wind induced deformations of its structure, because of production imperfections and because of accidental small misalignments of the constrictive elements. The resulting degrading effect on the beam pattern is negligible if the corresponding deformation of the reflector and the misalignment of the constructive elements (main reflector, sub reflector, receiver) are small compared to the wavelength of observation, i.e. smaller than $\lambda/16$. The degradation becomes noticeable and disturbing if the corresponding deformation is larger than $\lambda/10$ [1].

In our work we examined the different deformations influence on field distribution in antenna's aperture for ROT-54/2.6 Radio Optical Telescope. Even taking into considerations that the gravity and wind impacts are minimized

in ROT-54/2.6 because of constructive feature, we obtained simple formulas demonstrating each type of deformation influence on phase distortion as well as combined impact of deformations on overall antenna efficiency.

Introduction

Antennas used for radio telescopes usually have large dimensions and generally are composed by set of surface panels with supporting structure (also known as a backup structure) [2]. So far, the Arecibo Observatory Radio Telescope located on the island Puerto Rico has the largest spherical multi-reflector antenna in the world. The main collecting dish is 305 m in diameter, is constructed inside the depression, and the backup structure of it is the network of steel cables strung across the underlying karst sinkhole [3]. The only one Radio Optical Telescope in the world ROT-54/2.6 located in Armenia on the mountain Aragats has the second largest double-reflector spherical antenna. ROT-54/2.6 has been designed and constructed in Radiophisical Measurements Institute (Yerevan, Armenia) managed by famous Armenian scientist Paris Herouni in 1987 [4]. The main collecting dish is 54 m in diameter and is constructed inside the rock depression. It has a spherical shape and its surface consists of 3716 solid panels, specially melted and processed with high accuracy. The application areas of both these large double-reflector spherical antennas are radio astronomy and deep space communication.

In 2016 the Five-hundred-meter Aperture Spherical Telescope (FAST) in the Pingtang county in southwest China's Guizhou province was completed and became the largest in the world nowadays. Being 500 meters in diameter, the Radio Telescope is also nestled in a natural basin. Generally speaking, the working surface of the FAST antenna is not spherical but parabolic mirror constructed from special panels [3]. In such highly directional antenna systems of presented radio telescopes, the most optimal characteristics can be achieved only when the field distributions in the antenna aperture in terms of amplitudes and phases are close to uniform. These large dimensional antennas can have significant deformations of their backup structure and that has a direct effect to the filed distribution in the aperture of antenna which, in turn, affects the beam pattern and intensity. The associated wave-front deformation of the imperfections may be of both systematic and random nature, as well as of both of them. Systematic wave-front deformations usually produce a deformation of the main beam and the profile close to the main beam and a decrease in main beam intensity; random wave-front deformations usually produce an intensity decrease of the main beam and a much extended and more or less intense Gaussian type error beam. In the general situations the deformations consists of spatially small-scale random deformations, which usually do not change the structure of the beam pattern and the focus and pointing, and large-scale deformations, which may do so [5].

The main restriction when constructing antenna system is the phase distortion tolerance in the antenna aperture, which should be less than $\pi/2$ [6]. The ROT-54/2.6 antenna design conditionally can be divided into following parts (Fig. 1): large fixed spherical reflector 1, the small reflector 2 which moves with the help of construction 3 around the centre of the sphere.

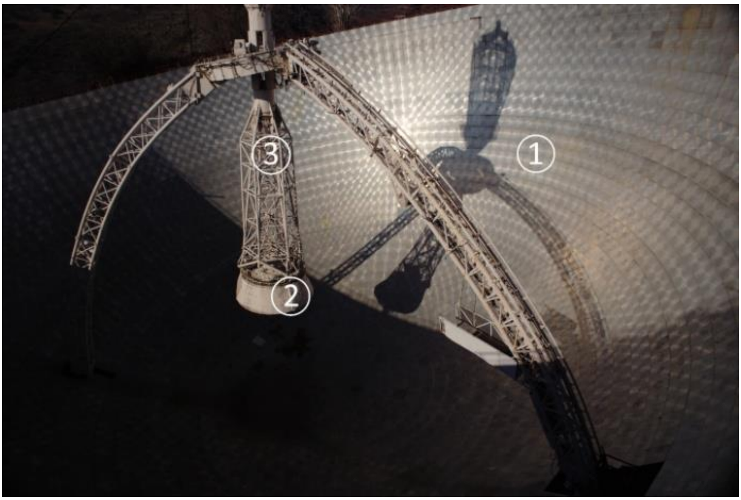

Fig. 1: Overall view of ROT-54/2,6 antenna construction.

The reflecting surface of the large reflector is the hemisphere of 54 m in diameter. Surface panels are casted from aluminium alloy and have spherical profile. The panels have a small gap between each other to ensure that thermal deformation of one panel will not affect the neighbour panels. The average size and weight of panels are accordingly 1100x1100 mm and 55 kg respectively. Overall quantity of panels is 3716. On the opposite side of panels, stiffening ribs exist to ensure stiffness of panels. The small reflector has a complex profile. In the focus of small reflector the feed and the supporting structure for receiver is mounted. The reflecting surface of small reflector is composed from titanium panels. The small reflector has the following dimensions: the deepness is 2643 mm and the aperture diameter is 5688 mm. In this paper the dependence of ROT-54/2.6 antenna parameters in the aperture of large reflector on accuracy of constructive elements is examined.

A theoretical research of the errors joint influence on the phase distortion

In highly directional antenna systems, the optimal characteristics can be achieved if the field distribution on the antenna aperture in terms of amplitude and phase are close to uniform. However, in real case, field distribution differs from uniform one because of several reasons.

One of the main reasons causing the non-uniform distribution of field in aperture is the surface error of reflectors and other constructive elements of the antenna system. When the antenna dimension significantly exceeds the wavelength, in antenna theory, the methods of geometrical optics become applicable. In this case the reflecting mirrors should provide the uniform distribution of the filed in the antenna aperture, i.e. the distances which each beam passes from feed to aperture being reflected by two mirrors should be equal. Regardless of reflectors profile and quantity the following equation can be written:

$$\sum x_i - \sum c_i = 0 , \tag{1}$$

where: c_i is the path of central beam in the mirror system, x_i is the same for current beam. The parameters c_i, x_i are functions of the antenna constructive parameters, thus Eq.1 can be considered as an expression for uniform phase distribution in the aperture. For real antenna, the geometrical dimensions would differ from calculated values. Correspondingly, parameters c_i, x_i would differ also from the calculated ones. The difference of the beams can be expressed as follows:

$$dS = dS_\theta - dS_o, \tag{2}$$

where

$$\left.\begin{aligned} dS_\theta &= \sum dx_i \\ dS_o &= \sum c_i \end{aligned}\right\} \tag{3}$$

The electrical length of

$$dS = \frac{d\varphi}{d\pi}\lambda, \tag{4}$$

where λ is a wave length and $d\varphi$ is a phase distortion. The limits for phase tolerance on the antenna aperture in antenna theory is $\pm\frac{\pi}{4}$, thus the limiting deviations would be $\pm\frac{\lambda}{4}$.

In Fig. 2 the main spherical reflector 1 and the corrective small reflector 2 are shown, the point of the system focus is F, the current point is M of phase front line in the aperture, and created beam has the length of a, b and r. All parameters are shown taking into consideration the misalignments. Also, there are the following notations:

x_0Oy_0 is the fixed coordinate system. The coordinate system centre matches with the centre of large hemisphere;

vOu is the movable coordinate system;

xO_2y is the fixed coordinate system regarding small corrective reflector; x,y,u,v are the coordinates of current point of the small corrective reflector, in the corresponding system coordinates;

x_0, y_0 are the small corrective reflector centre "O_1" moving coordinates in the system coordinates x_0Oy_0;

e is a point in the axis of small corrective reflector; f is the distance of focus from point $"O_1"$;

x_e is the distance of point “e” from the top of the smallcorrective reflector;

U_e is the distance of point “e” from axis “OV”;

U_f is the distance of focus from axis “OV”;

γ is the angle of rotation of small corrective reflector over point “e”.

Taking into consideration Eq.3, the following equation can be written:

$$dS_\theta = dn + db + da \tag{5}$$

In addition, we have:

$$\left.\begin{aligned}
n &= \frac{Cos\theta}{Cos\left(2\theta-\theta_1\right)} R \\
a &= \sqrt{\left(V_f - V\right)^2 + \left(U_f - U\right)^2} \\
b &= \sqrt{\left(n_1 - V\right)^2 + \left(r_1 - U\right)^2} \\
U_0 &= y_0 Cos\psi - x_0 Sin\psi \\
V_0 &= y_0 Sin\psi + x_0 Cos\psi \\
V_e &= V_0 + \sqrt{e^2 - \left(U_e - U_o\right)^2}
\end{aligned}\right\}$$

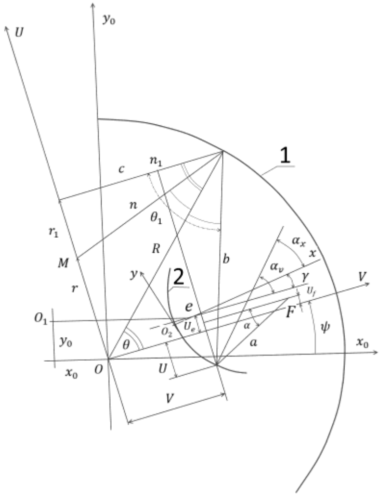

Fig. 2: Design scheme of a double reflector spherical antenna.

In Eq.6 the parameter α_x is the angle between the small corrective reflector current point normal dS_θ and the axis O_2x .

$$\left.\begin{array}{c}
V_f = V_0 + \sqrt{f^2 - (U_f - U_0)^2} \\
V_{02} = V_e - x_e Cos\gamma \\
U_{02} = U_e - x_e Sin\gamma \\
V = V_{02} + xCos\gamma - ySin\gamma, \\
U = U_{02} + yCos\gamma + xSin\gamma \\
\alpha_V = \alpha_x + \gamma \\
\theta_1 = 2\alpha_x + 2\gamma - \alpha \\
\alpha = arc\tan\dfrac{U_f - U}{V_f - V} \\
\theta = \theta_1 + arc\sin\left(\dfrac{U}{R}\cos\theta_1 - \dfrac{V}{R}\sin\theta_1\right) \\
n_1 = R\cos\theta \\
r_1 = R\sin\theta
\end{array}\right\} \qquad (6)$$

Parameters x and y can be calculated from the following equations [6]:

$$\left.\begin{aligned}
x &= A - l - p\cos 2\theta \\
y &= B - p\sin 2\theta_1 \\
A &= 1 - 2\left(1-\cos\theta\right)cos^2\theta \\
B &= sin\theta - \left(1-cos\theta\right)sin2\theta \\
p &= \frac{1}{2}\frac{c^2-\left(A-f\right)^2-B^2}{c-\left(A-f\right)cos2\theta - Bsin2\theta} \\
c &= 1-2l+f
\end{aligned}\right\} \tag{7}$$

where l is the distance between the vertex of the small corrective reflector and the center of the large hemisphere. Taking into consideration Eqs. 2–3, Eqs. 5–6, the total differential of dS can be expressed as follows:

$$\begin{aligned}
dS &= 2cos\theta dR - 2dR_\zeta + 2sin^2\theta cos\psi dx_0 + \\
&+2\,sin^2\theta sin\psi dy_0 + 2sin^2\theta de - \left(sin2\theta - sin\alpha\right)dU_e + \\
&+\left(cos2\theta + cos\alpha - 2\right)dx_e - \left(cos2\theta + cos\alpha\right)dx + 2dx_\zeta - \\
&-\left(sin2\theta - sin\alpha\right)dy - sin\alpha dU_f - \left(1-cos\alpha\right)dm + \\
&+\left(esin2\theta - sin\theta + msin\alpha\right)d\eta
\end{aligned} \tag{8}$$

where

$$\left.\begin{aligned}
m &= f - e \\
d\eta &= Rd\gamma \\
\alpha &= arcsin\left[\frac{y}{\sqrt{\left(f-x-l\right)^2+y^2}}\right]
\end{aligned}\right\} \tag{9}$$

dR_ζ is the error of large hemisphere at some point of its surface, when the point is located on the axis of small corrective reflector.

dX_y is the error of small corrective reflector surface on the axis O_2x.

In the Eq. 8 phase deviations are calculated from the intersection of central beam with the antenna's aperture plane, i.e. $\theta = x = y = r = 0$.

The Eq. 8 can be used to study systematic errors. For the current point of θ equation gives the linear dependency of phase deviation on errors of the antenna construction, however, the phase deviation on the antenna aperture is non-linear. The influence of each constructive error can be calculated separately assuming that other types of constructive errors do not exist.

The phase deviation dependency dS from the antenna aperture plane coordinates for each dx_n errors is shown in the Fig. 3.

The curves for Δx and Δx_1 ($\Delta \mathrm{y}, \Delta \mathrm{y}_1$) show the constructive error influence of $x(y)$ coordinate on phase distortion. The curve $\Delta x(\Delta y)$ takes into consideration the situation when the point of small reflector has constant error equal to 1 over $x(y)$. Curve $\Delta x_1(\Delta \mathrm{y}_1)$ shows the situation when errors change according to the law:

$$\Delta \mathrm{x} = \frac{x}{x_1} \Delta x_1$$

$$\Delta \mathrm{y} = \Delta x_1 tg 2\theta \frac{x}{x_1}$$

Random errors can be expressed using the RMS summation. If σ is the RMS error of the beam traveling distance from the antenna aperture plane to the focus and σ_i is the RMS error of corresponding constructive elements, then:

$$\sigma^2 = 4(cos\theta - 1)\sigma_R^2 + 4\sin^4\theta\cos^2\psi\sigma_{x_0}^2 + 4\sin^4\theta sin^2\psi\sigma_{y_0}^2 +$$
$$+4\sin^4\theta\sigma_e^2 + (\sin 2\theta - \sin\alpha)^2\sigma_{U_e}^2 + (\cos 2\theta + \cos\alpha - 2)\sigma_{x_e}^2 + \quad (10)$$
$$+(1-\cos\alpha)^2\sigma_m^2 + sin^2\alpha\sigma_{U_f}^2 + (\cos 2\theta + \cos\alpha)^2\sigma_x^2 +$$
$$+4\sigma_{x\zeta}^2 + (\sin 2\theta - \sin\alpha)^2\sigma_y^2 + (e\sin 2\theta - \sin\theta + m\sin\alpha)^2\sigma_\eta^2$$

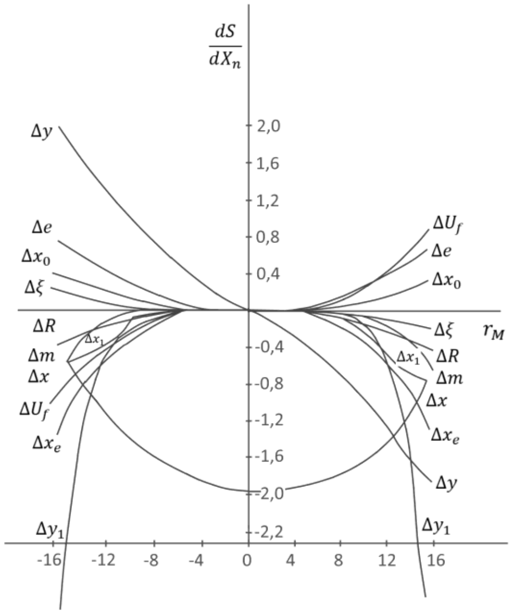

Fig. 3: The curves of phase deviation on the antenna aperture plane.

ROT-54/2.6 radio telescope temperature deformations caused by evenly heating

When real antenna is evenly heated, every separate element of construction is resizing strictly according to a specific law. Due to material differences, the conditions of equality of relational elongations are not ensured. This may cause the phase distortion in the antenna aperture plane.

The study of evenly heating is done for the following values of the antenna parameters (Fig. 4):

$R = 27000mm$, $l = 0,49R$, $f = 0,63R$

The foundation for the antenna is a reinforced concrete hemisphere with an internal radius of $R_1 = 28800mm$ and a wall thickness of $B_1 = 1500mm$. The main spherical reflector consists of separate shields with $b_1 = 60mm$ thickness. The shields are fixed on individual steel supports with a height of $H = 1740mm$. The movement system of small reflector with supported structure is also made of steel. The distance between main reflector axis of symmetry to the small reflector supporting structure foundation is $H_1 = 20000mm$. The small reflector is joined with mobile metalwork at a distance of $e = 14500mm$ from the center of the main reflector.

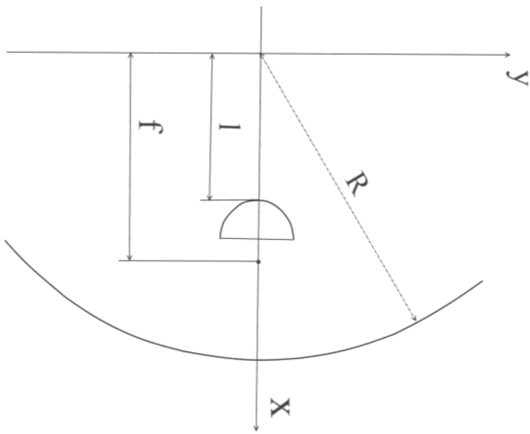

Fig. 4: The schematic view of parameters R, l and f.

For the moderate temperature range the errors of construction can be determined as follows:

$$\Delta x_i = x_i \beta_j t \quad (11)$$

where i is the current number of the construction element, j is the material, x is the corresponding dimensions, β is the coefficient of linear expansion, t is the temperature of uniform heating calculated from a certain average temperature.

The study of ROT-54/2.6 antenna shows, that, due to heating, reinforced concrete hemisphere inner radius changes according to the law [6]:

$$\Delta R_1 = 0,742 R_1 \beta_{r.c.} t \tag{12}$$

Due to asymmetry of small reflector supporting structure, uniform heating will cause the following error:

$$\left.\begin{aligned} &\Delta y_0 = 0 \\ &\Delta x_0 = 0,258 \frac{R_1^2}{H_1} \beta_{r.c.} t \end{aligned}\right\} \tag{13}$$

Obviously, the main reflector radius expansion will correspond to the linear law:

$$\Delta R = \Delta R_1 - \Delta H - \Delta b_1 \tag{14}$$

So, $\Delta R_y = \Delta R = Cosnt$, for every part of surface.

Considering that $\Delta x_y = \Delta U_e = \Delta U_f$

The phase distortion curve on the antenna aperture plane regarding to the function $r = sin\theta$, in the range $-0,5926 \ll r \ll 0,5926$, for the different values of ψ in the range of $-60^0 \ll \psi \ll 60^0$,

where t and λ are taken as 1, is shown in Fig. 5. Curves for ΔS show uniform heating and σ curves show random errors.

Fig. 5 shows that ΔS has the maximum value when r has the maximum value and ψ equals to 0.

So, the temperature range tolerance for the antenna construction elements can be written with quantitative coefficients as follows:

$$\Delta\varphi = \frac{2\pi}{\lambda} \begin{pmatrix} -0.389\Delta R + 0.702\Delta x_0 + \\ +0.702\Delta e - 1.331\Delta x_e - \\ -0.669\Delta x_1 + 1.883\Delta y_1 - 0.629\Delta m \end{pmatrix} \tag{15}$$

For the certain antenna dimensions and materials the temperature range tolerance should be $\pm 1.26\lambda_{deg.}$ (λ in mm) to ensure that phase distortion is less than $\pm\frac{\pi}{4}$.

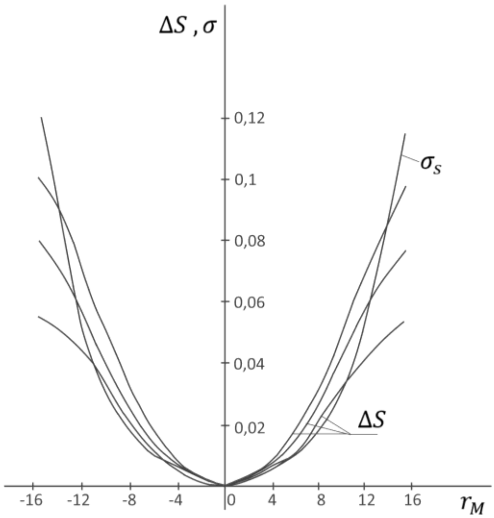

Fig. 5: The curves of phase deviation in the aperture plane.

Conclusions

In this paper we showed that in the theory of tolerances of large multi-reflector antennas, it is possible to obtain simple working formulas convenient for studying the joint influence of the antenna inaccuracies on phase distortion on the aperture plane with the help of differentials. This is the scientific value of the work.

Final working formulas were obtained for estimating both random and systematic errors of a double reflector spherical antenna with a large mirror diameter of 54,000 mm.

The ways of reducing the phase distortion on the antenna aperture plane are indicated caused by the evenly heating of the ROT-54/2.6 telescope main reflector.

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A DEVELOPMENT OF SIGNAL PROCESSING ALGORITHM FOR WATER VAPOUR RADIOMETER OPERATING IN INTENSIVE PRECIPITATION

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Abstract: The paper presents the results of development of an adaptive signal processing algorithm for the output signal of a water vapor radiometer (WVR) operating in quasi real-time. Land based WVR is used for continuous monitoring of the troposphere parameters, including periods of intensive precipitation. The algorithm is implemented in LabVIEW and uses Singular Spectrum Analysis (SSA) "Caterpillar" method and fuzzy logic techniques.