Effects of Deformation of Main Reflector of Double Reflector Spherical Antenna on Its Aperture Field – ROT-54/2.6 Antenna Case

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Abstract — The aim of this study is to model the impact of main reflector deformations in a double-reflector spherical antenna system on the phase distribution of the electromagnetic field across the aperture and the associated gain loss. The study focuses on the antenna of the ROT-54/2.6 radio-optical telescope (Herouni radio telescope) – a spherical double-reflector system with a fixed primary reflector with a 54 m diameter, composed of 3 738 panels. An analytical model is developed to evaluate phase distortions induced by deviations from the spherical geometry. The model computes local phase shifts across the aperture and predicts gain degradation using Ruze's formula which relates the RMS surface error to efficiency losses. This approach is important for pre-alignment procedures and functional restoration of the antenna, enabling geometry corrections prior to full-scale observations. Based on terrestrial laser scanning (TLS) data, the methodology allows for a quantitative assessment of structural phase errors and corresponding gain degradation, confirming its suitability for practical diagnostics of large reflector systems.

Keywords — antenna, radio-optical telescope, ROT-54/2.6, terrestrial laser scanning

1. Introduction

The prolonged conservation period of the ROT-54/2.6 radio optical telescope has resulted in the accumulation of stochastic structural deformations caused by environmental factors. Verification of the actual geometric configuration of the primary spherical reflector is a key milestone of a project aiming to revitalize the Herouni National Space Center. Restoration of the telescope's operational capability requires a comprehensive alignment procedure based on a comparative assessment of the present electrodynamic performance against the original design specifications.

The ROT-54/2.6 radio-optical telescope is a dual reflector spherical system designed for precision measurements of radio emissions from deep space sources over a wavelength range of 3 – 200 mm. The primary reflecting element has the shape of spherical reflector (54 m in diameter) composed of 3 738 aluminum–manganese panels, each with an area of approximately 1 m^2. The panels are mounted on a supporting framework with adjustable stanchions that provide alignment capability with an accuracy of several centimeters, thereby enabling maintenance of the required spherical precision of the primary reflector.

The geometry of the reflector ensures that a constant distance is maintained from any point on the surface to a sphere of 27 m, which corresponds to the curvature radius and determines the key geometric parameters of the telescope, including its sub-reflector profile, focal position, suspension height of the corrective sub-reflector, and related parameters. Efficient concentration of electromagnetic energy in the focal region within the sub-reflector requires that the profile accuracy of both reflectors be maintained within an error budget not exceeding 50 – 70 µm, which ensures operability at frequencies up to 100 GHz [1]–[4].

The ROT-54/32/2.6 (ROT-54/2.6) telescope is a distinctive large aperture dual reflector spherical telescope that combines a 54 m physical primary reflector with an effective aperture of 32 m and an optical reflector of 2.6 m. Owing to its scale and potential millimeter band performance, restoration of this telescope is scientifically significant, as it is an important national research infrastructure component that doubles as a facility capable of contributing to international observational programs requiring geographically distributed instruments and access to long-term observation campaigns.

The telescope is potentially useful for long-term variability monitoring of compact radio sources, spectral studies of stellar and interstellar media, and participation in distributed interferometric observations where improved $u-v$ coverage is critical [5].

Relaunch of the millimeter band capability of the ROT-54/2.6 telescope depends, to a critical degree, on high-precision refurbishment, alignment, and calibration of its optical and radiotechnical subsystems. First and foremost, it requires that the geometric accuracy of the reflecting surface and the mutual conformity of the dual-reflector system be restored.

After an extended conservation period, accumulated deformations and misalignments have led to aperture phase errors, reduced gain, and loss of focusing capability, thus preventing achievement of the designed sensitivity and angular resolution. To remedy this, targeted corrective procedures are required. Therefore, quantitative diagnostics of the as-is reflector geometry, an explicit measurement-to-model link between geometric deviations and aperture-phase structure, the

Fig. 1. ROT-54/2.6 radio optical telescope.

development of corrective alignment and subsequent calibration algorithms are the necessary elements of the restoration workflow.

Modeling the impact of stochastic displacements of the primary-reflector panels on the radiation characteristics is a critical stage of the pre-alignment procedure. In principle, costly mechanical adjustment of each panel can be partially substituted by a hardware–software approach that implements real-time feed position correction.

This procedure, however, is the objective of a separate, dedicated study. Any deviation of the primary-reflector panels from the ideal spherical surface, caused by structural and thermodynamic factors, introduces phase errors in the reflected field and distorts the wavefront over the aperture. This, in turn, reduces directivity and compromises overall gain of the telescope.

The development of a pre-alignment framework, based on hybrid modeling and combining archival data with terrestrial laser scanning, enables to compensate for the deformations accumulated during the prolonged period of inactivity, thereby restoring proper field focusing at the aperture without requiring complete reassembly of the reflector's surface. The present study examines the quantitative influence of such deformations on the phase structure of the aperture field [6]–[9].

2. Results and Analysis

For the ROT-54/2.6 radio-optical telescope, the mathematical phase distribution model differs from that of conventional paraboloidal reflectors. The main difference is the presence of a fixed spherical primary reflector combined with a movable feed located at the focus of a corrective subreflector with a specially designed profile. In an ideal spherical system, the phase in the aperture plane $z = 0$ at a point with a given radial coordinate can be expressed as:

$$\Phi(\rho,\phi) = k\left(\sqrt{(R+\delta(\rho,\phi))^2-\rho^2} + \Delta L_{(corr)(\rho)} + \Delta z\cos\theta\right) \tag{1}$$

where:

- $k = \frac{2\pi}{\lambda}$ is the wave number,
- R is the curvature radius of the primary reflector (54 m),
- $\Delta L_{corr}(\rho)$ is the optical path length in the double-reflector feed system (Herouni antenna system) introduced to compensate for spherical aberration,
- $\Delta z\ \cos\theta$ stands for a compensating term describing the axial displacement of the secondary reflector along the optical axis to minimize phase error.

To assess the geometry of the primary reflector of a double reflector spherical antenna after an extended conservation period, it is appropriate to employ the terrestrial laser scanning (TLS) technique. In contrast to contact-based methods, TLS allows to acquire a highly redundant point cloud (up to 10^6 measurements) with sub-millimetre accuracy, without imposing mechanical loads on the fragile panel-alignment assemblies.

This capability is important for identifying local deformations induced by fastener corrosion and long-term foundation settlement during decades of inactivity. Terrestrial laser scanning is therefore one of the most effective techniques for the initial pre-alignment stage.

The approach yields a dense point cloud (a Digital Twin concept) that captures the as-is reflector geometry with an accuracy on the order of 0.5 mm, which is sufficient for verification of its current structural state. The subsequent transformation of the TLS point cloud into phase error parameters constitutes a key step in the digital restoration workflow for the ROT-54/2.6 radio optical telescope [10].

In the initial theoretical stage of the study, the following antenna parameters should be analyzed:

where:

- root mean square (RMS) error of the geometric profile of an individual panel for various perturbations of five control points on each panel,
- cumulative surface error of a group consisting of several panels,
- phase deviations introduced by these deformations into the wavefront over the aperture,
- antenna gain losses caused by the resulting aggregate phase dispersion [6].

For a quantitative assessment of the geometric accuracy of the j-th panel, we introduce the RMS deviation of its surface relative to the ideal spherical profile. Let measurements be performed at N_p control points on the panel (typically $N_p = 5$: four corner points and one central point), and let $\Delta r_{j,i}$ denote the deviation of the i-th point of panel j from the nominal radial distance R_0:

$$\Delta r_{j,i} = r_{j,i} - R_0 \ , \tag{2}$$

where $r_{j,i}$ is the center of the measured distance from the sphere to the i-th point of the j-th panel and $R_0 = 27$ is the nominal radius of the spherical surface. The RMS profile error of the j-th panel is then defined as:

$$\sigma_j = \sqrt{\frac{1}{N_p} \sum_{i=1}^{N_p} \left(\Delta r_{j,i}\right)^2} \ . \tag{3}$$

where σ_j has the dimension of length and characterizes the typical magnitude of the deviations of a given panel from the ideal spherical surface.

The following notation is used:

- j – panel index, $j = 1, 2, \ldots, P$, where $P = 3738$ is the total number of primary reflector panels,
- i – control-point index, $i = 1, 2, \ldots, N_p$,
- N_p – number of control points per panel (typ. $N_p = 5$),
- $r_{j,i}$ – measured distance to point (j, i),
- R_0 – nominal (ideal) radial distance to the surface ($R_0 = 27$),
- $\Delta r_{j,i}$ – local deviation of point (j, i) from the ideal profile,
- σ_j – RMS profile error of the j-th panel.

To determine the overall surface error of the primary reflector, we introduce a global RMS deviation, σ_{group}, which relates the local RMS error of a representative deformed panel, σ_{pan}, to the number of such panels M and the total number of panels P:

$$\sigma_{group} = \sigma_{pan} \cdot \sqrt{\frac{M}{P}} = \sigma_{pan} \cdot \sqrt{f} \ , \tag{4}$$

where:

- σ_{group} – RMS surface error of the primary reflector (aperture-wide RMS),
- σ_{pan} – characteristic RMS profile error of a single deformed panel (if all M deformed panels exhibit the same error level),
- M – number of deformed panels,
- P – total number of primary reflector panels (for the ROT-54/2.6 radio-optical telescope $P = 3738$),
- $f = \frac{M}{P}$ – fraction of the aperture area associated with deformed panels.

This relationship shows that the contribution of each panel to the overall error is additive in power (i.e., additive in the squares of deviations). Consequently, σ_{group} increases with the square root of the number of deformed panels rather than linearly, reflecting the statistical nature of error accumulation.

To convert geometric surface deviations into wavefront phase errors, we use a relation that expresses the phase shift in terms of the measured radial error δz_i at the i-th control point:

$$\Delta\varphi_i = \frac{4\pi}{\lambda} \cdot \delta z_i \ , \tag{5}$$

where:

- $\Delta\varphi_i$ – phase error (phase shift) at the i-th point on the surface, expressed in radians,
- λ – operating wavelength,
- δz_i – deviation of the measured distance r_i from the ideal radius R_0,
- r_i – measured distance from the sphere to the i-th point on the surface,
- R_0 – nominal (ideal) distance from the center of the primary reflector to its surface (for ROT-54/2.6 $R_0 = 27$m) [11].

It is assumed that the measurements are performed for a spherical geometry such that the rangefinder measurement direction is aligned with the local surface normal and that the rays are considered in proximity of the optical axis. Under these conditions, the angular factor satisfies $\cos\theta \approx 1$.

The more general expression, which accounts for the incidence angle with the factor $\cos\theta$ is:

$$\Delta\varphi_i = \frac{4\pi}{\lambda} \cdot \delta z_i \cdot \cos\theta_i \ , \tag{6}$$

with $\cos\theta = 1$, it is reduced to Eq. (5). Thus, Eq. (5) provides a direct relationship between laser-measured deviation δz_i and phase distortion $\Delta\varphi_i$, which are subsequently used to calculate the RMS phase error, surface efficiency, and the related gain losses.

The phase change introduced by a deformed panel, for a wavelength $\lambda = 3$ cm and normal incidence ($\cos\theta \approx 1$), is given by:

$$\Delta\phi_{pan} = \frac{4\pi}{\lambda} \, \delta r_{pan} \ . \tag{7}$$

Substituting $\Delta\phi_{pan} = 2$ cm and $\lambda = 3$ cm, we obtain:

$$\Delta\phi_{pan} = \frac{4\pi}{3} \cdot 2 = \frac{8\pi}{3} \approx 8.38\,\text{rad} \ , \tag{8}$$

which is equivalent to approximately 480° (1.33 phase revolutions). Thus, even a 2 cm displacement of a single panel produces a big phase shift over the related local aperture region, although its contribution to the global antenna efficiency is determined by its fractional area.

The impact that cumulative phase errors exert on the antenna's gain is quantified by the Ruze formula, which relates the global RMS surface deviation σ to the relative efficiency η:

$$\eta = e^{-\left(\frac{4\pi\sigma}{\lambda}\right)^2} \ , \tag{9}$$

- η – relative gain efficiency (surface efficiency), $\eta = \frac{G}{G_0}$,
- G – actual antenna gain in the presence of surface errors,
- G_0 – ideal gain for a perfect (defect-free) surface,
- σ – total RMS surface deviation (in particular, σ_{group} may be substituted),
- λ – operating wavelength.

The exponential function indicates that even a moderate increase in the $\frac{\sigma}{\lambda}$ ratio results in a substantial reduction of η. In the limit $\sigma \to 0$, the formula yields $\eta \to 1$ (an ideal antenna). For σ comparable to $\frac{\lambda}{4\pi}$, the efficiency decreases approximately to $e^{-1} \approx 0.37$. With a further growth in σ, the impact of the distorted phase front becomes dominant and the actual gain degrades sharply [12].

Tab. 1. Estimated relative gain efficiency as a function of the number of deformed panels (Ruze model).

M	σ_{group}	η
1	0.032 cm	0.983 ($\approx 98.3\%$)
10	1.0 mm	0.839 ($\approx 83.9\%$)
50	2.24 mm	0.416 ($\approx 41.6\%$)
100	3.16 mm	0.173 ($\approx 17.3\%$)
500	7.07 mm	1.5×10^{-4} ($\approx 0.015\%$)
1000	10 mm	2.4×10^{-8} ($\approx 2.4 \times 10^{-6}\%$)

Consider the case in which a single panel of the main reflector is displaced as a rigid body along its local normal by an offset value such as:

$$\Delta r_{pan} = +2.0\,\text{cm}\ ,$$

with respect to the ideal spherical surface.

It is assumed that all $N_p = 5$ control points on this panel are assumed to have the same deviation:

$$\Delta r_{j,i} = \Delta r_{pan} = +2.0 \ \ \text{cm} \ \ i = 1, \ldots, 5\ .$$

Then, the error of the RMS profile error of this panel σ_j is computed using the standard RMS expression:

$$\sigma_j = \sqrt{\frac{1}{N_p} \sum_{i=1}^{N_p} \left(\Delta r_{j,i}\right)^2}\ . \qquad (10)$$

Substituting $\Delta r_{j,i} = \Delta r_{pan}$ for all five points, we obtain:

$$\sigma_j = \sqrt{\frac{1}{N_p} \sum_{i=1}^{N_p} \left(\Delta r_{pan}\right)^2} = \sqrt{\frac{1}{N_p} N_p (\Delta r_{pan})^2} \qquad (11)$$
$$= |\Delta r_{pan}| = 2.0\,\text{cm}\ .$$

Therefore, for a rigidly displaced panel, the surface error is numerically equal to the magnitude of the displacement [13] – [16].

We now consider an example that involves a larger number of deformed panels. Each deformed panel has the same RMS error $\sigma_{pan} = 2.0$ cm, and the total number of primary reflector panels is $P = 4000$. For a group of M-deformed panels, the global RMS surface deviation σ_{group} is estimated as:

$$\sigma_{group} = \sigma_{pan} \sqrt{\frac{M}{P}}\ . \qquad (12)$$

Next, applying Ruze's formula, one can estimate relative efficiency η (ratio between actual gain and ideal gain) for different values of M at $\lambda = 3$ cm and $\sigma_{pan} = 2.0$ cm.

The calculation results are summarized in Tab. 1. These values illustrate that for a fixed displacement of 2 cm per panel, an increase in the number of deformed panels leads to a statistical growth of the global RMS surface error and an exponential decrease in antenna gain.

3. Conclusions

This analysis demonstrates that even relatively small geometric deformations of the main reflector panels of the ROT-54/2.6 radio-optical telescope antenna result in noticeable phase distortions of the wavefront over the aperture. The conversion of measured radial deviations δz_i to phase errors $\Delta\varphi_i$, using relation $\Delta\varphi_i = \frac{4\pi}{\lambda} \cdot \delta z_i$, establishes a direct link between laser measurement data and the electrodynamic characteristics.

The introduction of RMS estimates σ_j for individual panels and σ_{group} for an ensemble of deformed panels allows to quantitatively describe the accumulation of errors across the aperture. It is shown that the global RMS error σ_{group} increases as $\sqrt{\frac{M}{P}}$, reflecting the statistical nature of the summation of local errors. The application of Ruze's formula to calculate the efficiency factor demonstrates an exponential reduction in gain as the $\frac{\sigma_{group}}{\lambda}$ ratio increases.

Numerical examples for different values of M indicate that, when many dozens of panels are deformed, the gain losses reach several tens of percent. When the number of affected panels reaches the order of hundreds or more, the antenna effectively loses it focusing capability.

Therefore, maintaining the geometric accuracy of the panels at the submillimeter level is a necessary condition for preserving the designed gain and ensuring the operability of the ROT-54/2.6 radio-optical telescope over the specified frequency range.

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