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ON THE PROBLEM OF CONSTRUCTING A MODERN, ECONOMIC RADIOTELESCOPE COMPLEX

A. F. Bogomolov, A. G. Sokolov, B. A. Poperechenko, and V. S. Polyak

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NASATM-75119
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A. F. Bogomolov, A. G. Sokolov, B. A. Poperechenko, and V. S. Polyak

ABSTRACT. We discuss the criteria for comparing and planning the technical and economic characteristics of large parabolic reflector antenna systems and other types used in radioastronomy and deep space communications. We generalize the experience gained in making and optimizing a series of highly efficient parabolic antennas in the USSR, including the original TNA-1500 radio telescope having a diameter of 64 m, and we indicate several ways for further improving the complex characteristics of similar antennas.

We show how our results can be applied in planning the characteristics of radiotelescopes which are now being built, in particular, the TNA-8000 with a diameter of 128 m.

One of the main problems at the present time in equipping and designing for long-term radioastronomical and applied research is that of extending the sensitivity of radiotelescopes and increasing their number. Consequently, it is important to optimize the arrangement of instruments combined together as interferometers and aperture synthesis systems. Increasing the sensitivity of the individual

*Numbers in the margin indicate pagination in the original foreign text.
radiotelescopes combined together allows us to increase the number of sources observed and to decrease the time needed for the observations. Also, given a limited amount of observing time, we can increase the positional accuracy. By selecting the most economic and highly efficient antennas, we will be able to solve these problems more quickly.

In the USSR in the past there has been great progress with respect to the research, development, and building of highly efficient radiotelescopes [1 - 6]. However, equipping radiotelescope installations for astronomy has been held back in the USSR because of the large amount of labor and high cost, and also because of unreliable technical and economic estimates for the large instruments being planned.

At the present time, besides the development of the technical aspects of radiotelescopes (efficiency, band width, and angular and flux resolution), the improvement of the scientific and technical principles for constructing radio-astronomical installations has acquired even greater current interest. It is very important to develop a methodical approach for improving the mechanical, technical, and economic characteristics of radiotelescope installations based on the experience of Soviet industry.

This report emphasizes fully steerable parabolic antennas which can be used singly or in groups, and which can be used in comparing technical and economic characteristics for other types of antennas. The optimization of separate antennas combined to form interferometric and aperture synthesis systems and construction of the required space-frequency characteristics is a separate problem and will not be discussed here.

The extensive experience gained in developing the Soviet THA antenna series for satellite and space communication is of great importance in analyzing the most promising antenna systems at this time. In addition, the first TNA-1500 series radiotelescope with a diameter of 64 m for use in the centimeter range can be compared
with other Soviet fully steerable parabolic reflectors, and with those built by other nations as well.

Turning now to the basic question, first of all we introduce the comparison and evaluation criteria which will indicate the procedures for optimization of antenna systems. The optimization of the antenna-receiver and the guiding system is independent of the antenna type, dimensions, and wavelength range, and can be expressed by the efficiency coefficient (EC):

\[ \mathcal{J}_1 = \frac{S_{\text{sys}}}{S_{\text{sys}}} = \frac{S_{\text{sys}}}{S_{\text{sys}}} = \eta KK, \]

where, besides the efficiency (\( \eta \)) and the surface coefficient (SC) allowing for the accuracy in guiding the beam (K), we introduce a system/coefficient based on the noise temperature (TC, \( K_T = \frac{T_{\text{sys}}}{T_{\text{sys}}} \)). Here, \( T_{\text{sys}} \) and \( T_{\text{sys}} \) are used to designate the corresponding actual and potential values of the total noise temperature of the system at the receiver input over the range of working position angles with the components: \( T_{\text{sys}} \) — actual antenna noise (\( T_{\text{sys}} \) is due only to sky noise in the direction of the main lobe radiation pattern); \( T_{\text{sys}, \text{np}} \) — uhf channel noise (\( T_{\text{sys}, \text{np}} = 0 \)), and \( T_{\text{sys}, \text{np}} \) — receiver noise (\( T_{\text{sys}, \text{np}} \) is taken to be the temperature of a maser amplifier (MA) cooled down to the temperature of liquid helium).

To evaluate the individual contributions of the antenna and receiver to the overall noise temperature of the system, the coefficient \( K_T \), in turn, can be expressed in terms of partial coefficients for the antenna with emitter (\( K_{\text{T,a}} \)) and for the uhf receiver channel (\( K_{\text{T,pr}} \)):

\[ K_T = K_{\text{T,a}} K_{\text{T,pr}}, \]

where:

\[ K_{\text{T,a}} = \frac{T_{\text{sys}} + T_{\text{sys}, \text{np}}}{T_{\text{sys}} + T_{\text{sys}, \text{np}}} = \frac{T_{\text{sys}}}{T_{\text{sys}} + T_{\text{sys}, \text{np}}}, \]

\[ K_{\text{T,pr}} = \frac{T_{\text{sys}} + T_{\text{sys}, \text{np}}}{\eta T_{\text{sys}} + T_{\text{sys}, \text{np}} + T_{\text{sys}, \text{np}}} = \frac{T_{\text{sys}} + T_{\text{sys}, \text{np}}}{T_{\text{sys}}}. \]
Table 1 contains the parameters for a series of modified Soviet and foreign antennas used in radioastronomy and deep space communication. The table does not give the parameters for the large, high-precision parabolic antennas (MT-22, FIAN, D = 22 m; Parkes, Australia, D = 56 m; Green Bank, U.S.A., D = 42 m; Haystack, U.S.A., D = 37 m, etc.) which represent the first stage in the development of large, fully steerable parabolic antennas. The original technical features of these examples are given in the table, but it is difficult to discuss these parameters in terms of their modernization, because there is little new data and no additional features would be introduced.

According to Table 1, the best Soviet examples have attained the world standard according to the surface coefficient ($K_s$ $\approx 0.7-0.75$, and at the limit of the range/0.65), but continue to lag behind the world standard according to the noise temperature coefficient ($K_T \leq 0.25-0.25$ versus 0.6 - 0.3). This is also true for the individual coefficients $K_T$ and $K_{T_{mp}}$ ($K_{T_{mp}} \leq 0.65-0.7$, while with regard to $K_T$, the comparison is approximately 1.5 times worse). The use coefficients for most antennas lie below 0.25 - 0.15, as opposed to 0.35 - 0.3 for the best examples.

The basic limitations in increasing TC and EC, first of all, are primarily related to inadequate mastery of reliable, operational, low-noise Soviet amplifiers (LNA), construction features which would permit their optimum arrangement into antennas with an overall increase in the uhf channel parameters as well. There are also several possibilities for increasing $K_T$ by further improving the precision in the construction of the reflector systems and by decreasing the scattering at the base of the irradiated system and at the edge of the reflector.

The connection between the technical and economic characteristics is extremely important when making comparative evaluations according to the criteria for large antenna complexes. Important generalizations from experience can be made by analyzing the
<table>
<thead>
<tr>
<th>No.</th>
<th>Antenna</th>
<th>Diam., m</th>
<th>Operat. range, cm</th>
<th>Collector type</th>
<th>Surface efficiency</th>
<th>$s_{at}$ at LNA entry, m$^2$</th>
<th>Efficiency, $\eta$</th>
<th>Position angle, $\beta$, deg.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>TMA-57 (Orbita), parabolic, short focus</td>
<td>12</td>
<td>30</td>
<td>Single reflector</td>
<td>0.7</td>
<td>0.93</td>
<td>50–10</td>
<td>$\beta = 5.5^\circ$</td>
</tr>
<tr>
<td>2</td>
<td>TMA-1500* (Medvezh' i ozera, Kalyazin), quasi-parabolic, medium focus</td>
<td>64</td>
<td>3, 7</td>
<td>Double reflector</td>
<td>0.65</td>
<td>2030</td>
<td>0.97</td>
<td>21–10</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.75</td>
<td>2360</td>
<td>0.95</td>
<td>$\beta = 5.5^\circ$</td>
</tr>
<tr>
<td>3</td>
<td>TMA-57F, parabolic w. modified counter-reflector, short-focus</td>
<td>12</td>
<td>7</td>
<td>Double reflector</td>
<td>0.61 with m.a.**</td>
<td>56</td>
<td>0.815</td>
<td>40–12</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.7 without m.a.**</td>
<td>64</td>
<td></td>
<td>$\beta = 5.5^\circ$</td>
</tr>
<tr>
<td>4</td>
<td>RT-79*, quasi-parabolic</td>
<td>70</td>
<td>30</td>
<td>Double reflector</td>
<td>0.65</td>
<td>2500</td>
<td>0.975</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.79</td>
<td>3040</td>
<td></td>
<td>$\beta = 5.5^\circ$</td>
</tr>
<tr>
<td>5</td>
<td>Raisting-I, FRG, parabolic, short-f.</td>
<td>25</td>
<td>7</td>
<td>Double reflector</td>
<td>0.55</td>
<td>260</td>
<td>0.95</td>
<td>40–14</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$\beta = 5.5^\circ$</td>
</tr>
<tr>
<td>6</td>
<td>Raisting-II, FRG, parabolic, short-focus</td>
<td>28.5</td>
<td>7</td>
<td>Double reflector</td>
<td>0.66</td>
<td>355</td>
<td>0.89</td>
<td>29–1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$\beta = 7.5^\circ$</td>
</tr>
<tr>
<td>7</td>
<td>Plumier-Boudouq-II, France, quasi-parabolic, medium-focus</td>
<td>27.5</td>
<td>7</td>
<td>Double reflector</td>
<td>0.77</td>
<td>540</td>
<td>0.9</td>
<td>34–8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$\beta = 5.5^\circ$</td>
</tr>
<tr>
<td>8</td>
<td>Fucino, Italy, quasi-parabolic, medium-focus</td>
<td>27.4</td>
<td>7</td>
<td>Double reflector</td>
<td>0.7</td>
<td>570</td>
<td>0.95</td>
<td>39–5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$\beta = 5.5^\circ$</td>
</tr>
<tr>
<td>9</td>
<td>Bonn, FRG, parabolic</td>
<td>100</td>
<td>11, 2.7</td>
<td>Double reflector</td>
<td>0.55</td>
<td>4200</td>
<td>0.97</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2800</td>
<td></td>
<td>$\beta = 5.5^\circ$</td>
</tr>
</tbody>
</table>

(Table continued on following page)
**TABLE 1. (continued)**

<table>
<thead>
<tr>
<th>No.</th>
<th>Antenna</th>
<th>$T_{\text{w}, \text{tr.}} / C$</th>
<th>$T_{\text{w}, \text{np.}} / K$</th>
<th>$T_{\text{m}} / K$</th>
<th>$K_{\gamma}$</th>
<th>$K_{\gamma, \text{np.}}$</th>
<th>$\delta$</th>
<th>$\delta_{\gamma} / K$</th>
<th>$\delta_{\gamma}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ThA-57 (Orbita), parabolic, short-focus</td>
<td>20</td>
<td>70</td>
<td>140–100</td>
<td>0.66–0.97</td>
<td>0.30–0.13</td>
<td>0.25–0.126</td>
<td>0.53–0.74</td>
<td>0.16–0.08</td>
</tr>
<tr>
<td>2</td>
<td>ThA-1500* (Medvezh'i ozera, Kalyazin), quasi-parabolic, medium-focus</td>
<td>10</td>
<td>9</td>
<td>40–29</td>
<td>0.67–0.74</td>
<td>0.70–0.66</td>
<td>0.5–0.49</td>
<td>50–70</td>
<td>0.31</td>
</tr>
<tr>
<td>3</td>
<td>ThA-57F, parabolic w. modified counter-reflector, short-focus</td>
<td>55</td>
<td>70</td>
<td>165–137</td>
<td>0.75–0.55</td>
<td>0.28–0.134</td>
<td>0.2–0.074</td>
<td>0.34–0.41</td>
<td>0.1–0.037</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.114–0.042</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Pt-70*, quasi-parabolic</td>
<td>7</td>
<td>10</td>
<td>27</td>
<td>0.74</td>
<td>0.71</td>
<td>0.52</td>
<td>92</td>
<td>0.34</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.33</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Raisting-I, FRG, parabolic short-focus</td>
<td>11</td>
<td>4.3</td>
<td>59–29</td>
<td>0.77–0.55</td>
<td>0.79–0.53</td>
<td>0.61–0.29</td>
<td>4.6–8.9</td>
<td>0.32–0.15</td>
</tr>
<tr>
<td>6</td>
<td>Raisting-II, FRG, parabolic, medium-focus</td>
<td>34</td>
<td>19</td>
<td>81–59</td>
<td>0.75–0.66</td>
<td>0.4–0.2</td>
<td>0.3–0.132</td>
<td>4.4–6.5</td>
<td>0.18–0.078</td>
</tr>
<tr>
<td>7</td>
<td>Plumer-Boudou II, France, quasi-parabolic, long-focus</td>
<td>29</td>
<td>15</td>
<td>78–52</td>
<td>0.81–0.7</td>
<td>0.52–0.28</td>
<td>0.44–0.2</td>
<td>6.9–10.4</td>
<td>0.31–0.14</td>
</tr>
<tr>
<td>8</td>
<td>Fucino, Italy, quasi-parabolic medium focus</td>
<td>15</td>
<td>15</td>
<td>65–35</td>
<td>0.82–0.88</td>
<td>0.64–0.32</td>
<td>0.52–0.28</td>
<td>8.8–16.3</td>
<td>0.35–0.19</td>
</tr>
<tr>
<td>9</td>
<td>Bonn, FRG, parabolic</td>
<td>8</td>
<td>20</td>
<td>33</td>
<td>0.8</td>
<td>0.375</td>
<td>0.3</td>
<td>127</td>
<td>0.17</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>18.5</td>
<td>0.66</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Computed values
** Motor accompaniment
*** UHF radiometer elements

*Commas in numbers represent decimal points.
accumulated and systematized empirical data, technical and economic, for uncovered Soviet parabolic antennas.

The approximate cost structure for high precision fully steerable, large-scale parabolic reflectors is given in Table 2. Table 3 contains the approximate relationship between cost and mass for the most expensive centimeter-range reflector system elements with a solid surface, as a function of reflector diameter. This is given for the most probable operating conditions. The curves in Figures 1 and 2 show the actual masses $P$ and costs $C$ (circles indicate empirical data, and crosses indicate the actual data) from the manufacture of specific reflector systems and supporting steering equipment (SSE), and their approximate corresponding relationships.

**TABLE 2**

<table>
<thead>
<tr>
<th>System elements</th>
<th>Average dimensions $(D = 15 - 30 \text{ m})$</th>
<th>dimensions $(D = 50 - 150 \text{ m})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antenna-feeder (AF)</td>
<td>15</td>
<td>25</td>
</tr>
<tr>
<td>Electric drive guiding system</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>Reflector</td>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td>Supporting steering equipment (SSE) without electric drive</td>
<td>35</td>
<td>35</td>
</tr>
<tr>
<td>Construction part</td>
<td>10</td>
<td>20</td>
</tr>
</tbody>
</table>

The scatter which occurs in the example parameters in relation to the approximating curve shows a correlation with the equipment characteristics (increasing or decreasing the rigidity and accuracy of the reflector systems, the load-carrying capacity and SSE precision, the relationship between the size of the metal structure
<table>
<thead>
<tr>
<th>System elements</th>
<th>Cost, C</th>
<th>Cost per 1 m² surface C₁</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Manufacture</td>
<td>Assembly</td>
</tr>
<tr>
<td></td>
<td>Mfg.</td>
<td>Assembly</td>
</tr>
<tr>
<td>Reflector (excluding tooling-up)</td>
<td>2.5 D³</td>
<td>(0.42 ± 0.32) D³</td>
</tr>
<tr>
<td>SSE (excluding tooling-up)</td>
<td>15 D³</td>
<td>0.75 D³</td>
</tr>
<tr>
<td>without electric drive</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Antenna structures</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total (without guiding system)</td>
<td>17.5 D³</td>
<td>(2.33±2.18) D³</td>
</tr>
<tr>
<td>System total</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Commas in numbers represent decimal points.

and its mechanisms whose separate cost for a one-ton mass differs by a factor of three and more, the speed and reliability of the guidance drive gears, etc.). The amount of scatter in the points agrees with the approximating curves. The empirical relationships shown in Tables 2 and 3 correspond to the actual construction of different antennas with diameters ranging from 2.5 m to 64 m, built over the last 20–25 years.

According to the statistical data, the structural mass is approximately proportional to the cube of the reflector antenna diameter, and the cost is approximately proportional to the square of the reflector antenna diameter. These data pertain to two similar theoretical families of curved P₁(D) and C₁(D). In both families, each curve corresponds to a fixed reflector construction design system with SSE [e.g., the Bonn radiotelescope system (D = 100 m) or the FIIN, RT–22 radiotelescope system], indicated.
by the index $i$, and characterized by a power law of the type $Q_i = q_i D^{m_i}$ (Figure 3). The exponent is nearly constant within the limits of each family, and for mass and cost is equal to $m_p \approx 3.2$ and $m_c \approx 2.6$, respectively [7, 8].

Each specific construction design system is optimized only for a definite relationship between the weight load, wind load, and dynamic load which depends on the antenna diameter. Therefore, the actual mass $P = q_p D^{m_p}$ and cost $C = q_c D^{m_c}$ relationships over a broad range of antenna diameters intersect the family of theoretical curves because of the change in construction design, and have different exponents $m_p \approx 3$ and $m_c \approx 2$.

Of course, this relationship is not suitable for all antenna system elements. A number of less expensive elements (antenna feed systems, building equipment, angular control and compensation for deformation, etc.) do not satisfy this approximation. Nevertheless, in practice not only the metal construction and mechanisms, but also
the system as a whole will have a quadratic relationship between cost and reflector diameter, or a linear relationship between cost and antenna area:

\[ C = A S_{400} = \left( \frac{A}{4} \eta K \right) D^2. \]

where \( A \approx 6.0 - 6.5 \) for \( K = 0.6 \).

The data given above was used to predict the cost of the "Orbit" antenna array (TNA-57, \( D = 12 \) m), and was found during the completion phase of the construction of the TNA-1500 radiotelescope (\( D = 54 \) m) (Figure 4). The prediction error for the TNA-57 antennas was 10 - 15%. In the building of the first TNA-1500 antenna, there was no significant departure from the predicted cost of 10 - 11 million rubles (even though the manufacture of all the basic equipment for the radio telescope and its erection were in practice completed in 1974, and the cost was determined according to the actual expense).

The data given in Table 3 may undergo further improvement in the optimization process for construction designs of individual types of antenna system equipment and the technology for their manufacture and erection. For example, by transferring the production of the reflecting system steel framework to specialized metal construction shops, we can lower the framework cost by a factor of two, and the cost of the reflector system as a whole by one-third (excluding
the tooling-up cost, which amounts to about one third of the cost of a single reflector).

Based on practical experience, the following approximate relationships were established for other parameters in the unified construction of parabolic antennas:

- maximum electric drive speed, deg/sec, \( \dot{\omega} = 150/D \) (for the velocity range \((0.5 - 2.0) \cdot 10^3\) and diameter \(D, \text{m}\));
- electric drive power rating, kW, \( W_n \approx 0.06D^2 \);
- SSE directional accuracy including the compensation system, \( \Delta \theta \approx 200 \sqrt{5-15}/D \).

The linear relationship between the cost of parabolic antennas and their effective area allows us to use the concept of cost per \(1 \text{ m}^2\) of effective area, and we can discuss this universal parameter for a wide range of antenna diameters.

We have already discussed the technical and economic characteristics for the antenna part of the system. The LNA is also included in the number of expensive antenna elements which directly determine the overall efficiency. The cost and sensitivity of this equipment are both interdependent. However, the very limited data with regard to concrete industrial examples of this equipment make this relationship less precise than for the antenna elements discussed above. Nevertheless, it is possible to put the relationship for the input units with a closed cooling cycle in the following analytic form:

\[ C_{np} \approx B/T_{\text{w, np}} \quad \text{for} \quad T_{\text{w, np}} > T_{\text{w, np}^0}, \]

where \( B = 6000 \) for continuing construction and \( B = (20,000 - 25,000) \) for the initial batches.

The \( C_{np}(T_{\text{w, np}}) \)/relationship includes the variation in the optimal change type of LNA with \( T_{\text{w, np}} \) in the same way that the \( P(D) \) and \( C(D) \)
relationships for antennas include the variation of construction
decisions with change of their diameter, which we discussed earlier.

By using the relationships for antenna cost $C_a$ and LNA cost $C_{np}$,
along with a given efficiency $\mathcal{E} = S_{\text{eff}} / T_w$, we can find the optimum values of
$S_{\text{eff, out}}$ and $T_{\text{w, np, out}}$ which correspond to minimum system cost.

The fact is that the system efficiency $\mathcal{E}$ can be realized for
different combinations of $S_{\text{eff}}$ and $T_w$. Thus, the overall system
cost $C = C_a + C_{np}$ for different combinations of $S_{\text{eff}}$ and $T_w$ will not be
the same. By varying one of the parameters $T_w$, $S_{\text{eff}}$, $C_{np}$ and $C_a$ for a
fixed $\mathcal{E}$, we can find the minimum overall system cost $C$ from the
equation:

$$\frac{\partial C}{\partial C_{np}} = \frac{\partial C_a}{\partial C_{np}} + 1 = \frac{\partial (A\mathcal{E}T_w)}{\partial C_{np}} + 1 = A \frac{\partial (\frac{B}{T_{w, np}})}{\partial C_{np}} + 1 =$$

$$= AB \mathcal{E} \left( - \frac{1}{c_{np, out}^2} \right) + 1 = 0.$$

From our approximation, it follows that:

$$C_{np, out} = \sqrt{AB \mathcal{E}} \text{ and } T_{w, np, out} = \sqrt{B/A \mathcal{E}},$$
$$S_{\text{eff, out}} = \mathcal{E} (\eta T_{w, a} + T_{w, tr}) + \sqrt{B \mathcal{E} / A} \text{ and } C_a, \text{out} = A S_{\text{eff, out}}.$$

In practice, it is more advantageous to take somewhat larger
values for $T_{w, np}$ and $S_{\text{eff}}$, since the accuracy and economy of LNA
operation usually turns out to be less than for antennas. Besides
this, in practice the choice of these parameters is dictated by the
availability of equipment with similar characteristics.

As an example, in Table 4 we give the optimum system parameters
for two values of the efficiency, 1 and 50. Thus, we have
$\eta T_{w, a} + T_{w, tr} \approx 35K$ and $K = 0.6$. In particular, the table indicates
that the application of relatively more expensive (experimental)
LNA samples makes a better contribution toward increasing antenna
dimensions than does the achievement of high LNA efficiency.
By using these data, it is also possible to solve the reverse problem: determining the maximum radiotelescope efficiency for a fixed cost.

<table>
<thead>
<tr>
<th>System parameters</th>
<th>Efficiency $\epsilon$, W/K</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\frac{\eta}{\lambda}$ (LNA series)</td>
</tr>
<tr>
<td>$C_{\text{opt} \cdot \text{celt}}$</td>
<td>1.4</td>
</tr>
<tr>
<td>$T_{\text{m}\cdot\text{np} \cdot \text{celt}}, K$</td>
<td>4.3</td>
</tr>
<tr>
<td>$S_{\text{np} \cdot \text{celt}}, m^2$</td>
<td>2000</td>
</tr>
<tr>
<td>$D_{\text{celt}}, m$</td>
<td>65</td>
</tr>
<tr>
<td>$C_{\text{celt}}$</td>
<td>12</td>
</tr>
<tr>
<td>$C_{\text{celt}}$</td>
<td>13.4</td>
</tr>
<tr>
<td>$C_{1 \cdot \text{celt}}$</td>
<td>270</td>
</tr>
</tbody>
</table>

* Commas in numbers represent decimal points.

The optimization method described here is good for antennas which are not too large, and whose cost is commensurate with the cost of more sensitive LNA or less ($T_{\text{m}\cdot\text{np} \cdot \text{min}} \approx 5+10 K$, $C_{\text{np} \cdot \text{celt}} \approx 1.2+0.6$). Usually these systems are characterized by an efficiency $\epsilon \leq 10+40$ for a series of LNA when $\eta T_{\text{m} \cdot \text{a}} + T_{\text{m} \cdot \text{tp}} \approx (15+40) K$ over the position angle range. This corresponds to reflector diameters $D \leq (32+45)$ m. In practice, further improvement in the optimum antenna system efficiency is possible only by increasing the antenna diameter. This means that it is economically advisable to employ receivers with the highest possible sensitivity. The limiting values for $\epsilon$ and $D$ for the experimental LNA examples are shifted toward larger values.

The cost per unit efficiency of a system for average ($D \leq 32+45$) and large antennas is, respectively,

$$C_{\text{celt} \cdot \text{cp}} = \frac{C_{\text{celt}}}{\epsilon} = A(\eta T_{\text{m} \cdot \text{a}} + T_{\text{m} \cdot \text{tp}}) + 2\sqrt{AB/\epsilon}$$
and

\[ C_{\text{cont.6}} = AT_{\text{ш.шнн}} + B/\mathcal{E}T_{\text{ш.шнн}}. \]

The actual cost per unit efficiency falls monotonically in proportion to increasing system efficiency. However, this lowering of the cost is of little significance with respect to the parameters for average and large antennas:

\[ \mathcal{E} \gg 4 \frac{B}{A} \frac{1}{(\eta T_{\text{ш.шнн}} + T_{\text{ш.тр}})^2} \approx (15 - 3), \]

i.e., \( S_{\text{эфф}} > (6000 - 900) \text{ m}^2 \) and \( D > (85 - 35) \text{ m} \);

\[ \mathcal{E} \gg \frac{B}{A} \frac{1}{T_{\text{ш.шнн}} T_{\text{ш.пр.шнн}}} \approx 4, \]

i.e. \( S_{\text{эфф}} > 1300 \text{ m}^2 \) and \( D > 50 \text{ m} \).

Thus, we would expect a significant economic savings by increasing the area of large-size antennas \((D > 50 \text{ m})\). A further extension of the efficiency will primarily be determined by the technical requirements and possibilities of applying new economic construction and technological designs. In this connection, the limiting characteristics of high-efficiency guidance and focal-angle deformation compensating systems, which ensure the necessary working wavelength, are of major importance.

The restrictions in relation to the limiting wavelength for high-precision construction, without shielding, are characterized at the present time by the least overall operational errors: for the beam guidance system \( \Delta \theta_{\text{шнн}} \approx (5 - 10)^\circ \), and for the reflector system geometry \( \Delta \theta_{\text{шнн}} \approx (0,5 - 1) \). The values chosen for \( \Delta \theta_{\text{шнн}} \) and \( \Delta \theta_{\text{шнн}} \) are borne out by the experience from constructing Soviet and foreign antennas in the centimeter and millimeter range, for which the increased accuracy has not led to their sharply increased cost [3, 10, 11]. Assuming the admissible conditions

\[ \Delta \theta_{\text{шнн}} \leq \frac{2 \theta_{\text{шнн}}}{\lambda_{\text{шнн}}} \frac{\lambda_{\text{шнн}}}{D_{\text{шнн}}}, \]

and

\[ \frac{\lambda_{\text{шнн}}}{D_{\text{шнн}}} \approx \frac{7 - 10}{7 - 10} \approx 0.25 - 10^4 \frac{\lambda_{\text{шнн}}}{D_{\text{шнн}}}. \]
\[ \Delta \lambda_{\text{min}} \leq \frac{\lambda_{\text{min}}}{(15 - 20)} \]

and substituting into these equations the values for \( \Delta \lambda_{\text{min}} \) and \( \lambda_{\text{min}} \), we obtain \( D_{\text{min}} \leq (5000 - 3000)\lambda_{\text{min}} \) and \( \lambda_{\text{min}} \geq (1 - 1.5) \) cm.

Consequently for \( \lambda_{\text{min}} \approx 3 - 5 \) cm, we can calculate the economic variations for radiotelescopes with diameters up to approximately 150 m, and the additional extension of the minimum working wavelength allows us to increase the antenna dimensions even further.

In this connection, it should be noted that one of the growing questions concerning the technical and economic optimization of different types of antennas is the appearance of a relationship between the mass and cost of antennas having a fixed size, and the minimum working wavelength and allowable efficiency losses. In view of the choice for each \( \lambda_{\text{min}} \) for optimum construction, there is a minimum cost of construction. Out of necessity, high precision construction should be fitted with protective shielding, which should be included in the overall construction complex undergoing technical and economic optimization.

Data which is still being developed from astronomical transits, as well as data concerning the coefficient for use when working in one or another wavelength range, including the value for radiotelescope information, would permit us to choose \( \lambda_{\text{min}} \) and the type of construction for each size and class of antenna which was economically justified. We emphasize the importance of even now developing a single methodical approach for accumulating and subsequently analyzing these data. The criteria suggested above may serve as a basis for such an approach.

In the last few years, a large new radiotelescope project has been started, the TNA-8000 (RT-128) with a diameter of 128 m. Our accumulated practical experience is being used in the process, and new designs are being worked out for further optimizing the construction of similar radiotelescopes. This is being done not only with respect to precision characteristics, but also for complex technical and economic characteristics.
Figure 5 is a model for a basic radiotelescope design, an assumed constructionally-autonomous system with a deformation law ensuring a high degree of homology in the antenna shape. Special attention was given to creating optimum operating conditions for the reflector framework. The design preserves the favorable properties of yielding capacity which, for example, is characteristics of the TNA-1500 or the 100-meter Bonn radiotelescope (FRG). At the same time, in contrast, this design allows the elevation-rotation axes to be located at any point, including the reflector center of gravity. In this way, there are no restrictions on the height of the reflector framework in its central part, on which its rigidity depends.

The position of the elevation-rotation axes is the optimum variation in this direction, such that they pass through the reflector system center of gravity. In this case, the necessity of constructing counterweights which often exceed the mass of the reflector systems is no longer important. As a result, a significant (by a factor of two) decrease in the mass rotating in the vertical plane is achieved, and a decrease in the moments of inertia. The moment of inertia is also decreased as a result of the significant shortening of the distances to the elevation axis. In addition, this construction arrangement leads to a significant decrease in the wind moments, which are due to the convergence of the external wind force with the rotation axis. Predictions concerning the mass and cost of the RT-128 are given in Table 5.

Due to the improved design for operating the elevation axis in comparison with the TNA-1500, the reflector mass is assumed to be decreased by a factor of about 1.3. In addition, because of the arrangement of the elevation axis and the reflector system center
of gravity, the mass of the supporting construction and mechanisms can also be reduced by about a factor of two. According to a comparison with the design of the TNA-1500 and the approximations made earlier in the complex optimization of the RT-128 system, it is possible to reduce the overall SSE mass by about a factor of 2.7 (see Table 6). The cost estimate for the TNA-8000 antenna system is the largest, about 35 - 40 million rubles.

TABLE 5

<table>
<thead>
<tr>
<th>No.</th>
<th>Antenna system elements</th>
<th>Mass, t</th>
<th>Manufacturing cost, thousands of rubles</th>
<th>Erection cost, thousands of rubles</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Foundation and base</td>
<td>-</td>
<td>500</td>
<td>200</td>
</tr>
<tr>
<td>2</td>
<td>Reflector system:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>reflecting surface</td>
<td>500</td>
<td>2,900</td>
<td>1,150</td>
</tr>
<tr>
<td></td>
<td>load-carrying structure</td>
<td>4,100</td>
<td>4,700</td>
<td>1,900</td>
</tr>
<tr>
<td>3</td>
<td>Steering system:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>load-carrying structure</td>
<td>6,200</td>
<td>6,900</td>
<td>2,700</td>
</tr>
<tr>
<td></td>
<td>supports and mechanisms</td>
<td>2,500</td>
<td>8,600</td>
<td>3,400</td>
</tr>
<tr>
<td>4</td>
<td>Equipment cabs and maint-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>enance system</td>
<td>500</td>
<td>700</td>
<td>250</td>
</tr>
<tr>
<td>5</td>
<td>Orientation system with</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>electric drive</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>Antenna-feeder</td>
<td>300</td>
<td>100</td>
<td></td>
</tr>
</tbody>
</table>
| 7   | Guiding system with elec-
|     | tric drive              | 2,400   | 700                                    |                                    |
|     | Total for radiotelescope| 27,000  | 11,000                                 |                                   |

TABLE 6

<table>
<thead>
<tr>
<th>Radio-telescope diameter, m</th>
<th>Structural system acc. to telescope type</th>
<th>Structural mass, t</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Main reflector framework</td>
<td>Support structure, mechanism</td>
</tr>
<tr>
<td>64</td>
<td>TNA-1500</td>
<td>750</td>
</tr>
<tr>
<td></td>
<td>TNA-8000 (RT-128)</td>
<td>400</td>
</tr>
<tr>
<td>128</td>
<td>TNA-1500</td>
<td>6,500</td>
</tr>
<tr>
<td></td>
<td>TNA-8000 (RT-128)</td>
<td>4,600</td>
</tr>
</tbody>
</table>
TABLE 7*

<table>
<thead>
<tr>
<th>Wind velocity at ht. h = 10 m above Earth's surface, m/sec</th>
<th>Total avg. quadratic distortion, mm (orientation w. $\beta_R$ up to 60°)</th>
<th>Partial coefficient for decreasing SC from shape distortion and corresponding $S_m$ in the position of the radiotelescope axis to the horizontal for wavelength $\lambda$, cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>1.10</td>
<td><img src="" alt="Table Data" /></td>
</tr>
<tr>
<td>10</td>
<td>0.68</td>
<td><img src="" alt="Table Data" /></td>
</tr>
<tr>
<td>7.5</td>
<td>0.55</td>
<td><img src="" alt="Table Data" /></td>
</tr>
<tr>
<td>5</td>
<td>0.50</td>
<td><img src="" alt="Table Data" /></td>
</tr>
</tbody>
</table>

*Commas in numbers represent decimal points.

Some idea of the decrease in SC for the RT-128 radiotelescope influenced only by construction factors in the use of homologous principles, and characterized by the partial coefficient $\eta_{\text{hom}}$, is given in Table 7. Along with $\eta_{\text{hom}}$, Table 7 contains the computed values of the equivalent geometrical areas $S_{\text{eq}} = \eta_{\text{hom}} S_{\text{hom}}$ for constructing a reflector system which takes into account shape distortion on a wavelength scale. For example, from Table 7, we can see that, under the condition of about half the maximum wind velocity, the structures are able to maintain a sufficiently efficient working reflector at wavelengths up to 8 mm, having a partial loss only when the shape is distorted by a factor of about 1.5.

The RT-128 construction scheme can also be successfully applied to smaller diameter antennas ($D>25-45$ m) whose weight loads clearly dominate over other loads, whose homology remains sufficiently high, and whose focus-angle deformation system does not significantly complicate the antenna system. The computed results for the TNA-3000 radiotelescope project create preconditions for the further accuracy...
of the approximate relationships between cost, mass, and antenna
diameters based on a more profound optimization. The final solution
to this question is possible only at the initial radiotelescope
construction stage when the first empirical data become available.

In addition to the new progressive construction designs, the
realization of specific construction and technological principles
has important significance for further improvements in the economy
of large antenna structures.

Among these principles, for example, is the choice of antennas
with a minimum overall number of axes of rotation and movable con-
struction elements, which require electromechanical and electronic
guidance equipment. This makes it possible to reduce the fraction
of the cost for the mechanisms and guidance systems in relation to
the less expensive elements, metal construction. The application of
unified examples of this construction will allow us to increase
their operational accuracy.

One way to speed up the construction of radiotelescopes and to
improve their economic characteristics is to simplify their metal
construction and assembly technology. In particular, the refusal
to assemble most of the large TNA-1500 units at the factory and the
transfer of this operation to the erection site led to a significant
decrease in the amount of mechanical preparation of their inter-
mediate butt joints which were only necessary for transporting the
dismantled assemblies. Thus, it became possible to do away with
their being hauled from the factory to the site as large, low-mass
blocks.

At the same time, a specially developed operational method for
assembly orientation at the site ensures the required accuracy of
the metal construction without the accumulation of errors. Because
of the more economical use of transport, there is less of a problem
in the factory industrial area for assembly of the large structures,
and an uninterrupted erection cycle is assured at the site without
having to solve the problem of keeping precise track of the delivery and erection schedules.

It should be mentioned that the same technological principles have already been used in constructing other types of non-antenna metal structures [11]. However, in our experience in the Soviet Union regarding the building of large parabolic antennas, this is the first time such a method has been adopted. It is a significant improvement over the traditional methods for assembly and erection.

Our experience in producing the first TNA-1500 radiotelescope has confirmed the advisability of these construction and technological designs not only for subsequent TNA-1500 production, but also for larger structures such as the TNA-8000 radiotelescope.

References


6. Polyak, V. S. Sovershenstvovaniye konstruktivnoy formy polnopovorotnych parabolicheskikh zerkal'nykh anten s tsel'yu povyshenya effektivnosti ikh paboty (Improving the Shape of Fully Steerable Parabolic Reflecting Antennas


