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ON THE PROBLEM OF CONSTRUCTING A MODERN, ECONOMIC RADIOTELESCOPE COMPLEX

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and V. S. Polyak

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A. F. Bogomolov, A. G. Sokolov, B. A. Poperechenko,
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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. /106* /107

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

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*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 /108 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):

$$Э_1 = \frac{Э}{Э_0} = \frac{\dfrac{S_{\text{эфф}}}{T_{\text{ш}}}}{\dfrac{S_{\text{геом}}}{T_{\text{ш0}}}} = \eta K K_{\text{т}},$$

where, besides the efficiency (η) and the surface coefficient (SC) allowing for the accuracy in guiding the beam (K), we introduce a system use coefficient based on the noise temperature (TC, $K_T = \frac{T_{\text{ш0}}}{T_{\text{ш}}}$). Here, $T_{\text{ш}}$ and $T_{\text{ш0}}$ 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: $T_{\text{ш.а}}$ — actual antenna noise ($T_{\text{ш.а0}}$ is due only to sky noise in the direction of the main lobe radiation pattern); $T_{\text{ш.тр}}$ — uhf channel noise ($T_{\text{ш.тр0}}=0$), and $T_{\text{ш.пр}}$ — receiver noise ($T_{\text{ш.пр0}}$ 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 ($K_{\text{т.а}}$) and for the uhf receiver channel ($K_{\text{т.пр}}$):

$$K_{\text{т}} = K_{\text{т.а}} K_{\text{т.пр}},$$

where:

$$K_{\text{т.а}} = \frac{T_{\text{ш.а0}} + T_{\text{ш.пр0}}}{T_{\text{ш.а}} + T_{\text{ш.пр0}}} = \frac{T_{\text{ш0}}}{T_{\text{ш а}} + T_{\text{ш.пр0}}},$$

$$K_{\text{т.пр}} = \frac{T_{\text{ш.а}} + T_{\text{ш.пр0}}}{\eta T_{\text{ш.а}} + T_{\text{ш.тр}} + T_{\text{ш.пр}}} = \frac{T_{\text{ша}} + T_{\text{ш.пр0}}}{T_{\text{ш}}}.$$

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 (RT-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, /109 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 ($\eta K \approx 0{,}7 \div 0{,}75$, and at the limit of the range of about 0.65), but continue to lag behind the world standard according to the noise temperature coefficient ($K_{\text{т}} \lesssim 0.45 - 0.25$ versus 0.6 - 0.3). This is also true for the individual coefficients $K_{\text{т.а}}$ and $K_{\text{т.пр}}$ ($K_{\text{т.а}} \lesssim 0.65 - 0.7$, while with regard to $K_{\text{т.пр}}$ 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 $K_{\text{т.а}}$ 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

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TABLE 1[†]

No.	Antenna	Diam., m	Operat. range, cm	Collector type	Surface efficiency, K	$S_{эфф}$ at LNA entry, m^2	Efficiency, η	Position angle β, deg.
1	TNA-57 (Orbita), parabolic short focus	12	30	Single reflector	0,7	73	0,93	50–10 β = 5÷90
2	TNA-1500* (Medvezh'i ozera, Kalyazin), quasi-parabolic, medium focus	64	3 7	Double reflector	0,65 0,75	2030 2360	0,97 0,98	21–10 15–8 β = 5÷90
3	TNA-57F, parabolic w. modified counter-reflector, short-focus	12	7	Double reflector	0,61 with m.a.** 0,7 without m.a.**	56 64	0,815	40–12 β = 5÷90
4	RT-70*, quasi-parabolic	70	3 30	Double reflector	0,65 0,79	2500 3040	0,975	10 12,5 β = 90
5	Raisting-I, FRG, parabolic, short-f.	25	7	Double reflector	0,55	260	0,96	40–14 β = 5÷90
6	Raisting-II, FRG, parabolic, short-focus	28,5	7	Double reflector	0,66	355	0,89	29–8 β = 7÷90
7	Plumier-Boudou-II, France, quai-parabolic, medium-focus	27,5	7	Double reflector	0,77	540	0,9	31–8 β = 5÷90
8	Fucino, Italy, quasi-parabolic, medium-focus	27,4	7	Double reflector	0,7	570	0,95	39–5 β = 5÷90
9	Bonn, FRG, parabolic	100	11 2,7	Double reflector	0,55	4200 2800	0,97 without uhf***	5 β = 90

(Table continued on following page)

TABLE 1. (continued)

No.	Antenna	$T_{\text{ш.тр}}$, K	$T_{\text{ш.пр}}$, K	$T_{\text{ш}}$, K	$K_{\text{т.в}}$	$K_{\text{т.пр}}$	$K_{\text{т}}$	Э, м²/K	Э₁
1	T_NA-57 (Orbita), parabolic, short-focus	20	70	140—100	0,66—0,97	0,38—0,13	0,25—0,126	0,53—0,74	0,16—0,08
2	T^NA-1500* (Medvezh'i ozera, Kalyazin), quasi-parabolic, medium-focus	10 6	9 20	40—29 41—34	0,67—0,74 0,63—0,7	0,75—0,66 0,52—0,42	0,5—0,49 0,32—0,28	50—70 58—69	0,31 0,23—0,2
3	TNA-57F, parabolic w. modified counter-reflector, short-focus	55	70	165—137	0,75—0,55	0,28—0,134	0,2—0,074	0,34—0,41	0,1—0,037 0,114—0,042
4	PT-70*, quasi-parabolic	7	10	27 29,5	0,74 0,81	0,71 0,52	0,52 0,42	92 103	0,34 0,33
5	Raisting-I, FRG, parabolic short-focus	11	4,3	59—29	0,77—0,55	0,79—0,53	0,61—0,29	4,6—8,9	0,32—0,15
6	Raisting-II, FRG, parabolic, medium-focus	34	19	81—59	0,75—0,66	0,4—0,2	0,3—0,132	4,4—6,0	0,18—0,078
7	Plumier-Boudou-II, France, quasi-parabolic, long-focus	29	15	78—52	0,84—0,7	0,52—0,28	0,44—0,2	6,9—10,4	0,31—0,14
8	Fucino, Italy, quasi-parabolic medium focus	15	15	65—35	0,82—0,88	0,64—0,32	0,52—0,28	8,8—16,3	0,35—0,19
9	Bonn, FRG, parabolic	8 —	20 —	33 150 with uhf***	0,8 —	0,375 —	0,3 0,11	127 18,5	0,17 0,06

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*Computed values

**Motor accompaniment

***uhf radiometer elements

†Commas in numbers represent decimal points.

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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

System elements	Fraction of manufacturing and erection cost, %, to the total cost for various dimensions			
	Average dimensions (D = 15 - 30 m)		dimensions (D = 50 - 150 m)	
Antenna-feeder (AF)	15	40	25	
Electric drive guiding system	25			
Reflector	15	50	20	55
Supporting steering equipment (SSE) without electric drive	35		35	
Construction part	10		20	

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 3*

System elements	Wt. P, kg	Cost, C		Cost per 1 m^2 surface C_1		
		Manufacture	Assembly	Geometrical ($K = 1$)		Total efficiency ($K = 0,6$)
				Mfg.	Assembly	
Reflector (excluding tooling-up)	$2,5\ D^3$	$(0,42 \div \div 0,32) D^2$	$(0,21 \div \div 0,16)\ D^2$	(0,54—0,41)	(0,27—0,20)	(1,35—1,04)
SSE (excluding tooling-up) without electric drive	$15\ D^3$	$0,75\ D^2$	$0,35\ D^2$	0,96	0,45	2,34
Antenna structures	—	$0,60\ D^2$		0,77		1,27
Total (without guiding system)	$17,5 D^3$	$(2,33 \div 2,18)\ D^2$		(3,0—2,8)		(4,96—4,65)
System total	—	$(3,0 + 2,85)\ D^2$		(3,8—3,6)		(6,4—6,1)

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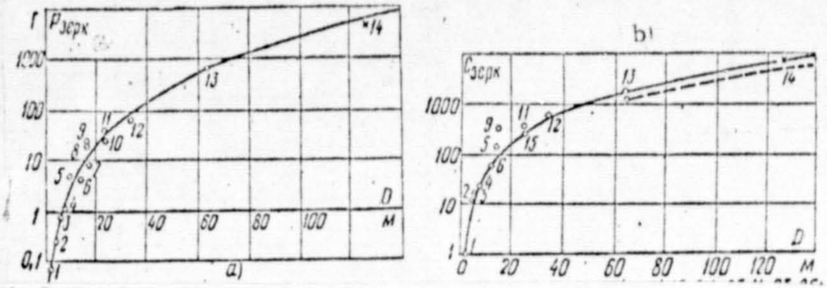
* Commas in numbers represent decimal points.

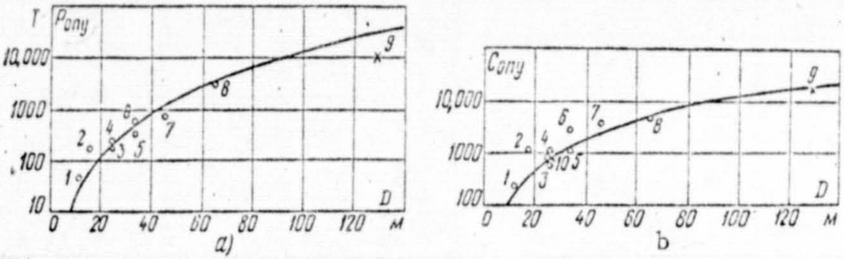
and its mechanisms whose separate cost for a one-ton mass differs by a factor of three and more, the speed and reliability of the guidance drive gears, etc.). The amount of scatter in the points agrees with the approximating curves. The empirical relationships shown in Tables 2 and 3 correspond to the actual construction of different antennas with diameters ranging from 2.5m to 64 m, built over the last 20 - 25 years. /113

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 $P_i(D)$ and $C_i(D)$. 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



1 - TNA-2.5; 2 - RT-5; 3 - RT-7; 4 - B-8; 6 - TNA-57; 7 - RT-18; 8 - SM-16; 9 - TNA-110 (RT-16); 10 - SM-25; 11 - RT-25; 12 - TNA-400 (RT-32) 13 - TNA-1500 (RT-64) 14 - TNA-8000 (RT-128); 15 - M

Figure 1



1 - TNA-57; 2 TNA- 110; 3 TNA-2105; 4 - RT-25; 5 - TNA-4005; 6 - TNA-400; 7 - RT-45; 8 - TNA-1500; 9 - TNA-8000 (RT-128) 10 - M.

Figure 2

by the index i, and characterized by a power low of the type $Q_i=q_iD^{m_\kappa}$ (Figure 3). The exponent is nearly constant within the limits of each family, and for mass and cost is equal to $m_p\approx3.2$ and $m_c\approx2.6$, 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 $P=q_pD^{m_p}$ and cost $C=q_cD^{m_c}$ relationships over a broad range /114 of antenna diameters intersect the family of theoretical curves because of the change in construction design, and have different exponents $m_p\approx3$ and $m_c\approx2$.

Of course, this relationship is not suitable for all antenna system elements. A number of less expensive elements (antenna feed systems, buiding 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:

$$C_{\text{а}} = AS_{\text{эфф}} = \left(A\frac{\pi}{4}\eta K\right)D^2,$$

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 errection were in practice completed in 1974, and the cost was determined according to the actual expense).

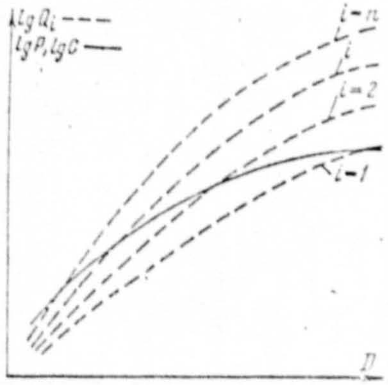


Figure 3

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

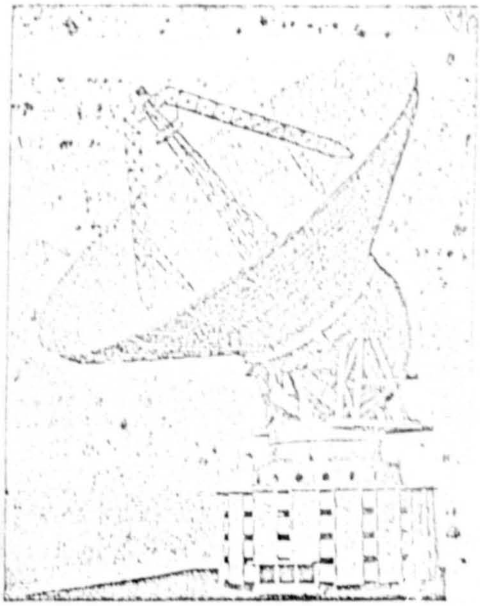


Figure 4

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, $\omega=150/D$ (for the velocity range (0.5 - 2.0) · 10^3 and diameter D, m);

— electric drive power rating, kW, $W_{\text{п}}\approx 0.06D^2$;

— SSE directional accuracy including the compensation system, /115
$\Delta\theta\approx 2\theta_{0.5}/(10-15)\approx[(5-15)/D]'$.

The linear relationship between the cost of parabolic antennas and their effective area allows us to use the concept of cost per 1 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:

$$C_{\text{пр}}\approx B/T_{\text{ш.пр}} \text{ for } T_{\text{ш.пр}}\geqslant T_{\text{ш.пр0}},$$

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

The $C_{\text{пр}}(T_{\text{ш.пр}})$/derived relationship includes the variation in the optimal type of LNA with $T_{\text{ш.пр}}$/change in the same way that the P(D) and C(D)

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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 $C_{\text{а}}$ and LNA cost $C_{\text{пр}}$, along with a given efficiency $Э=S_{\text{эфф}}/T_{\text{ш}}$, we can find the optimum values of $S_{\text{эфф.опт}}$ and $T_{\text{ш.пр.опт}}$ which correspond to minimum system cost.

The fact is that the system efficiency $Э$ can be realized for different combinations of $S_{\text{эфф}}$ and $T_{\text{ш}}$. Thus, the overall system cost $C=C_{\text{а}}+C_{\text{пр}}$ for different combinations of $S_{\text{эфф}}$ and $T_{\text{ш}}$ will not be the same. By varying one of the parameters $T_{\text{ш}}$, $S_{\text{эфф}}$, $C_{\text{пр}}$ and $C_{\text{а}}$ for a fixed $Э$, we can find the minimum overall system cost C from the equation:

$$\frac{\partial C}{\partial C_{\text{пр}}}=\frac{\partial C_{\text{а}}}{\partial C_{\text{пр}}}+1=\frac{\partial (AЭT_{\text{ш}})}{\partial C_{\text{пр}}}+1=AЭ\,\frac{\partial\left(\frac{B}{T_{\text{ш.пр}}}\right)}{\partial C_{\text{пр}}}+1=$$
$$=ABЭ\left(-\frac{1}{C^2_{\text{пр.опт}}}\right)+1=0.$$

From our approximation, it follows that:

$$C_{\text{пр.опт}}=\sqrt{ABЭ}\ \text{ и }\ T_{\text{ш.пр.опт}}=\sqrt{B/AЭ},$$
$$S_{\text{эфф.опт}}=Э(\eta T_{\text{ш.а}}+T_{\text{ш.тр}})+\sqrt{BЭ/A}\ \text{ и }\ C_{\text{а.опт}}=AS_{\text{эфф.опт}}.$$

In practice, it is more advantageous to take somewhat larger values for $T_{\text{ш.пр}}$ and $S_{\text{эфф}}$, 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 $\eta T_{\text{ш.а}}+T_{\text{ш.тр}}\approx 35$ K 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 4*

System parameters	Efficiency Э, м²/K			
	50 (LNA series)	50 (LNA exper.)	1 (LNA series)	1 (LNA exper.)
$C_{\text{пр.опт}}$	1,4	2,65	0,2	0,38
$T_{\text{ш.пр.опт}}$, K	4,3	8,2	30	57
$S_{\text{эфф. опт}}$, м²	2000	2200	65	92
$D_{\text{опт}}$, м	65	68	12	14,5
$C_{\text{а.опт}}$	12	13,2	0,42	0,55
$C_{\text{опт}}$	13,4	15,85	0,62	0,93
$C_{1\,\text{опт}}$	270	315	620	930

*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 $(T_{\text{ш.пр.мин}} \approx 5 \div 10\ \text{K},\ C_{\text{пр.макс}} \approx 1{,}2 \div 0{,}6)$. Usually these systems are characterized by an efficiency $\text{Э} \lesssim 10 \div 40$ for a series of LNA when $\eta T_{\text{ш.а}} + T_{\text{ш.тр}} \approx (15 \div 40)\ \text{K}$ over the position angle range. This corresponds to reflector diameters $D \lesssim (32 \div 45)$ 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 /117 highest possible sensitivity. The limiting values for Э and D for the experimental LNA examples are shifted toward larger values.

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

$$C_{1\text{опт.ср}} = \frac{C_{\text{опт}}}{\text{Э}} = A(\eta T_{\text{ш.а}} + T_{\text{ш.тр}}) + 2\sqrt{AB/\text{Э}}$$

and

$$C_{1\text{опт.б}} = AT_{\text{ш.мин}} + B/ЭT_{\text{ш.мин}}.$$

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:

$$Э \gg 4\,\frac{B}{A}\,\frac{1}{(\eta T_{\text{ш.а}} + T_{\text{ш.тр}})^2} \approx (15-3),$$

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

$$Э \gg \frac{B}{A}\,\frac{1}{T_{\text{ш.мин}}\,T_{\text{ш.пр.мин}}} \approx 4,$$

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

Thus, we would expect a significant economic savings by increasin the area of large-size antennas ($D > 50$ м). 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. /118

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 $\Delta\theta_{\text{мин}} \approx (5-10)''$, and for the reflector system geometry $\Delta_{\text{мин}} \approx (0{,}5 \div 1)$. The values chosen for $\Delta\theta_{\text{мин}}$ and $\Delta_{\text{мин}}$ 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

$$\Delta\theta_{\text{мин}} \lesssim \frac{2\theta_{0.5}}{7-10} \approx \frac{\left(0{,}25\cdot 10^6\,\frac{\lambda_{\text{мин}}}{D_{\text{макс}}}\right)''}{7 \div 10}$$

and

$$\Delta_{\text{мин}} \lesssim \frac{\lambda_{\text{мин}}}{(15-20)}$$

and substituting into these equations the values for $\Delta\theta_{\text{мин}}$ and $\Delta_{\text{мин}}$, we obtain $D_{\text{пред}} \lesssim (5000-3000)\lambda_{\text{мин}}$ and $\lambda_{\text{мин}} \gtrsim (1-1.5)$ cm.

Consequently for $\lambda_{\text{мин}} \approx 3-5$ 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 $\lambda_{\text{мин}}$ 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 $\lambda_{\text{мин}}$ 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. /119

In the last few years, a large new radiotelescope project has been started, the TNA-8000 (RT-128) with a dimaeter 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.

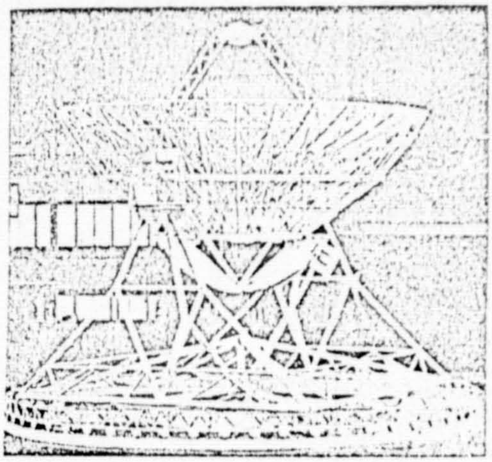

Figure 5

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. /120

Due to the improved design for operating the elevation axis in comparison with the TNA-1500, the relfector 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

TABLE 5

No.	Antenna system elemtns	Mass, t	Manufacturing cost, thousands of rubles	Erection cost, thousands of rubles
1	Foundation and base	-	500	200
2	Reflector system:			
	reflecting surface	500	2,900	1,150
	load-carrying sturcture	4,100	4,700	1,900
3.	Steering system:			
	load-carrying structure	6,200	6,900	2,700
	supports and mechanisms	2,500	8,600	3,400
4.	Equipment cabs and maintenance system	500	700	250
5.	Orientation system with electric drive	-	-	800
6.	Antenna-feeder	-	300	100
7.	Guiding system with electric drive	-	2,400	700
	Total for radiotelescope		27,000	11,000

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 /121 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 6

Radiotelescope diameter, m	Structural system acc. to telescope type	Structural mass, t	
		Main reflector framework	Support structure, mechanism
64	TNA -1500	750	3 250
	TNA -8000 (RT-128)	400	800
128	TNA 1500	6 500	25 000
	TNA -8000 (RT-128)	4 600	8 700

TABLE 7*

Wind velocity at ht. h = 10 m above Earth's surface, m/sec	Total avg. quadratic distortion, mm (orientation w. β_K up to 60°	Partial coefficient for decreasing SC from shape distortion and corresponding $S_{эк}$ in the position of the radiotelescope axis to the horizontal for wavelength λ, cm			
		3	1,5	0,8	0,4
15	1,10	$\frac{0,84}{1,09\cdot10^4}$	$\frac{0,59}{0,76\cdot10^4}$	$\frac{0,20}{0,26\cdot10^4}$	—
10	0,68	$\frac{0,95}{1,23\cdot10^4}$	$\frac{0,76}{0,98\cdot10^4}$	$\frac{0,44}{0,57\cdot10^4}$	$\frac{0,10}{0,13\cdot10^4}$
7,5	0,55	$\frac{1,00}{1,29\cdot10^4}$	$\frac{0,86}{1,11\cdot10^4}$	$\frac{0,53}{0,68\cdot10^4}$	$\frac{0,15}{0,20\cdot10^4}$
5	0,50	$\frac{1,00}{1,29\cdot10^4}$	$\frac{0,88}{1,14\cdot10^4}$	$\frac{0,60}{0,77\cdot10^4}$	$\frac{0,20}{0,26\cdot10^4}$

*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 $\eta_{констр}$, is given in Table 7. Along with $\eta_{констр}$, Table 7 contains the computed values of the equivalent geometrical areas $S_{эк}=\eta_{констр}S_{геом}$ 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. /122

The RT-128 construction scheme can also be successfully applied to smaller diameter antennas (D>25—45 м) 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-8000 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 construction 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 intermediate 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. /123

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.

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