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STUDIES FOR THE CONSTRUCTION OF THE 100-M TELESCOPE

Studien zur Konstruktion des 100-m-Teleskops

by

O. Hachenberg

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ABSTRACT

An analysis of the development of radio astronomical research within the last five to ten years shows that large single telescopes as well as arrays are required to obtain all the measurements urgently needed by radio astronomy. Moreover, such an analysis makes it possible to fix for both types of telescopes the range of their particular fields of operation. One of the main reasons for building a large single telescope was its broader field of operation.

A comparison of both types of equipment also shows that in the years to come a large telescope with a continuous aperture surface will mainly be used in the cm-wave range (for $\lambda \leq 25$ cm).

If, however, a paraboloid is to be chiefly used in the wavelength range of $1 < \lambda < 25$ cm, the precision of the reflector surface must be very high. In this case, the deviations of the surface from an ideal paraboloid must, in any position of the telescope, not exceed a root mean square error of $\sigma = 1$ mm. This implies the factor σ/D of a telescope must reach 10^{-5}. The deviations of the surface from the ideal paraboloid are mainly due to elastic deformation of the steel framework. This is most difficult to correct.

In the fifth section, of this paper different reflector constructions are critically examined with regard to their elastic properties. As a result of this, it is not to be expected that an 100-m-reflector with a σ/D of 10^{-5} can be built by simply increasing the size of a known construction.

Special precautions have to be taken in order to reduce elastic deformations. For this purpose, various suggestions have been made and are discussed in the sixth section.

For the first time, in the feasibility studies for the 100-m-telescope, the idea was consequently pursued that a certain deformation should be allowed. However, it should be of such a kind that the parabolic surface, once adjusted at zenith position, is, by the deformation converted into a series of new paraboloids when the telescope is tilted about its elevation axis. The new paraboloids may have other axial directions and different focal lengths. The resulting displacement of the focal point can be corrected by an adequate displacement of the feed.

The steel framework must, therefore, have the property that deviations from a best fit paraboloid of all those joints which are situated in the reflector surface itself are minimum in any position of the telescope.

To achieve this, in the case of four different types of construction — a) a dish construction with 4 point support, b) a truss construction, c) a dish construction with 8 point support, and d) a dish construction with axial mounting — the dimensions of member groups and single members were changed by successive approximations. For each of them, the displacements of the joints in the reflector surface itself were calculated and the deviations from the best fit paraboloid determined. This procedure was repeated until the deviations had been reduced to a minimum.

For all four types of construction this procedure turned out to be successful. While the real elastic displacements at single points of the construction may come to about 65 mm, the deviations of the surface from the best fit paraboloid remain below 3 mm or the root mean square errors $\sigma < 1$ mm. The mean deviations of the real surface from the ideal paraboloid as well as the displacements of apex and focus of the newly yielding paraboloids in comparison with the original one are shown in tables 1—4, section VIII. On the dish construction with axial mounting the deviations are most insignificant; thus it was chosen for the construction of the telescope.

Finally, the limits to the use of this construction imposed by wind and variations of temperature are discussed.

STUDIES FOR THE CONSTRUCTION OF THE 100-m TELESCOPE*

I. Introduction: Observations on the development of radio-astronomy and the requirements anticipated for new telescopes.

When a large new piece of scientific equipemnt is to be constructed, its scientific purpose must be clearly determined even before the instrument itself is planned. This is important in planning a radio-telescope inasmuch as the development of the instrument is proceeding in two different directions. On the one hand, large single telescopes are being constructed, and on the other, the construction and development of antenna arrays is making rapid progress. To be able to decide in which of these directions to go, it is necessary to analyze the development of radio-astronomy in the last few years more carefully so as to evaluate the field of application of the one or the other type of telescope. In the following section, the considerations proposed by us will be outlined briefly.

An analysis of the development of radio-astronomy in the last five to ten years reveals a number of focal points where developments have been particularly productive. At the same time, it indicates the points where the most significant problems will occur even in the years to come. The focal points that emerged during the past year are:

1. The line spectroscopy of interstellar matter.

2. The synchrotron radiation from the galactic system.

3. Investigations of individual objects of the galactic systems.

4. The extragalactic objects.

5. Special problems at the sun and the other members of our planetary system.

1. The significance of line spectroscopy is evidenced by the successes achieved with the 21-cm-hydrogen line. Recently, the OH radical lines as well as the high hydrogen-transition lines have been added. The latter now make it possible to include the ionized hydrogen clouds of the HII-region in the investigation. Finally, the high transition lines of other elements have also to be found. In general, this group of lines may be expected to occur predominantly in the lower centimeter or the millimeter wave region.

The line-spectroscopic investigations find their major application in our galactic system. An angular resolving power of the antenna of some 10 to 30 minutes of arc is sufficient for the examination of great portions of the Milky Way; for special investigations of individual objects in the system, however, an angular resolving power of 1' and 8' is certainly necessary. Increasingly in these investigations, higher-frequency resolving power, together with the lowest possible receiver background noise, is required.

Only for line-spectroscopic investigations of extragalactic systems is a resolving power of less than a minute of arc - about 10 seconds of arc - required.

2. In the meantime, studies of the intensity distribution of the galactic continuum radiation (SURWEYS) have been made in the northern sky at various frequencies with an angular resolving power of about 1 deg. Investigations at higher angular resolving powers will further increase our knowledge; in the southern sky, supplementary measurements are still required, which should be made at the same frequencies as in the northern sky whenever possible. With this, the measurements of the intensity distribution along the Milky Way appear to be somewhat at a standstill. The measurements of the polarization of the radiation, on the other hand, have only just begun. Investigations of the polarization of microstructures of the continuum radiation as well as determinations of the Faraday rotation of the polarization plain of the linearly polarized radiation of discrete sources promise to be one of the main future sources of our knowledge of the galactic magnetic field. In general, an angular resolving power of 10' to 20' is quite sufficient for the polarization measurements.

3. Investigations of individual objects in the galactic system - such as star clusters, HII regions, supernova residues - will increasingly have to rely on line-spectroscopic types of measurements - whether they be HI- or HII-line measurements - as well as on measurements of continuum at several frequencies. The latter will be made particularly in the centimeter-wave region between 10-cm and 6-mm wavelengths; in this region, nonrandom measurements of the lines of the high hydrogen transitions will also be made. The completeness of the measurements will be a decisive factor in a successful discussion. In general, a resolving power between 1' and 5' should be quite sufficient for these investigations.

4. In the studies of extragalactic objects, the most extreme constraints are applied to the measuring technique. On the one hand, the number of objects up to the weakest radiation intensities is required for cosmologic interrogations; to be able to separate the weakest objects from the galactic background radiation, however, the antenna must have a large effective antenna surface and an angular resolving power of a few minutes of arc - on the other hand, the spectrum of the radio emission up to the highest frequencies is of the greatest significance for the discussion of the emission process. Thus, it is necessary to aim for the highest gain in the centimeter-wave region for the antennas and, at the same time, for the highest total sensitivity for the receivers. The angular resolving power again need only amount to a few minutes of arc for such studies. In addition, the apparent magnitude of the emission regions and the intensity distribution over the objects are of significance. To measure the intensity distribution, an angular resolving power of a few seconds of arc is desireable; only then can the radio-emission distribution be compared successfully with the optical image. By far the most stringent demand is made of the angular resolving power in determining the diameters of the emission regions of quasars. An angular resolution of 0".01 is aimed for, a resolving powe that by far exceeds that of even the largest optical telescopes and can

only be obtained using interferometers with very great base lengths.

5. In problems of solar physics, the need for high angular resolving powers is also considerable, although the availability of a resolution of less than 1' would prove satisfactory in this case. Since, on the other hand, the radiation intensity at the sun is high , special antenna systems will be developed and used for problems of solar physics that we need not consider here.

As can be seen from the preceding comments, the need for equipping an institute for radio-astronomy with modern technical measuring instrumentation is extremely many-faceted. On the one hand, the highest-frequency resolving power is required together with very low receiver background noise, so that even the smallest differences in intensity can be discerned in the line spectra; at the same time, the angular resolving power can be average. On the other hand, the greatest possible effective antenna surface and highest sensitivity of the receivers over a wide frequency range -- particularly at high frequencies (f>5 GHz) -- are required to detect the weakest radio sources and to determine their spectral intensity distribution; finally, to determine the angular diameters of quasars, an extremely high angular resolving power is needed, together with a large effective antenna surface. All of these different requirements cannot be satisfied by a single instrument.

The development of radio-astronomical facilities has to date been accomplished in two different ways and has led, as is well known, to two fundamentally different types of instruments -- the antenna arrays and the telescope with a continuous-aperture surface. Thanks to their different properties, it is possible to satisfy, basically, the above requirements with the two types of telescopes.

The development of the multi-element antennas -- or arrays -- was a departure from the Christiansen cross-coil antenna (Ref. 1). Like the latter, the array is composed of several average-size parabolic antennas arranged in a line or in form of a cross or of an L, a T, or a Y. If the input absorbed by the individual antennas is combined, with the aid of an electronic computer, in proper intensity and phase according to the method of von Ryle et al. (Ref. 2) and the aperture-synthesis procedures given in Ref. (3), a result can be derived from the consecutive measurements that will have the same angular resolution at the sky as if the measurements had been made with an antenna whose aperture surface corresponded to the circle described around the individual elemtns. Such antenna arrays are under construction or in the planning stage at various locations on earth.

The telescopic array also has the advantage of permitting an angular resolving power equal to that of a smaller optical telescope (about 3") to be attained. It also offers the possibility of making the effective antenna surface almost any size without technical difficulties. It is a further advantage that, the terrain permitting, such an installation can later be enlarged in stages, so to speak.

It is a peculiarity of the array that the definition of the image point is a function of the number of settings of the individual elements with respect to one another; similarly, the resolving power is a function of the position of the object in the sky. Another disadvantage is the fact that a change in the observation frequency involves considerable electronic consumption under certain conditions, and requires some time for readjustment.

The use of the array at higher frequencies (f>3GHz) runs into increasing difficulties because of the required phase constancy at the foot of each individual antenna and because of the relative fluctuations of the atmospheric index of refraction. For line-spectroscopic investigations, too, for which a high-frequency resolving power is required, the array can be used only with difficulty.

The large, fully steerable radio-telescope with a continuous-aperture surface -- generally constructed as a parabolic antenna -- can certainly be increased several times in size over the presently existing equipment. The effective antenna surface, which increases with the square of the diameter, can therefore be considerably enlarged -- certainly to 20,000 m^2 or more. On the other hand, this type of telescope does not offer the possibility of achieving a higher angular resolving power. The halfwidth H' of the principal lobe of the antenna directional diagram, measured in minutes of arc, is known to be

$$H' \approx 3800\lambda/D$$

Accordingly, the antenna would, for example, have to have a diameter $D = 3800\lambda$ to reach an angular resolving power of 1'. At λ=10, D = 380 m already exceeds the limits that are technically feasible today.

The remaining advantages of this type of antenna are the known definition of the image point, the relatively high attenuation of the minor antenna lobes, the ease of changing the observation frequency in a broader frequency range, and the fact that all points in the sky can be reached with the same resolving power.

If one weighs the properties of the two types of instruments against one another, one reaches the following conclusion:

Only the array makes it possible to determine the intensity distribution of extragalactic objects and of certain objects in our galactic system with the necessary angular resolving power. The exact measurement of the positions of sources for identification will also be a job for the array. It will further have to be used for line-spectroscopic work with lower-frequency resolving power for extragalactic objects. All of these studies will, for the first few years, be made above a wavelength of 10 cm.

The large radio-telescope, on the other hand, will concentrate on the lower centimeter-wave range ($\lambda \leq 10$ cm) in the future. It will enable us to extend the spectral intensity distribution of extragalactic objects to a wavelength of 1 cm or even further into the millimeter-wave range. It will further be the task of the large single antenna to measure, by means of interferometry, the diameters of the emission regions of far distant radio sources and quasars over enormous distances at an angular resolving power up to 0".01.

The most important studies of our galactic system -- the absolute radiation measurements, the polarization measurements of the galactic continuum, and the line=spectroscopic investigations of the interstellar matter -- will also be assigned to the large telescope. In combination with a multi-channel spectrometer, it will be able to measure details in the line contours that will never be accessible to the array.

Examining the situation, it is clear that the complete outfitting of an institute would have to consist of the construction of a large telescope as well as a sufficiently large array. Unfortunately, the "complete" outfitting generally remains a wishful dream in view of the costs. A decision must therefore be made.

The fact that a large single telescope has a much greater performance range than the array and that it is more flexible in its applications -- i.e., that it can be changed from one measuring task to another in the shortest time -- led to the decision in favor of a large telescope. This decision was influenced also by the fact that the Bonner Institute for Radio-Astronomy has for several years been using the 25-m telescope for line-spectroscopic work as well as studies of the galactic coninuum, and that this work should be continued with more efficient equipment. Last but not least, it was also significant in terms of the decision that a large "synthesis radio telescope" has been under construction in Holland for some time, and that it would be better to aim for a mutually complementary arrangement of the two facilities than a parallel arrangement of two similar facilities of the same size within Europe.

If we begin with the actual planning of a large telescope, two points of view emerge from the above observations that have a decisive influence on the direction of these considerations:

1. The centimeter-wave range is becoming increasingly significant in radio-astronomy. Thus the telescope must, if possible, be usable up to the centimeter waves.

If, therefore, the centimeter-wave range is given special emphasis in the planning, the feasibility of being able to attain an angular resolving power of 1 minute of arc or even less with a parabolic antenna becomes apparent. This might be possible if, for example, a 100-m-diameter reflector could be devised that could still be used for a wavelength of 2.5 cm.

This does open the way for the following difficulties: The quality requirements for the surface become so stringent that they can be satisfied only with great difficulty. The same is true for the steering; at a lobe width of 1 minute of arc, the steering errors must be less than 6 seconds of arc. This means that an instrument weighing several thousand tons, which is, in addition, exposed to the wind and the thermal effect of the atmosphere, must be adjustable and steerable with the precision of an average-size telescope.

2. The antenna construction must take into particular account the development of the high-frequency measuring technique.

The radiated powers to be measured in the centimeter-wave range are very small. The weakest sources still measurable at present using the 25-m telescope at the STOCKERT at $\lambda = 10$ cm yield

$$3 \cdot 10^{-27}\ Watt \cdot m^{-2} \cdot Hz^{-1}$$

To be able to measure such weak radiation, as much interfering background radiation as possible must be kept away from the receiver. Not only the noise of the receiver but also that of the antenna lead and the radiation from the ground over the side lobes of the antenna diagram must be considered background interference. Thus, not only must the receiver be cooled, but the structure of the antenna must be such that the background radiation over the side lobes is minimized. Measurements in the centimeter-wave range therefore have the same character as in the infrared-wave region. There, too, not only the receiver but also the radiation-limiting apertures should be low-temperature-cooled to minimize the interfering background radiation.

The effects of both points of view are to be considered even in the first decision that we must make.

II. CHOICE OF THE PARABOLIC FORM

The parabolic form of the reflector is described by the aperture ratio D/f here, we wish to use the aperture angle Θ in the focus for characterization. Our question is: Is there an optimum value of Θ for the reflector of the radio telescope?

If we consider the noise that reaches the receiver input across the side lobes of the antenna diagram, then we must confirm that this portion of the noise decreases -- or at least is easier to reduce -- with increasing aperture angle.

We have performed several series of measurements on model antennas and have determined the noise contribution as a function of the elevation angle of the antenna. In the zenith position of the telescope, the noise portion that enters across the side lobe -- assuming the same type of input -- may be shown by the solid curve in Fig. 1.

On the other hand, as we shall see later, it is simpler to build a flat reflector, which retains high precision at all elevation positions, than a reflector with large Θ . The broken line in Fig. 1 shall represent the degree of difficulty involved in building a reflector of the same quality but with increasing aperture angle. The weight, and ultimately the price, too, of the reflector dish increase proportionately with the aperture angle.

Naturally, there is a certain amount of play in terms of the significance assigned to one or the other argument. We selected a value of

$\Theta = 150^{\circ}$ for the reflector. Since the reflector is also to be equipped with a guard ring, the noise contribution is reduced so as to make Θ effectively 155°. In Fig. 1, the data thus determined for the telescope are marked by two points.

III. STRUCTURAL PRECAUTIONS TO MINIMIZE NOISE FROM THE ANTENNA AND THE ANTENNA LEAD

Every antenna absorbs radiation not only from the object at which it happens to be pointed but also from the surroundings across the side lobes of the antenna diagram. The presence of noise sources in the immediate vicinity must therefore be avoided under all circumstances. However, as we have already determined, there still remains the thermal radiation of the ground and the atmosphere, which is absorbed by the antenna and causes a certain amount of voltage in its terminals.

This noise contribution can be reduced by high-frequency technique, using special feed antennas. By means of these, it is possible to reduce the side lobes of the antenna diagram. The development of special horn reflectors is still in progress.

In addition, structural measures are provided which also contribute to minimizing antenna noise.

In order to keep the noise contribution of the antenna lead small, a sufficiently large focus cabin was provided, which can accommodate the receivers and thus makes it possible to keep the leads to the feed antennas as short as possible.

For the wave range 6 cm $<\lambda<$ 15 cm, a housing over a Gregory-mirror is also provided. The Gregory-reflector is elliptical in shape; it is located behind the focus and reflects the focal plane in a secondary image plane near the apex of the principal reflector. The reflector can be mounted on the floor of the focus cabin; it has an opening in the center, through which a feed antenna can be brought into the primary focus without difficulty, without having to dismount the reflector.

The Gregory-reflector is provided with a shielding collar at the rim, which extends to the juncture line between the focus and the rim of the paraboloid (Fig. 2). The Gregory-reflector and shielding collar provide a space around the focus that is well shielded against sweep (interference) radiation and has a very low noise temperature.

Further shielding is obtained by means of a collar attached to the rim of the principal reflector. Both of these measures have the effect that the horn emitter in the primary focus can no longer be hit by direct radiation. Measurements made on models confirmed the effect of the shielding.

In the following section, the possibilities of producing reflecting surfaces of great precision will be examined.

IV. THE PRECISION OF THE REFLECTOR SURFACE

Deviations of the reflector surface from the ideal paraboloid are caused by errors in the production of the tin plates (panels) that compose the reflector surface and by errors in adjustment when they are mounted. Furthermore, errors appear that are caused by the elastic deformation of the supporting steel structure. The latter are particularly apparent when the reflector is turned about the elevation axis.

The deviations from the ideal parabolic surface have the effect that the waves reflected by the individual parts of the reflector surface do not arrive at the focus in phase with the remaining waves and are partially extinguised there by interference. The reflector surface therefore sacrifices some of its efficiency. J. RUZE (Refs. 4, 5) has studied the effect of errors that are randomly scattered across the reflector surface on the electrical properties. If σ is the root-mean-square error of the surface, then its efficiency is reduced by a factor η_s:

$$\eta_s = e^{-\left(4\pi\frac{\sigma}{\lambda}\right)^2}$$

This relation makes it possible for us to determine the permissible error σ, if we wish to use the reflector up to a threshold wavelength λ_0. Figure 3 shows η_s as a function of the value σ/λ.

If, for example, $\eta_s \geq 0.67$, then σ must remain $\leq 1/20$. If, therefore, we wish to use our reflector for $\lambda_0 = 2$ cm, σ must be equal to 1 mm, and the maximum errors cannot exceed 2.5 mm.

The accuracy constraints for the surface are quite high for an 80- or 100-m-diameter reflector, too. In order to characterize the quality of the reflector surface, we shall use the quotient σ/D.

Since the panels of which the reflector surface is composed are about 3 to 5 m^2 in size, we can make the assumption that the fabrication as well as the mounting and adjustment errors of these parts can be controlled and maintained within narrow limits. Thus, only the errors caused by the elastic deformations of the support structure remain. We must pay particular attention to these and try to find a way to keep them, too, within the required limits. Although the errors due to deformations of the support structure are not in general randomly distributed over the reflector surface -- rahter, they are of a systematic nature, as the following picutres of the surface deformations show clearly -- we shall still require that the root-mean-square value of the surface deviations, determined at many, regularly distributed measuring points, be $\sigma = 1/20\ \lambda_0$.

Many different ways have been tried to obtain reflector surfaces with the greatest possible accuracy. Telescopes with a variety of structures have been devised. We shall now consider in more detail the structures used to date in terms of their particular properties.

V. REVIEW OF THE MOST IMPORTANT REFLECTOR STRUCTURES USED TO DATE

From the structural point of view, one has the difficult task in the construction of steerable parabolic reflectors of supporting the actual weight of the reflector -- as well as the wind velocities that must be added -- in the two bearing points of the elevation axis without causing the appearance of great surface deformations. The way in which this problem is solved is the decisive factor in determining the efficiency of the telescope.

A. Construction With Rigid Elevation Axis

In this type of construction, the two bearing points of the elevation axis are bridged by as rigid a girder as possible, which, if necessary, can also have multiple supports in the center. A number of brackets are mounted perpendicular to this, resulting in a rectangular space framework for the reflector dish. This structure is presented schematically in Fig. 4. Since the gravitational forces always act perpendicular to the elevation axis when the reflector is tilted about the elevation axis, the rectangular space framework appears to offer certain advantages; however, with respect to the deformation of the surface, this opinion could not be clearly confirmed. The size of the reflector surface is a function of the length of the brackets; the deformation at the rim of the reflector is determined by their rigidity. In this type of construction, one is finally led to an elliptical form for the reflector. The Mark II telescope at Jodrell Bank is constructed in this way; it confirms the fact that telescopes with reflector surfaces up to 800 m^2 can be constructed in this manner, which can achieve a $\sigma \approx 1$ mm (Ref. 6).

B. Construction With Rigid Central Hub

The basic idea of this type of construction is related to that discussed above. The point of origin is a rigid central cylinder -- a hub. Mounted on this are radial brackets. At first, it was the intention here, too, to keep deformations of the reflector surface to a minimum by corresponding dimensioning of these radial supports.

The computer treatment of similar systems showed that the introduction of annular supports makes a definite contribution to increasing rigidity. An additional improvement is obtained by attaching outer and inner cross connections between the radial supports. The introduction of annular supports and cross connections makes it possible to reduce the weight of the radial supports somewhat, without sacrificing any of the rigidity of the system. The 64-m telescope in Parkes (Australia) is typical of this type of construction, as seen in Fig. 5 in cross-section (Ref. 6). A $\sigma/D = 3.6 \cdot 10^{-5}$ was achieved with this telescope. The elastic deformations of the surface during inclination of the reflector from 90° to 30° elevation are shown in Fig. 6 (H. MINNETT, Ref. 7). The maximum structural height of the radial support is considerable at 1/7 D. The 45-m telescope in Algonquin Park in Canada was constructed in a similar manner. However, in this case, the reflector surface itself was apparently used as a bearing element in the structure. The surface was composed of 3-mm-thick steel plates, and the individual plates were welded together.

C. Annular Support

The fact that a cantilevered bracket has a bend at its free end which increases more than with the square of its length makes it appear advisable not to make the radial supports so long, if possible.

Furthermore, one must take into consideration that, as the reflector radius is increased by Δr, the surface increases by $\Delta F = 2\pi r \Delta r$. This additional surface ΔF must be carried exclusively at the outer end of the radial supports. Therefore, their load at the outer end also increases linearly with r; it becomes increasingly more unfavorable as the surface is enlarged.

On the basis of these points, the attempt was made to produce as rigid a ring as possible in the type of structure to be described, which would have a diameter of about 0.3 to 0.5 that of the reflector. Shorter radial supports were mounted on this ring. The inner aperture of the ring only had to be bridged.

The radial support themselves excercise torsional forces on the ring which must be removed. This is accomplished by an outer annular support that holds the radial supports together at their outer ends. A cross connection that is attached in the center of the principal annular support, however, serves the same purpose. Figure 7 shows the annular-support structure schematically. The reflector in Adlershof is a typical example of this type of construction. Here, the radial supports have a length of $\sim 1/3\ D$; they are prestressed by the outer annular support, like an open umbrella. The height of the structure at the annular support could be kept very low with $1/30\ D$. Figure 8 shows the rear view of the reflector at Adlershof (Ref. 9).

The Stockert reflector, too, is constructed in this way. The outer diameter of the annular support is 12.5 m, i.e., 0.5 D (Ref. 10).

In some respects, the Mark I 76-m telescope at Jodrell Bank also belongs to this type; its principal annular support is mounted at the rim of the reflector, and brackets are not used at all.

D. Dish Structures

Great rigidity of the reflector structure, particularly in radially symmetric systems, is achieved by inserting the important radial supports into a system of annular supports and upper and lower cross-connections. Unfortunately, only very approximate data can be given about the necessary number of radial supports and annular supports, as well as about their dimensions such as height, strength, etc. These values must, rather, be determined by computer for each individual case. Nevertheless, one can see that these considerations lead to the construction of relatively rigid reflector dishes, whose upper side carries the reflecting surface. We can include this type of reflector under the designation "dish structures."

However, the reflectors must be movable; the task remains of finding a good solution for the connection between the dish and the elevation axis. If the dish structure is supported only along the elevation axis, or perhaps only in the two bearing points, strong elastic deformations will appear in the plane perpendicular to the elevation axis at the rim of the dish.

Two further supporting points can easily be produced by strengthening the reflector dish at the back with a pyramid standing on its tip. The pyramid is attached across two rods to the bearing points of the elevation axis; the other two rods support the reflector at two points which are perpendicular to the elevation axis at the same distance from the center of the reflector as the bearing points. The supporting points thus obtained can take over a part of the weight of the dish. The portion depends on the dimensions of the rods of the pyramid. We have thus achieved a four-point support of the dish, with two rigid support points and two auxiliary points whose rigidity can be regulated.

The 90-m telescope at Green Bank is built on this principle. The four support points of the dish are again connected by a square framework; this is clearly visible in Fig. 9. The reflector was also measured photogrametrically. Figure 10 shows the measured deviations of the surface from the best-fit paraboloid in the inclined position of the telescope (39 deg elevation) (Ref. 11).

The effect of the bearing points and the support points is not clearly evident in the diagram. However, the surface errors have a σ of 5.7 mm; they appear to overlap the deformation errors throughout.

E. The Intermediate Support Systems

In order to get away from the two-point support of the dish and its damaging deformation, an intermediate support system must be introduced.

The simplest form of such a support system is the "whip" (balance), whose structure, as will be seen in Fig. 14, makes possible a true four-point support in which all four points carry an equal amount of the dish weight. With the four-point support, the maximum deformations of the dish are about one fourth those of the two-point support. In four-point support, the position of the supporting points relative to the elevation axis also plays a certain role. This influence must be examined separately for each case.

It is evident that the maximum deformations can be further reduced if the number of support points for the reflector dish is increased even more. KALATSCHEFF refers to a construction with 17 supporting points in "Telescope," though for a very light dish structure (Ref. 12).

In his proposal, he starts with a cylindrical support similar to a whip. A square framework rests on the four independent support points of the whip. The extensions of the four sides of the square form eight brackets, at whose ends eight support points are produced on an

0.8-D placed on the whip, nine more support points are produced on an inner circle of 0.4 D. Figure 11 shows the entire system.

The principle of supporting the reflector dish is comparable in many respects with the support of the mirror in the optical telescope.

In judging the intermediate support systems, it is important to take into consideration that all support points actually have the same properties, which is not necessarily the case for some of the points in the above proposal.

VI. WAYS OF REDUCING THE ELASTIC DEFORMATIONS OF THE REFLECTOR

None of the structures discussed is convincingly distinct from the others in terms of having particular advantages so that they could be adopted without changes for the construction of a 100-m telescope with maximum surface accuracy ($\sigma/D \leq 1 \cdot 10^{-5}$). The mere increase in size generally leads to disadvantageous solutions, as can easily be seen.

We must therefore again discuss the possibilities available to keep the elastic deformations small.

A. Automatic Adjustment of the Reflector Surface

One way that makes it possible to avoid the elastic deformations in the reflector surface entirely was first used in planning the telescope in Sugar Grove, West Virginia. It was planned to use a servo control for the individual panels of the reflector surface through which the surface would automatically regulate itself to the desired parabolic surface in any position of the telescope (Ref. 13). The individual panels were to have an area of 17 X 17 m; they were to be regulated at the four corners by motors and controlled by an optical system. A total of 90 panels was to be installed. Although the compensation of the elastic deformations can be achieved in this way, this solution of making all of the panels adjustable is undoubtedly very expensive. The Sugar Grove project was finally abandoned. The procedure was not developed further.

This procedure will certainly regain significance in future telescope developments. If the deformations are computed for a given structure and only the critical parts of the surface are corrected, the expense can be reduced considerably and kept within sensible limits.

B. Use of Several Equivalent Support Points

If one starts with a dish construction and, per KALATSCHEFF (Ref. 12), increases the number of equally weighted support points, one will certainly achieve a reduction in the maximum elastic deformation of the surface. However, intermediate support systems become complex and difficult. The costs of such a construction are high.

C. The Use of Relief Systems

Since the deformation of the dish can generally be precisely computed, it is possible to allow for auxiliary forces in the construction which will effect a reduction in the deformation, particularly at the critical points.

If, for example, the paraboloid surface is adjusted in the zenith position, the upper rim will go forward in a 90° inclination of the telescope, while the bottom rim will move backward a little. During the inclination, the areas of greatest deformation are mostly in the upper and lower rim zones. It is now easy to visualize pulling the upper rim back and pushing the lower rim forward. Ths could considerably reduce the deformation in the critical regions of the dish. The technical possibilities for solving such problems are different for each structure. In the haystack antenna, removal of the load was accomplished in the construction by the addition of weights. In the course of planning the 100-m telescope, the use of hydraulic members was considered to balance residual deformation errors. However, such measures proved unnecessary in the end.

In the 130-m telescope of the Northeast Radio Observatory Corporation which was in the planning stage at the time, the elastic deformations were to be compensated for by the introduction of relief forces alone. The structure is based on the system described above under A with a rigid elevation axis. Each of the brackets lying perpendicular to the elevation axis will receive its own compensation system (Ref. 14).

D. Homologous Deformation

The idea of permitting a certain deformation in the reflector construction was first pursued in the present studies. However, the deformations were to be such that the paraboloid surface in the zenith position would again be converted into a parabolic surface as the telescope moved about the elevation axis. The new paraboloid may have a changed axial inclination and a different focal length. These changes can easily be corrected by a corresponding change in the feed antenna.

A construction method is to be sought in which the deviation of the actual deformed surface of a best-fit paraboloid would be a minimum. Precisely expressed,

$$\Sigma d^2 = \Sigma(\Delta Z \cdot \cos \phi)^2 \rightarrow minimum$$

should be the case, if d is the vertical distance of the actual surface of the paraboloid at a measuring point in the surface (cf. Fig. 13).

This structural principle received the appropriate designation "homologous deformation" from S. VON HOERNER. Von Hoerner then investigated the possibility of homologous deformation theoretically (Refs. 15, 16).

How can a construction with these properties now be realized in practice? Attempts to find solutions for the principle did not appear very promising at the beginning of our studies in 1964 because of the complexity of the statistical problems that appeared.

We therefore preferred working with approximation procedures. With the aid of a computer, it became possible to compute the displacement of each joint in three coordinates under load conditions, even for complicated space frameworks. Because of the free choice of rod dimensions and the properties of the materials, the steel framework has enough free parameters to be able to affect the displacement of the joints in a plane or surface to a certain extent. Thus, there are some prospects that, if a few points on the framework are fixed, it may be possible to satisfy the conditions of homologous deformation for the points in the reflector surface.

The questions -- which of the constructions used thus far is best for such investigations, to what extent the procedure is actually feasible, and to what degree it makes sense to carry out the procedure -- can be decided only by repeated experiments.

VII. STUDIES OF SPECIAL MODELS

From a series of preliminary designs, four were selected for closer investigation. We shall first discuss a dish construction that was developed and computed by MAN.

A. The MAN Dish Model

A reflector dish with a diameter of 80 m, composed of 36 radial supports, annual supports, and cross connections, served as the point of departure. In Fig. 14, the type of support used can be seen on a model. For this construction, the deformation by the specific weight in the various positions as well as the deformation by wind and ice load were to be investigated. For this purpose, the electronic computer was first used to compute the displacement of each joint in three coordinates; then the deformation of those joints was studied which lie in the reflector surface, that is, the joints which determine the reflector surface. A best-fit rotation paraboloid was placed through these joints, and the deviations of the points from this paraboloid were determined. The calculations were simplified in this case by the fact that the reflector structure was circularly symmetrical and that, in addition, the choice of the supporting points provided a double symmetry. It was enough to make the calculations for only a quarter of the reflector. But even in this portion there were up to 146 joints to be calculated. For the computation, a program developed by MAN was used; later the FRAN-program was also employed.

In several of the computations, the cross-sections of the individual rods and of groups of rods were changed in steps in order to reduce the deviations of the joints in the reflector surface of the best-fit paraboloid to a minimum, and also to obtain the smallest possible total weight. The procedure was interrupted when it became apparent that no further improvement could be achieved.

In all, six basic steps were calculated, which made the importance of the outer annular support for the rigidity of the dish clearly evident.

The success of the procedure can perhaps best be indicated if the maximum deformation appearing on the reflector surface during inclination from the zenith position to 5° elevation is compared with the best-fit paraboloid. The deformation of the surface at the upper rim is +23 mm, that at the lower rim -19 mm. The maximum deviations from the best-fit paraboloid amount to about ±4 mm, that is, only about a sixth of the actual deformation.

The perpendicular deviations of the surface from the best-fit paraboloid are reproduced in Fig. 15 in the form of contour lines; the reflector was adjusted in zenith and then regulated to 5° elevation, and the deformations were measured.

In the figure, the effect of the support points on the deformation of the reflector surface is clearly visible. After the inclination, the two upper support points become noticeable through a region of positive deviation with a maximum of +3 mm, the two lower points giving rise to regions with a lesser negative deviation. If further improvement in the construction is desired, obviously the number of support points must be increased, or a more favorable distribution must be found.

To be able to judge the result further, it is important to know by what amounts the best-fit paraboloid is displaced with respect to the originally adjusted paraboloid.

The displacement is first described by the displacement of the zenith. The latter is displaced in the direction of the paraboloid axis -- that is, in direction of the Z-axis -- about Z_s on the one hand, and then a displacement perpendicular to the elevation axis and to the Z-axis in the direction of the Y-axis about Y_s appears. Displacements in the direction of the elevation axis are not to be expected because of the symmetry of the forces (see Fig. 16).

In addition, the change in the axis direction of the new paraboloid and the change in the focus f must be given.

The identifying data for the respective best-fit paraboloids are given in Table 1 for three different elevation angles. The values were derived so that the adjustment of the ideal parabola in the load-free case followed separately for each elevation angle, then the system was subjected to the force of gravity and the deformations that appeared were computed. Thus, three independent values for the root-mean-square deviation σ were also obtained. These values serve principally for judging the deformations in the individual positions; in the actual operation of the telescope, only the relative deformations will be effective.

If we look over the results, we notice that the deviations of the best-fit paraboloid of the original surface are minor. The displacements of the zenith amount to only a few millimeters, and the focal width of the paraboloid, too, changes by only a few millimeters. The position of the focus, which is determined additively from the displacement of the zenith about Z_s and the change in the focal width, is displaced by 11 mm during the inclination of the reflector from 5° to 90° elevation. The corrections which would have to be made on the feed antenna are thus minor; at longer waves, $\lambda > 10$, they are not taken into consideration. (The deformation of the feed mounting has thus far not been taken into account.)

If the fabrication errors of the reflector surface are small, the reflector would be usable for $\lambda = 2$ cm at a surface efficiency of $\eta_s = 0.7$.

B. KRUPP Truss Construction

A structure that deviates from the "dish model" was suggested and fabricated by KRUPP. The treatment was also based on a reflector size of 80-m diameter.

In this structure, the radial beams behind the reflector surface were extended to a point on the paraboloid axis (see Fig. 16). The rods that meet at the tip form a cone. The beams are constructed as trusses, which is what gave the structure the name "truss construction." The beam structure consists of twelve such trusses attached in pairs. The trusses are kept equidistant in the center -- near the zenith of the reflector -- by a wheel with spokes; at the reflector rim, they are held together by an annular support. If the appropriate stresses are introduced, the structure is comparable in effect to an open umbrella.

Like an umbrella, the "unfolded" reflector is also held at two points that lie along the axis. One support point is the tip of the cone, the second is the wheel hub near the zenith of the paraboloid.

An independent support system is required for mounting the reflector. It consists, in its simplest form, of a tetrahedon, one of whose beams bridges the bearing points as the elevation axis. This beam penetrates the truss construction in the outer portion without touching it and grips the hub of the spoke-wheel with a pin. Two other beams of the tetrahedon run from the elevation bearings to the tip of the cone and are attached there; they carry the reflector mainly in the zenith position. The rest of the rods are used principally for auxiliary support of the reflector at the point of the hub when the reflector stands at an angle. Figure 18 shows the support system schematically.

The studies of the elastic deformation of the system were carried out in a similar manner as those of the preceding type. The rod measurements of the support system were optimized in stages, and the deformation for the joints was determined in three coordinates using the FRAN program.

The success of the procedure can again be determined by comparing the maximum absolute deformation of the reflector surface at the rim with the best-fit paraboloid. The absolute deformation is presented in its entirety in Fig. 19; the maximum deviation at the upper rim is +33 mm, at the lower rim -33 mm. The maximum deviation of the best-fit paraboloid is only about ±1.3 mm; thus, it is only ~1/25 of the actual deformation.

The deviations of the best-fit paraboloid appearing perpendicular to the surface are again shown in the form of contour lines in Fig. 20. The data for the best-fit paraboloid are presented in Table 2 in the same form as for the preceding case.

The truss construction is unquestionably a type of structure distinguished by very minor deviations from the best-fit paraboloid, and therefore comes very close to the "homologous deformation" requirement. The weights of the dish construction, too, are low; the reflector structure weighs only 360 t. However, the very broad cone on the back of the reflector results in quite a difficult tower structure.

C. Dish Construction With 8-point Support (MAN)

Favorable results encourage one to continue the studies in the same direction. Therefore, a dish construction with 8-point support was examined more closely in another study.

Compared to the simple "whips" carried by the reflector dishes in the first construction, a stronger intermediate supporting structure must now be used. An eight-rod pyramid was selected for this purpose, whose tip is attached with two independent rods to the bearing points on the elevation axis, and whose base is formed into a rigid disk including the elevation axis. The reflector dish is mounted on this disk at eight points. The structure is shown in Fig. 21.

This time, a diameter of 100 m and a focal width of $\sim$30 m is prescribed for the reflector dish. The preceding investigations had shown that an 80-m reflector with optimum dimensions must absolutely be usable up to 2.5 cm wavelength. Accordingly, the reflector surface should be of a continuous design. Otherwise, as shown by earlier wind-tunnel experiments (Refs. 17 and 18), a fully extended reflector surface will tend toward vorticity at the rims in a wind; a perforated outer rim alleviates this phenomenon considerably. Taking this experience into consideration, it was therefore determined that the surface was to be fully extended up to a diameter of 85 m; in the 85- to 100-m-diameter ring, a transition from the fully extended surface to a light wire mesh was to be provided. The wire mesh of the outer ring was to be usable for $\lambda = 6$.

For the rest, the same computer process as above was used, and a stepwise optimization of the construction was again carried out.

This time, the dish construction was composed of 28 radial supports, five annular supports, and a number of cross connections in the final solution. The structure was lighter than that of case A. The result can again be grossly characterized by a comparison of the maximum deformation during inclination of the reflector with the maximum deviations appearing in the best-fit paraboloid. The maximum deformation of the surface at the upper rim is +60 mm, at the lower rim -22 mm. The maximum deviations from the best-fit paraboloid are only ±3 mm, thus being only about 1/15 of the actual deformation.

The deviations from the best-fit paraboloid appearing perpendicular to the surface are again shown in the form of contour lines in Fig. 22. In the figure, the effect of the quadripod is particularly evident; the regions of greatest deviations are caused by the upper and lower legs in the 0° position; it was not possible to reduce this effect further.

The data for the best-fit paraboloid are presented in Table 3 in the usual form.

D. Dish Construction With Axial Mounting

Using the "truss construction" as a starting point, KRUPP produced a structure that approaches the dish construction. Here, the dish is made into a unit, with the supporting cone in the back. The cone has 24 rods; that is, each radial support is supported by a rod in the tip of the cone. The base of the cone forms a wheel with 24 spokes. The spokes are again parts of the radial supports (see Fig. 23).

The dish and cone are again held at only two points - the tip of the cone and the hub of the wheel. A special support structure is required for the mounting, which is extended to an octahedron here. The quadripod of the focus cabin is included in the octahedron.

The study was again based on a reflector with a diameter of 100 m. The reflector surface was to be covered with metal plates to a diameter of 84 m and a wire mesh cover usable for $\lambda \geq 6$ cm was provided for the outer ring.

The computation again used the same procedure, and the optimization of the construction was made in several steps.

In the first approximation, the result can again be characterized by comparing the deviations appearing at the rim during inclination of the reflector about the elevation axis with the maximum deviations of the surface of the best-fit paraboloid. The deformation at the upper rim is 82 mm and at the lower rim 53 mm. The maximum deviations of the best-fit paraboloid are only ±1.8 mm, which is 1/36 of the actual deformation.

The vertical deviations of the surface of the best-fit paraboloid are shown in Fig. 24 for the region up to a diameter of 90 m. This is the region that can be provided with a continuous reflector cover against the effects of wind. In this part of the surface, the deviations are small. The root-mean-square error of the surface, caused by elastic deformations, is only 0.56 mm. With respect to this portion of the surface, it appears possible to construct a reflector with $\sigma/D \leq 1 \cdot 10^{-5}$. Even the errors caused by the fabrication of the panels and their adjustment can be contained in this.

The characteristic values for the best-fit paraboloids are given in Table 4. The change in the focal width is a maximum of 20 mm and the change in the axis inclination a maximum of 1140 seconds of arc. These values must be compensated automatically by moving the feed antenna in the focus. Corrections that cannot be neglected are required even for the Gregory mirror.

VIII. CONCLUSIONS FROM THE INVESTIGATIONS OF THE MODELS

The good results of the various studies show clearly that the way selected appears particularly appropriate to the problem of constructing reflectors with great accuracy.

The steel framework of the reflector is not a rigid body in the sense of the glass block of an optical mirror telescope. A multiple-point support, which offers the only possibility of keeping the deformations of optical mirrors small, also results in a reduction of the elastic deformation of the reflector framework, but if we depend on it alone, we overlook the fact that the inner mechanism of the reflector dish -- the structure -- is flexible and can be fabricated within wide tolerances.

It may be surprising to the reader that the possibility exists of building a reflector in such a way that once a paraboloid surface has been adjusted, it is constantly transformed into new paraboloid surfaces as the reflector rotates about the elevation axis. But a natural idiosyncrasy of the reflectors meets such a requirement. This can be seen in the simple example of a very flat reflector, or better yet, of a disk. If a circularly symmetrical disk is supported in the center and gravity is permitted to affect it, the center remains unchanged and only the rims sink down. The surface formed by a plane becomes a rotation paraboloid in the first approximation. The deviations of the rotation paraboloid can be kept small through a circularly symmetrical distribution of reinforcements. If this surface is now inclined about an axis in the plane, the gravitational force decreases in the direction of the axis with cos z. A series of rotation paraboloid surfaces is gone through. At $Z = 90^{\circ}$, the axial force is equal to zero; the force in the disk plane, which now appears alone, causes only minor deformations of the surface itself; it can therefore be neglected in the first approximation.

These simple considerations are not valid for reflectors with large aperture ratios; here elastic deformations also appear in the case of antimetric force; now the computer must assist in approximating solutions.

The approximations have the disadvantage that the quality of the solution depends on when the procedure was interrupted. The computational process is technically of an experimental nature; an error estimate is not possible. Thus, one cannot state definitively that the axial mounting of the reflector is to be preferred to a four-point or six-point support of the dish, even though it does appear that way. All one can do is to give a few general instructions that are useful in carrying out the procedure.

1. One should avoid having one or more of the principal reflector supporting points be in the reflector surface itself. The possibility of the remaining joints of the surface forcing a ratio that would correspond to a homologous deformation would be slight in such a case.

2. An attempt must be made to avoid single loads in the surface. Thus, one must avoid, if possible, mounting the quadripod that supports the focus cabin and feed in the surface itself.

3. According to the above results, a rotation-symmetrical structure of the surface has certain advantages over the unsymmetrical constructions. However, the answer to this question may still be influenced strongly by successes resulting from the studies of other systems.

An evaluation of the results obtained led to the selection of the "dish construction with axial mounting" for the 100-m telescope. The preference for the axial mounting of the surface and, finally, the constraint-free mounting of the focus cabin were decisive factors in this decision. A renewed study of this system is in process, based on an improved, detailed structure.

Figures 25 and 26 show the selected structure as a model; in Fig. 27, the support system is particularly easy to recognize.

IX. THE PROCEDURAL LIMITATIONS OF THE HOMOLOGOUS DEFORMATION

The method selected made it possible to produce reflector surfaces whose maximum deviation from the best-fit paraboloid amounted to less than 1/30 of the actually appearing elastic deformations. The result was obtained through approximation procedures; according to these, the possibility is not to be excluded that complete solutions might have been reached through further adroit experimentation.

In actual practice, however, there are limits to the further improvement of the behavior of the reflectors.

A. Effect of the Wind

In a wind, the reflector surface is exposed to strong additional forces which sometimes degrade the quality of the surface even when they deform it for only a very short time.

The effect of the wind can easily be estimated if the telescope is focused on a point on the horizon (or set at $+5^{\circ}$ elevation) and a consistently strong wind blows on the surface from the front -- in the direction of the negative Z-axis. The surface is then exposed to a steady additional force, which, in the first approximation, again turns it into a paraboloid. Therefore, it is not surprising that in Table 1 the changes in the surface at a wind velocity of 18 m/sec cause an increase in the σ of only 1.02 and 1.29.

However, the wind cannot be assumed to be equally strong over an entire surface of 8000 m^2. The elements of the turbulence are undoubtedly smaller than the surface itself. The forces that affect the surface will thus not be the same everywhere.

It is therefore of particular interest to know by what amounts the surface is actually deformed. The computer program yields these values, too, without trouble. For various points along a radial support of the dish model with distances R from the center, the displacements in the Z- and X-direction are computed for different wind velocities and are listed in Table 5 (Z-direction = axis of the paraboloid, X-direction>radial direction).

At a wind velocity of 12 m/sec, with a squall factor of 0.5 over the surface, relative deviations of 1.1 mm could appear according to the table. At wind velocities above 20 m/sec, the surface disturbances due to wind forces will become greater than the elastic deformations. The telescope can therefore be used only up to a wind velocity of 20 m/sec.

B. The Effect of Solar Radiation

The reflector structure changes not only as a result of wind load. Solar radiation on part of the structure, too -- while other portions are in the shade -- results in differential thermal deformations. Anyone who has ever taken part in the survey of a paraboloid knows that during the day in sunshine, considerable deformations appear. During the survey of the 36-m telescope in Berlin, we determined surface fluctuations of ±2 mm. This value corresponds to a root-mean-square $\sigma \approx 0.7$ mm. If similar ratios are assumed for the 100-m reflector, then the thermal errors in sunshine will exceed the purely gravitational deformation. The effect of solar radiation can, however, be lessened considerably through appropriate painting of the structure. After painting with TiO_2-white, the relative temperature differences of the structure will remain less than 5°.

C. Atmospheric Temperature Gradient

While the effects of solar radiation can be definitively estimated only with difficulty, the thermal effect of a temperature gradient in the atmosphere can be determined exactly.

If we assume that the mirror is focused on a point near the horizon and that a temperature gradient of 5° exists from the ground to an altitude of 100 m, a deformation is obtained which is shown in Fig. 28 along one of the radial supports. The deformation causes an inclination of the axis of 5". On the other hand, the relative deviations of the surface are small compared to the residual gravitational deformations. Thus, atmospheric temperature gradients cause little degradation in the quality of the surface.

The examples given should demonstrate that the influences of the surroundings are definitely capable of degrading the quality of the reflector surface noticeably. An improvement in the construction such that the residual deviations from the best-fit paraboloid are smaller than 1/30 of the actual elastic deformation does not appear purposeful in view of this. A further improvement in the construction will have the result that the times during which the surface is fully effective for the smallest usable wavelength will be limited to good hours of the night.

For the construction proposed by us, a reduction in the effectiveness of the surface at $\lambda<4$ is to be expected for only 5 to 6% of the total observation time in the local climate.

X. RADOMES

At this point, a brief remark about the radome is in order.

The difficult-to-control effects of wind and sun can be avoided by enclosing the telescope in a radome. A rigid radome could have been made for a 100-m telescope, too. However, this would cause a reduction in the sensitivity of the telescope of from 10 to 15%. The losses are further increased by rain through a film of water on the surface of the radome. In addition, the water film increases the noise in the telescope and causes a constant, irregular drift of the null line of the receiver during astronomical measurements. The unprotected telescope is insensitive to moisture -- at least in the case of a double horn -- even in the centimeter-wave range. The radome requires a considerable sacrifice of observation time in our climate and therefore has no decisive advantage for radio-astronomical observations. Considering the additional costs, it was therefore decided not to use a radome in this case.

XI. STEERING PROBLEMS

The studies of the elastic deformation of the reflector dish yielded the result that a reflector of about 100-m diameter with $\sigma/D \leq 1 \cdot 10^{-5}$ can be constructed which can be used up to 2-cm wavelength with a surface effectiveness of approximately 60%. It is to be expected that the principal cone of the antenna diagram will have a halfwidth of 1 minute of arc or even somewhat less.

If the adjustment accuracy of the telescope is required to be so exact as not to exceed a possible error of 1/10 the cone width, then the adjustment error or the error between the precalculated and the first position of the telescope must not exceed 6 seconds of arc during steering.

From this requirement, we extrapolate that the angle indicator at the telescope axes must have a registration precision of about 2". There are several means of achieving this precision.

It is more difficult to keep the displacements with time of the optical telescope axis with respect to the angle-indicator readings within the limits of about 6". The changes consist first of the shifts in the azimuth axis due to setting of one side of the base. A one-sided setting of the base ring by 1 mm causes a deviation of 5" at a support distance of 45 m. Secondly, there is a possibility of errors due to a displacement of the elevation axis as a result of differential thermal expansion of the azimuth towers. If thermal radiation causes one of the towers to become 2° warmer than the other one, errors in the axis direction of a maximum of 5" are to be expected. Only special painting of the towers can maintain the temperature differences below these values. Thirdly, a direct displacement of the optical axis can occur in an inclined position of the telescope as a result of a vertical temperature gradient in the atmosphere. As may be seen in Fig. 28, at a temperature gradient of 5° per 100 m of height, a displacement of the optical axis by 4" appears. The effects of wind and squalls on the displacement of the axis are difficult to estimate.

In the most unfavorable case, the possible errors exceed the upper limits set.

A portion of the displacements of the optical axis could be avoided through the use of an optical steering equatorial in the axial intersection. The telescope at Parkes , in which an equatorial is used, has had good experiences in this regard. Accordingly, the discussion of the pros and cons of an equatorial was extensive. However, the space in the axial intersection of the telescope must be kept open for the equatorial; but this is also the space that is urgently needed for the creation of a low-deformation reflector. Since the creation of a good reflector is the basic purpose of the telescope construction, the use of an equatorial had to be avoided.

Thus, the steering must be supported exclusively by a processing computer. This has the advantage for the steering of the telescope of making it possible to store correction functions, which can be applied to any desired position. However, the correction cannot be too extensive with respect to the storage capacity of the computer.

The reduction of the enumerated errors by structural means is thus still the most important step in the construction of the telescope.

XII. TECHNICAL TELESCOPE DATA

The final construction of the telescope was based on the following data:

Reflector diameter	100 m
Focal width	30 m
Gregory reflector	6.5 m
Focal width in the Gregory focus	360 m
Azimuth trajectory diameter	64 m
Height of the elevation axis above the beam circle	50 m
Elevation axis (support distance)	45 m
Elevation ring gear (radius)	28 m
Azimuth field of traverse	$\pm 360^{\circ}$
Elevation field of traverse	$+5^{\circ}$ to 94°

Accuracy of the mirror surface at 80° zenith distance, when the surface is adjusted in azimuth

Root-mean-square value for $D < 80$ m RMS 0.7 mm
Root-mean-square value for $80 < D \leq 100$ m RMS 1.2 mm

Measurement Velocities	Azimuth	Elevation	Steering and Position Accuracy
Slow measurement velocity	2°/min	1°/min	6"
Average measurement velocity	20°/min	10°/min	10"
Maximum adjustment velocity	40°/min	20°/min	-
Maximum acceleration	$0.2^{\circ}/sec^2$	$0.2^{\circ}/sec^2$	

XIII. STATUS OF THE WORK IN SEPTEMBER 1968

After the construction method for the telescope had been decided, the work on the final structure was begun. Except for the details, such as, for example, the focus cabin and the apex cabin, the work has been completed.

Studies of the natural frequencies of the system and further studies of the drive and steering were performed. A friction drive over 16 axes was provided for the azimuth axis. Eight of the sixteen axes will take over the drive in the measuring operation, while the remainder will serve for braking to avoid backlash in the gears. The elevation axis is operated over a 28-m-diameter toothed wheel gear by four motors. Here, too, care is taken to avoid any play in the drive.

Studies were made of the mirror covering. On the basis of the results, it was decided that the inner portion of the covering would be constructed of sandwich plates up to a diameter of 60 m, and the adjacent ring from 60 to 80 m diameter is to be fabricated from aluminum panels in a plate type of construction; perforated aluminum is provided for the region from 80 to 90 m diameter, and only the outer, 5-m-wide ring will be made of 8-mm-mesh wire netting.

The construction site was also decided on. An area in the northern valley of the Ahr near Effelsberg was selected. It was a decisive element in this choice that the possibilities of interference in the centimeter-wave range be minimal. Through measurements at 10 and 6 cm wavelength at the construction site and the neighboring mountains, it was found that interference -- if it existed at all -- was below the measuring accuracy. In the meantime, the foundations have been completed at the construction site; the erection of the steel structure will begin in October. According to the time plan, completion of the erection of the steel structure is scheduled for February 1970.

The computations for the dish construction were made by a group of engineers at MAN under the guidance of Mr. SCHNEIDER and Dr. SCHONBACH. The computations and final design of the dish model with axial mounting were carried out by a group of engineers at KRUPP under the guidance of Messrs. GELDMACHER, ALTMANN, and RUSEL. The Institute was supported by Mr. HOOGHOUDT (Eng.) as consulting engineer. Members of the Institute who participated are Dr. ROHLFS, Dr. GRAHL, Dr. FEIX, and Dipl. Phys. GIRNSTEIN. Heartfeld appreciation is expressed here to all participants.

TABLES

Table 1. Characteristic values of the best-fit paraboloid for the dish construction with 4-point support

D	Load	Elevation	σ	Y_s	Z_s	f	β
m		*degrees*	*mm*	*mm*	*mm*	*mm*	*seconds of arc*
	Weight of the steel structure	5	1.20	1.89	0.52	26099.5	68
		45	1.09	1.61	1.08	26096.7	50
		90	0.99	0.0	-5.75	26104.5	0
80							
	Weight and wind load (18m/sec	5	1.29	-2.21	0.55	26099.5	72

Table 2. Characteristic values of the best-fit paraboloid for the truss construction

D	Load	Elevation	σ	Y_s	Z_s	f	β
m		*degrees*	*mm*	*mm*	*mm*	*mm*	*seconds of arc*
80	Weight of the steel structure	0	0.23	+129	-0.96	26100	520
		45	0.305	+ 91.8	-	26109	370
		90	0.372	0.0	-	26112	0

Table 3. Characteristic values of the best-fit paraboloid for the dish construction with 8-point support

D	Load	Elevation	σ	Y_s	Z_s	f	β
m		*degrees*	*mm*	*mm*	*mm*	*mm*	*seconds of arc*
90	Weight of steel structure	5	1.9	0.10	+ 1.51	30600.9	171
		45	1.6	0.07	+12.3	30607.6	121
		90	1.1	0.0	-17.3	30610.7	0

Table 4. Characteristic values of the best-fit paraboloid for the dish construction with axial mounting

D	Load	Elevation	σ	Y_s	Z_s	f	β
m		*degrees*	*mm*	*mm*	*mm*	*mm*	*sec of arc*
90	Weight of steel structure	0	0.28	-337.6	+1.06	29361.7	1140
		45	0.46	-240.5	-1.62	29379.2	846
		90	0.50	0.0	-3.05	29386.7	0
100		90	0.83	0.0	-3.76	29383.3	0

Table 5. Deformation of the surface for three different wind velocities (in m/sec) (Δx and Δz in mm)

R	12 m/sec → 9 kg/m^2		18 m/sec → 20 kg/m^2		42 m/sec → 110 kg/m^2	
m	Δx	Δz	Δx	Δz	Δx	Δz
0.0	0.0	-0.63	0.0	-1.45	0.0	- 7.7
11.4	0.01	-0.63	0.02	-1.40	0.09	- 7.7
22.8	0.01	-0.55	0.03	-1.25	0.11	- 6.7
34.2	0.03	-0.55	0.07	-1.21	0.4	- 6.7
45.6	0.08	-0.66	0.18	-1.5	1.0	- 8.1
57.0	0.12	-0.76	0.27	-1.7	1.4	- 9.9
68.5	0.15	-0.85	0.34	-1.91	1.9	-10.4
80.0	0.15	-0.86	0.38	-1.94	1.9	-10.5

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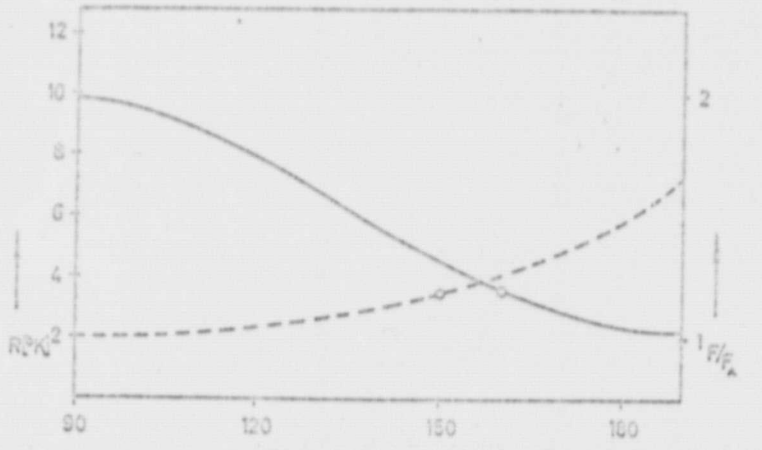
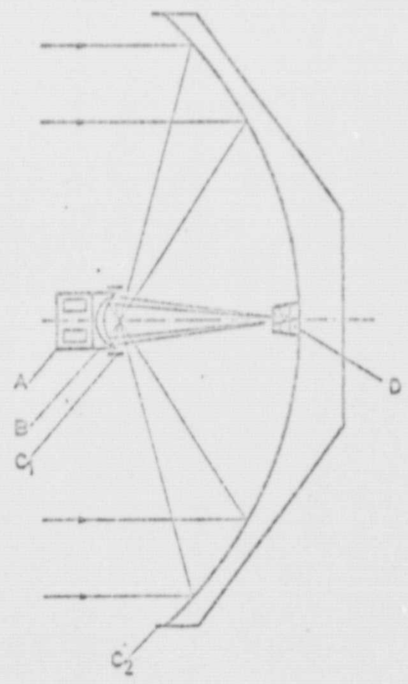
FIGURES

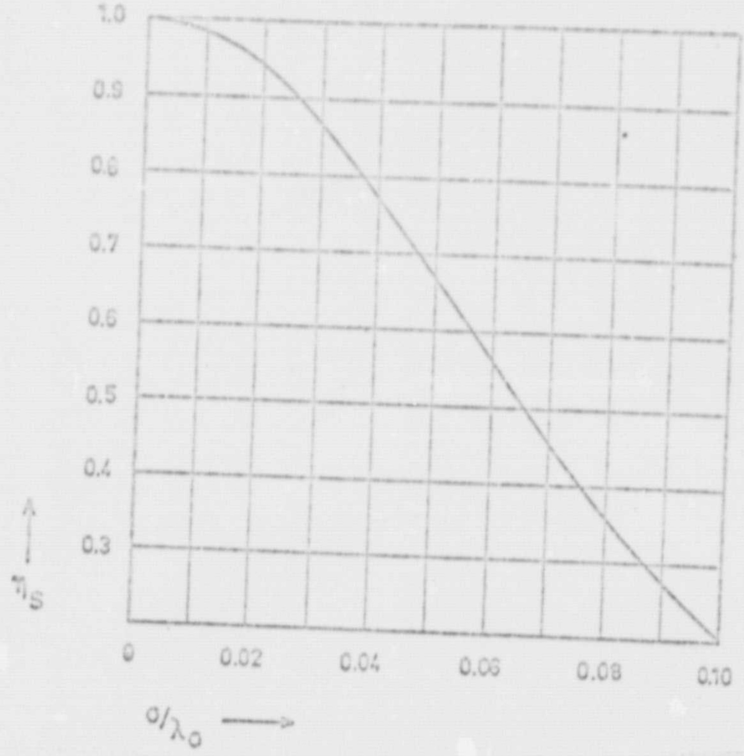


1. Noise temperature *R* of the antenna (solid curve) and relative surface magnitude *F* of the reflector (broken curve) as a function of the aperture angle.

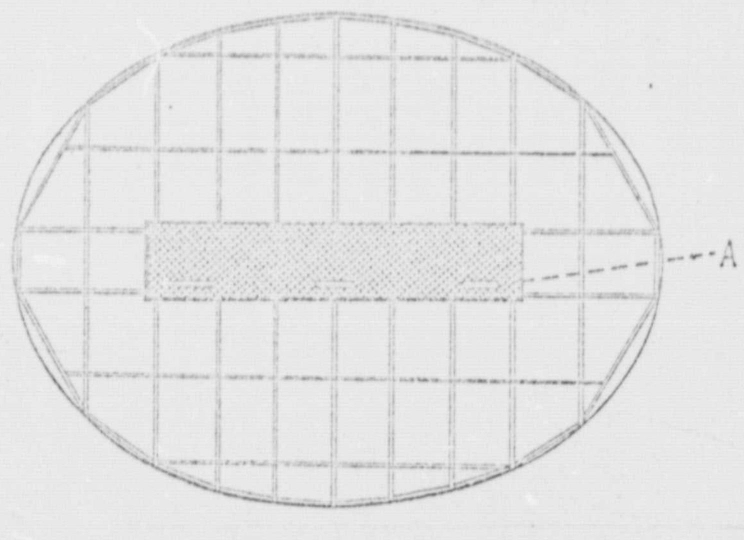


2. Radiation path of the parabolic antenna with Gregory auxiliary reflector.

   A Focus cabin,
   B Elliptical auxiliary reflector,
   C_1, C_2 Shielding
   D Apex cabin.

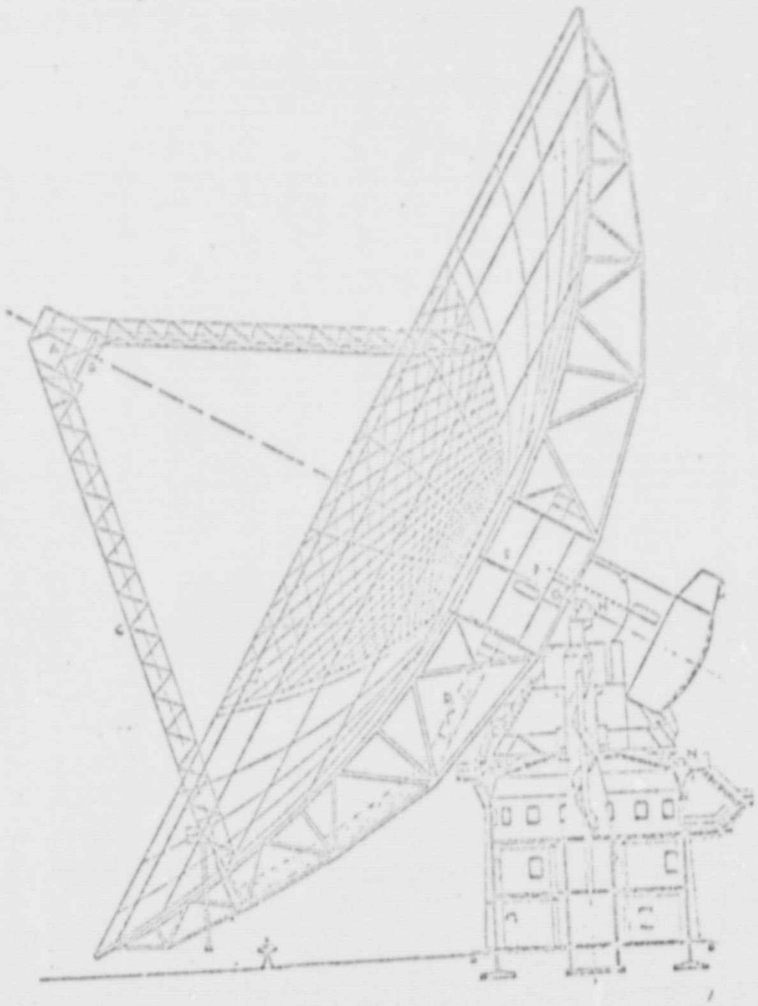


3. Effectiveness η_s of the reflector surface as a function of σ/λ_0 (σ = root-mean-square error of the surface; λ_0 = smallest usable wavelength).



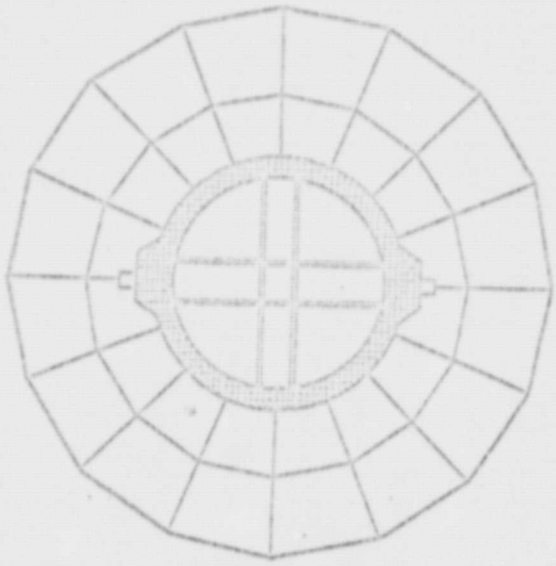
4. Schematic representation of the construction with rigid elevation axis.

A = elevation bearing.



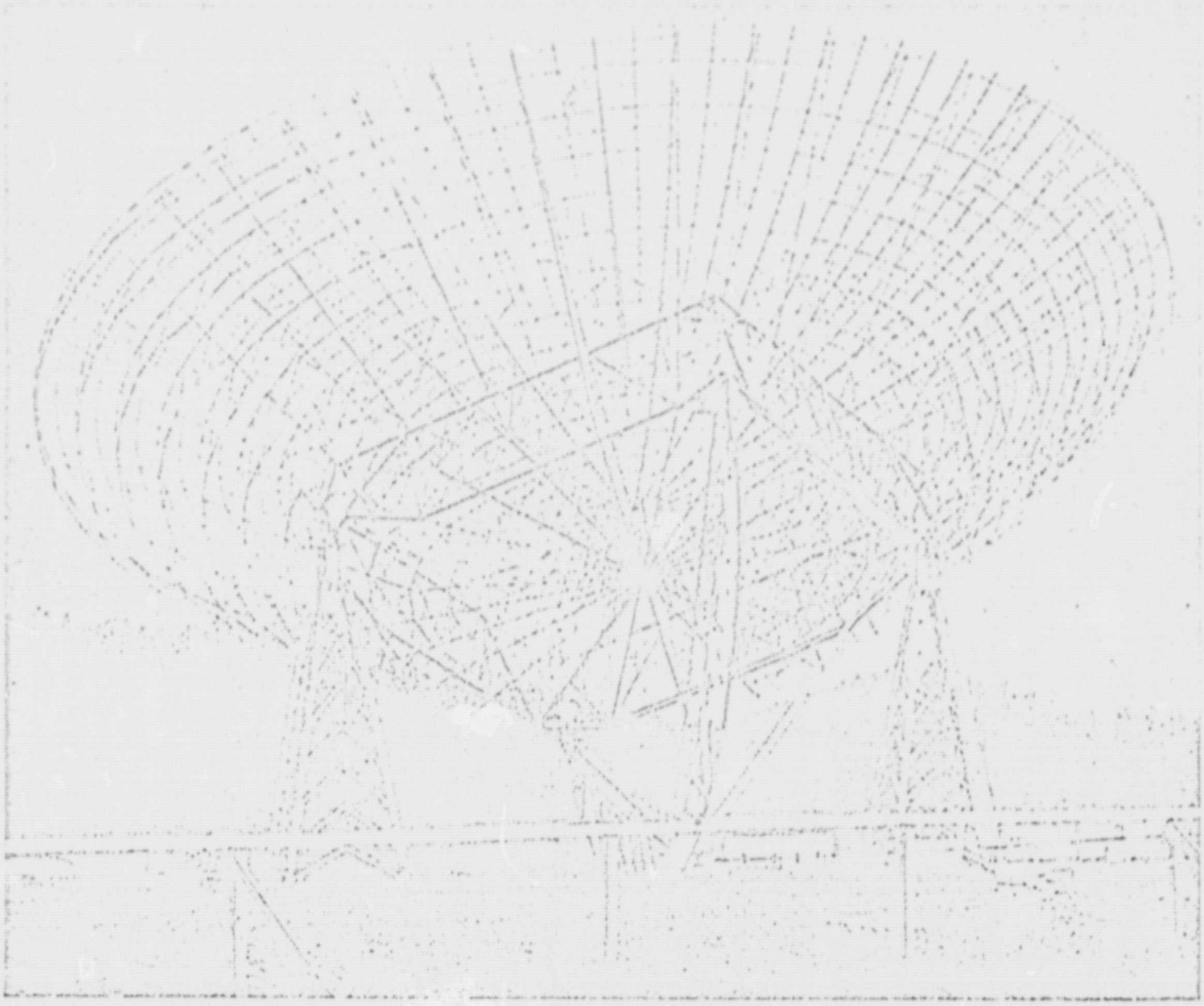
5. Schematic representation of the 64-m telescope in Parkes (Australia). *A* focus cabin, *B* plane of the feed antennas, *C* focus-cabin supports, *E*,*F* receiver spaces, *G*,*H* optical steering,

6. Deformation diagram of the 64-m telescope at 60° inclination. The position of the focus-cabin supports is indicated by the three radial lines.



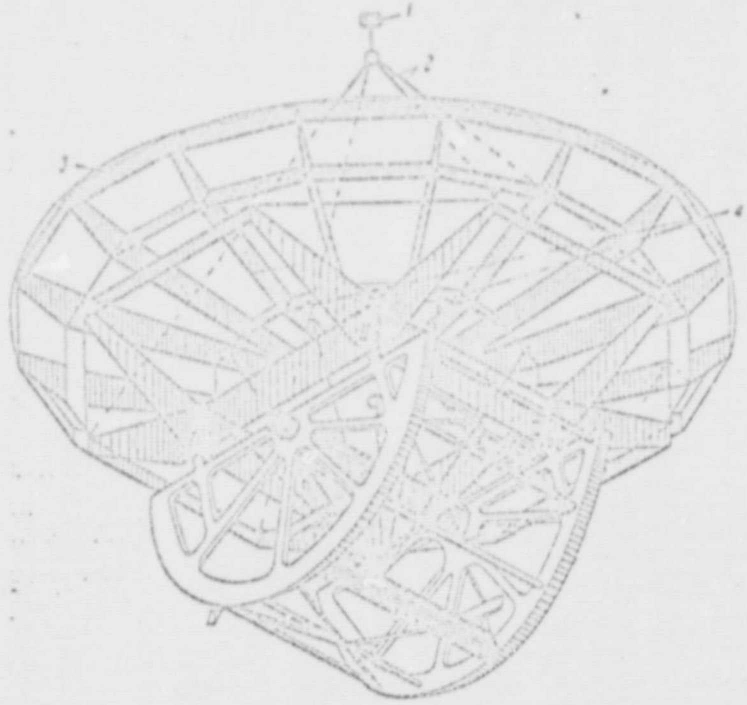
7. Ring construction, schematic.

8. 36-m telescope in Berlin-Adlershof (rear view).

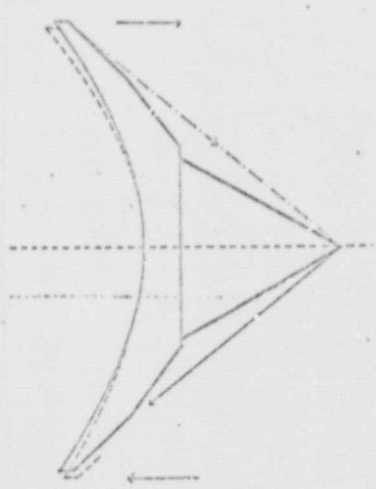


9. 90-m telescope in Green Bank (USA).

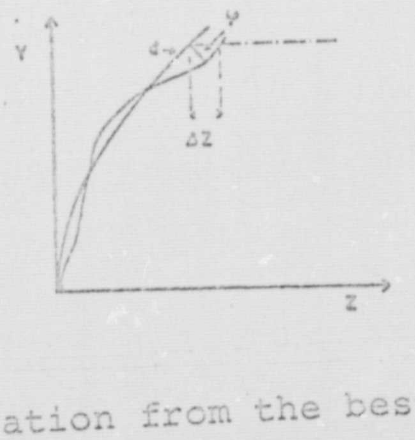
10. Deformation diagram of the 90-m telescope in Green Bank at 38°36 elevation. (Numbers in millimeters.) After J.W. FINDLEY (Ref. 11).



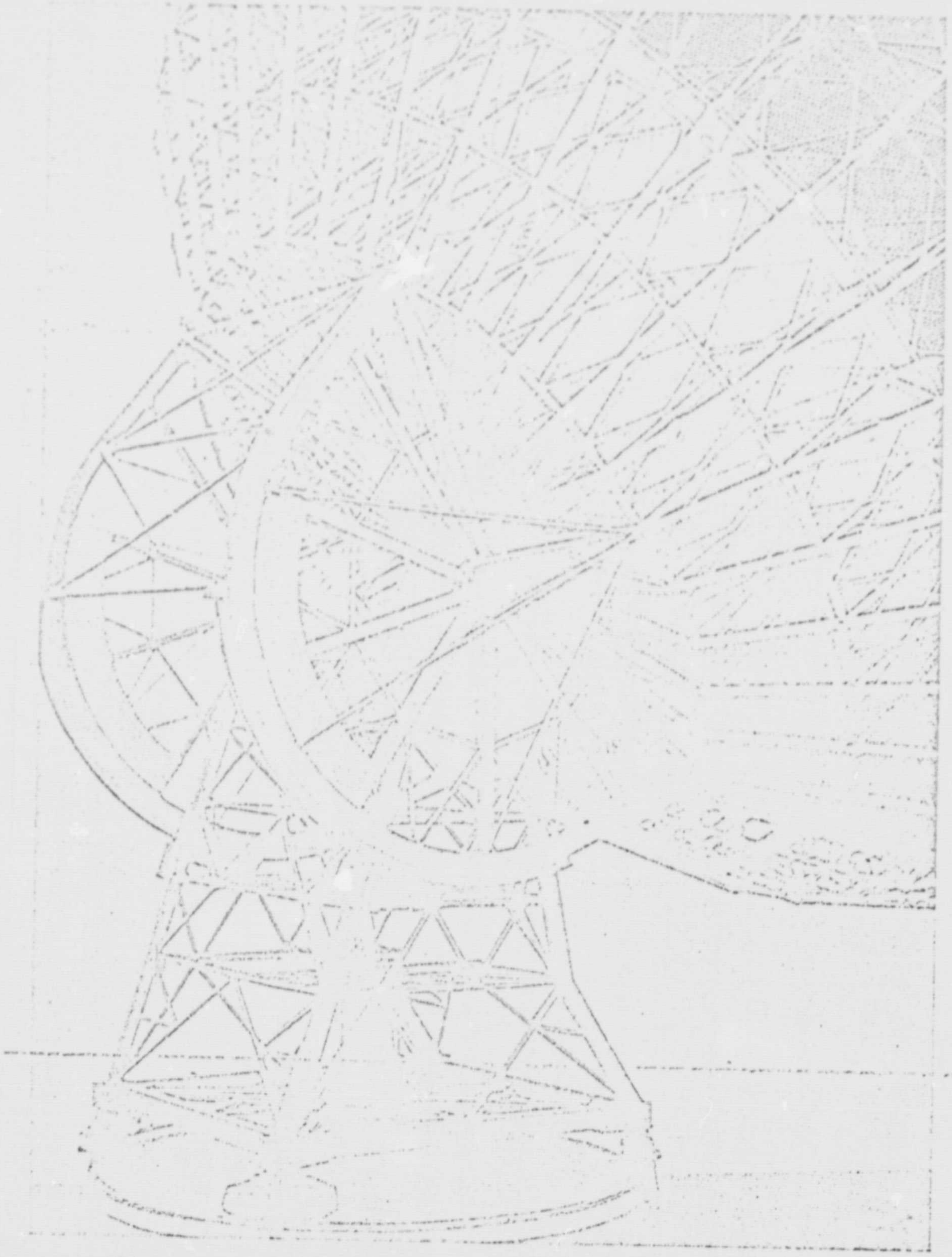
11. Construction proposal for a 64-m telescope with 19 supporting points of the dish (after KALATSCHEFF, Ref. 12).



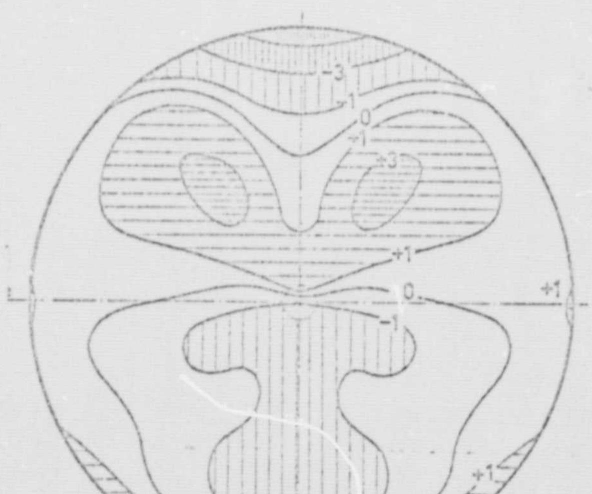
12. Typical deformation of a reflector dish during inclination about the elevation axis. (Dotted line -- the deformed contour.) The arrows show the direction of the forces to be introduced.



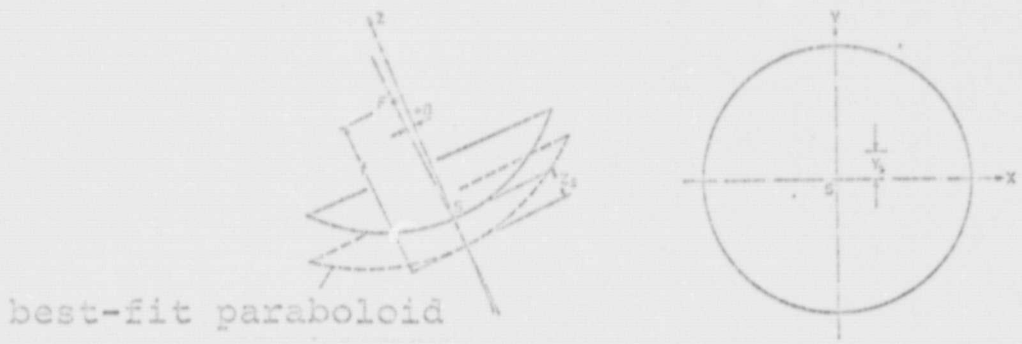
13. The deviation from the best-fit parabola.



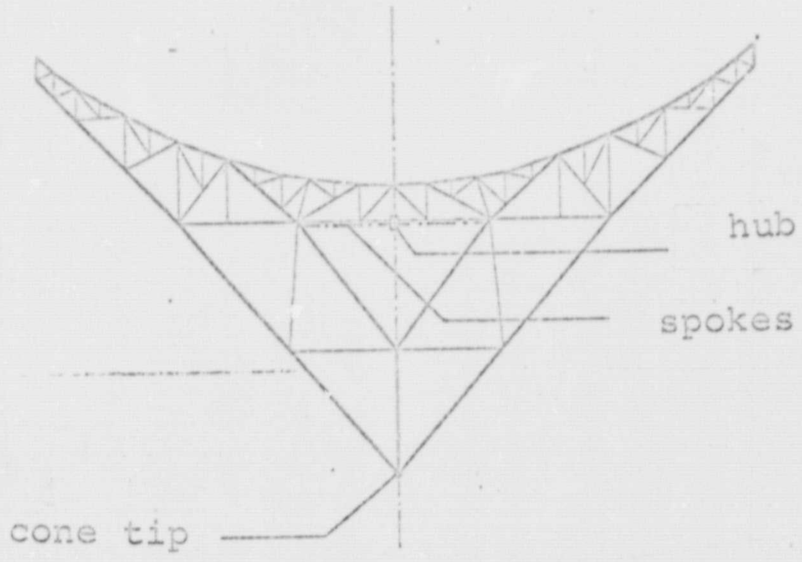
14. Dish construction with 4-point support. (MAN model)



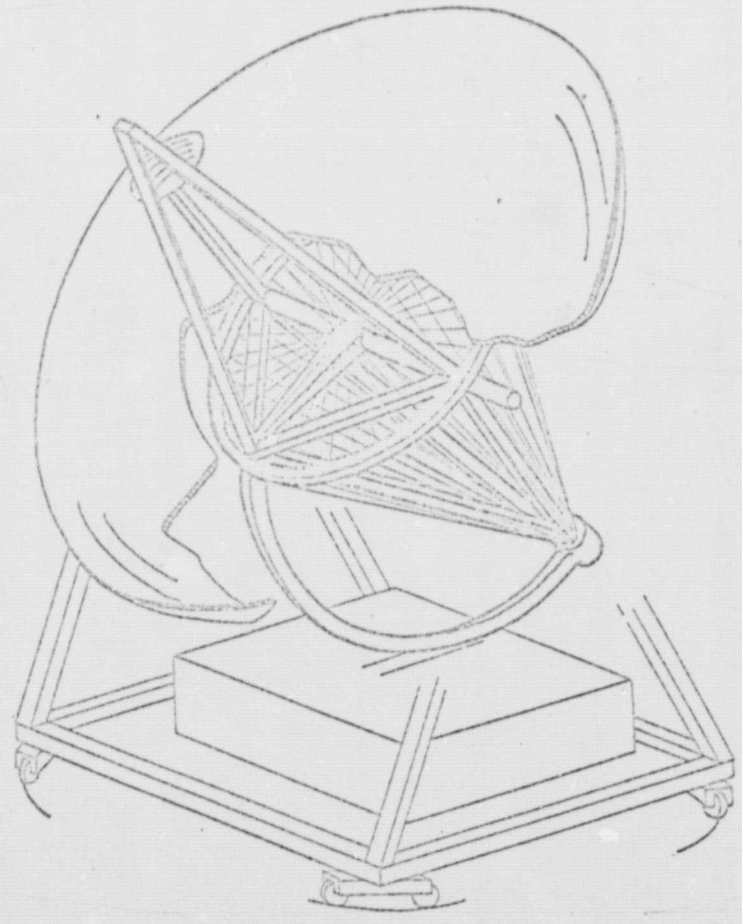
15. Deformation diagram of the dish construction at 90° inclination of the telescope.



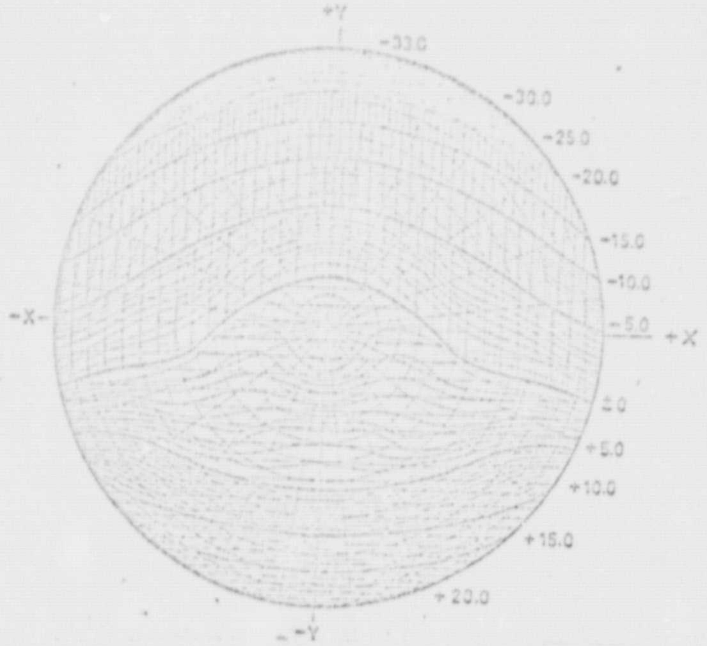
16. Displacement of the best-fit paraboloid compared to the originally adjusted paraboloid surface.



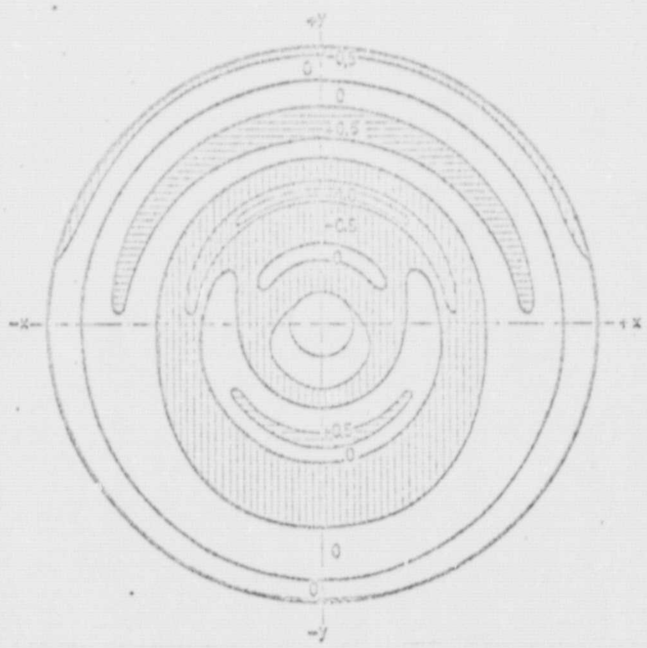
17. Truss construction (KRUPP).



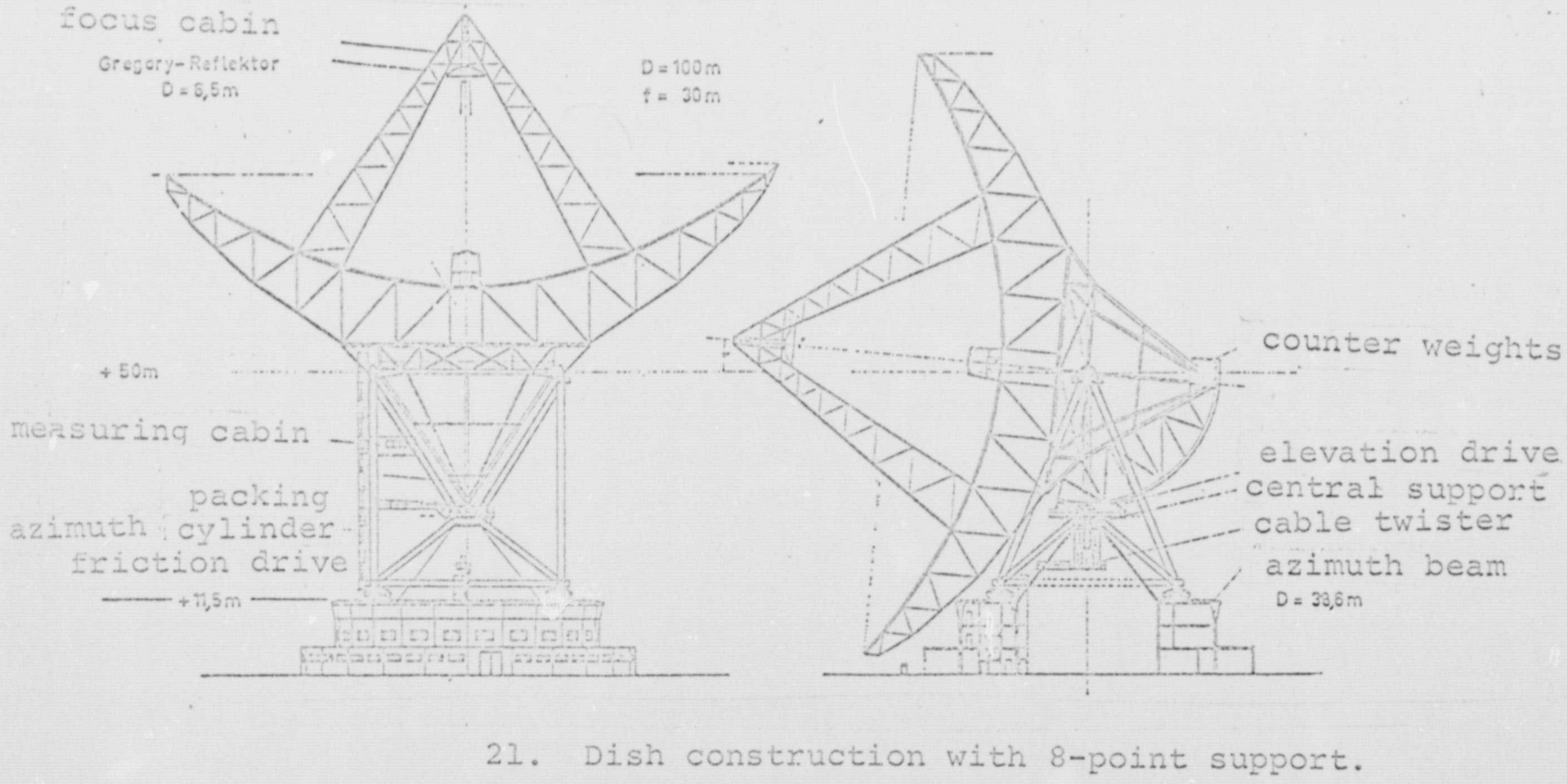
18. Support system of the truss construction, schematic.



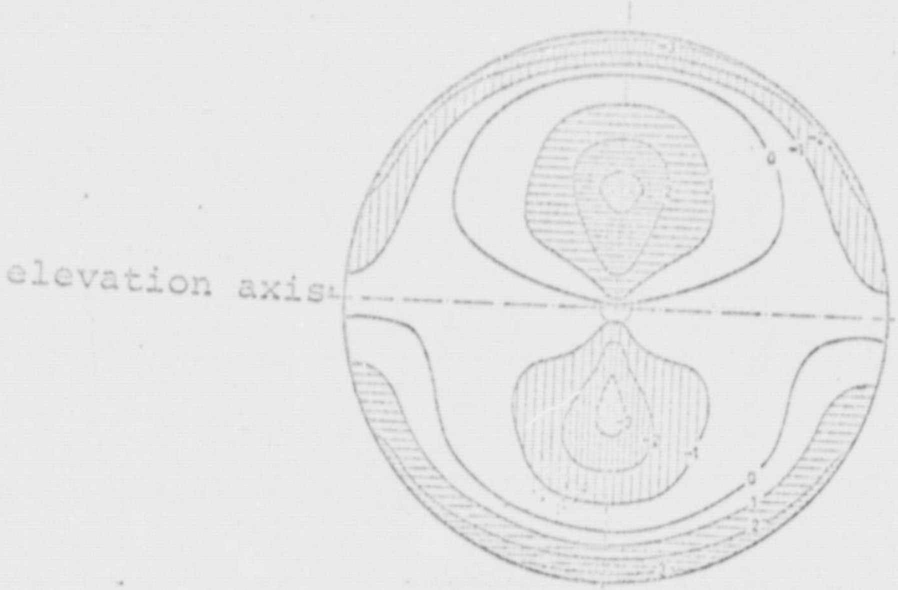
19. The absolute deformation of the reflector of the truss construction at 90° inclination.



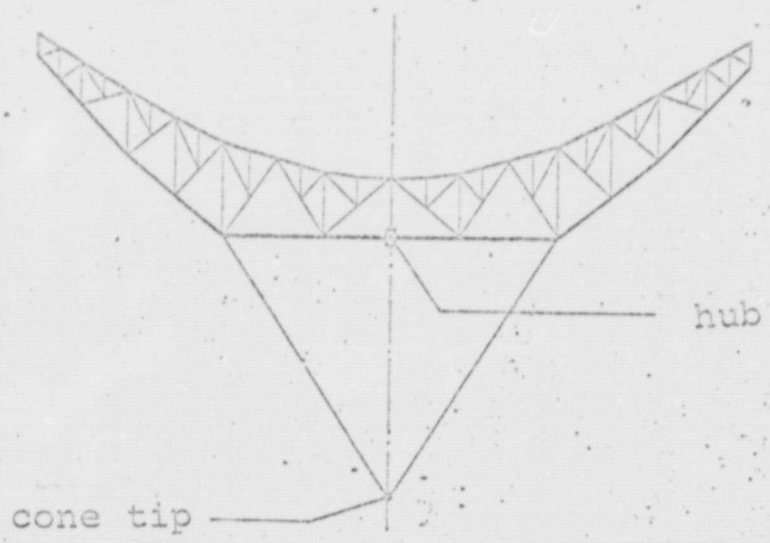
20. Deformation diagram of the truss construction at 90° inclination of the telescope.



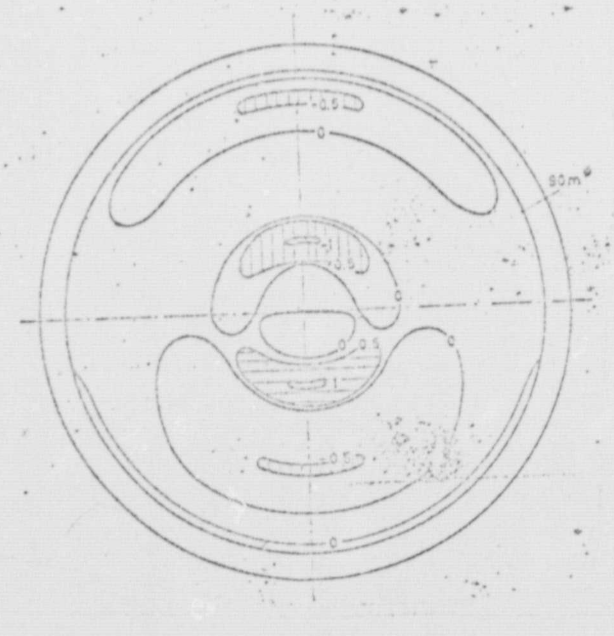
21. Dish construction with 8-point support.



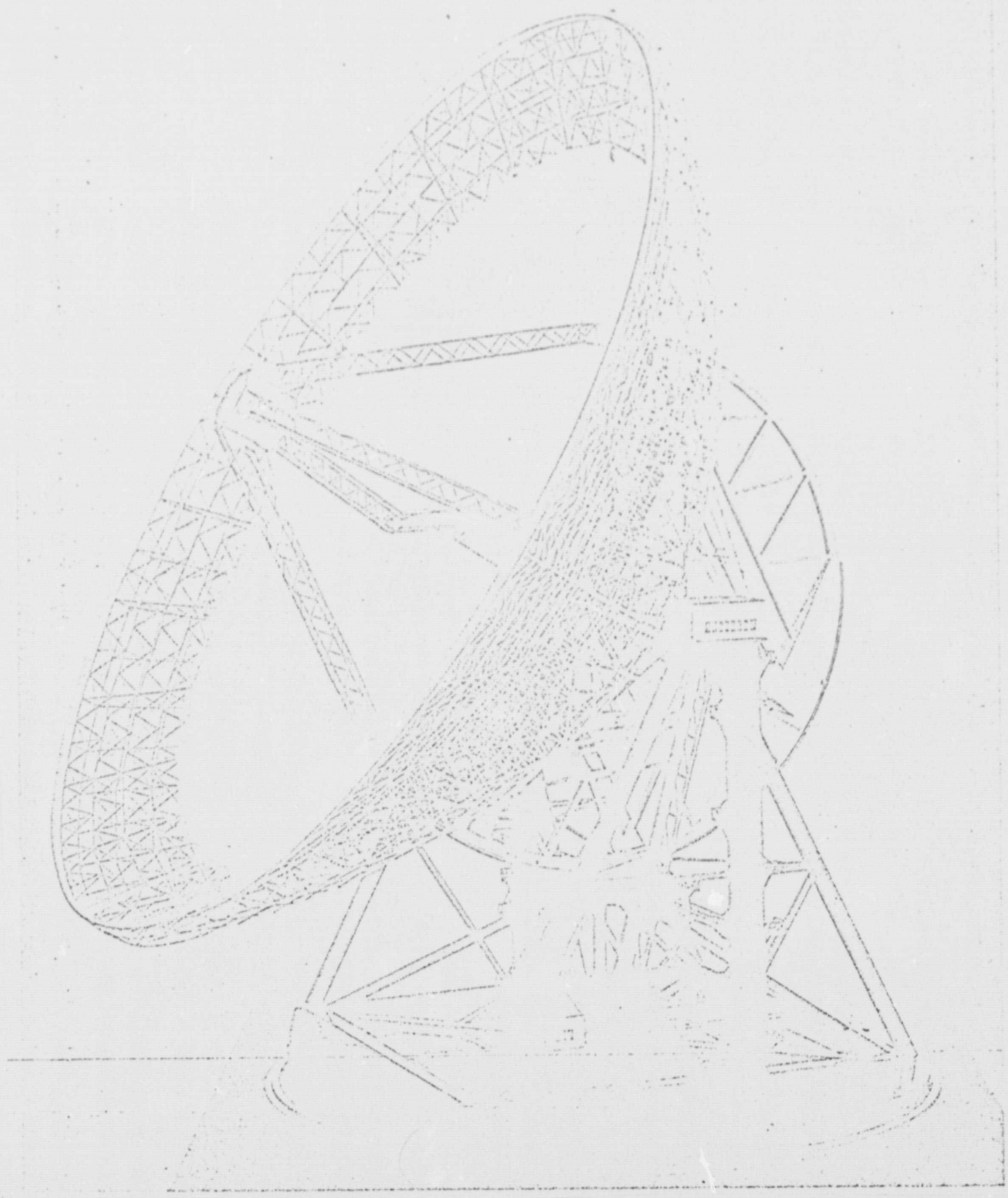
22. Deformation diagram of the dish construction with 8-point support at 90° inclination of the telescope.



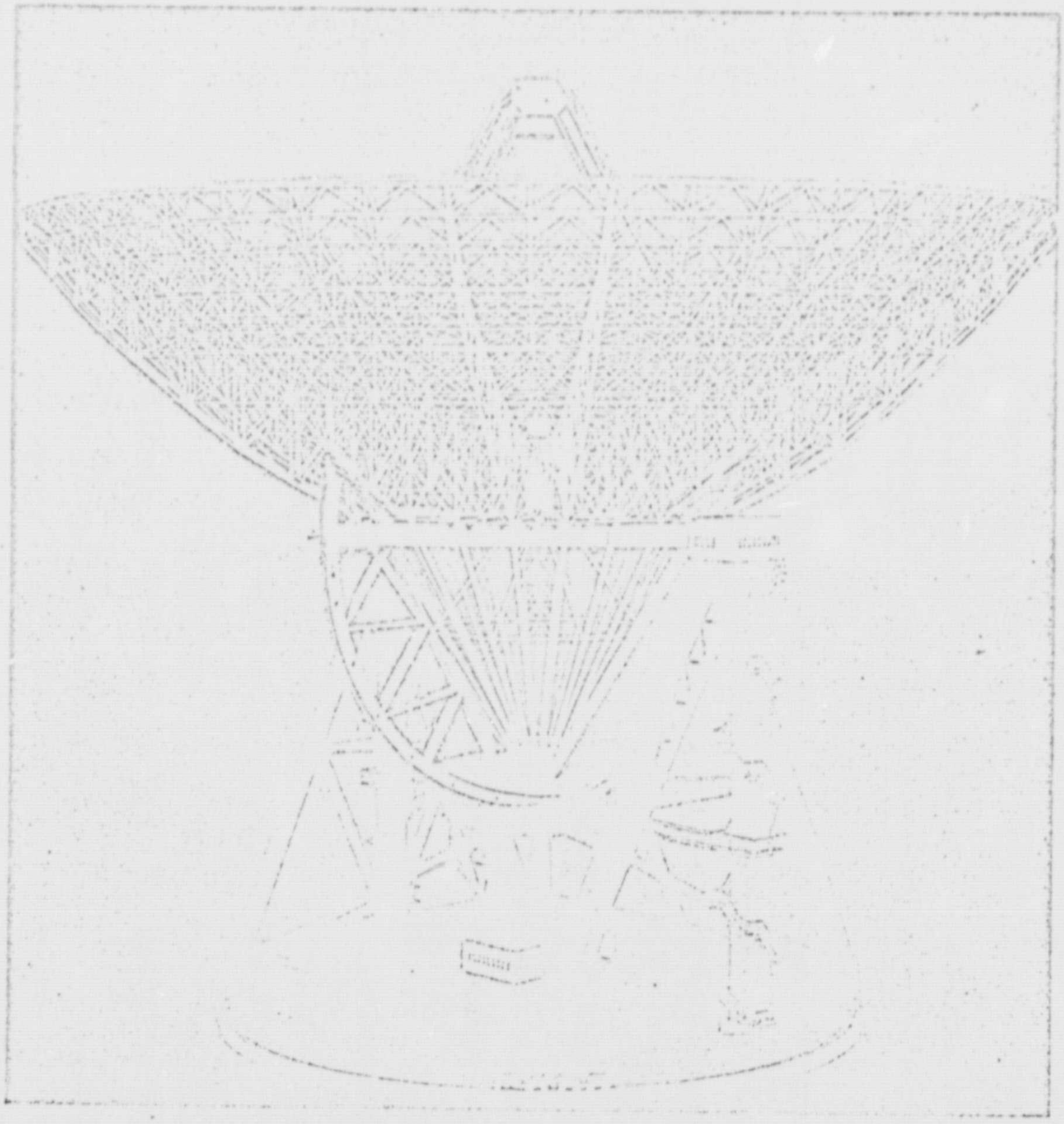
23. Dish construction with axial mounting (schematic).



24. Deformation diagram of the dish construction with axial mounting at 90° inclination of the telescope.

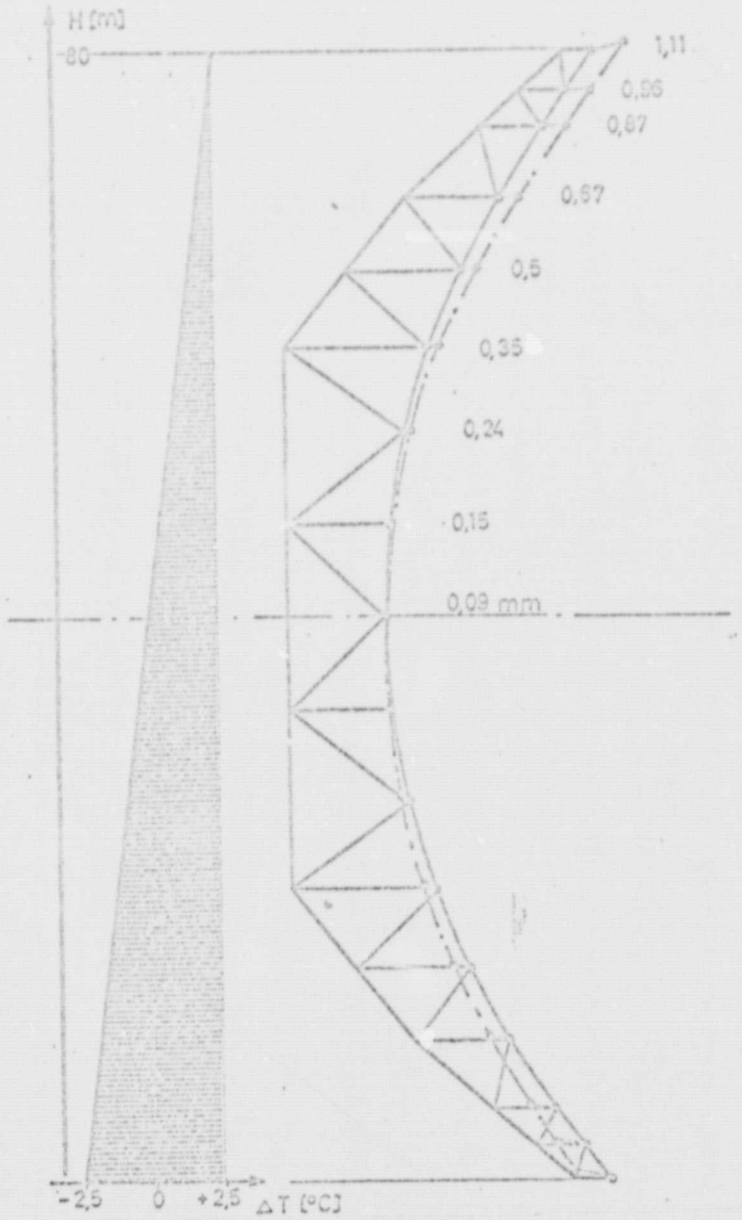


25. Telescope model.



26. Telescope in azimuth setting.

27. Partial view of the telescope, with particularly good view of the support system.



28. Deformation of the reflector at a temperature gradient of 5° per 100 m of height.