NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Technical Memorandum 33-685

Lightweight 3.66-Meter-Diameter Conical Mesh Antenna Reflector

Donald M. Moore

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During the design and development of this antenna, the technology for fabricating large conical membranes of knitted mesh was developed. As part of this technology a FORTRAN computer program, COMESH, was developed which permits the user to predict the surface accuracy of a stretched conical membrane.

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PREFACE

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ABSTRACT

This report describes a 3.66-m (12-ft) diameter nonfurlable conical mesh antenna incorporating the line source feed principle recently developed at JPL. The weight of the mesh reflector and its support structure is 162 N (36.5 lb). An area weighted RMS surface deviation of 0.28 mm (0.011 in.) has been obtained. RF performance measurements showed a gain of 48.3 dB at 8.448 GHz, corresponding to an efficiency of 66%.

During the design and development of this antenna, the technology for fabricating large conical membranes of knitted mesh was developed. As part of this technology a FORTRAN computer program, COMESH, was developed which permits the user to predict the surface accuracy of a stretched conical membrane.

I. INTRODUCTION

During the past several years the JPL Applied Mechanics Division has been developing large furlable spacecraft antennas with conical main reflectors. Two novel concepts, the conical-Gregorian and conical-quadreflex, have been developed, constructed, and RF-tested (Refs. 1, 2).

The conical main reflectors of these antennas were constructed of aluminized Mylar film, providing a lightweight surface with good RF reflectivity. However, reservations exist regarding the use of this material for flight spacecraft antenna reflectors. Thermal distortion and long-term stability of mechanical properties of the film under ultraviolet radiation remain potential problem areas. Also, to produce conical reflectors of good accuracy it was found necessary to construct the conical surface from a number of separate gores to avoid unacceptable wrinkling and puckering. So far, the procedure for constructing conical antenna reflectors using film materials has been highly empirical.

To avoid the above difficulties, a knitted mesh material has been substituted for the Mylar film. Knitted mesh materials have many desirable characteristics. They can be produced from many different yarn materials, providing considerable selection latitude. The low in-plane stiffness of knitted materials permits the mesh to be prestretched, thus minimizing wrinkles and reducing sensitivity to thermal distortion. It was also felt that a continuous conical surface could be fabricated from a knitted mesh, thus making the shape of the surface amenable to a relatively simple analysis using membrane theory. To demonstrate the feasibility of producing a large flight-like conical antenna reflector employing a knitted mesh material, a 3.66-m (12-ft) nonfurlable conical mesh antenna was designed, constructed, and RF-tested.

The 3.66-m (12-ft) diameter was considered large enough to demonstrate feasibility and also of appropriate size for present flight projects (MJS'77) employing nonfurlable antennas.

The JPL Telecommunications Division recently developed a novel antenna configuration which employs a conical main reflector and a line source feed along the axis of the cone. This concept was RF-tested on a

1.83-m (6-ft) boiler-plate conical reflector. RF performance measurements at 8.448 GHz show a gain of 42.6 dB, corresponding to an efficiency of 70% (Ref. 3), which represents a significant improvement over previous concepts. Therefore, development work on conical antennas for the immediate future includes the line source feed principle.

These considerations established the basic configuration of the 3.66-m antenna discussed in this report. Figure 1 shows the basic geometric configuration of the line source feed conical antenna. Figures 2 and 3 show two views of the 3.66-m (12-ft) conical mesh antenna with the line source feed installed.

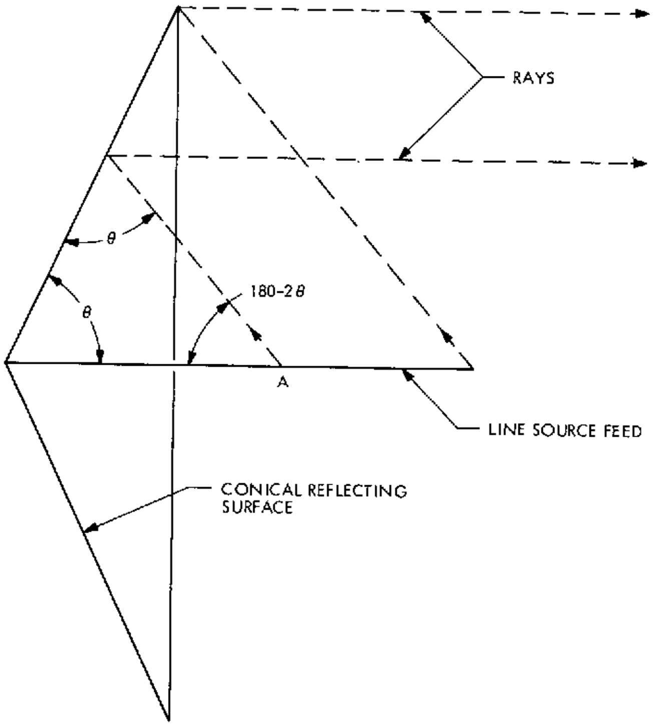


Fig. 1. Line source feed conical antenna

This report emphasizes the mechanical and structural aspects of the design and manufacture of the conical mesh reflector. The results of the RF test are reported but not discussed.

Fig. 2. Front view of 3.66-m (12-ft) conical mesh antenna with line source feed installed

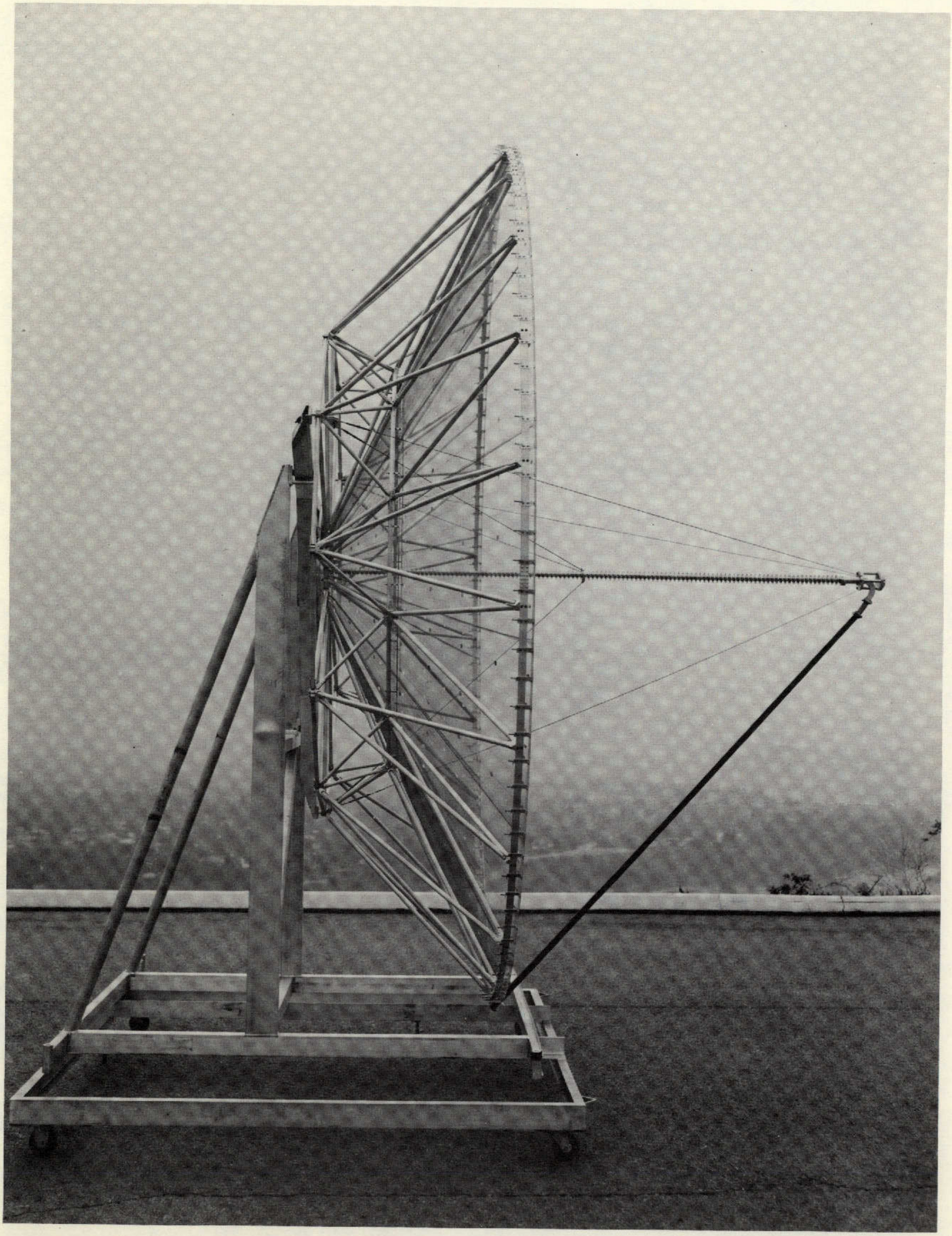


Fig. 3. Side view of 3.66-m (12-ft) conical mesh antenna with line source feed installed

II. CONICAL MESH REFLECTOR

The desired objective was to produce an accurate conical RF reflective surface by stretching a knitted mesh material between two circular rings which define the desired conical surface.

A. LAMPSHADE EFFECT

A true conical surface can be produced by stretching a weightless membrane between two circular rings which lie on the surface of the cone, provided there is no circumferential tension in the membrane. To eliminate wrinkling and puckering and provide for thermal expansion, finite circumferential tension is required. This circumferential tension causes the membrane to bow inward toward the cone axis between the rigid rings and produces the "lampshade" shape shown in Fig. 4. The degree of lampshading can be considerably reduced by installing tensioned cables between the circular rings which bound the desired cone. These spokes are placed on the inside surface, so they need not be attached to the membrane.

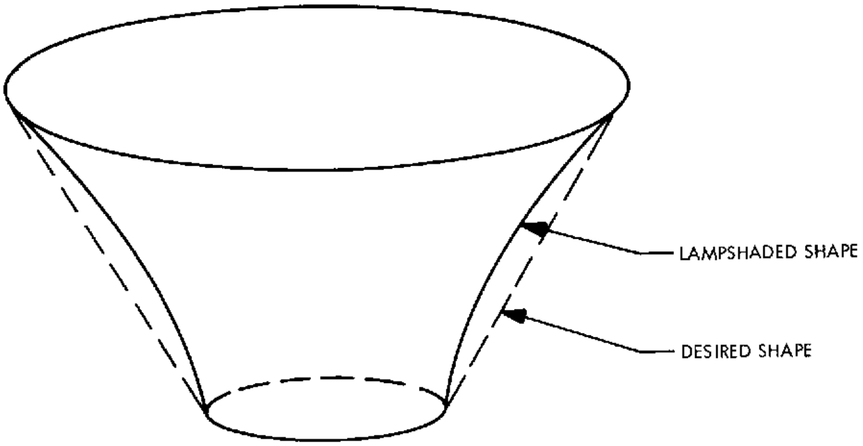
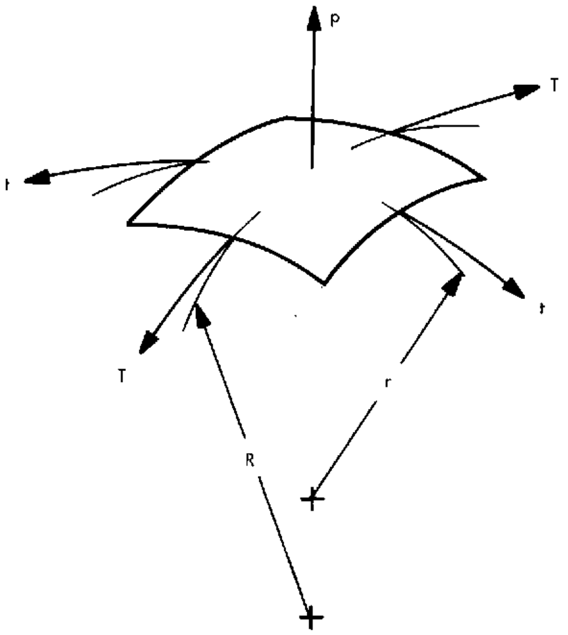


Fig. 4. Stretched conical membrane, showing "lampshade effect"

B. CONICAL MEMBRANE THEORY

The development of the equations describing the shape of a stretched membrane is based on the condition for static equilibrium of an element of a thin membrane (Fig. 5).



$$\frac{T}{R} + \frac{t}{r} = p$$

Fig. 5. Free-body of membrane element

The parameters R and r are local radii of curvature at a point on the membrane taken normal to the membrane in mutually perpendicular planes. They are considered positive when the surface is concave toward the inside of the membrane. A stretched membrane represents a special case of a thin shell where no compressive loads are carried by the membrane. Therefore, T and t reduce to unit tension forces in the membrane acting tangential to R and r, and p is the weight per unit area acting normal to the membrane.

Consider the axisymmetric shape produced by stretching a membrane between two circular disks which are perpendicular and concentric to a common axis as shown in Fig. 6.

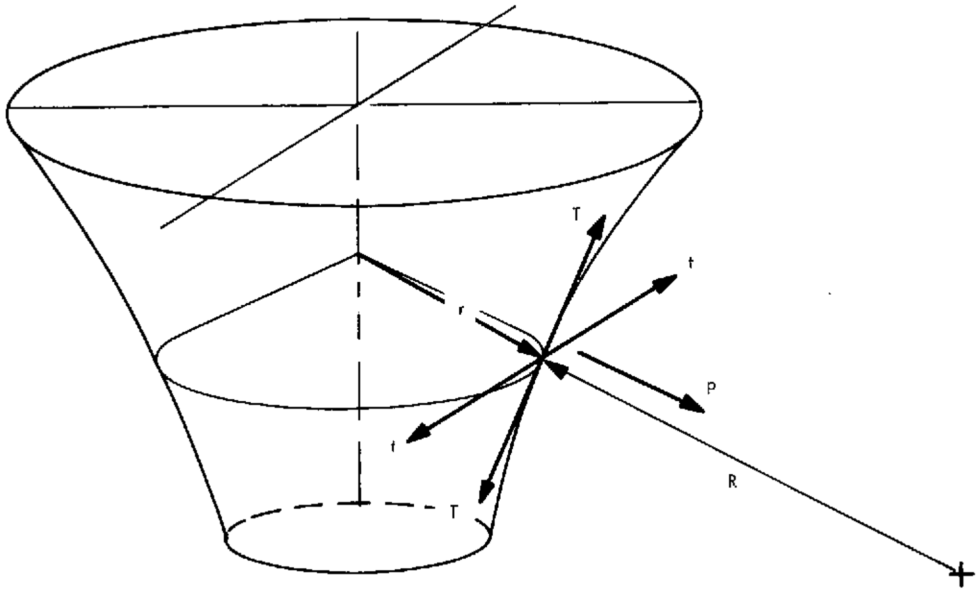


Fig. 6. Stretched axisymmetric membrane

Equation (1) applies to the stretched membrane and may be rewritten as follows:

$$R = \frac{T}{p - \frac{t}{r}} \tag{2}$$

where R is the radius of curvature of the membrane measured in a plane through the axis of symmetry, r is the radius of curvature measured from the axis of symmetry perpendicular to the membrane surface, and T is the unit tension in the membrane measured perpendicular to R in a plane through the axis of symmetry and is called the radial tension. The circumferential tension t is measured perpendicular to r and T.

The deviation of the stretched membrane from the true cone is small, and r can be taken as the normal radius of curvature of the true cone. For a pretensioned mesh, the tension field (T and t) is known. The force per unit area normal to the membrane is a function of the weight per unit area of the membrane acting normal to the membrane. Therefore, all terms on the right side of Eq. (2) are known, and the radius of curvature R may be evaluated at any given point on the membrane surface.

It will be noted that this procedure is essentially the reverse of the one used to calculate the stresses in a thin-walled pressure vessel, where the stresses are computed as a function of loading and radii of curvature. In the case of a pretensioned membrane, we calculate the shape as a function of loading p and the unit tensions T and t in the membrane. Also note that in the stress analysis of shells it is assumed that the geometry is not significantly changed by the loading, whereas in the determination of the shape of a stretched membrane, we assume that the known tension field is not significantly altered by changes in shape of the pretensioned membrane.

Certain general conclusions regarding the shape of a stretched "conical" mesh may be formulated at this time. Examining the case where the membrane is weightless, $p = 0$, we may rewrite Eq. (2) as follows:

$$R = -\frac{T}{t} r \tag{3}$$

In order that the stretched membrane should closely approximate a true cone, the radius of curvature R should be very large. Equation (3) shows that R becomes large under the following conditions:

(1) The normal radius of curvature about the axis of symmetry r is large. However, r is predetermined for a given cone geometry.

(2) The circumferential tension t is very low. As will be discussed later, there are certain practical constraints on how low the circumferential tension can be made.

(3) The radial tension T is very high. The constraints on making T very high are imposed by structural weight considerations for the support structure reacting this load.

The application of the analysis to the shape of a stretched "conical" membrane is further developed in the following section.

C. AXISYMMETRIC MEMBRANE SHAPE ANALYSIS

It is desired to calculate the shape of a mesh stretched between two circular disks which are the bases of the desired right circular cone. Consider the cross section through the axis of the cone shown in Fig. 7.

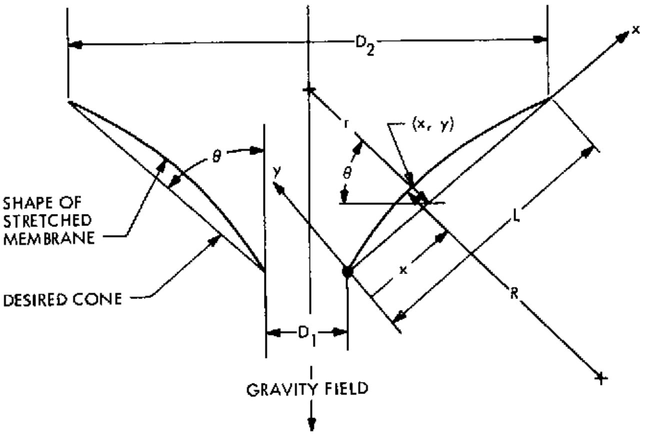


Fig. 7. Section through axis of stretched "axisymmetric" membrane

The stretched membrane is axisymmetric, so that the shape of the membrane may be described by its deviation from the straight line cone element. The shape may be described by the x-y coordinate system shown, where y represents the deviation from the cone element at some point x along the cone element.

The following additional symbols are defined: D_1 and D_2 are the small and large base diameters of the cone respectively, L is the length of the truncated cone element, θ is the half angle of the cone, r is the radius of curvature of the desired cone measured from the axis of the cone, perpendicular to the surface, and R is the radius of curvature of the membrane measured in a plane through the axis of the cone.

The determination of the shape of the membrane involves finding the radius of curvature R of the membrane at various points x along an element of the "cone." The radius of curvature R is found from Eq. (2). The radial tension T is the radial load per unit length of membrane circumference. The radial membrane tension includes the spoke tension and the membrane tension per unit membrane circumference at point x. We have

$$T = \frac{n_s T_s}{\pi(D_1 + 2 x \sin \theta)} + T_m \tag{4}$$

where T_m is the unit radial tension in the membrane itself, T_s is the individual spoke tension, and n_s is the number of equally spaced radial spokes.

The effective load per unit area p is equal to the component of membrane weight per unit area acting normal to the surface of the cone. That is,

$$p = wG \sin \theta \tag{5}$$

where w is the membrane weight per unit area, and G is the fraction of earth gravity acting parallel to the axis of the cone. On earth, with the axis of the cone vertical and the apex of the cone down, G = +1. If the apex of the cone is up, G = -1.

The normal radius of curvature of the conical surface measured from the cone axis is

$$r = \frac{\frac{D_1}{2} + x \sin \theta}{\cos \theta} \tag{6}$$

Using Eqs. (2), (4), (5), and (6), the radius of curvature of the membrane R can be calculated for any point x along the length of the cone element.

This information permits us to calculate the shape of the membrane, that is, the deviation y = f(x) of the membrane from the conical element. Consider a short segment of the membrane, having an average radius of curvature $\overline{R}$ between points I and J as shown in Fig. 8.

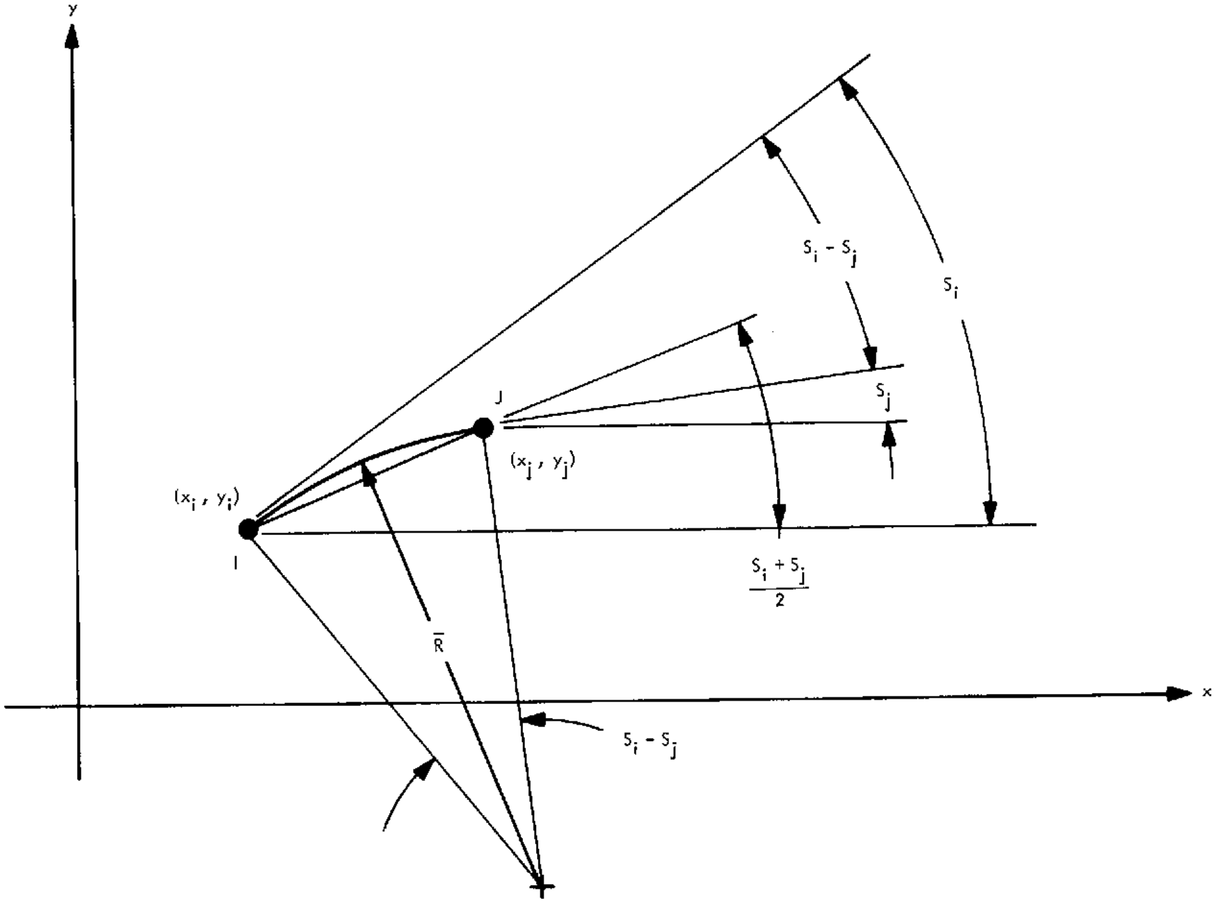


Fig. 8. Short arc $\widehat{IJ}$ of stretched membrane

From the geometry,

$$y_j - y_i = (x_j - x_i) \tan \frac{s_i + s_j}{2} \tag{7}$$

For small angles,

$$y_j - y_i = (x_j - x_i) \frac{s_i + s_j}{2} \tag{8}$$

Also the arc $\widehat{IJ}$ is

$$\widehat{IJ} = \bar{R} (s_i - s_j)$$

and assuming arc IJ is very nearly equal to chord IJ

$$s_i - s_j = \frac{\sqrt{(x_j - x_i)^2 + (y_j - y_i)2}}{\bar{R}} \tag{9}$$

where the average radius of curvature between I and J is

$$\bar{R} = \frac{R_i + R_j}{2} \tag{10}$$

For convenience and simplicity assume that the length L of the cone element is divided into n equal parts L/n long, so that

$$x_j - x_i = \frac{L}{n}$$

Eliminating $y_j - y_i$ from Eqs. (8) and (9) we obtain an expression for the slope s_j, in terms of s_i, $\bar{R}$, L/n:

$$s_j = \frac{-B \pm \sqrt{B^2 - 4AC}}{2A} \tag{11}$$

where

$$A = 4\bar{R}^2 - \left(\frac{L}{n}\right)^2$$

$$B = -8\bar{R}^2 - 2\left(\frac{L}{n}\right)^2 s_i$$

$$C = 4\bar{R}^2 s_i{}^2 - 4\left(\frac{L}{n}\right)^2 - \left(\frac{L}{n}\right)^2 s_i{}^2$$

The sign in front of the radical in Eq. (11) is chosen according to the following rule: If the radius of curvature $\bar{R}$ is negative, then the minus sign is used; if the radius of curvature $\overline{R}$ is positive, then the plus sign is used.

Finally, the surface deviation at J, y_j can be expressed in terms of y_i, L/n, s_i, and s_j.

$$y_j = y_i + \left(\frac{L}{n}\right)\left(\frac{s_i + s_j}{2}\right) \tag{12}$$

Equations (11) and (12) permit a numerical solution for the shape of the stretched membrane as follows:

(1) The length L of the cone element is divided into n segments L/n long.

(2) Starting at the origin, x_1, y_1, and s_1 are set equal to zero.

(3) $x_2 = x_1 + L/n$.

(4) The radii of curvature R_1 and R_2 at x_1 and x_2 are calculated using Eqs. (2), (4), (5), and (6).

(5) The average radius of curvature $\overline{R}$ between x_1 and x_2 is calculated from Eq. (10).

(6) s_2 is calculated from Eq. (11).

(7) y_2 is calculated from Eq. (13).

(8) The above procedure is repeated starting with Eq. (4), where $x_3 = x_2 + L/n$, and is repeated n times until $x_{n+1} = L$.

This procedure yields the deviations from the true cone y for various points x along the length of the cone element. However, we started at the origin with $x_1 = 0$, $y_1 = 0$, and $s_1 = 0$. This is true for x_1 and y_1, since the mesh is attached at this point. On the other hand, the slope of the membrane at the origin s_1 is not zero. The result is that the calculated shape of the mesh will look like the dotted curve in Fig. 9.

Because the mesh is attached to the frame at $x_{n+1} = L$, y_{n+1} must be zero. Therefore, the value of y_{n+1} at x_{n+1} is a measure of the error

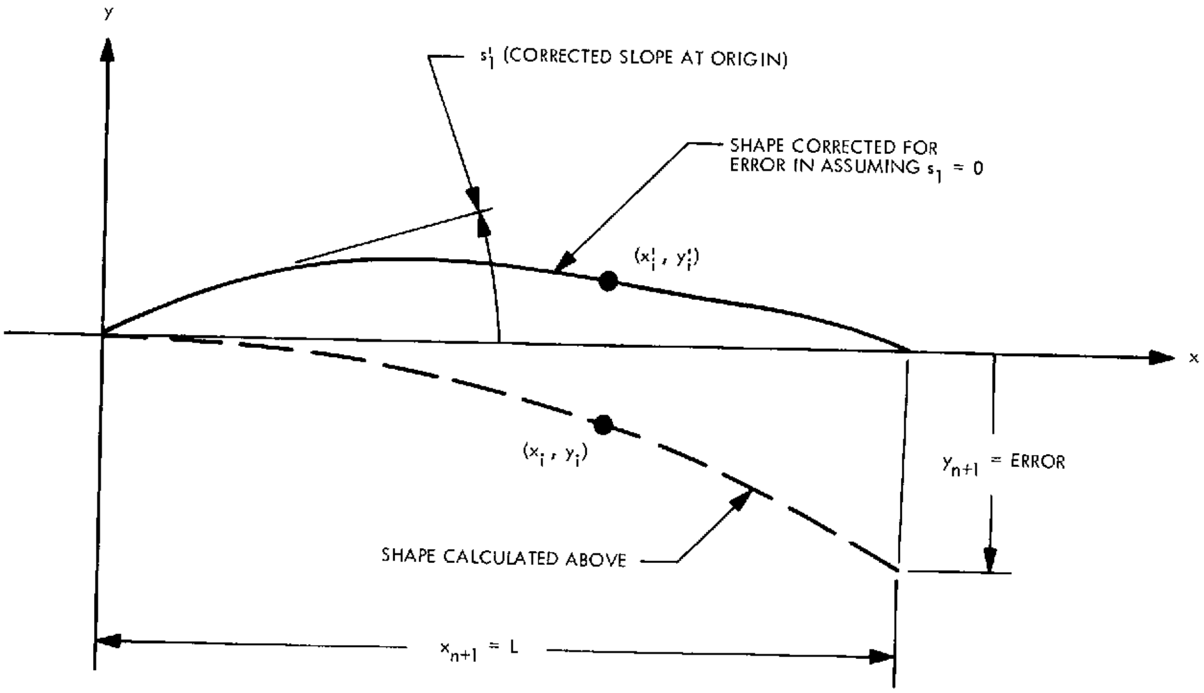


Fig. 9. Error in shape of membrane resulting from assuming $s_1 = 0$

resulting from assuming $s_1 = 0$, and also provides a means to correct the previously calculated shape as follows:

$$s_i' = s_i - \frac{y_{n+1}}{L} \tag{13}$$

$$y_i' = y_i - x_i \frac{y_{n+1}}{L} \tag{14}$$

The corrected shape for the stretched membrane is given by x_i, y_i', s_i', and R_i.

The predicted rms deviation of the stretched membrane from the desired conical surface can then be computed. We already have the deviation y_i' of the membrane from the desired cone for various points x_i along the length of the cone element. The average of these deviations from the desired cone $\overline{y}$ represents the best fit straight line which is parallel to the desired cone, so that the rms surface deviation is given by

$$\text{RMS} = \frac{\left(y_1' - \overline{y}\right)^2 + \left(y_2' - \overline{y}\right)^2 + \cdots \left(y_{n+1}' - \overline{y}\right)^2}{n+1} \tag{15}$$

A FORTRAN computer program, COMESH, has been designed to perform the analysis described above automatically. Listing and sample output for COMESH are included in Appendix A.

This analytical procedure for determining the shape of a stretched "axisymmetric" membrane has been verified experimentally. Prior to the installation of the radial spokes, it was found that the mesh bowed inward from a true cone a maximum of 30 mm (1.2 in.). The predicted maximum inward bow using COMESH without spoke tension was 37 mm (1.5 in.). This discrepancy was attributed to the sewn seams in the actual mesh membrane. These sewn seams are considerably stiffer than the mesh, thereby increasing the effective radial tension and reducing the inward bow.

D. MESH SELECTION

Desirable properties of mesh materials for spacecraft antenna reflector surfaces are enumerated below:

(1) Low cost.
(2) High RF reflectivity.
(3) Corrosion resistant.
(4) Low weight.
(5) Low creep.
(6) Radiation stability.
(7) Bidirectional compliance.
(8) Run and snag resistant.
(9) Wrinkle resistant.
(10) Low solar absorptance/emittance ratio.
(11) Low thermal expansion coefficient.
(12) Puncture resistant.
(13) Adherent coating (if coated).
(14) High strength.

In general, the desired mechanical properties are primarily a function of mesh construction (knit) and the mechanical properties of the knitting yarn. The desired electrical properties, corrosion resistance, and low solar absorptivity, however, are often achieved by coating the basic mesh material before or after knitting.

The RF reflectivity depends on "geometric reflectivity," which is dependent on the gauge (yarn spacing) of the mesh and the yarn diameter. For high geometric reflectivity, the conductor spacing must be a small fraction of the RF wavelength at the operating frequency. Conductor diameter should be small compared to conductor spacing. For operation at X-band (8.448 GHz), mesh materials with a conductor spacing of approximately 2 mm (0.08 in.) have performed well.

For a given geometric reflectivity, low dc electrical resistance of the mesh produces high RF reflectivity. Low surface resistivity (ohms/square) depends on low resistance along the mesh conductors and low contact resistance at conductor junctions. This may be accomplished by using a low resistance material to knit the mesh or by coating the mesh with a material having low electrical resistance. As indicated, the surface contact resistance at mesh fiber junctions must be low. Many materials have low internal resistance but exhibit high contact resistance because of corrosion at fiber junctions. For this reason, the noble metals, especially gold, are often considered as good coatings for antenna meshes. Gold is less than ideal, however, because of its high solar absorptance-to-emittance ratio, which results in a mesh temperature of approximately 200°C (400°F) in earth orbit (1 sun). Clearly, this temperature is too high for most nonmetallic substrate yarns. Silver has excellent conductivity and a lower solar absorptance/emittance ratio, but may have high contact resistance because of atmospheric corrosion.

Compared to other weaves or knits, a diamond tricot knit inherently provides better bidirectional compliance, low thermal expansion coefficient, high puncture resistance, and run resistance. Candidate metallic fibers for the knitting yarn are Chromel-R (nickel/chromium alloy), beryllium, copper, tungsten, and stainless steel. Nonmetallic fibers under consideration are Dacron, Draylon, Kevlar, and beta fiberglass. The nonmetallics look very attractive from the standpoint of high strength-to-weight ratio and low cost, but their resistance to creep and radiation degradation has not been established at this time. Further discussion of knitted mesh materials for use as spacecraft antenna reflectors may be found in Refs. 4 to 6.

The mesh selected for the 3.66-m (12-ft) conical reflector may be broadly described as a gold/silver-plated nickel/chromium alloy mesh, which is of two bar half set knit construction with 2-mm (0.08-in.) diamond-shaped openings. This material is shown actual size in Fig. 10 and 16 times actual size in Fig. 11. The knitting yarn consists of five 0.018-mm (0.0007-in.) nickel/chromium filaments stranded together. Its composition is 75% Ni, 20% Cr, 3% Al, and 2% Co. After knitting, the mesh is plated with 1 μm (40 μin.) of silver followed by 0.2 μm (8 μin.) of gold.

The RF reflectivity of the mesh was measured by placing small samples of the material in a waveguide. This procedure is described in Ref. 6. Average RF reflectivity loss at 8.448 GHz for seven samples was 0.03, 0.03, and 0.05 dB for the 0, 45, and 90 deg positions, respectively. These losses compare to 0.09, 0.12, and 0.08 dB, respectively, reported for a similar mesh (Ref. 4). The improvement in reflectivity may be attributed to the fact that the present mesh has a thick layer of silver applied prior to the final gold plating, whereas the previous mesh had only a thin gold plating. RF reflectivity losses less than 0.10 dB are considered excellent for mesh materials.

Some shortcomings in the mesh material were noted. Examination of the mesh material with an electron microscope (see Figs. 12 and 13) revealed that the plating adherence is questionable, so that particle shedding and RF performance degradation may be a problem for some applications. When the mesh was removed from its shipping container, it was badly wrinkled. The vendor indicated that this wrinkling occurs in the plating bath where the material is folded to fit in the bath. A bath large enough to avoid folding the mesh would be prohibitively expensive in terms of the amount of gold required to have the desired bath composition. To remove most of these wrinkles, it was necessary to use higher tensions in the mesh than would otherwise have been used.

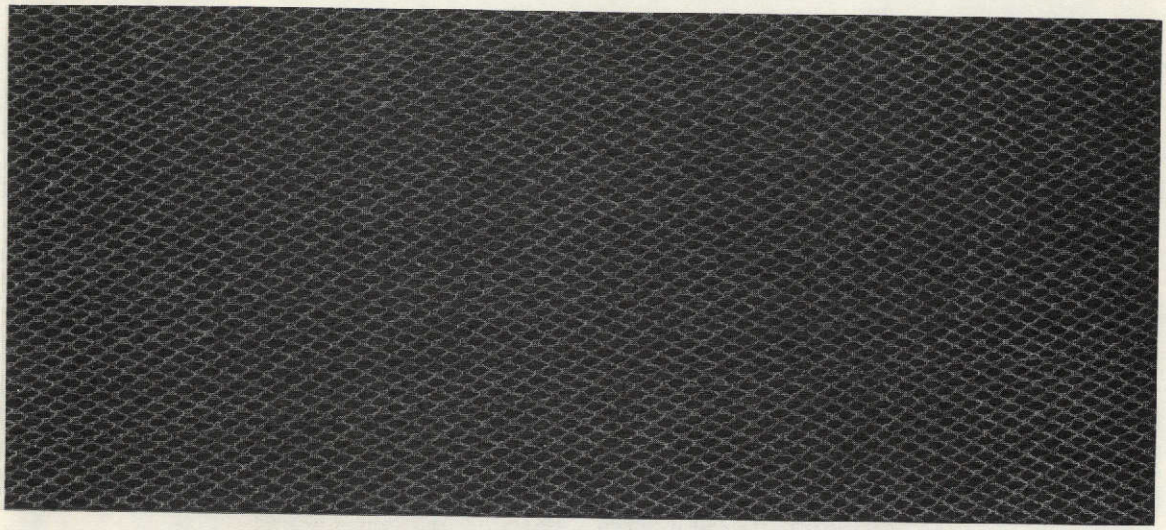


Fig. 10. Gold/silver-plated nickel/chromium alloy tricot knit wire mesh (actual size)

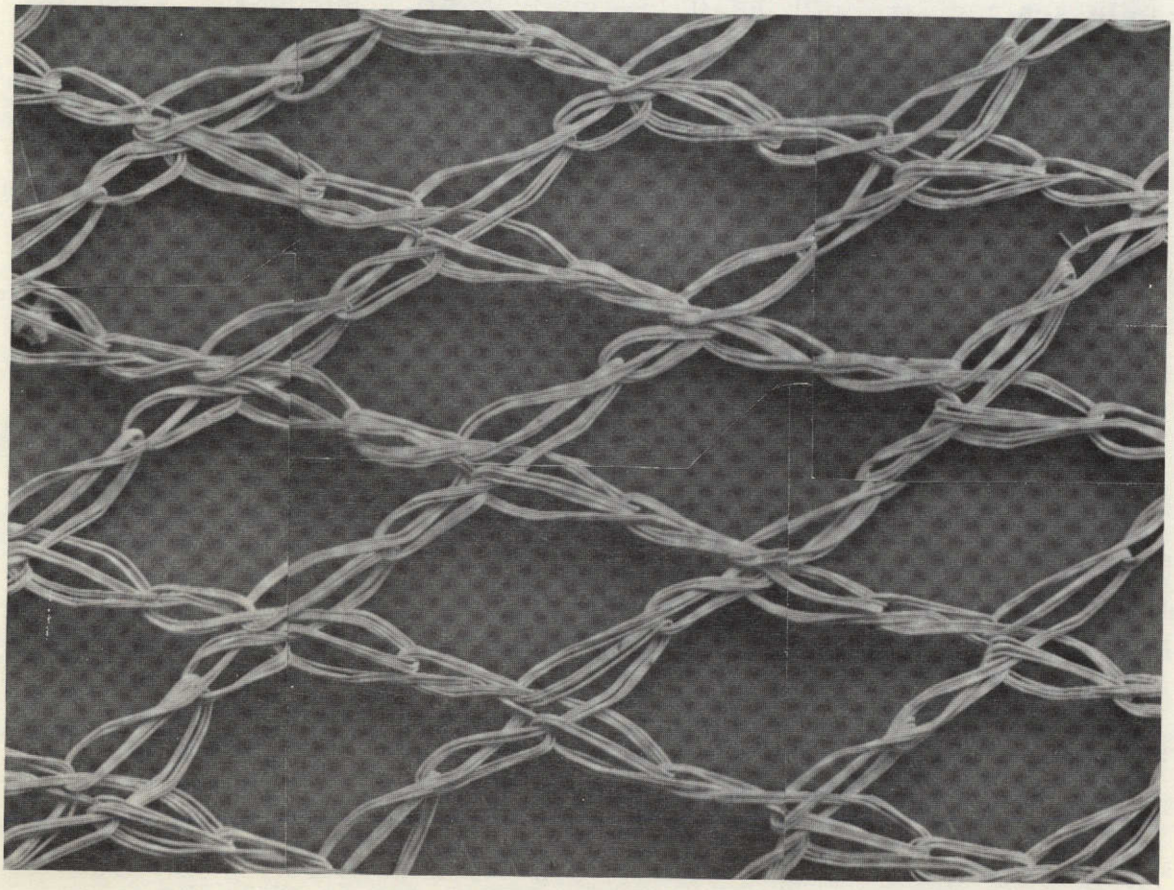


Fig. 11. Gold/silver-plated nickel/chromium alloy tricot knit wire mesh (16× actual size)

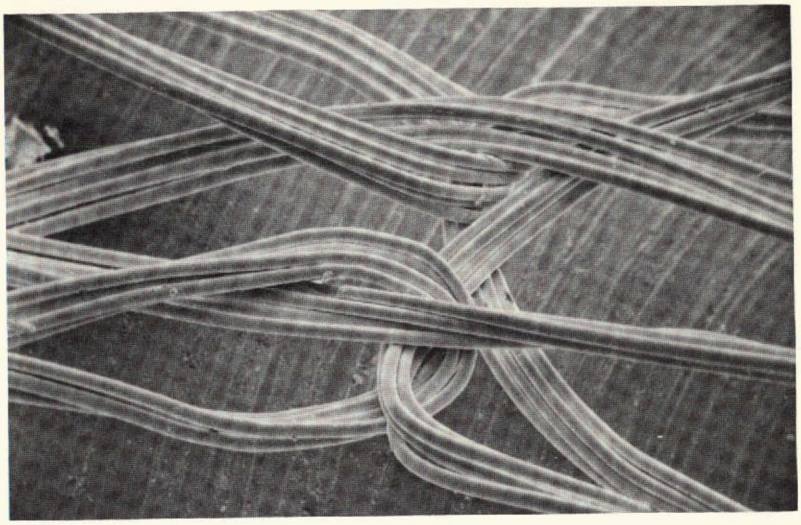


Fig. 12. Gold/silver-plated nickel/chromium alloy tricot knit wire mesh (80X actual size)

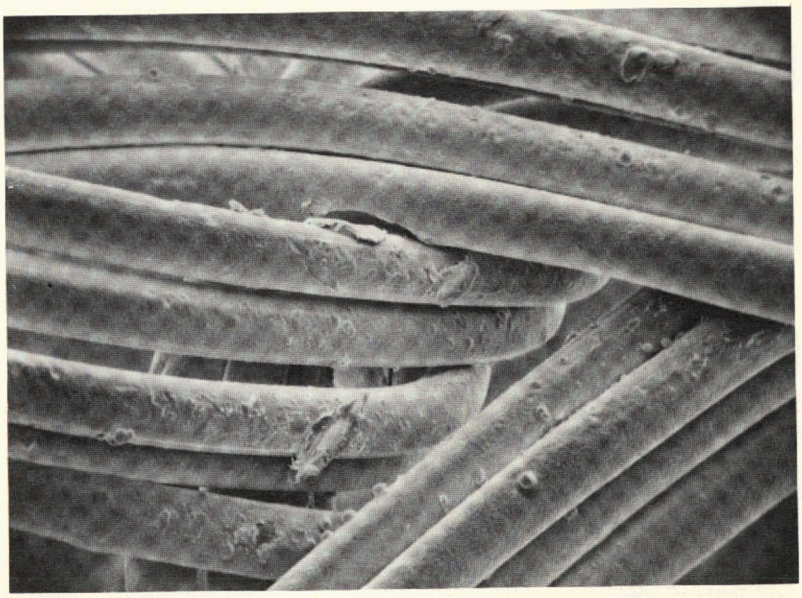


Fig. 13. Gold/silver-plated nickel/chromium alloy tricot knit wire mesh (400X actual size)

E. MESH MEMBRANE REFLECTOR DESIGN

It was mentioned previously that a membrane stretched between two circular disks, which form the support for the desired cone, will produce a true conical shape only if the circumferential tension in the membrane is zero. The foregoing is also subject to the additional constraint that the membrane be weightless.

Neither of these requirements is practical, and therefore the reflector design consists of a series of engineering tradeoffs to achieve an approximate conical surface of acceptable accuracy. The following design criteria were established:

(1) The rms surface deviation to be less than 0.38 mm (0.015 in.). This produces low RF losses for X-band.

(2) Membrane-induced structural loads on the support frame to be kept at a practical minimum.

(3) The mesh reflector to be designed so that gravity effects on surface accuracy would not preclude meaningful RF testing in a 1-g environment.

Employing the computer program COMESH, it was established that, for a weightless membrane, the ratio of radial tension in the mesh to circumferential tension in the mesh (called tension ratio) must be of the order of 100 to 1 or higher to achieve an rms surface deviation less than 0.38 mm (0.015 in.) for the reflector configuration considered here (3.66-m diameter and 65-deg half angle cone). For the gold/silver-plated nickel alloy mesh selected for this program, tension ratios less than 10 to 1 must be used to avoid waves in the mesh. For this reason spokes were fitted along the generatrices of the cone between the cone support rings.

As mentioned before, by placing the spokes at the inside surface of the desired cone the tendency of the membrane to lampshade is controlled. As long as the membrane presses against the spokes, the radial tension in the mesh/spoke system is, in effect, the sum of the radial tension in the mesh and the spoke tension. Since 120 spokes were used, the surface deviation due to faceting of the membrane between spokes is negligible.

Avoiding surface deviations which would preclude RF testing in a 1-g environment establishes a criterion for a minimum circumferential mesh tension. A conical membrane under the influence of gravity with its axis horizontal will tend to assume the shape shown in Fig. 14.

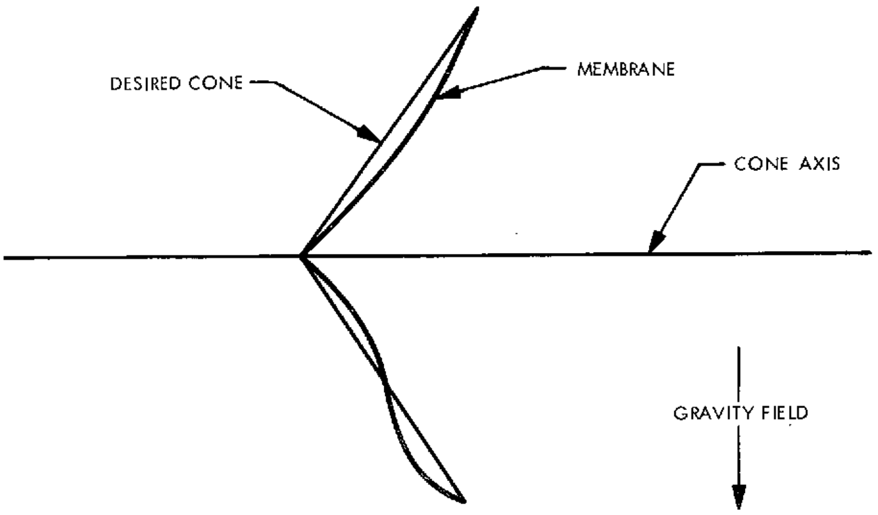


Fig. 14. "Conical" membrane with nonaxisymmetric gravity loading

That portion of the membrane above the axis tends to lampshade more. The portion below the horizontal axis tends to lampshade less, even to the extent that it may assume the S-curve shown or hang completely below the desired cone surface. Since the spokes mentioned previously are inside the cone surface, they cannot control the membrane if it hangs outside the desired cone. The mesh could have been tied to the spokes, but this was considered an undesirable complexity.

The above effect is described analytically by Eq. (2). Remember that the sign of R, the radius of curvature of the membrane measured in a plane through the axis of the cone, describes the direction that the membrane bulges. Examination of Eq. (2) shows that R can be positive, infinite, or negative, depending on the denominator of the right side of the equation. To prevent bulging outside the desired cone, we want to prevent R from assuming a positive value. In attaining a positive value for R, notice that the denominator passes through zero, corresponding to an infinite radius of curvature. Therefore, the minimum circumferential tension can be found by equating the denominator of Eq. (2) to zero. With the cone axis horizontal, $w \cos \theta$ is the component of unit mesh weight acting normal to the mesh surface and $D_2/2 \cos \theta$ is the radius of curvature of the membrane measured from the cone axis perpendicular to the desired cone surface at the outer rim of the antenna. We obtain

$$t_{min} = \frac{wD_2}{2} \tag{16}$$

the minimum circumferential tension required in the membrane.

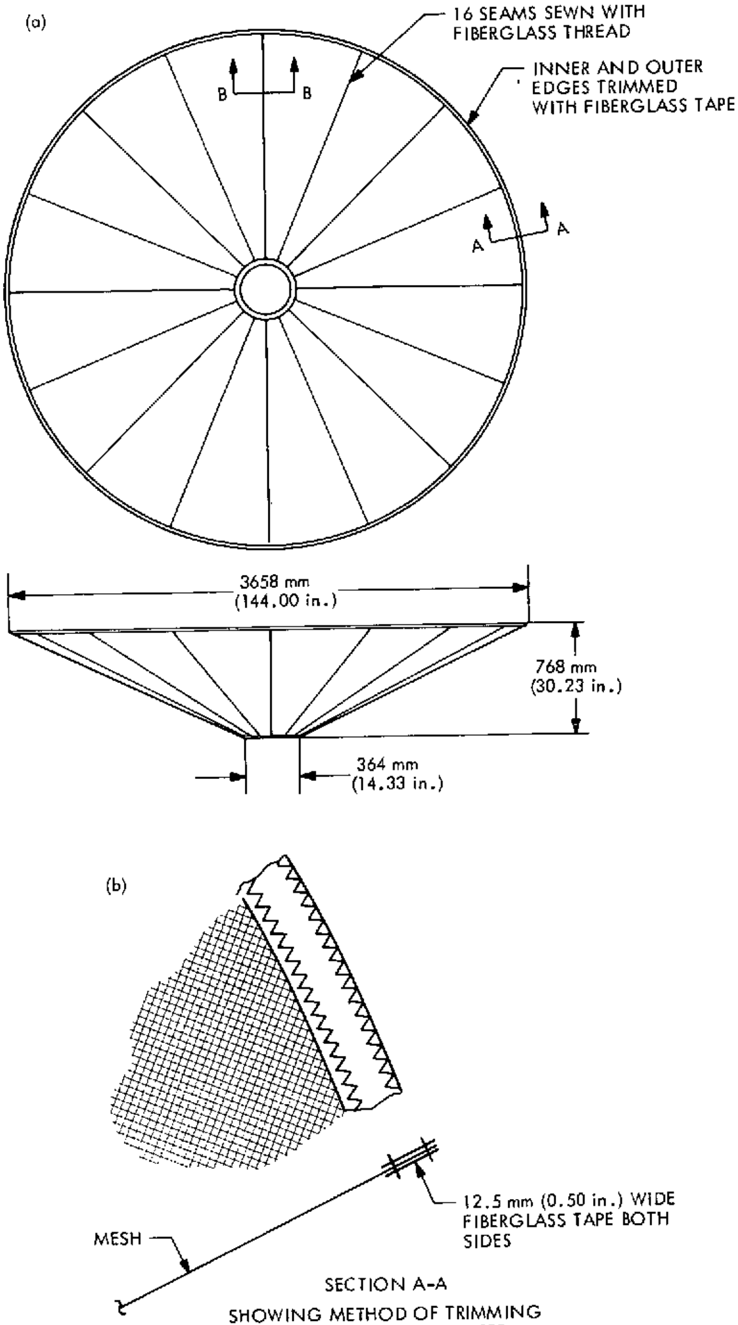
For the 3.66-m (12-ft) antenna reflector the unit weight of the mesh is 0.72 N/m^2 (0.015 lb/ft^2), so that the minimum circumferential tension to prevent the membrane from bulging outside the desired cone is 0.013 N/cm (0.0075 lb/in.). However, it was found that a minimum circumferential (transverse) tension of 0.033 N/cm (0.019 lb/in.) was required to eliminate creases in the gold/silver-plated nickel alloy mesh used to fabricate this antenna reflector.

Having established the minimum circumferential tension required in the mesh, studies were conducted to determine the radial mesh/spoke tension required to produce a membrane acceptably close to the desired conical surface. The radial load required to accomplish this for a membrane/spoke system which is supported only at the outside and inside diameters of the entire 3.66-m (12-ft) reflector surface was considered too high. For this reason, the mesh was supported at an intermediate diameter as shown in Fig. 15. The resulting mesh and spoke loads to achieve a predicted rms surface deviation of 0.19 mm (0.0075 in.) (see Appendix A) were:

T_c = circumferential tension = 0.033 N/cm (0.019 lb/in.)
T_r = radial tension = 0.11 N/cm (0.062 lb/in.)
S = spoke tension = 18 N (4 lb)

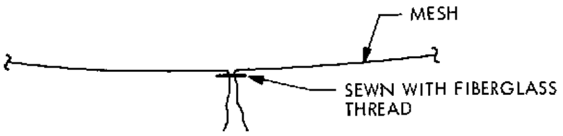
F. DESIGN DETAILS AND FABRICATION

Design details of the mesh reflector are shown in Fig. 15. The complete reflector surface is made up of 16 gores of the gold/silver-plated



SECTION A-A

SHOWING METHOD OF TRIMMING INNER AND OUTER EDGES; SEE ALSO FIG. 21a



SECTION B-B

SHOWING METHOD OF JOINING GORES

Fig. 15. Mesh membrane reflector

nickel/chromium knitted mesh. The number of gores was selected so that two gores could be obtained from standard width material as shown in Fig. 16.

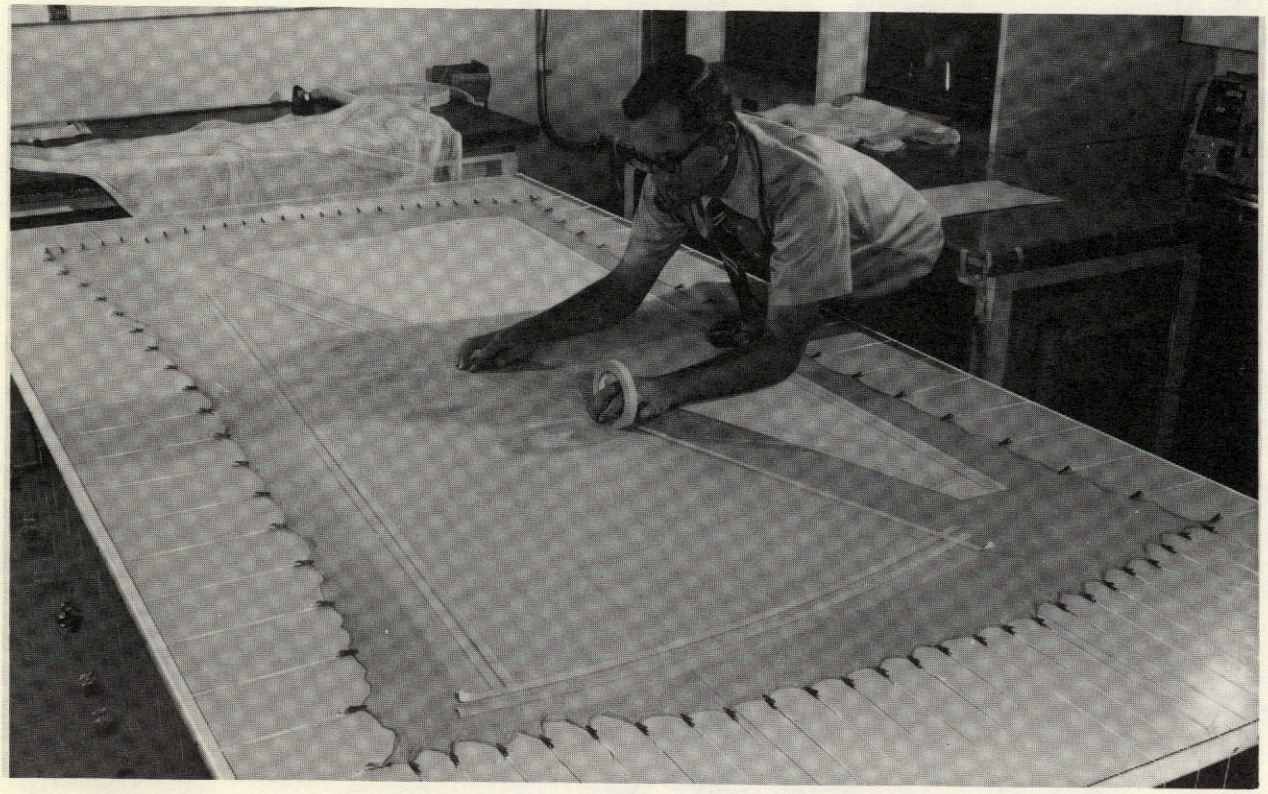


Fig. 16. Pre-tensioning the mesh and marking gores with masking tape

This figure also shows the procedure used to pre-tension the mesh to the desired circumferential and radial tensions.

As shown, the mesh is stretched on a special table constructed for the purpose. The weights, which provide the desired tension field, are attached to the mesh with alligator clips and hang over the edge of the table. The surface of the table is waxed Formica, and the edge of the table is trimmed with Teflon to reduce friction. The table top is vibrated to further reduce static friction loads. In this way, the desired tension field is established in the mesh.

True-shape gore patterns drawn on Mylar drafting film are placed between the mesh and the table surface. The outline of the gore pattern is marked by applying 12.5-mm (0.50-in.) wide masking tape to the mesh surface. Note that the inside edge of the tape being applied in Fig. 16 defines the seam or finished width of the gore. The inside edge of the outer tape shown at the large end of the gore defines the outside diameter of the antenna. Additional reference marks defining attachment points of the completed mesh reflector to the support frame are transferred from the Mylar pattern to the masking tape marking system. Note that the masking tape delineates the true shape of the gore patterns at the desired pretension even after the weights are removed. The mesh gores are cut out along the outside edge of all masking tape markers shown. At this time the mesh gores are 12.5 mm (0.50 in.) larger on all sides than the finished dimensions.

The complete antenna reflector is now assembled. The adhesive sides of the masking tape markers defining the seams of adjacent gores are stuck together. Seams are sewn through both layers of mesh immediately inside the masking tape seam markers. A 0.40-mm (0.016-in.) diameter Teflon-coated sewing thread was used. When the masking tape markers are removed, a seam as shown in Fig. 15b is produced.

The outside edges of the mesh reflector were trimmed with 12.5-mm (0.50-in.) wide Mystic 7000 fiberglass tape. This material is used extensively to trim the edges of spacecraft thermal blankets. The trimming was accomplished as follows. The entire length of tape required to trim the outside edge of the mesh was pre-tensioned to 18 N (4 lb). One hundred twenty reference points were marked on the pre-tensioned tape at intervals equal to the true distance between mesh attachment points on the reflector support frame. A fiberglass tape, so marked, was installed on each side of the mesh reflector. The tape was installed between the two masking tape markers shown in Fig. 16. The reference marks on the fiberglass tape were aligned with corresponding reference marks on the masking tape markers. This procedure produces a 36-N (8-lb) preload in the fiberglass tape at the outside edge of the reflector when it is installed on the support frame at the reference marks.

The mesh and masking tape outside the fiberglass trim tape were then cut off. Both layers of the fiberglass trim tape with the mesh sandwiched between were sewn with the fiberglass sewing thread, using a wide and narrow zig-zag stitch at the outer and inner edges of the fiberglass trim tape as shown in Fig. 15b.

The inside diameter of the mesh reflector was trimmed in a similar manner, except that the fiberglass tape was not tensioned. The weight of the completed mesh reflecting surface is 10 N (2.24 lb). A detailed weight breakdown is given in Appendix B.

III. REFLECTOR SUPPORT FRAME

A. DESIGN CONSIDERATIONS

The purpose of the support frame is to position the mesh membrane reflecting surface as close as practicable to the desired conical surface. It must sustain the static loads due to mesh tension and spoke tension. The frame was designed to support the mesh and withstand the steady-state and dynamic loads imposed by the launch environment. In addition, RF testing in a 1-g environment imposes an overall frame stiffness requirement for minimum deflection.

Design loads for the reflector support frame were based on the superposition of mesh and spoke static loads and estimates of the dynamic response of similar spacecraft components, derived from system level qualification tests.

An additional important design consideration was fabrication cost. The frame described in the paragraphs which follow was considered the least complex and costly of several competing configurations, all of the fully triangulated space frame type.

B. DESCRIPTION OF REFLECTOR SUPPORT FRAME

The reflector support frame shown in Fig. 17 is a rigid, three-dimensional truss formed by 120 tubular members joining the inner hub and outer rim. Twelve tubular truss members emanate radially from the central hub and perpendicular to the cone axis. These members are joined at their outer ends by 12 chordwise members. The other 12 members that radiate from the hub are disposed approximately parallel to the reflecting surface.

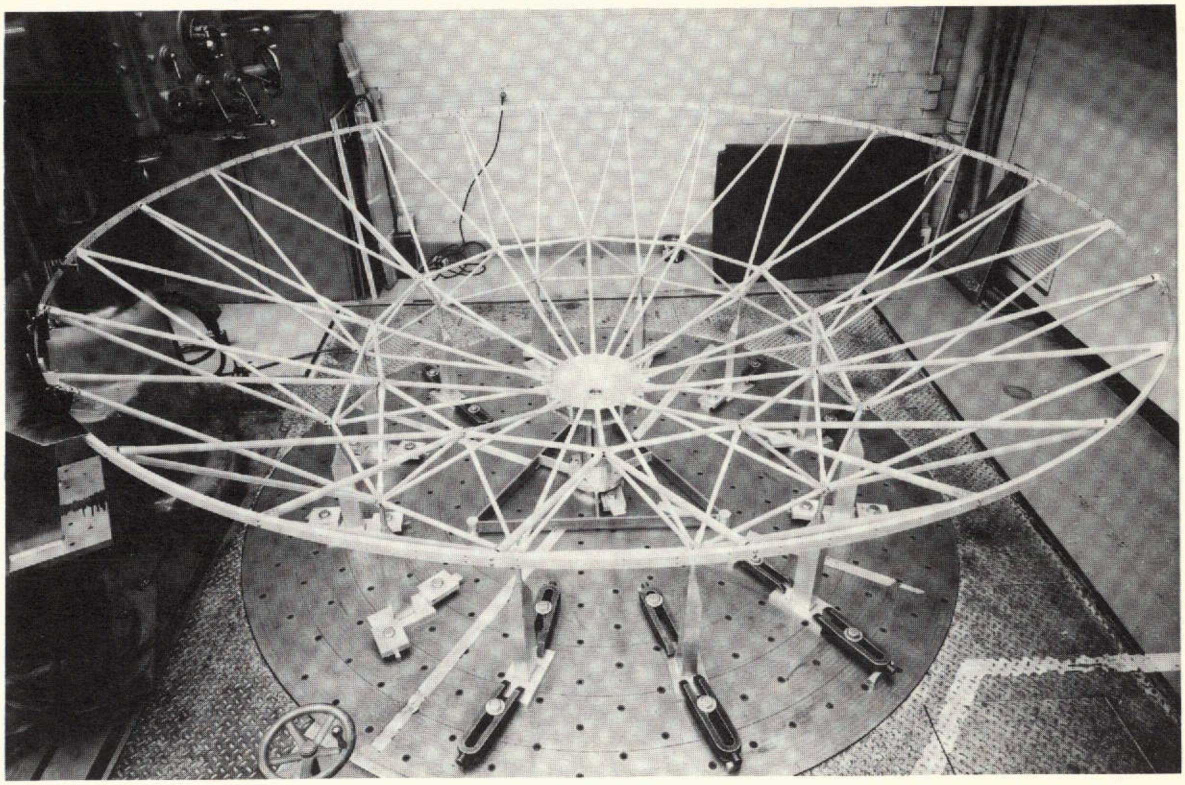


Fig. 17. Reflector support frame

They are also joined at their outer ends by 12 truss members. The outermost points of both sets of radial members described are joined with a W-truss. This forms the very rigid kernel of the support frame as shown in Fig. 18. The outer rim of the antenna is supported at 24 points by outrigger bipods attached to the kernel. With the exception of rivets, bolts, and threaded inserts, the entire support frame was fabricated from 6061-T6 aluminum alloy. The inner hub (Fig. 19) of the support frame is a circular ring girder. It provides a faying flange for attaching the sheet aluminum cone which forms the innermost portion of the reflector surface. The hub also incorporates tangs to which the tubular truss members are riveted. The outer ring was made by rolling a standard rectangular tube to the desired radius and subsequently chem-milling the outside surface of the tube to obtain the desired wall thickness. A closed section for the outer ring was required to resist torsion loading due to off-center mesh and spoke tension loads. Its rectangular shape was chosen for convenience of attaching mesh/spoke attachment clips, which are discussed later. The tubular members

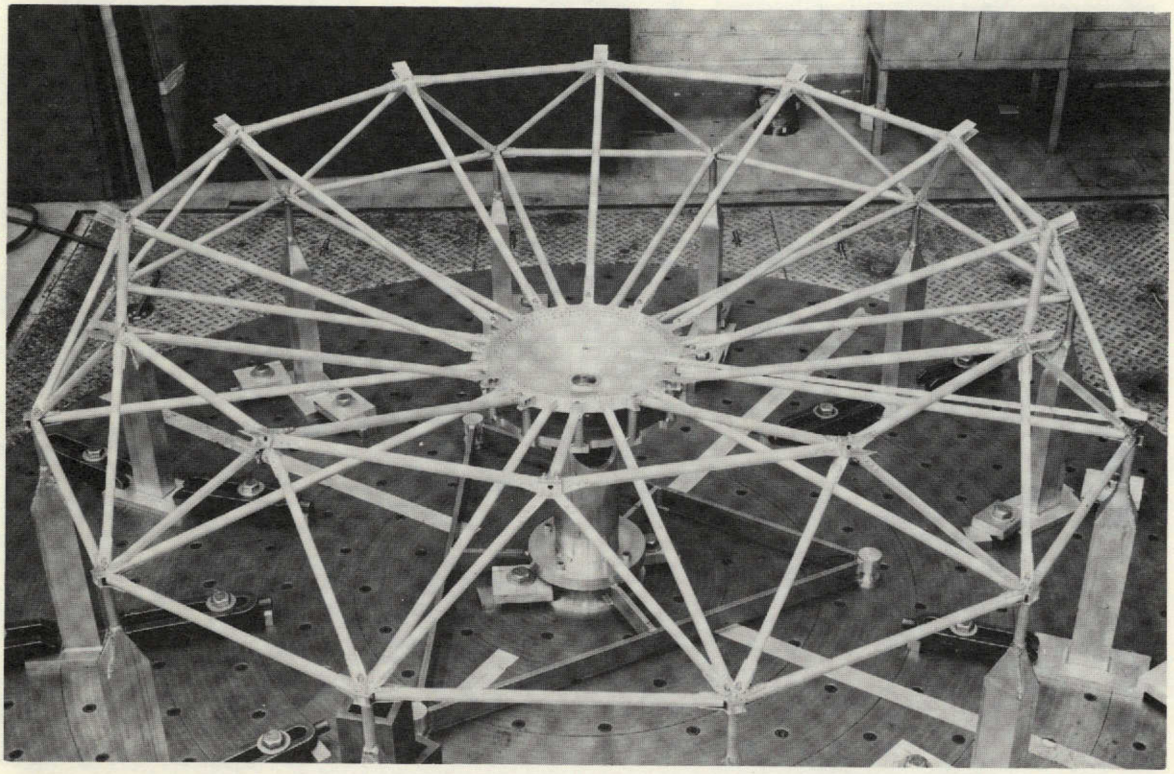


Fig. 18. Kernel of reflector support frame

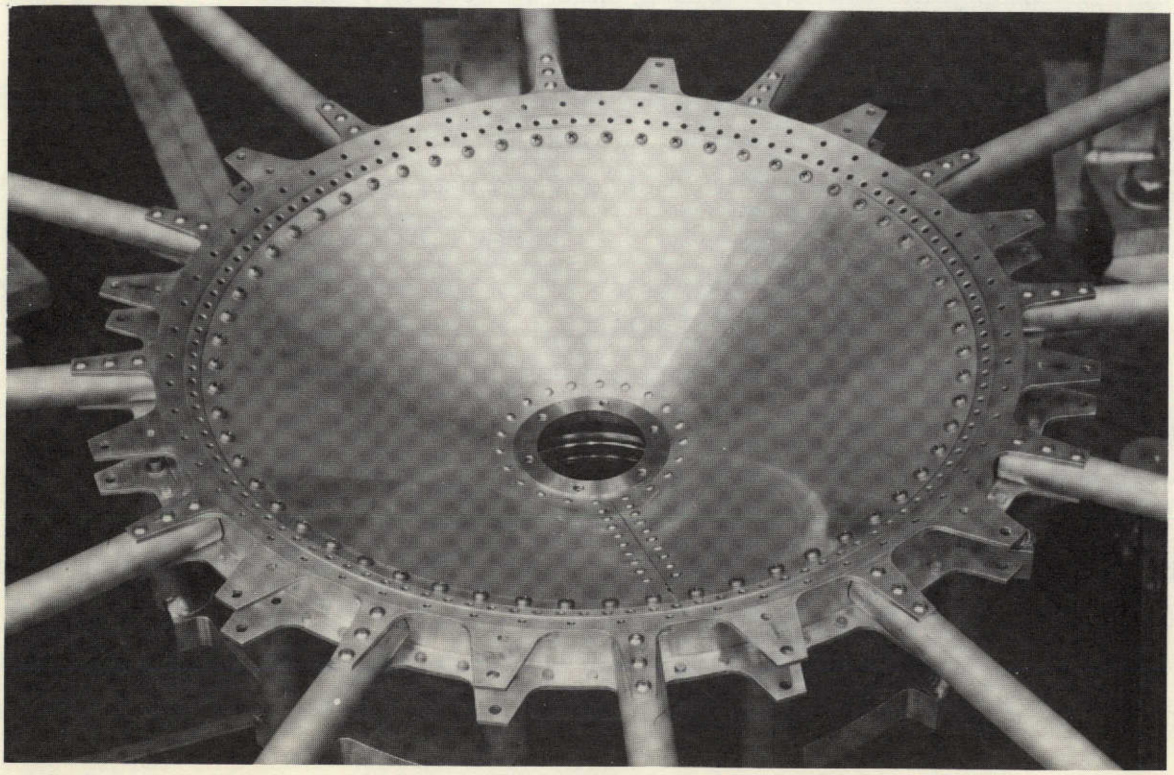


Fig. 19. Inner hub of reflector support frame

which join the inner hub and outer ring are 19.4-mm (0.750-in.) diameter × 0.51-mm (0.020-in.) wall aluminum tubing.

Machined fittings join the various members at the panel points. These fittings sandwich the ends of the tubular members between two tangs, which are blind-riveted to the tubes. The complete reflector support frame weighs 152 N (35 lb).

IV. MESH REFLECTOR ATTACHMENT/ADJUSTMENT

The mesh reflector is attached to the support frame at its inner diameter, outer diameter, and an intermediate diameter. The attachment points must also locate the mesh on the desired conical surface. To permit reasonable manufacturing tolerances and to compensate for static deflections of the frame due to tensioning the mesh and spokes, adjustment is provided at the intermediate and outer attachment points.

The mesh is attached to the frame at points on the frame corresponding to the reference marks on the mesh established while the mesh was pre-tensioned as discussed in Section II-F. This reestablishes the desired preload in the mesh.

The mesh reflector is attached at its inner diameter to the hub of the support frame by screws installed through the fiberglass trim tape as shown in Fig. 20. Because there is no provision for adjustment at the inner hub, this establishes an immovable reference circle on the desired conical surface. The other attachment points must be adjusted to lie on a conical surface of the proper cone angle that passes through this reference circle.

There are 120 equally spaced attachment clips provided at the outside diameter of the reflector. As shown in Fig. 21, these clips serve to attach the mesh and spokes and adjust the mesh surface. The reflector is fastened to the clip with a flat head, tubular eyelet installed through the fiberglass trim tape at the edge of the mesh reflector. The spokes pass through the hollow eyelet and are fastened to the clip as shown. The springs shown in Fig. 21b were provided to measure the spoke tension and would not be required on a flight antenna. Reflector surface adjustment at the outside

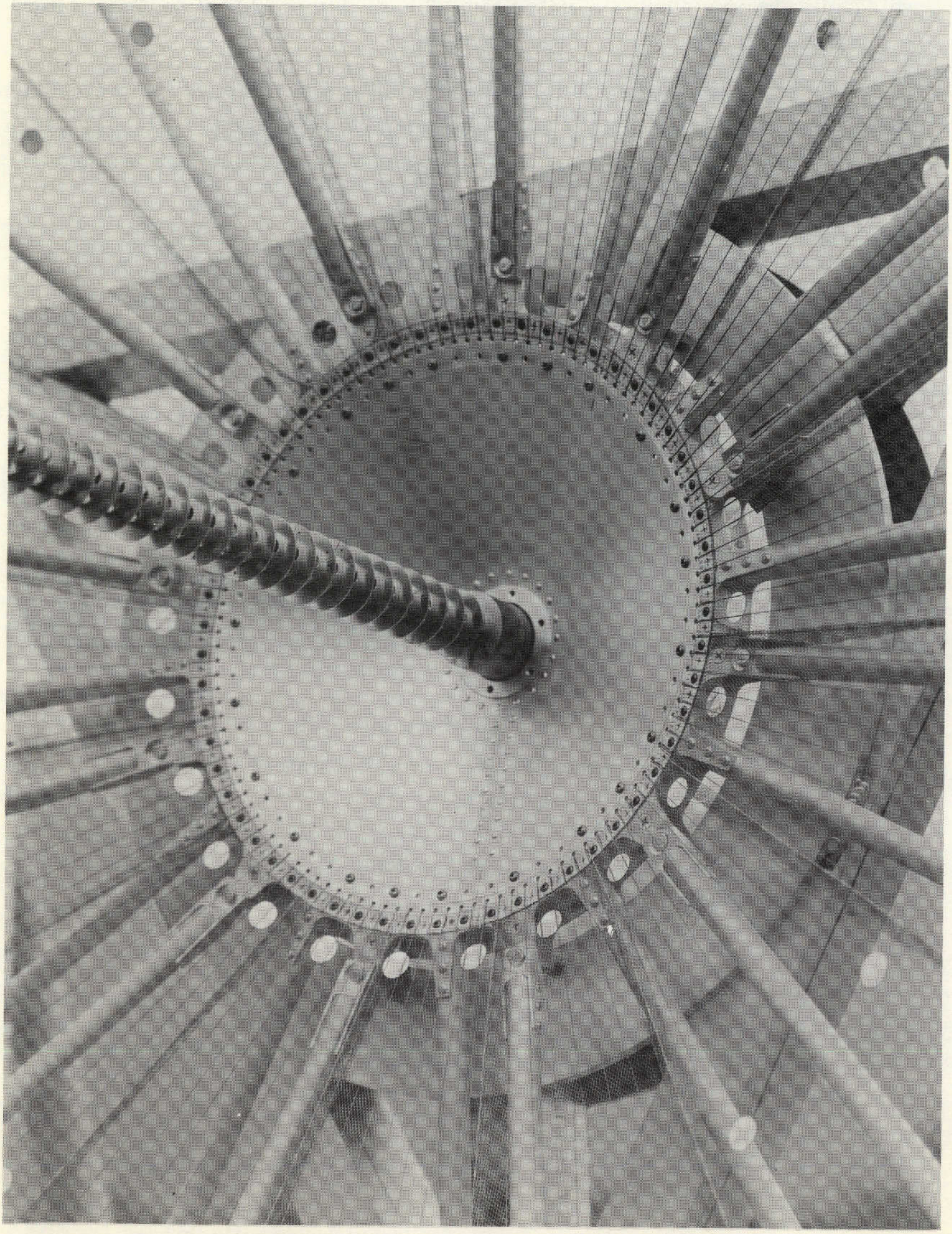


Fig. 20. Mesh reflector attachment at inner hub

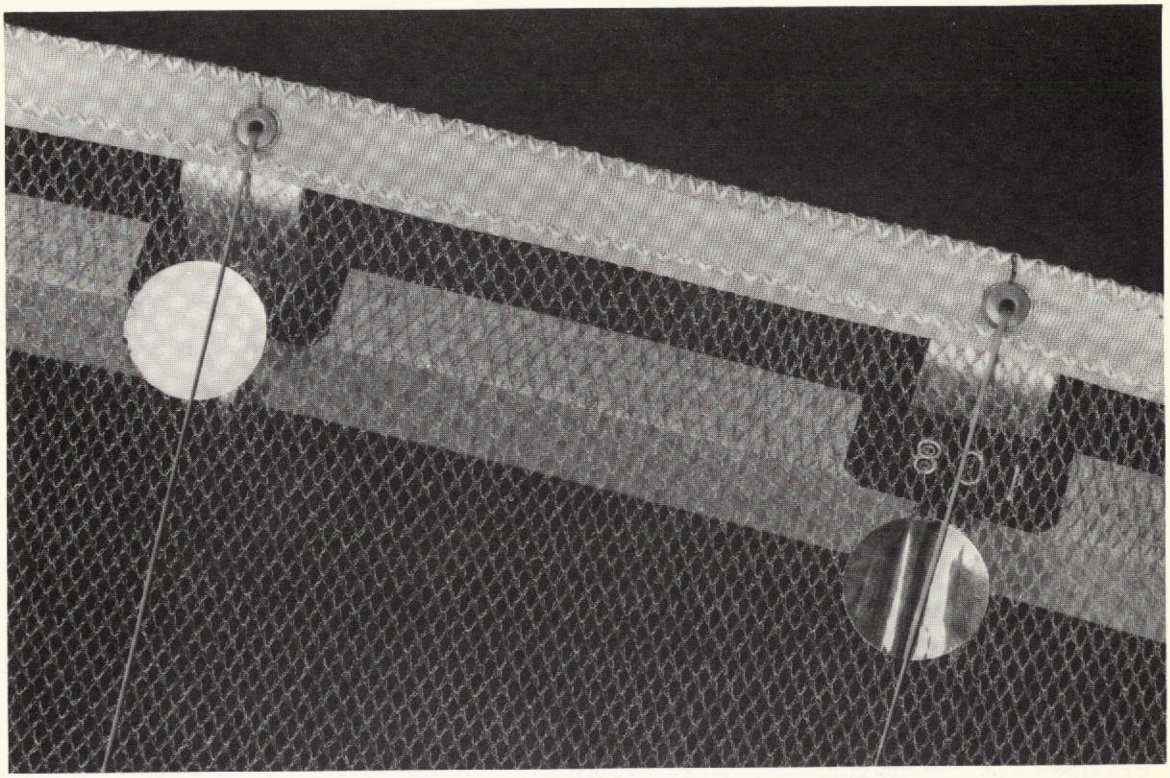


Fig. 21(a). Top view, mesh and spoke attachment/adjustment clips at outer rim of antenna

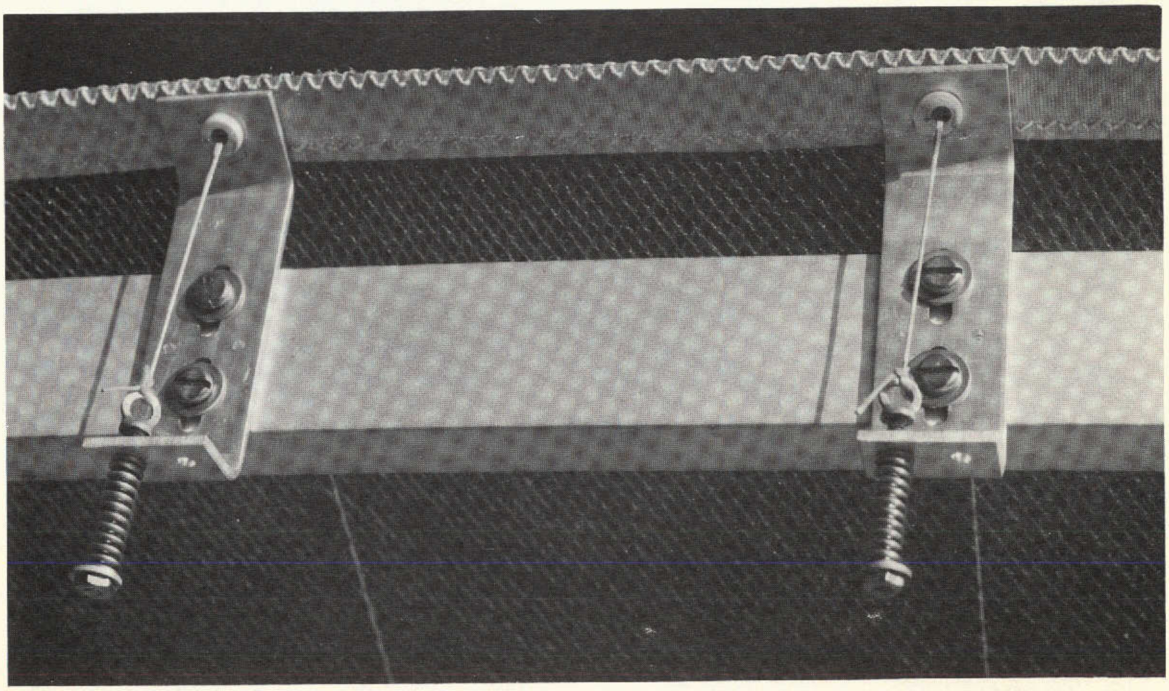


Fig. 21(b). Bottom view, mesh and spoke attachment/adjustment clips at outer rim of antenna diameter of the reflector is accomplished by moving the clips with respect to the support frame and tightening the screws which hold the clips to the frame.

The spoke tension required to control the "lampshading" of the mesh membrane over the entire span from inner to outer diameters would be excessive. For this reason, an intermediate support ring was provided. This ring is not required to tension the membrane or the spokes. The intermediate support ring reacts only the small loads required to pull the "lampshaded" membrane back to the desired conical surface. The intermediate support ring is shown in Fig. 22. It is attached to the support frame by means of 24 standoffs, which also provide adjustment of the conical surface. Note that the spokes are on the far side (inside) of the mesh in Fig. 22. After the mesh and spokes are installed and tensioned, the spokes are tied to the intermediate support ring as shown.

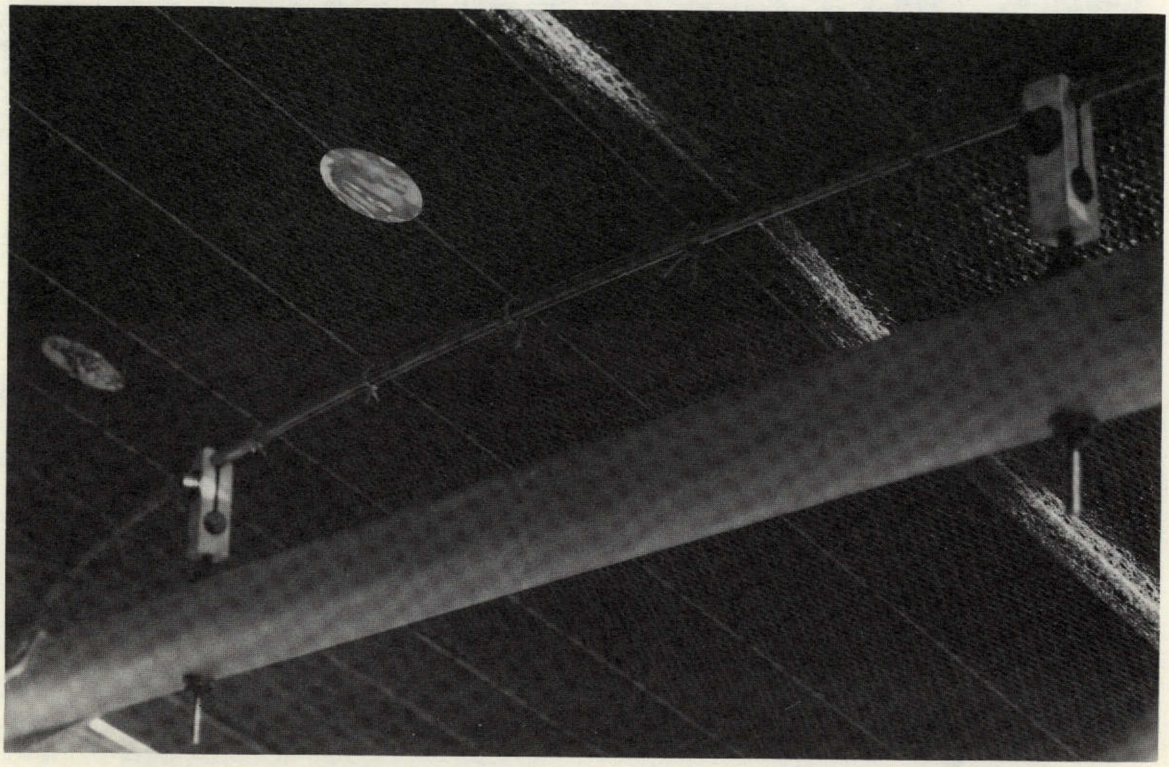


Fig. 22. Intermediate mesh and spoke support ring

V. SURFACE DEVIATION MEASUREMENT

The RF performance of antennas is strongly influenced by the surface accuracy of the reflecting surfaces. It is therefore desirable to know the surface accuracy of the reflector so that the RF loss attributable to surface inaccuracies can be estimated.

At the JPL antenna test range, RF testing is performed with the axis of the antenna horizontal. This results in an unsymmetrical gravity field on the antenna reflecting surfaces. This unsymmetrical gravity load causes reflecting surfaces above the antenna axis to deflect toward the antenna axis and reflecting surfaces below the antenna axis to deflect away from the antenna axis. These effects cannot be discounted for large, lightweight antennas. It was decided, therefore, to measure the surface deviation of the conical mesh reflector with the cone axis horizontal, as it would be during RF measurements.

Figures 23, 24, and 25 show the tools and technique used to measure the surface deviation of the mesh cone with the cone in any position relative to gravity. The lightweight aluminum box beam shown in Fig. 23 has a precision rail surface which is parallel to the desired conical surface. When the beam is rotated about the cone axis, this reference rail generates an imaginary conical surface parallel to the desired cone. It can be seen that, when the beam is above the cone axis, gravity deflects it away from the desired cone surface; when it is below the cone axis, it deflects toward the cone surface. The beam was designed to keep these deflections negligible compared to the measurement accuracy required.

Figure 25 shows a counterweight affixed to the same rotating hub as the reference beam. This counterweight balances the weight of the beam so that there are no moments on the hub. This serves two purposes. First, it eliminates additional errors in the position of the reference beam due to deflections at the hub. Second, it makes the reference beam easy to rotate about the cone axis.

A micrometer head is attached to a mount which can be moved radially along the precision guide rail of the reference beam. Thus, by rotating the beam about the cone axis and moving the micrometer radially,

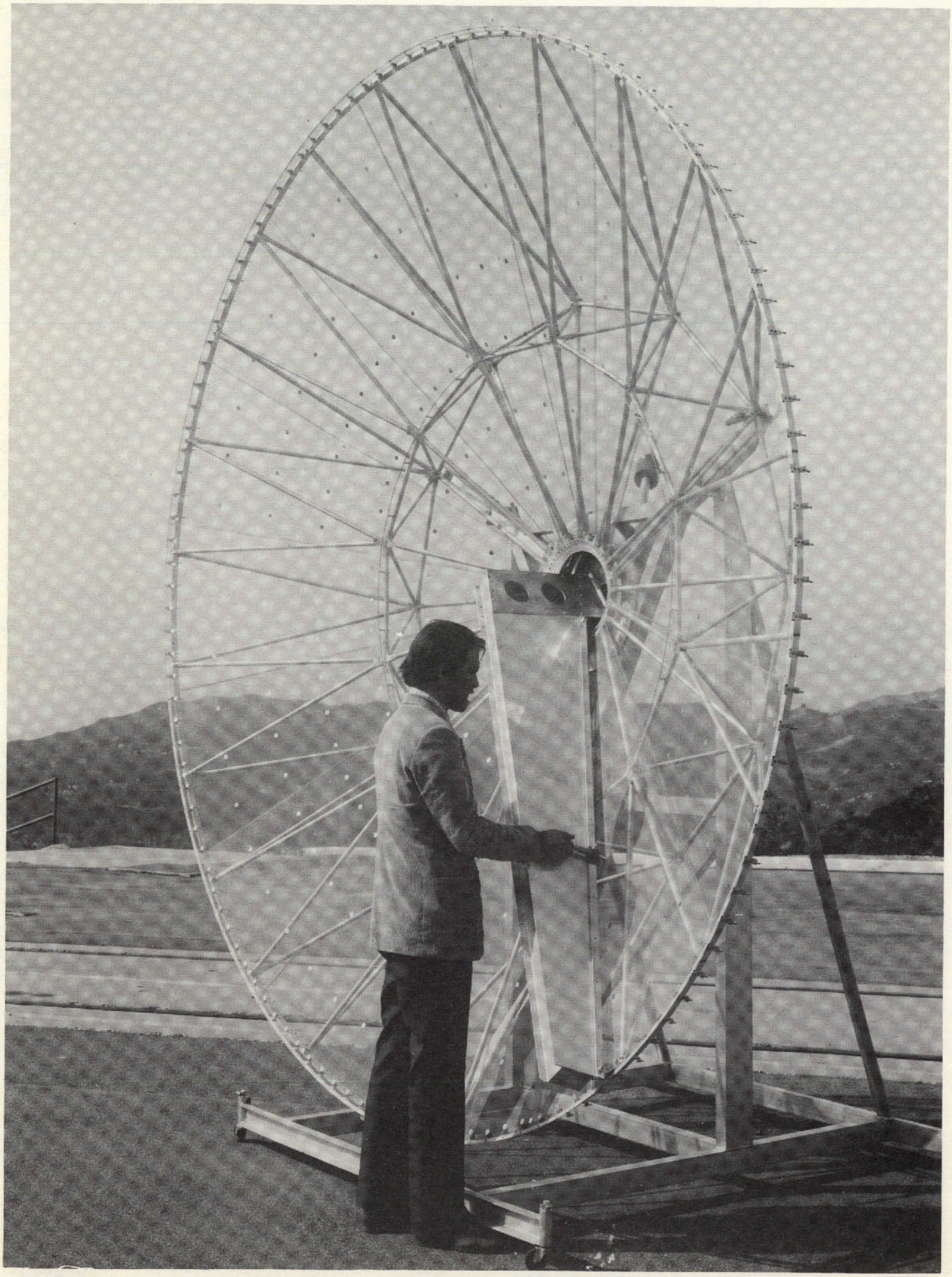


Fig. 23. Surface deviation measuring fixture

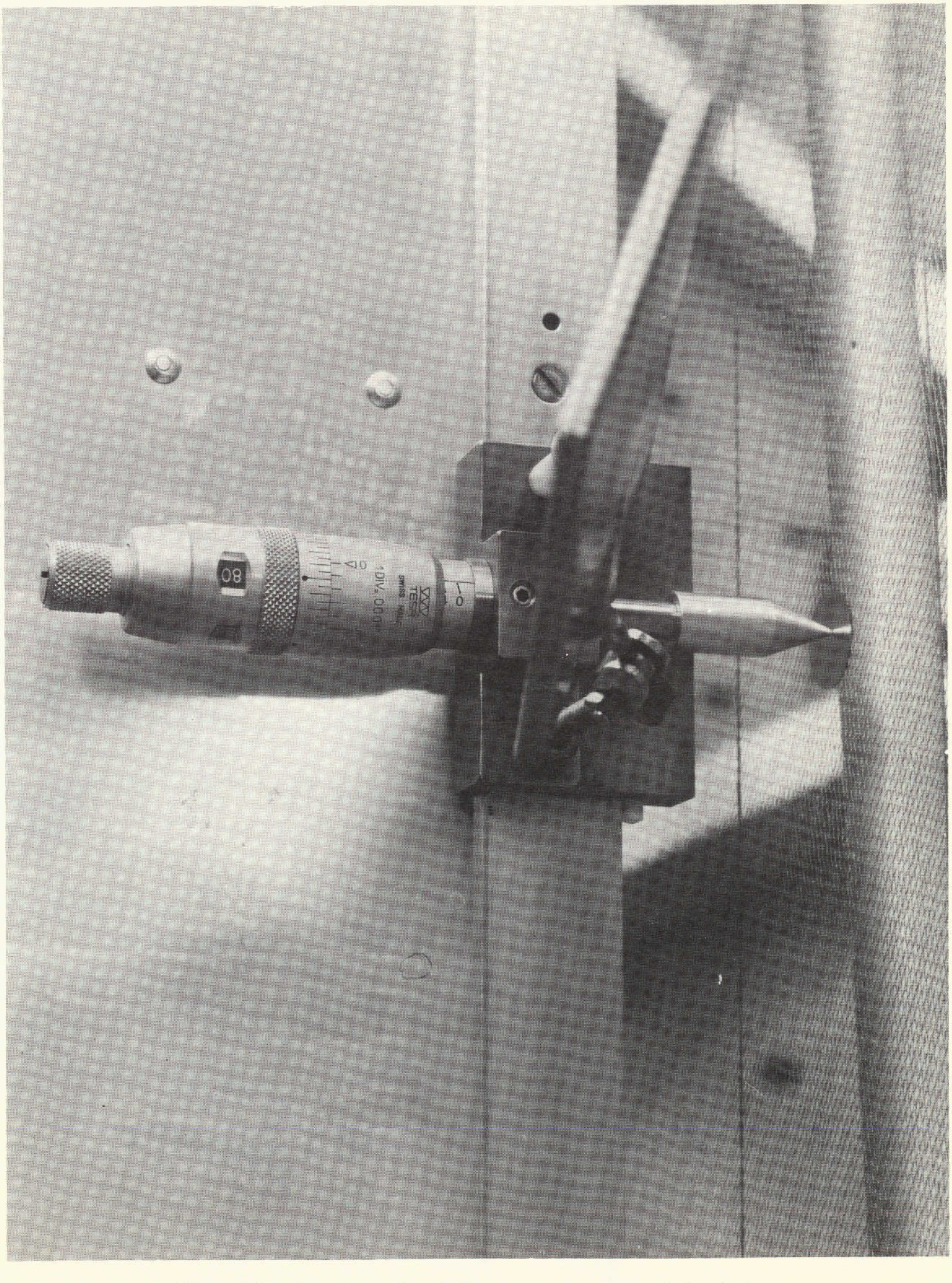


Fig. 24. Surface deviation measurement technique

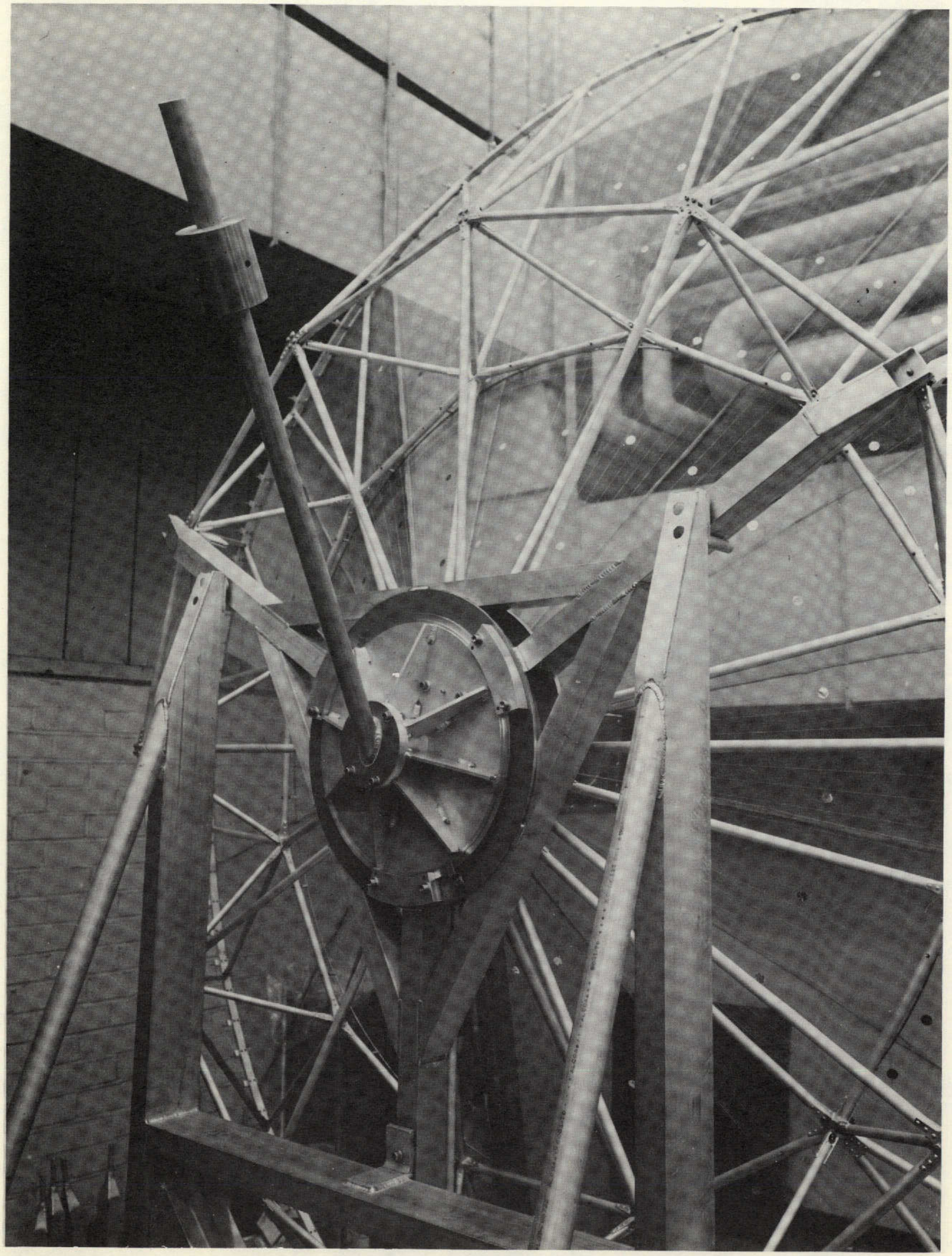


Fig. 25. Counterweight for surface measurement reference beam

the position of any point on the reflector surface can be measured. Because the mesh is very soft normal to the cone surface, it would be very difficult to sense the micrometer spindle touching the mesh. To provide a means to "see" the position of the surface, shiny foil disks were affixed to the mesh. As shown in Fig. 24, the position of the mesh surface is established when the pointer on the micrometer spindle appears to meet its reflection in the shiny foil disks. In Fig. 2 these disks appear as a pattern of 336 regularly spaced dots on the reflector surface.

Readings obtained in this way were averaged, thus defining the best fit cone of the required cone angle. The difference between the micrometer reading at a target and the average of all such readings represents the surface deviation at that target. The root mean square of these deviations is called the rms surface deviation.

After the antenna was completed and adjusted, an rms surface deviation of 0.28 mm (0.011 in.) was obtained.

VI. CONCLUSIONS

The design, fabrication, assembly, and surface accuracy measurement of the 3.66-m (12-ft) conical mesh antenna reflector spanned a time period of eight months. Techniques for prestretching, marking, sewing and fabricating RF reflective knitted mesh materials into a complete antenna reflecting surface were developed. An analytical procedure to predict the surface shape and accuracy of an axisymmetric "conical" membrane was formulated and used to predict the surface accuracy of the subject antenna reflector. The results of this analysis were verified on the completed antenna reflector, employing the tools and techniques developed for measuring the surface shape and accuracy.

The 3.66-m (12-ft) conical mesh antenna reflector compares favorably with current paraboloidal antenna reflectors employing solid main reflectors. The demonstrated rms surface deviation of 0.28 mm (0.011 in.) compares to 0.20 mm (0.008 in.) anticipated for the 3.66-m (12-ft) MJS'77 paraboloidal antenna reflector. The MJS antenna reflector is of sandwich construction, utilizing an aluminum honeycomb core with graphite/epoxy face skins. The anticipated weight of the MJS antenna reflector is 304 N (68 lb) compared to

162 N (36.5 lb) for the 3.66-m (12-ft) conical mesh reflector. The fabrication cost for the conical mesh reflector was considerably less than the fabrication cost for the MJS reflector.

The technology for designing and fabricating large conical reflecting surfaces of knitted mesh material developed during this program is directly applicable to the design and construction of large furlable conical antenna reflectors.

REFERENCES

1. Ludwig, A. C., Woo, K., Gustincic, J. J., and Hardy, J. C., "Recent Development of Conical Reflector Antennas," paper presented at the IEEE International Symposium, Boulder, Colorado, Aug., 1973.

2. Oliver, R. E., and Wilson, A. H., Furlable Spacecraft Antenna Development: An Interim Report, Technical Memorandum 33-537, Jet Propulsion Laboratory, Pasadena, Calif., Apr. 15, 1972.

3. Oliver, R. E., and Wilson, A. H., Furlable Spacecraft Antenna Development: Second Interim Report, Technical Memorandum 33-606, Jet Propulsion Laboratory, Pasadena, Calif., May 15, 1973.

4. Fisher, J. G., "Mesh Materials for Deployable Antennas," in Supporting Research and Advanced Development, Space Programs Summary 37-65, Vol. III, pp. 122-125, Jet Propulsion Laboratory, Pasadena, Calif., Oct. 31, 1970.

5. Levy, Donald J., and Momyer, William R., "Advanced Antenna Meshes for Spacecraft Unfurlable Reflectors," LMSC/D307132, Lockheed Palo Alto Research Laboratory, Palo Alto, Calif., June 15, 1972.

6. Woo, K., and Otoshi, T. Y., "Spacecraft Antenna Research: An RF Study of Reflector Surface Materials for Spacecraft Antennas," in Supporting Research and Advanced Development, Space Programs Summary 37-61, Vol. III, pp. 99-106, Jet Propulsion Laboratory, Pasadena, Calif., Feb. 28, 1970.

APPENDIX A

LISTING OF FORTRAN COMPUTER PROGRAM COMESH

```
C             SHAPE OF STRETCHED CONICAL MEMBRANE WITH SPOKES
C            ------------------------------------------------
C THIS PROGRAM COMPUTES THE SHAPE OF A CONTINUOUS MEMBRANE AND A FINITE
C NUMBER OF SPOKES STRETCHED BETWEEN TWO CIRCULAR DISKS WHICH ARE THE
C LARGE AND SMALL BASES OF THE DESIRED TRUNCATED CONE.
C
C THE USER ENTERS THE FOLLOWING INFORMATION
C
C NC=NUMBER OF CASES TO BE CONSIDERED
C D1=SMALL BASE DIAMETER IN INCHES
C D2=LARGE BASE DIAMETER IN INCHES
C HA=HALF ANGLE OF CONE IN DEGREES
C WM=WEIGHT OF MEMBRANE IN POUNDS PER SQUARE FOOT
C CT=CIRCUMFERENTIAL TENSION IN MEMBRANE - LB/IN
C RT=RADIAL TENSION IN MEMBRANE - LB/IN
C NS=NUMBER OF SPOKES
C ST=SPOKE TENSION IN POUNDS
C G =G-LOAD PARELLEL TO CONE AXIS-PLUS TOWARD APEX
C N =NUMBER OF SEGMENTS INTO WHICH L IS DIVIDED
C
C THE FOLLOWING ARE A NUMBER OF VARIABLES USED IN THIS PROGRAM WHICH ARE
C NOT DEFINED ELSEWHERE.
C
C HAR =HALF ANGLE OF CONE IN RADIANS
C ERT =EFFECTIVE RADIAL TENSION IN MEMBRANE-INCLUDES SPOKE TENSION
C RCC =RADIUS OF CURVATURE OF CONE MEASURED FROM CONE AXIS PERPINDICULAR
C      TO SURFACE OF CONE
C RCM =RADIUS OF CURVATURE OF MEMBRANE MEASURED IN A PLANE THROUGH THE
C      CONE AXIS-POSITIVE IS CONCAVE IN.
C CORY=CORRECTED Y
C CORS=CORRECTED S
      REAL HA,L
      DIMENSION X(52),Y(52),CORY(52),S(52),CORS(52),RCM(52),TR(52)
      READ(5,10)NC
   10 FORMAT(I5)
   20 J=J+1
      READ(5,30)D1,D2,HA,WM,CT
   30 FORMAT(5F10.0)
      READ(5,40)RT,NS,ST,G,N
   40 FORMAT(F10.0,I10,2F10.0,I10)
      HAR=HA*3.1415926/180.
      H  =((D2-D1)/2.)/TAN(HAR)
      L  =((D2-D1)/2.)/SIN(HAR)
      P  =WM*G*SIN(HAR)/144.
      X(1)=0.0
      Y(1)=0.0
      S(1)=0.0
      NP1=N+1
      DO 50 I=1,NP1,1
```

```
      X(I+1)=X(I)+L/N
C FIND THE EFFECTIVE RADIAL TENSION AT X(I) AND X(I+1)
      ERTI=(NS*ST)/(3.1415926*(D1+2.*X(I)*SIN(HAR)))+RT
      ERTIP1=(NS*ST)/(3.1415926*(D1+2.*X(I+1)*SIN(HAR)))+RT
C FIND THE TENSION RATIO AT X(I)
      TR(I)=ERTI/CT
C FIND THE RADIUS OF CURVATURE OF THE DESIRED CONE AT X(I) AND X(I+1)
      RCCI=(D1/2.+X(I)*SIN(HAR))/COS(HAR)
      RCCIP1=(D1/2.+X(I+1)*SIN(HAR))/COS(HAR)
C FIND THE RADIUS OF CURVATURE OF THE MEMBRANE AT X(I) AND X(I+1)
      RCM(I)=ERTI/(P-CT/RCCI)
      RCMIP1=ERTIP1/(P-CT/RCCIP1)
C FIND AVERAGE RADIUS OF CURVATURE OF MEMBRANE BETWEEN X(I) AND X(I+1)
      AVRCM=(RCM(I)+RCMIP1)/2.
      A=4.*AVRCM**2-(L/N)**2
      B=-8.*AVRCM**2*S(I)-2.*(L/N)**2*S(I)
      C=4.*AVRCM**2*S(I)**2-4.*(L/N)**2-(L/N)**2*S(I)**2
C IF THE AVERAGE RADIUS OF CURVATURE BETWEEN X(I) AND X(I+1) IS POSITIVE
C THEN THE + SIGN IN THE QUADRATIC FORMULA FOR SLOPE IS USED.  IF THE
C AVERAGE RADIUS OF CURVATURE IS NEGATIVE, THEN THE - SIGN IS USED.
      IF(AVRCM.GT.0.0)S(I+1)=(-B+SQRT(B**2-4.*A*C))/2./A
      IF(AVRCM.LT.0.0)S(I+1)=(-B-SQRT(B**2-4.*A*C))/2./A
C FIND AVERAGE SLOPE OF MEMBRANE BETWEEN X(I) AND X(I+1)
      AVS=(S(I)+S(I+1))/2.
      Y(I+1)=Y(I)+(L/N)*AVS
   50 CONTINUE
      NP1=N+1
      DO 60 I=1,NP1,1
      CORY(I)=Y(I)-Y(NP1)*(X(I)/L)
      CORS(I)=S(I)-Y(NP1)/L
   60 CONTINUE
      SUM=0.0
      DO 70 I=1,NP1,1
      SUM=SUM+CORY(I)
   70 CONTINUE
      AVGY=SUM/NP1
      SUMSQ=0.0
      DO 80 I=1,NP1,1
      SUMSQ=SUMSQ+(ABS(CORY(I))-ABS(AVGY))**2
   80 CONTINUE
      RMSY=SQRT(SUMSQ/NP1)
      WRITE(6,100)
  100 FORMAT('1       SHAPE OF STRETCHED CONICAL MEMBRANE WITH SPOKES')
      WRITE(6,110)
  110 FORMAT('       ------------------------------------------------')
      WRITE(6,120)
  120 FORMAT(' THIS PROGRAM COMPUTES THE SHAPE OF A CONTINUOUS MEMBRANE
     1AND A'/' FINITE NUMBER OF SPOKES STRETCHED BETWEEN TWO CIRCULAR DI
     1SKS'/' WHICH ARE THE LARGE AND SMALL BASES OF THE DESIRED TRUNCATE
```

```
   1D CONE.'//' THE USER ENTERS THE FOLLOWING INFORMATION'/)
    WRITE(6,130)D1
130 FORMAT(' D1=SMALL BASE DIAMETER IN INCHES                 =',F9.4)
    WRITE(6,140)D2
140 FORMAT(' D2=LARGE BASE DIAMETER IN INCHES                 =',F9.4)
    WRITE(6,150)HA
150 FORMAT(' HA=HALF ANGLE OF CONE ANGLE IN DEGREES           =',F9.4)
    WRITE(6,160)WM
160 FORMAT(' WM=WEIGHT OF MEMBRANE IN POUNDS PER SQUARE FOOT  =',F9.4)
    WRITE(6,170)CT
170 FORMAT(' CT=CIRCUMFERENTIAL TENSION IN MEMBRANE - LB/IN    ',F9.4)
    WRITE(6,180)RT
180 FORMAT(' RT=RADIAL TENSION IN MEMBRANE - LB/IN            =',F9.4)
    WRITE(6,190)NS
190 FORMAT(' NS=NUMBER OF SPOKES                              =',I4)
    WRITE(6,200)ST
200 FORMAT(' ST=SPOKE TENSION IN POUNDS                       =',F9.4)
    WRITE(6,210)G
210 FORMAT(' G =G-LOAD PARALLEL TO CONE AXIS-PLUS TOWARD APEX =',F9.4)
    WRITE(6,220)N
220 FORMAT(' N =NUMBER OF SEGMENTS INTO WHICH L IS DIVIDED    =',I4)
    WRITE(6,230)
230 FORMAT(/' THE FOLLOWING QUANTITIES ARE COMPUTED'/)
    WRITE(6,240)H
240 FORMAT(' H =HEIGHT OF CONE IN INCHES                      =',F9.4)
    WRITE(6,250)L
250 FORMAT(' L =LENGTH ALONG ELEMENT OF CONE IN INCHES        =',F9.4)
    WRITE(6,260)P
260 FORMAT(' P =EQUIVALENT INTERNAL PRESSURE IN LBS/SQ.INCH   =',F9.8)
    WRITE(6,270)
270 FORMAT(/' THE SHAPE COMPUTED IS SHOWN IN THE TABLE BELOW,WHERE:'//
   1' X =COORDINATE MEASURED ALONG CONE ELEMENT WITH ORIGIN AT SMALL B
   1ASE'/' Y =COORDINATE PERPINDICULAR TO CONE ELEMENT REPRESENTING DE
   1VIATION'/'    OF MEMBRANE FROM TRUE CONE(POSITIVE TOWARD INSIDE OF
   1 CONE)'/' S =LOCAL SLOPE OF MEMBRANE'/' R =LOCAL RADIUS OF CURVATU
   1RE OF MEMBRANE'/' TR=LOCAL TENSION RATIO - RATIO OF THE RADIAL TEN
   1SION IN MEMBRANE'/'     (INCLUDING SPOKES) TO THE CIRCUMFERENTIAL T
   1ENSION IN MEMBRANE'/)
    WRITE(6,280)
280 FORMAT('/       X',11X,'Y',11X,'S',11X,'R',11X,'TR')
    WRITE(6,290)
290 FORMAT('       ---',9X,'---',9X,'---',9X,'---',9X,'----')
    WRITE(6,300)(X(I),CORY(I),CORS(I),RCM(I),TR(I),I=1,NP1,1)
300 FORMAT(F12.4,F12.6,E12.4,F12.2,F12.2)
    WRITE(6,310)RMSY
310 FORMAT(//' RMSY=ROOT MEAN SQUARE DEVIATION OF Y FROM AVG Y ='F8.5)
    IF(J.EQ.NC)GO TO 500
    GO TO 20
500 END
```

```
      SHAPE OF STRETCHED CONICAL MEMBRANE WITH SPOKES
      -----------------------------------------------
   THIS PROGRAM COMPUTES THE SHAPE OF A CONTINUOUS MEMBRANE AND A
   FINITE NUMBER OF SPOKES STRETCHED BETWEEN TWO CIRCULAR DISKS
   WHICH ARE THE LARGE AND SMALL BASES OF THE DESIRED TRUNCATED CONE.

   THE USER ENTERS THE FOLLOWING INFORMATION

   D1=SMALL BASE DIAMETER IN INCHES                        =  14.3300
   D2=LARGE BASE DIAMETER IN INCHES                        = 144.0000
   HA=HALF ANGLE OF CONE ANGLE IN DEGREES                  =  65.0000
   WM=WEIGHT OF MEMBRANE IN POUNDS PER SQUARE FOOT         =    .0150
   CT=CIRCUMFERENTIAL TENSION IN MEMBRANE - LB/IN               .0190
   RT=RADIAL TENSION IN MEMBRANE - LB/IN                   =    .0620
   NS=NUMBER OF SPOKES                                     =   0
   ST=SPOKE TENSION IN POUNDS                              =    .0000
   G =G-LOAD PARALLEL TO CONE AXIS-PLUS TOWARD APEX        =   1.0000
   N =NUMBER OF SEGMENTS INTO WHICH L IS DIVIDED           =  14

   THE FOLLOWING QUANTITIES ARE COMPUTED

   H =HEIGHT OF CONE IN INCHES                             =  30.2331
   L =LENGTH ALONG ELEMENT OF CONE IN INCHES               =  71.5375
   P =EQUIVALENT INTERNAL PRESSURE IN LBS/SQ.INCH          =.00009441

   THE SHAPE COMPUTED IS SHOWN IN THE TABLE BELOW,WHERE:

   X =COORDINATE MEASURED ALONG CONE ELEMENT WITH ORIGIN AT SMALL BASE
   Y =COORDINATE PERPINDICULAR TO CONE ELEMENT REPRESENTING DEVIATION
      OF MEMBRANE FROM TRUE CONE(POSITIVE TOWARD INSIDE OF CONE)
   S =LOCAL SLOPE OF MEMBRANE
   R =LOCAL RADIUS OF CURVATURE OF MEMBRANE
   TR=LOCAL TENSION RATIO - RATIO OF THE RADIAL TENSION IN MEMBRANE
      (INCLUDING SPOKES) TO THE CIRCUMFERENTIAL TENSION IN MEMBRANE

          X           Y            S            R            TR
         ---         ---          ---          ---          ----
        .0000     .000000      .1661+00       -60.41         3.26
       5.1098     .691419      .1045+00      -105.75         3.26
      10.2196    1.126000      .6555-01      -157.20         3.26
      15.3295    1.390555      .3800-01      -216.10         3.26
      20.4393    1.532023      .1737-01      -284.19         3.26
      25.5491    1.580017      .1411-02      -363.80         3.26
      30.6589    1.554998     -.1120-01      -458.13         3.26
      35.7688    1.471977     -.2129-01      -571.67         3.26
      40.8786    1.342458     -.2940-01      -710.96         3.26
      45.9884    1.175542     -.3593-01      -885.88         3.26
      51.0982     .978617     -.4115-01     -1112.11         3.26
      56.2080     .757801     -.4528-01     -1416.09         3.26
      61.3179     .518253     -.4848-01     -1846.24         3.26
      66.4277     .264379     -.5089-01     -2501.65         3.26
      71.5375    -.000001     -.5259-01     -3622.08         3.26

   RMSY=ROOT MEAN SQUARE DEVIATION OF Y FROM AVG Y =  .53969
```

```
        SHAPE OF STRETCHED CONICAL MEMBRANE WITH SPOKES
        -----------------------------------------------
THIS PROGRAM COMPUTES THE SHAPE OF A CONTINUOUS MEMBRANE AND A
FINITE NUMBER OF SPOKES STRETCHED BETWEEN TWO CIRCULAR DISKS
WHICH ARE THE LARGE AND SMALL BASES OF THE DESIRED TRUNCATED CONE.

THE USER ENTERS THE FOLLOWING INFORMATION

D1=SMALL BASE DIAMETER IN INCHES                     =  68.2000
D2=LARGE BASE DIAMETER IN INCHES                     = 144.0000
HA=HALF ANGLE OF CONE ANGLE IN DEGREES               =  65.0000
WM=WEIGHT OF MEMBRANE IN POUNDS PER SQUARE FOOT      =    .0150
CT=CIRCUMFERENTIAL TENSION IN MEMBRANE - LB/IN            .0190
RT=RADIAL TENSION IN MEMBRANE - LB/IN                =    .0620
NS=NUMBER OF SPOKES                                  = 120
ST=SPOKE TENSION IN POUNDS                           =   4.0000
G =G-LOAD PARALLEL TO CONE AXIS-PLUS TOWARD APEX     =    .0000
N =NUMBER OF SEGMENTS INTO WHICH L IS DIVIDED        =  14

THE FOLLOWING QUANTITIES ARE COMPUTED

H =HEIGHT OF CONE IN INCHES                          =  17.6731
L =LENGTH ALONG ELEMENT OF CONE IN INCHES            =  41.8180
P =EQUIVALENT INTERNAL PRESSURE IN LBS/SQ.INCH       =.00000000

THE SHAPE COMPUTED IS SHOWN IN THE TABLE BELOW,WHERE:

X =COORDINATE MEASURED ALONG CONE ELEMENT WITH ORIGIN AT SMALL BASE
Y =COORDINATE PERPINDICULAR TO CONE ELEMENT REPRESENTING DEVIATION
   OF MEMBRANE FROM TRUE CONE(POSITIVE TOWARD INSIDE OF CONE)
S =LOCAL SLOPE OF MEMBRANE
R =LOCAL RADIUS OF CURVATURE OF MEMBRANE
TR=LOCAL TENSION RATIO - RATIO OF THE RADIAL TENSION IN MEMBRANE
   (INCLUDING SPOKES) TO THE CIRCUMFERENTIAL TENSION IN MEMBRANE

       X            Y            S            R            TR
      ---          ---          ---          ---          ----
     .0000       .000000      .2117-02    -9777.22      121.17
    2.9870       .005869      .1812-02    -9798.12      112.50
    5.9740       .010828      .1508-02    -9819.02      105.02
    8.9610       .014877      .1204-02    -9839.92       98.49
   11.9480       .018021      .9006-03    -9860.83       92.76
   14.9350       .020259      .5980-03    -9881.73       87.67
   17.9220       .021594      .2961-03    -9902.63       83.13
   20.9090       .022029     -.5230-05    -9923.53       79.05
   23.8960       .021564     -.3059-03    -9944.44       75.38
   26.8830       .020202     -.6060-03    -9965.34       72.04
   29.8700       .017945     -.9054-03    -9986.24       68.99
   32.8570       .014794     -.1204-02   -10007.14       66.21
   35.8440       .010752     -.1502-02   -10028.05       63.65
   38.8310       .005820     -.1800-02   -10048.95       61.29
   41.8180      -.000000     -.2097-02   -10069.85       59.11


RMSY=ROOT MEAN SQUARE DEVIATION OF Y FROM AVG Y =  .00746
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APPENDIX B

WEIGHT BREAKDOWN FOR 3.66-M (12-FT) CONICAL REFLECTOR*

Support frame	Newtons	(Pounds)
Outer ring, including splice plates	11.43	(2.57)
Tubular truss members	74.46	(16.74)
Fittings at panel points, including rivets	33.18	(7.46)
Inner hub	7.56	(1.70)
Fasteners, bolts at builtup joints	7.38	(1.66)
Reflector attachment clips at outer ring, including mounting hardware	9.39	(2.11)
Intermediate reflector support ring, including mounting hardware	1.82	(0.41)
Sheet metal inner core	2.31	(0.52)
Miscellaneous	4.45	(1.00)
Subtotal	151.98	(34.17)
Reflector		
Nickel/chromium knitted mesh	8.72	(1.96)
Fiberglass edge trim tape	.97	(0.22)
Fiberglass sewing thread	.27	(0.06)
PRD -49 (Kevlar) spokes	.40	(0.09)
Subtotal	10.36	(2.33)
Total for support frame and reflector	162.35	(36.50)

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*The weight breakdown included here is for the complete antenna reflector assembly. It does not include the spacecraft adapter, the line source feed, or flight-like provisions for supporting the feed.

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