A FOLDABLE 4.27-METER (14 FOOT) SPACECRAFT ANTENNA

By Donald J. Starkey*

ABSTRACT

The problems and solutions associated with the design, fabrication, and testing of a large, lightweight, radial-rib, folding, spacecraft antenna reflector are discussed in this report. The antenna reflector was designed as a highly efficient communications system for outer-planet missions extending as far as approximately 59.839×10^{11} meters (40 astronomical units) from the sun. The methods used to obtain a lightweight precision rib surface, the evaluation and fabrication of the metallic reflector mesh surface, and the surface-evaluation techniques used on the assembled antenna reflector are included in this report.

INTRODUCTION

The design, analysis, fabrication, assembly, and testing of a lightweight, foldable, radial-rib, parabolic antenna reflector was undertaken to establish that the weight and volume requirements of future outer-planet missions could be met while maintaining antenna-surface accuracy to comply with the communications criteria. The primary effort was concentrated on the mesh-covered area of the reflector because that area comprised the majority of the total reflector surface. An analytical prediction and the subsequent verification of the mesh surface (when it was subjected to the interactions inherent in the antenna design) were included. The structural, gravitational, and thermal interactions on the mesh surface also were analyzed.

DESIGN REQUIREMENTS

The need for a highly efficient antenna design became evident during an outer-planet-mission study early in 1969, when the following design requirements were placed on the antenna reflector.

1. Weight: 16.8 kilograms (37 pounds)
2. Deployed diameter: 4.27 meters (14 feet)
3. Stowed diameter: 1.57 meters (62 inches)

---

*Jet Propulsion Laboratory, Pasadena, Calif.

4. Stowed height: 1.98 meters (78 inches)

5. Feed access: 0.61 meter (24 inches)

6. Surface accuracy: 0.89 millimeter root mean square
(0.035 inch root mean square)

7. Deployment: one-g field

8. Temperature range: 366.45° to 33.15° K
(93.3° to -240° C)

9. Focal length/diameter: 0.42

10. Natural frequency: 8-hertz lateral
3-hertz torsional

11. Gain: 49 decibels

12. Feed system: Cassegrainian

ALTERNATIVE CONCEPTS

An industry search was initiated in 1969 to determine the antenna designs that were available to fulfill the design requirements. Two designs considered were an antenna flex-rib and an expandable-truss antenna. The flex-rib, radial-rib-type antenna is folded by wrapping the carpenter-tape-shaped ribs and copper-plated Dacron reflector mesh circumferentially around the hub. The extendable-truss design has many triangular, deep-truss modules that are hinged at and fastened together with spider joints. This design involves the use of a Chromel-R mesh that is fastened to the concave side of the truss network by means of a system of cables and springs.

An evaluation of these antennas concluded that either could fulfill most of the future outer-planet needs. Both antennas provided limited feed-access area, and the flex-rib design appeared to have a lower natural frequency than required in the torsional mode. Because both antennas would have required an extensive developmental effort to satisfy all requirements, they were not considered further.

A third antenna design (the radial rib) was then investigated. This design evolved from an antenna that was proposed for a Mariner vehicle in the early 1960's. The radial-rib-antenna design satisfied all the requirements and provided a good base on which to check the evaluation analysis of the surface conformance of any parabolic antenna. When the design details for the radial-rib antenna were completed, it was discovered that a company concerned with radiation research had also designed and built a similar radial-rib antenna that had a small hub and constant-section tubular radial ribs that are folded forward around the feed. Because investigation showed that that antenna would have also required extensive redesign in the hub area to meet the design requirements, the Jet Propulsion Laboratory version was pursued.

RADIAL-RIB ANTENNA

Hub

The Jet Propulsion Laboratory radial-rib-antenna-reflector structural configuration (fig. 1) was based on a stiff central hub. This hub provides the hinge support points and the rib adjustment surfaces for the 48 radial ribs, together with the mounting surface for the central dish, the deployment mechanism, and the forward subdish support structure. The outer-planets spacecraft configuration required that the antenna be offset from the spacecraft geometric centerline to correct a center-of-gravity imbalance. Accounting for this antenna offset, the hub diameter was sized at 1.37 meters (54 inches), which held the folded antenna components inside the given envelope. It was advantageous to use a large central dish because it would be far easier to build a large, precise, central-dish surface instead of having to control the mesh-covered surface. In addition, the hub size had to be reasonably large to provide for the 0.61-meter (24 inch) central feed-access hole. Also, the minimum hub circumferential length had to be large enough to allow assembly space for the 48 rib hinges. Sizing the hub, using these criteria, provided sufficient volume for the rib-deployment mechanism that was selected.

Ribs

The hub sizing and the deployed antenna diameter provided the end points for determining the rib lengths. Accounting for the parabolic contour, the final rib length was 1.56 meters (61.58 inches). The aluminum ribs (fig. 2) were formed from a round, tubular cross section as a trade off between the structural and thermal requirements. Because this antenna was to be pointed at a continually receding sun, the thermal-design group preferred flat, thin-plate ribs to minimize thermal gradients that would in turn reduce the thermal distortions. The structure-analysis group preferred greater depth than width to increase the stiffness of the ribs in the highest-stress direction. The round, aluminum, tubular cross section was chosen as a compromise that would keep the thermal gradients through the ribs and the resulting thermal distortions within an acceptable level. It also provided the ribs with adequate structural stiffness to withstand the handling and flight loads.

For weight reduction and structural efficiency, the rib diameters were tapered from 2.79 centimeters (1.10 inches) at the hub to 0.95 centimeter (0.375 inch) at the outer end. This tapered-tube configuration, while being structurally efficient, provided an almost insurmountable fabrication problem. The 0.51-millimeter-wall (0.020 inch) aluminum tubes were passed through a compressive roller die in five separate steps to obtain the full taper, which produced many dogleg bends and apparently extensive surface defects. Upon completion of the initial tapering process, a precise internal mandrel was placed inside the tapered tubes and the compressive roller die was again passed over the full length of each tube. The result was a perfectly tapered straight tube. An etching process removed the surface defects, which were very small, and the final tubes were perfect.

It became evident early in the rib-development program that it would be very difficult and extremely costly to contour a tapered tubular rib to a precise ±0.25-millimeter (0.010 inch) parabolic shape. The solution that evolved was to add a machinable surface to the concave side of the tubular rib, once the rib had been contoured by hand to within 0.29 centimeter (0.125 inch) of the nominal parabolic shape. This machinable surface was an inverted T-section fastened to the tubular rib. The T-section was then machined to a precise contour in a horizontal mill while the rib assembly was held in as close to a free state as possible. The result of this precision contouring operation was that, in the worst case, the rib shape was less than 0.15 millimeter (0.006 inch) from nominal.

The 48 radial ribs and hub provide the principal structural support for the total reflector-surface area. Therefore, most of the structural and thermal analysis was concentrated on the hub and ribs.

Mesh Evaluation

The material chosen to cover the radial-rib area of the reflector was a gold-plated Chromel-R yarn formed into a mesh using a tricot weave. This mesh material is commonly used as the reflective surface in lightweight folding antennas. The mesh material has many problems for space applications but was chosen primarily because of its availability. The Chromel-R material is readily available in fine filament form because it is commonly used in wire-wound resistors and it has a very high strength (180 klb/in^2). The wire filaments can be formed into several yarns. The one chosen for this application had seven wires per strand. The available tricot-mesh patterns also vary. A mesh pattern of 7 ends/inch appeared to be cost effective for this application. The unplated Chromel-R mesh, as woven, has a much higher radio-frequency (RF) loss (0.3 compared with 0.1 decibel) than was required to meet the RF efficiency goal. To reduce the RF losses in the mesh to an acceptable level (0.1 decibel), the mesh was electroless gold plated, temporarily solving the mesh RF loss problem but creating a materials problem.

The electroless gold is very brittle and will not adhere to the passive Chromel-R wire. When the mesh is flexed during fabrication and antenna furling, the gold cracks and tends to flake off, reducing the RF efficiency of the mesh slightly in addition to creating a contamination problem. Several alternatives were investigated to solve the gold-flaking problem. The first was using electrolytic gold plating. The applied gold from this process is quite ductile but still does not adhere to the Chromel-R. This increased ductility reduced the gold cracking and subsequent flaking but was still considered unsatisfactory. A second alternative involved materials that had low RF losses without being plated. Several precious-metal alloys were woven into a mesh and tested for RF reflection losses. One silver-base material most nearly met the RF reflection criteria but was not readily available in large quantities and had a somewhat lower strength, which could result in greater mesh-surface deviations.

Tests were performed on the gold-plated Chromel-R mesh to establish its physical properties for the antenna-surface analysis. Such data as the effective Young's modulus of the mesh, stiffness, strength, and thermal expansion were needed to analyze and predict the mesh shape when it is placed on the antenna ribs. Because of the compliant nature of the mesh and the interaction between the two orthogonal directions, these physical characteristics were difficult to determine. Instead of precise quantities, ranges were established for most of the unknowns, which proved sufficient for analyzing the mesh shape.

Tests were run to establish the desired tension field for the mesh by tensioning the mesh to various values in the two orthogonal directions and checking the RF reflection efficiency, in addition to the mechanical out-of-plane distortions. Once the mesh tension range was established, the next problem was to determine a ratio between the two orthogonal tensions that would result in the least geometric surface error and still not adversely deflect the ribs. The ratio was set at 1 to 3, low in the radial direction and high in the circumferential direction. The higher the tension ratio, the lower the geometric surface error. In actuality, the circumferential tension is limited on the upper end by deformation in the mesh loops, thereby reducing or eliminating the compliant feature of the mesh, which could result in large local thermal distortions. The radial lower tension limit is also bounded because the mesh surface has a tendency to wrinkle as this value is reduced.

Mesh Reflector Fabrication

Once the tension ratio was established, the fabrication of the mesh skirt was begun. The uncut mesh panels were stretched over a rectangular frame. The pattern was marked on the stretched mesh, and the gores were cut out. The marked edges were matched and then fastened together by sewing. Sewing techniques were developed using both a metallic and an organic thread. The metallic thread is a must for long-term space missions. The poor availability of a good-quality metallic thread that was compatible with a specially modified sewing machine made development of this technique difficult. The only metallic thread that finally proved satisfactory had a Teflon coating. Both the metallic and organic sewing techniques were used to assemble the full mesh skirt. The skirt was then stretched to match the ribs, and, once the match was made, the tension ratio was again at the proper value.

Deployment Mechanization

Several deployment mechanization schemes were studied: a drum, pulley, and cable mechanism; several bar-linkage arrangements; and an individual rib-deployment design. The linkage-and-cable devices were abandoned because of their complexity and the limitation that they remain almost wholly within the hub envelope. The individual rib-deployment scheme was incorporated; it consisted of a pair of constant-force springs located at each rib (fig. 3).

ANALYSIS

The analysis effort was concentrated on the reflector-surface evaluation and was initiated by developing a computer program that would mathematically describe the antenna-reflector surface. The analysis was continued by estimating the error sources, determining the thermal effects, and establishing the deployment dynamics. The reflector surface to be analyzed was composed of a compliant mesh material that was placed in biaxial tension and supported by a semistiff parabolic structure.

Reflector Surface

The variable inputs to the reflector-surface evaluation program are the mesh tensions, major and minor diameters, numbers of support elements (ribs), and the geometric shape of the rib elements. The program was designed to optimize all these elements so that the final antenna-reflector surface would have the lowest possible geometric surface error. The computer program begins with a parabolic-rib support structure and modifies the rib shape to minimize the mesh pillowing effect (geometric surface error). This process is continued until a minimum surface deviation is achieved. The mesh tension is then removed mathematically by the program while accounting for the rib-support structural stiffness, and the resultant is the rib free-state manufacturing geometry. This analysis has been verified through the use of antenna-segment test fixtures that provide for membrane tension variations and will accommodate any compliant membrane material. The program, when applied to the 4.27-meter (14 foot) 48-rib antenna, yielded a maximum geometric error of 0.57 millimeter root mean square (0.022 inch root mean square).

Error Analysis

An error analysis was developed early in the design of this antenna. The error budget was established as a design goal and appeared to be reasonable. At that time, a 0.51 millimeter root mean square (0.020 inch root mean square) was assigned as the geometric error. The remainder of the errors were assigned maximum values and were root mean squared to determine the resultant surface error. The number assigned to the mechanical rib-surface deviations was ±0.25 millimeter (0.010 inch); for deployment repeatability, ±0.25 millimeter (0.010 inch); and for thermal distortion, 0.13 millimeter (0.0005 inch). All these numbers were determined on the basis of experience with prior error magnitudes associated with similar components on past developments. These errors were combined as follows to provide the following surface accuracy capabilities.

$$\Sigma = 0.51 \text{ mm} + \left[(0.25)^2 \text{ mm} + (0.25)^2 \text{ mm} + (0.13)^2 \text{ mm}\right]^{1/2} = 0.89 \text{ mm}$$

$$\Sigma = 0.020 \text{ in.} + \left[(0.010)^2 \text{ in.} + (0.010)^2 \text{ in.} + (0.005)^2 \text{ in.}\right]^{1/2} = 0.035 \text{ in.} \quad (1)$$

Thermal Analysis

The antenna was developed for a mission that proceeds into deep space away from the earth and sun. This type of trajectory would result in an antenna temperature of approximately 366.15° K (93° C) near earth and then it would be cooled steadily to a temperature of 33.15° K (-240° C) near Neptune. This temperature condition was complicated because directly behind the antenna and at one edge of the spacecraft was located a group of radioisotope thermoelectric generators, which have a surface temperature of 533.15° K (260° C). As the spacecraft travels farther away from the sun, the radioisotope thermoelectric generators have a more pronounced thermal effect on the antenna. By the time the spacecraft is approaching Neptune, the thermal gradient across the antenna dish could be as large as 513.15° K (240° C), resulting in thermal distortions and subsequent surface deviations significantly above the acceptable values. The solution was to place a multilayer, superinsulation thermal blanket behind the dish to thermally isolate it from the generators. In addition to the generator isolation, the thermal blanket reduced the thermal gradient through the depth of the ribs by providing reflected solar energy to heat the back sides.

The thermal analysis, assuming a thermal blanket covering all the back of the reflector, resulted in a maximum antenna-surface distortion of 0.18 millimeter (0.007 inch) throughout the mission, which could be further reduced to almost zero by an inflight focal-point movement of 2.8 millimeters (0.11 inch). The focal-point movement is equivalent to best fitting a new parabola through the distorted antenna surface.

Deployment Analysis

The deployment dynamic analysis was initiated using the redundant constant-force springs as a given parameter. These springs were sized so that each would deploy a rib and mesh against gravity from a vertically downward orientation to a horizontal position. Once each rib had a pair of these springs applying the full deployment force and the antenna was positioned so that the ribs had a gravitational assist, the deployment velocity was much too great. The analysis showed that the yield strength of the ribs would be exceeded at the instant they hit the stops on the hub. Reducing the spring force or removing the redundancy was considered as a solution, but this was inconsistent with the project requirements. However, the final solution was to add a rotary-shear viscous damper on every fourth rib. This damper was designed and built and reduced the deployment velocity to an acceptable level.

OPERATION

Surface Evaluation

The operational phase of antenna development initially included three parts: RF testing, surface adjustment, and deployment repeatability.

Radio-Frequency Testing

A brief study revealed two primary concerns associated with RF testing: (1) the unsymmetrical rib deflections in the gravitational field and (2) the wind load deflections. Any analytical predictions for these effects would have to be verified through extensive testing that would be time consuming and, therefore, costly. These predictions were not fully evaluated. The wind deflection could be eliminated through the use of an RF transparent dome, and the gravitational droop could be alleviated through the use of a special support structure. This special test equipment was not available at the Jet Propulsion Laboratory, and the constraining support structure, if used, could lead to higher RF efficiencies than are obtainable in space. Because this type of testing at the Jet Propulsion Laboratory would be wasteful of resources, the whole RF testing idea was eliminated.

Surface Adjustment

Because a fixture had been assembled to adjust the antenna surface, it seemed reasonable to try to measure the antenna-surface deviations with the same fixture. Once the rib tips were positioned mechanically, a proximity sensor was installed on the fixture to measure the surface variations. The data reduction from this operation proved to be very unsatisfactory. A closer evaluation showed that the proximity sensor not only measured the air-gap variations but also the variations in the gold-plating quality. A second mechanical measurement was tried using a dial indicator. This scheme also proved to be unsatisfactory because the pressure from the dial indicator deflected the rib and mesh surface in varying degrees. It became evident that one way an antenna surface could be measured to within the required precision was through a noncontacting process such as photogrammetry. This type of measurement technique has another advantage in that the antenna surface can be measured in the face-up and face-down position; and, by averaging these two measurements, the gravitational distortions are theoretically reduced to zero. This technique was not pursued because of budgetary limitations. A third measuring technique, using a depth micrometer and an electrical-contact indicating device, was used with good results. This measuring system is limited in that it is only good for determining the antenna-surface deviations in one orientation.

Deployment Repeatability

Because of the low sensitivity of the initial measurement system, it seemed almost impossible to get a precise number for the deployment repeatability. The initial deployment tests resulted in rib-tip deviations in the 1.27- to 2.54-millimeter (0.050 to 0.100 inch) range. An investigation showed that in addition to the measurement problem, two mechanical conditions caused these large variations. The constant-force deployment springs were inadvertently positioned so that when the ribs were fully opened and adjusted, the spring force was nearly zero (small preload). Secondly, the hub cone seats for the rib adjustment screws had some mechanical deviations that kept the ribs from fully seating against the stops. Once these conditions were corrected and the micrometer measuring system was used, the rib-deployment repeatability tests provided deviations in the 0.25-millimeter (0.010 inch) range as predicted.

CONCLUDING REMARKS

Designing, building, and testing the 4.27-meter (14 foot), lightweight, folding antenna reflector verifies that the technology exists to fulfill the future outer-planet-mission requirements. The design uses a compliant mesh material in conjunction with a semi-stiff support structure. This concept has several advantages. The surface distortion resulting from unsymmetrical surface heating is all but eliminated, the mesh provides a very low-weight-per-unit area reflector material, the mesh folds up easily and does not take a permanent set, and varying the mesh tension over a wide range does not result in significant surface distortions. The antenna described has the capability of satisfying the initial set of outer-planet requirements. By incorporating a false-rib technique in the design, the total surface error could probably be reduced by half. A complete surface evaluation was curtailed because of a subsequent reduction in the estimated future planet communication requirements.

DISCUSSION

J. K. Riedel:

You mentioned that tapering the ribs caused a problem. What was the problem and, in view of the problem, would you recommend not tapering the ribs?

Starkey:

The problem was a result of the taper per unit length in conjunction with a wall-thickness decrease. The degree of taper per unit length using aluminum tubing turned out to require the use of a new process. Similar tapering had been performed many times in the past on stainless-steel tubing with excellent results; however, the aluminum required that a completely new manufacturing technique be worked out. The technique for tapering aluminum tubes from 1.1 inch in diameter down to 0.38 inch in diameter in 61.5 inches of length has now been developed and it provided excellent results. I would not hesitate to recommend the tapered tubes for any similar application now that the manufacturing technique has been developed.

W. A. Stewart:

Please indicate the maximum deviation in the surface. Also, please indicate the relationship among deviation permitted, rib spacing, and the antenna frequency.

Starkey:

The maximum deviation was approximately 0.070 inch. This antenna was designed for a frequency of 8.4 GHz. The rib spacing or number of ribs directly affects the surface deviations. The greater the number of ribs, the more precise the resulting surface. This design required 48 ribs to obtain a geometric surface deviation of 0.020 inch root mean square.

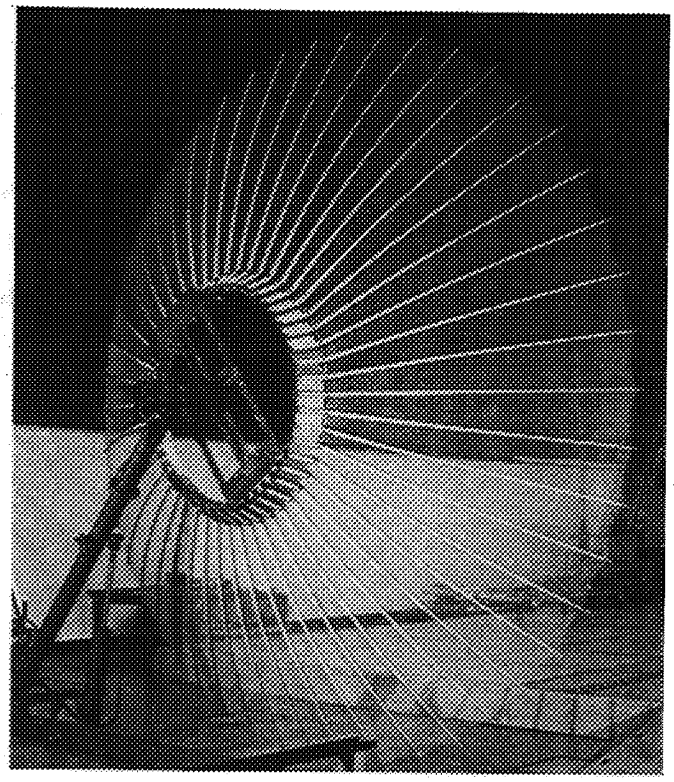

Figure 1. - Antenna reflector.

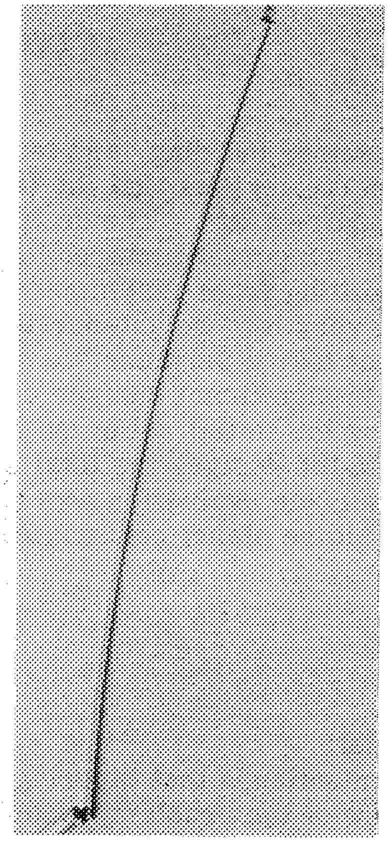

Figure 2. - Antenna rib.

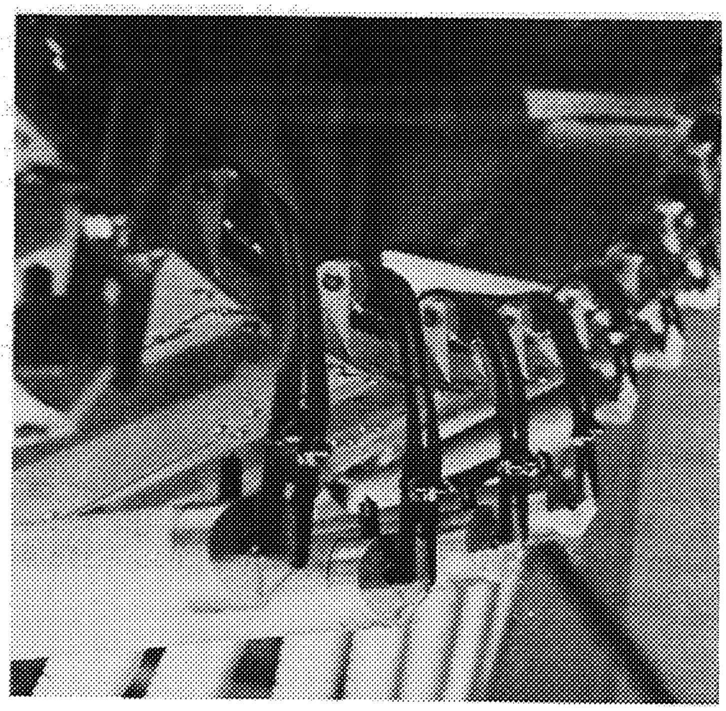

Figure 3. - Deployment mechanism.