DEPLOYABLE REFLECTOR DESIGN
FOR
KU-BAND OPERATION
NAS1-11444
SEQUENCE NUMBER 4317-01
PREPARED FOR
LANGLEY RESEARCH CENTER
PREPARED BY
ELECTRONIC SYSTEMS DIVISION OF
HARRIS CORPORATION
P.O. BOX 37
MELBOURNE, FLORIDA 32901
SEPTEMBER, 1974
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SECTION 1.0

INTRODUCTION
1.0 INTRODUCTION

In the past, operation at Ku-band frequencies (11 to 18 GHz) was considered possible only with solid surface reflectors due to surface tolerance requirements. However, the packaging and weight restrictions of such reflectors limit their practicality in the larger sizes, particularly where severe volume limitations are imposed. The objective of this program was to extend the deployable antenna technology state-of-the-art through the design, analysis, construction, and testing of a lightweight (31 pounds maximum with a 25 pound goal) high surface tolerance (0.020 inches rms surface error) 12.5-foot diameter reflector for Ku-band operation. A secondary objective of the program was to ensure, to the extent possible, the applicability of the reflector design to the Tracking and Data Relay Satellite (TDRS) Program.

This final report presents a complete documentary of the total program. The remainder of this section presents a results summary. Section 2.0 describes the performance requirements used to guide and constrain the design. Section 3.0 presents a detailed description of the design. Section 4.0 presents RF, structural/dynamic, and thermal performance results and includes analysis/test correlation where applicable. Section 5.0 discusses the applicability of the reflector design to the TDRS Program. Section 6.0 presents the conclusions and recommendations of the program. Appendices are utilized to provided detailed test data and the detailed fabrication drawings for the reflector.

Results Summary

The reflector design is illustrated in Figure 1.0-1. The parabolic reflective surface consists of 12, 1.5-inch diameter, tubular aluminum ribs which shape and support the metallic mesh. The choice of 12 ribs was based on a trade-off study considering weight, surface tolerance, and deployed dynamic performance. The "double mesh" technique is used to obtain the high surface accuracy required for Ku-band operation. This technique consists of two mesh surfaces which are separated by the rib thickness and tee bars and connected by tensioned metallic ties. By properly tensioning the connecting tie wires, the reflector surface (front mesh) can be contoured to a precision parabolic shape.

The conical feed support structure is the primary structural member of the stowed antenna. A conical structure was chosen because, in this application, the RF aperture blockage is no more severe than that of a spar support and the conical structure is more efficient than a spar system from weight and structural standpoints. A dielectric ogive radome is provided as an enclosure for the RF feed. The ogive geometry was selected because of its high electrical efficiency over other geometries.

The stowed antenna is restrained by top and midsection restraint systems which force the stowed antenna to act as a single stiff structural member, thereby providing a high stowed resonant frequency. The reflective surface is deployed at a controlled rate by the mechanical deployment system (MDS) (Figure 1.0-2). The MDS consists of a disc-shaped carriage mounted to the moving section of a recirculating ball nut on a ball screw shaft. The carriage and the ribs are connected by linkages that transmit the force and motion required for deployment to the ribs. Redundant drive system power is supplied to the ball screw by a spring motor and...
Figure 1.0-2. The Mechanical Deployment System (MDS) Provides Controlled Deployment, Redundant Drive Power, and Is Self-Locking in the Deployed Condition.
Figure 2.2. 12.5 Foot Reflector
two electric torque motors. The probability of successful reflector deployment is 0.993 as based on test data from this and previous programs. The controlled deployment rate eliminates the transfer of any deployment forces to the spacecraft and also prevents impact loading of the ribs and mesh, thus, assuring the preset parabolic surface is not distorted by the deployment action. Repeatability of the reflector surface over successive deployments was measured as ±0.002 inches rms (see Appendix B).

The measured weight of the completed reflector (reflective surface, feed support, and deployment system) is 26.2 lbs. Previous technology would have resulted in a total weight of no less than 40 lbs.

The projected surface error under worst-case orbital conditions is 0.022 inches rms as shown in Figure 1.0-3. The manufacturing error of 0.020 inches is a measured value. The thermal error contribution is determined by analysis (see Section 4.3). The gravity deflection error occurs in orbit once the gravity force is removed. Upon removal of the gravity force, the mesh assumes an equilibrium position different from that in the gravity field. This error is minimized by setting the reflector along horizontal radial lines where the gravity effects are essentially nullified. The surface error when the reflector is oriented in the face-side range test condition (as shown in Figure 1.0-5) is 0.030-inches rms.

<table>
<thead>
<tr>
<th>Error Source</th>
<th>Magnitude, Inches RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal</td>
<td>0.008</td>
</tr>
<tr>
<td>Manufacturing</td>
<td>0.020</td>
</tr>
<tr>
<td>Gravity</td>
<td>0.006</td>
</tr>
<tr>
<td>Total RSS Error</td>
<td>0.022</td>
</tr>
</tbody>
</table>

Figure 1.0-3. Surface Error Budget for Worst-Case Orbital Conditions

The minimum lateral frequency of the stowed reflector is 57 Hz and the minimum longitudinal frequency of the stowed reflector is 93.1 Hz. These high stowed resonant frequencies minimize deflections and structural coupling with the lower frequencies of excitation introduced by the launch vehicle. They also allow the reflector to be structurally qualified as a component in dependent of the total spacecraft. The minimum resonant frequency of the deployed reflector is 8.3 Hz. This high deployed resonant frequency ensures minimal structural coupling of the deployed reflector with the spacecraft attitude control system or with other large flexible structures, e.g., antenna support booms, solar panels, etc. Figure 1.0-4 shows the test configurations during stowed and deployed vibration testing of the reflector.

Figure 1.0-5 shows the RF test arrangement for the reflector. Figures 1.0-6 and 1.0-7 show the measured reflector patterns at 2 GHz and 15 GHz respectively. Figure 1.0-8 summarizes the RF range gain measurement results.
Stowed Vibration Test Configuration

Deployed Vibration Test Configuration

Figure 1.0-4. High Stiffness in the Stowed and Deployed Conditions Allows Qualification of the Reflector as a Component
Figure 1.0-5. RF Range Measurements Validate Ku-Band Performance
Figure 1.0-7. Reflector Patterns at 2.1 GHz
### Gain

<table>
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<tr>
<th>FREQUENCY</th>
<th>AAFE&lt;sup&gt;1&lt;/sup&gt;</th>
<th>TDRS&lt;sup&gt;2&lt;/sup&gt;</th>
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<tr>
<td>2.1 GHz</td>
<td>35.3 dB</td>
<td>35.3 dB</td>
</tr>
<tr>
<td>15.0 GHz</td>
<td>51.5 dB</td>
<td>51.9 dB</td>
</tr>
</tbody>
</table>

<sup>1</sup> Measured gain in gravity

<sup>2</sup> Projected orbital gain

**Conclusion:**

RF performance is adequate to meet TDRS requirements.

---

Figure 1.0-8. Gain Measurement Summary at S- and Ku-Band
SECTION 2.0

DESIGN PERFORMANCE REQUIREMENTS
2.0 DESIGN PERFORMANCE REQUIREMENTS

This section presents the basic performance requirements, constraints, and philosophies considered essential in the 12.5-foot diameter model antenna development to ensure a coordinated electrical/structural/mechanical design.

Contained in this section are the following:

a. Applicable documents and definition of terms
b. Basic objectives and philosophy of design
c. Conditions and environments for which the antenna is analyzed and designed
d. Load requirements and other factors used for design
e. Environmental and stiffness criteria
f. Weight and balance criteria
g. Structural/mechanical performance requirements
h. Electrical performance criteria

2.1 Applicable Documents

The following documents of the issue and date indicated form a part of these requirements to the extent specified herein. In the case of conflict between this document and the documents referenced herein, this document governs:

MIL-HDBK-5B Metallic Materials and Elements for Aerospace Vehicle Structures


2.2 Design Philosophy and Definition of Terms

2.2.1 Design Philosophy

Nonflight conditions and environments influenced the design to the minimum extent. Where practicable, means were devised for assembling, handling, transporting, and storing which do not require an increase in the flight weight over that for the flight conditions.

The allowable stress values and materials properties used to substantiate the performance of the antenna were obtained from MIL-HDBK-5B or from test values when appropriate. Strength allowables and other mechanical properties are consistent with the loading conditions, design environments, and stress states for each structural member.

The materials of construction were chosen for compatibility with the space environment. Materials with low levels of outgassing have been utilized.

2.2.2 Structural Design Procedures

The following procedures, material allowables, and strength requirements were used as guidelines for all structural design and analysis. Procedures for all stress calculations are consistent with those in MIL-HDBK-5B.

2.2.2.1 Definition of Terms

Limit Loads - The maximum loads the antenna is expected to experience for the design condition under consideration

Yield Design Loads - Limit loads multiplied by the yield design load factor of safety

Ultimate Design Load - Limit loads multiplied by the ultimate design load factor of safety

2.2.2.2 Allowable Stress Values

For antenna members that are critical in buckling, the minimum guaranteed properties (A values in MIL-HDBK-5B) and minimum thicknesses were used for stress calculations. For all other conditions, the minimum guaranteed properties and the nominal thickness were used.
### 2.2.2.2 Margin of Safety

To achieve a lightweight structure, the antenna is designed to attain the smallest practical margin of safety greater than zero, except where stiffness requirements dictate additional structure. The following structural elements, which are susceptible to random type failures due to manufacturing and load distribution inconsistencies, were restricted to have the following margins of safety:

<table>
<thead>
<tr>
<th>Antenna Part</th>
<th>Minimum Margin of Safety</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fasteners in Shear</td>
<td>+.15</td>
</tr>
<tr>
<td>Bolts in Tension</td>
<td>+.50</td>
</tr>
<tr>
<td>Fittings</td>
<td>+.15</td>
</tr>
<tr>
<td>Lugs</td>
<td>+.25</td>
</tr>
<tr>
<td>Welds and Brazed Joints</td>
<td>+.50</td>
</tr>
<tr>
<td>Epoxied Joints</td>
<td>+.75</td>
</tr>
</tbody>
</table>

In determining the margin of safety, the effect of combined loads or stresses was considered.

### 2.2.2.3 Factors of Safety

The following factors of safety were applied to the limit loads to obtain the structural design loads.

- Yield Design Load: 1.15
- Ultimate Design Load: 1.25

### 2.2.2.4 Fatigue Considerations

The structural design of the antenna accounts for the effects of repeated loads. Efforts were made to avoid residual stresses and stress concentrations wherever possible.
2.2.2.5 Component Preload Requirements

All joints which depend upon preload for adequate performance are designed with sufficient preload such that no mechanical separation occurs due to limit loads.

2.3 Performance Requirements

This section describes those performance requirements used as a guideline for developing the design. Whenever possible these requirements were based on the Tracking and Delta Relay Satellite mission. As such, launch via a Delta 2914 booster and a synchronous equatorial orbit was assumed.

2.3.1 Weight and Packaging

The 12.5-foot diameter test model weight is not to exceed 31.0 pounds. A weight design goal of 25 pounds was established. The test model includes the following items: rib-and-mesh reflector, feed support structure and radome, mechanical deployment system and central hub, and the launch restraint system.

Maximum packaging envelope dimensions are not to exceed those defined by a right circular cylinder of 75 inches height and 30 inches diameter.

2.3.2 Reflector Tolerance

The antenna gain loss due to reflector surface error shall not exceed 0.50 dB at 15 GHz for a nominal sun angle of 60 degrees to antenna boresight axis. This requirement limits the maximum rms surface error to 0.020 inch.

The antenna gain loss due to feed defocusing for a nominal sun angle of 60 degrees to antenna boresight shall not exceed 0.50 dB at 15 GHz with 0.25 dB budgeted to linear displacement and 0.25 dB budgeted to beam mispointing. The maximum allowable linear displacement tolerance and feed offset angle to achieve this gain loss specification are:

- Axial defocusing 0.15 inch
- Feed offset angle 0.7°

2.3.3 Reflector f/D

Since no specific mission requirements dictated an f/D value, a trade-off study was conducted to develop a representative value. The evaluation of the f/D ratio involved consideration of three areas: electrical performance, stowed volume, and launch stiffness.
For general application, both broadband and narrowband, the optimum f/D from an electrical standpoint falls between 0.35 and 0.5 with 0.4 a good nominal value.

The maximum physical length of the stowed antenna as described in Paragraph 2.3.1 places an upper bound on the f/D and, likewise, the maximum diameter of the stowed antenna (as per Paragraph 2.3.1) places a minimum bound on the f/D.

For launch (resonance) performance a low value of f/D is desirable to reduce the stowed antenna height.

Based on the above considerations, an f/D range of 0.38 to 0.42, with a nominal value of 0.417 was chosen as a median value satisfying all limiting conditions.

2.3.4 Structural Design Requirements

The launch environment and qualification test requirements for the Delta booster are comprehensively described in Reference 1. The dynamic environment is defined at the interface between the booster and the spacecraft. This information was used to establish environmental design criteria for the antenna.

The TDRS spacecraft is, at this time, not adequately defined to allow an estimate of the transmission of energy through the spacecraft to the antenna. Because of this, the values given in Reference 1 were increased by an appropriate amount to account for unknown effects of the spacecraft. The resulting design criteria for the antenna are given in Table 2.3.4.

<table>
<thead>
<tr>
<th>Antenna Configuration</th>
<th>Antenna Axis</th>
<th>Fundamental Frequency, Hz</th>
<th>Maximum Vibration Response G Ultimate</th>
<th>Maximum Shock Response G Ultimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stowed</td>
<td>Lateral</td>
<td>40</td>
<td>25</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>Longitudinal</td>
<td>90</td>
<td>35</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>Torsional</td>
<td>15</td>
<td>--</td>
<td>10</td>
</tr>
<tr>
<td>Deployed</td>
<td>Lateral</td>
<td>4.5</td>
<td>2.2</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>Torsional</td>
<td>4.0</td>
<td>2.0</td>
<td></td>
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</table>
The minimum launch frequency requirements for the spacecraft are 40 Hz and 25 Hz in the longitudinal and lateral directions, respectively. The antenna is a component of the spacecraft and requires higher values. The values of 90 Hz and 40 Hz in the longitudinal and lateral directions for the stowed antenna are considered typical values based on the spacecraft requirements. No torsional frequency requirement is given in Reference 1. A value of 15 Hz minimum torsional frequency for the stowed antenna was assigned based on past experience.

The design acceleration values of 25 G laterally and 35 G longitudinally were determined after evaluation of the qualification test requirements for sine and random vibration, steady state accelerations, and pyrotechnic shock from Reference 1. The critical condition was found to be response to sinusoidal vibration. From Table 3-1, Reference 1, in the lateral axis the required input from 14 to 100 Hz is 1.5 G limit. Typical measured amplification by the antenna at resonance is 17, resulting in a maximum response of 25 G ultimate. In the longitudinal axis, the input is 2.3 G ultimate from 23 to 100 Hz. Typical longitudinal amplification at resonance is approximately 15, resulting in a maximum longitudinal response of 35 G limit. The above values assume a rigid spacecraft and attachment fixture. To determine actual response it is necessary to perform a coupled dynamic analysis of the antenna, spacecraft, attachment fixture, and Delta booster. However, based on the data available at this time these values are recommended for use as criteria for sizing the antenna structural members.

The qualification test requirement for random vibration is 9.2 G\textsubscript{rms} with a PSD of 0.045 from 300 to 2000 Hz and rising from 20 to 300 Hz at +3 dB/octave. The lateral response is approximately 4 G\textsubscript{rms}. Three sigma values are 12 G\textsubscript{o-p}. In the longitudinal axis the response is approximately 7 G\textsubscript{rms} and three sigma values are 21 G\textsubscript{o-p}. Thus, the random vibration is less severe than sine vibration.

The shock spectra at the spacecraft interface for the mamon-type clamp and the explosive nut separation systems are similar. Values are 1400 G at 0.3 ms and 1600 G at 0.8 ms, respectively. The level is reduced through the interfaces and with distance to the source. This reduction is estimated to be a factor of 0.1 to 0.4. Using a value of 0.3, the amplitudes become 420 G and 480 G, respectively. The estimated maximum response in the antenna is less than 10 G. This, again, is less severe than the sine vibration.

The acoustic overall noise level is 146 dB. This is considered much less severe than the vibration. Tests reported in the Shock and Vibration Bulletin 33, Part III, indicate 146 dB corresponds to approximately 9 G\textsubscript{rms}.

The deployed frequency values shown were developed based on previous experience. A high deployed resonant frequency, such as shown, is desirable to assure no coupling of the reflector and other deployed structures (e.g., solar panels) occurs.

### Other Design Considerations

A number of other environmental considerations are normally applied as design constraints in a flight hardware program. Typical examples of such constraints are given.
below. While complete satisfaction of such requirements was not to be demonstrated on the present program, they have been given consideration in the antenna design.

2.3.5.1 Deployment Reliability

The antenna design should be such as to provide a probability of proper deployment of 0.99 or greater in the space environment. Proper deployment is defined as release of the launch restraint system and operation of the deployment system which results in a tensioning of the mesh surface to the required levels.

2.3.5.2 Angular Rates and Accelerations

The basic angular rates linking the TDRS to the user spacecraft are low (on the order of 0.75 radian per hour). Slewing maneuvers can increase these rates. Slewing is required when the antenna must sign off one satellite and acquire another. Since the minimum potential communication time to a user satellite is approximately 37 minutes, rapid slewing does not appear to be of great importance. A reasonable slew rate of 0.1 radian per second with potential accelerations of 0.1 radian/sec² have been selected. This rate allows the entire field of view to be scanned in 10 seconds.

2.3.5.3 Particle Radiation

Radiation from trapped electrons and protons will be encountered in the space environment. The materials used are such as to ensure that the antenna can perform its intended function under the effects of such radiation for the life of the mission.

2.3.5.4 Life

The antenna design considers a minimum orbital mission life of 5 years.
SECTION 3.0
DESIGN DESCRIPTION
3.0 DESIGN DESCRIPTION

The final 12.5-foot diameter antenna design is illustrated in Figure 3.0-1. The antenna is designed for a nominal f/D of 0.417. The measured weight of the entire antenna is 26.2 pounds. The minimum stowed lateral frequency is 57.0 Hz and the minimum deployed resonance frequency is 8.3 Hz. The high stowed resonant frequency minimizes deflections and structural coupling with the lower frequencies of excitation introduced by the launch vehicle. The high deployed resonant frequency ensures minimal coupling of the deployed reflector with the spacecraft attitude control system or with other large flexible structures such as the antenna support booms and solar panels on a three-axis spacecraft or the antenna support mast and/or booms on a spin stabilized spacecraft.

The major antenna elements can be categorized as:

- Reflective Surface
- Feed Support Structure
- Mechanical Deployment System (MDS)
- Launch Restraint System

Each of these areas is discussed in the following paragraphs. Figure 3.0-2 summarizes the design parameters used in this design. Detailed fabrication drawings are presented in Appendix A.

3.1 Reflective Surface

The parabolic reflective surface consists of 12, 1.5-inch diameter, tubular ribs which support and shape the metallic mesh. The choice of 12 ribs was based on a trade-off study considering weight, surface tolerance, and dynamic performance.

Figure 3.1-1 presents weight and deployed dynamic performance as a function of the number of ribs. All data has been normalized relative to the parameter values for 12 ribs. As shown, increasing the number of ribs improves the deployed resonant frequency; however, the resulting increase in weight is severe. The general conclusion to be derived from the data is to use the minimum number of ribs possible within the surface tolerance and deployed resonant frequency requirements. Based on dynamic analyses, and on achievement of the surface tolerance requirements with the "double mesh" design technique, a selection of 12 ribs was made. The double mesh technique utilizes two mesh surfaces which are separated by the rib thickness and connected to one another by tensioned metallic ties. Prior to the development and demonstration of this concept the surface accuracy of the rib-and-mesh design was directly proportional to the number of ribs. This dependency resulted because the largest contribution to surface error was the reverse bulge effect of the mesh between the ribs. The general nature of this effect is shown in Figure 3.1-2. The mesh membrane is pulled tight between the two curved, relatively rigid ribs. Due to the curvature of the ribs, the mesh takes a doubly curved shape, bowing in
Figure 3.0-1. The Double Mesh Design Allows Achievement of High Surface Accuracy
<table>
<thead>
<tr>
<th>Element</th>
<th>Design Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ribs</td>
<td>• Number: 12&lt;br&gt;• Diameter: 1.5 inches&lt;br&gt;• Wall Thickness: Tapered from 0.008 (base) to 0.012 (mid) to 0.006 (tip)&lt;br&gt;• Cross Section: Circular&lt;br&gt;• Material: 6061-T6 Aluminum&lt;br&gt;• Shape: Modified parabolic&lt;br&gt;• f/D: 0.417&lt;br&gt;• Thermal Control: Polished aluminum exterior with three layers of multilayer insulation</td>
</tr>
<tr>
<td>Mesh (Front)</td>
<td>• Material: Chromel-R wire, 0.7 mil by 5 strands per end&lt;br&gt;• Geometry: Tricot knit, 14 ends per inch&lt;br&gt;• Coating: Electroless nickel, electroless gold, electrolytic silver and electroless gold&lt;br&gt;• Loading: 0.02 lb./in. tangential&lt;br&gt;0.01 lb./in. radial</td>
</tr>
<tr>
<td>Mesh (Rear)</td>
<td>• Material: Chromel-R wire, 0.7 mil by 5 strands per end&lt;br&gt;• Geometry: Raschel knit, 2 ends per inch&lt;br&gt;• Coating: Electroless nickel covered with electroless gold&lt;br&gt;• Loading: 0.03 lb./in. tangential&lt;br&gt;0.005 lb./in. radial</td>
</tr>
<tr>
<td>Center Support</td>
<td>• Type: Truncated support cone with dielectric ogive radome&lt;br&gt;• Cone Material: 6061-T6 Aluminum, 0.020 inch thick (base), stepping to 0.015 inch from the midsection to the ogive</td>
</tr>
</tbody>
</table>

Figure 3.0-2. Design Description
<table>
<thead>
<tr>
<th>Element</th>
<th>Design Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radome</td>
<td>0.01 inch thick, high modulus fiberglass and epoxy laminate skins, with phenolic (1/4-inch cell) honeycomb, 3/8 inch thick.</td>
</tr>
<tr>
<td>Thermal Control</td>
<td>Three layers of multilayer insulation separated by three layers of nylon net on the cone. White paint ($\alpha/\varepsilon = 0.28/0.86$) on the radome.</td>
</tr>
<tr>
<td>Attachment to Hub</td>
<td>Removable</td>
</tr>
<tr>
<td>Central Hub</td>
<td>Geometry: Extension of feed support cone geometry</td>
</tr>
<tr>
<td></td>
<td>Material: 0.050-inch thick 6061-T6 aluminum</td>
</tr>
<tr>
<td></td>
<td>Thermal Control: 15 layers of multilayer insulation separated by 15 layers of nylon net.</td>
</tr>
<tr>
<td>Mechanical Deployment System</td>
<td>Type: Over center type toggle action using a ball screw and carrier with linkages to each rib pivot arm. Over center condition gives positive deployed latching.</td>
</tr>
<tr>
<td></td>
<td>Redundancy: Either the spring motor or dc motor is capable of deploying the antenna in a 1 G field.</td>
</tr>
<tr>
<td></td>
<td>Upper restraint provides moment joint at rib tip. Rib tips restrained and preloaded by a pretensioned, captured cable.</td>
</tr>
<tr>
<td></td>
<td>Restraint Release: Two redundant pyrotechnic cable cutters.</td>
</tr>
<tr>
<td>Feed System</td>
<td>Ku-band apex type feed assumed for design. 0.55-pound weight budget assumed for feed, brackets and cabling in all structural and dynamic analysis.</td>
</tr>
</tbody>
</table>

Figure 3.0-2. Design Description (Continued)
Figure 3.1-1. Weight and Deployed Resonant Frequency Versus Number of Ribs for 12.5-Foot Diameter Antenna
Figure 3.1-2. Reverse Bulge Effect
towards the concave side. This error is essentially eliminated by the double mesh concept as illustrated in Figure 3.1-3. The concept utilizes a second mesh as a drawing surface for contouring the front reflector mesh. The second mesh is attached to the back of the ribs and is tied to the front mesh by tensioned wires. By properly tensioning these tie wires, the reflector surface can be contoured to a precision parabolic shape. A manufacturing surface accuracy of 0.020-inch rms was achieved on the 12.5-foot diameter reflector using this concept. The design eliminates surface tolerance dependency on the number of ribs and thereby provides the flexibility to meet a wide range of structural and surface tolerance requirements with low weight.

A surface accuracy of 0.020-inch rms (representing 0.5 dB loss at 15 GHz) is a goal for the present application. As seen from Figure 3.1-4, the surface accuracy of a single mesh design is dependent on the number of ribs and a surface accuracy of 0.020 inch rms is not possible within the specified weight requirement. Conversely, the surface accuracy of the double mesh design is weight independent since the desired accuracy is achieved through the use of more or less ties between the two mesh layers. To attain the required surface tolerance within the specified weight, it is necessary that the double mesh design be utilized for this application.

The mesh is constructed from 5-strand bundles of 0.7-mil Chromel-R wire which is knitted into a highly elastic wire screen. The front mesh is knitted with 14 ends per inch of width. This size was selected to ensure satisfactory RF reflectivity. The back mesh is knitted with 0.375-inch openings. This size opening is sufficient to allow the back mesh to be utilized as a secondary drawing surface for contouring the front mesh while minimizing the antenna weight. After knitting, the front mesh is plated with electroless nickel, silver, and gold platings, respectively. The nickel/silver/gold plating provides the necessary properties for electrical reflectivity and is also compatible with the thermal control design of the antenna. Figure 3.1-5 shows electron photomicrographs of the plated mesh. As seen in Figure 3.1-5, discontinuities in the plating are few in number and are localized in effect. Similarly plated samples of mesh have exhibited no measurable change in RF reflectivity and thermal surface properties after repeated folding and flexing operations over long periods of time. The finished mesh is a low spring rate, elastic material. The use of this soft mesh with the rigid ribs results in a rib-dominated reflector surface which is relatively unaffected by changing mesh forces and orbital thermal variations throughout the antenna life. The mesh is attached to the ribs in a pretensioned state. The tension levels are based on the value of tension required to maintain a flat, unwrinkled condition throughout the orbital life of the reflector.

The prestress loading on the mesh is 0.02 pound per inch in the circumferential direction and 0.01 pound per inch in the radial direction for the front mesh. The back mesh is pretensioned to 0.03 pound per inch in the circumferential direction by 0.005 pound per inch in the radial direction.

The rear mesh is attached to the rib through a series of fiberglass T-bars. The T-bars are bonded on the rib and the mesh is bonded directly to the bars. The T-bars are necessary to insulate heat flow in the area of the mesh attachment. Figure 3.1-6 shows the attachment technique.
Figure 3.1-3. Double Mesh Concept Design
Figure 3.1-4. Weight Versus Surface Error for Single Mesh and 12-Rib Double Mesh Design
Figure 3.1-5. Electron Photomicrographs of Ni/Au/Ag Plating
Figure 3.1-6. Rear Mesh Attachment
The front mesh is supported by a combination of standoffs and intercostals (Figure 3.1-7) at the rib tips and roots only. In between these areas the mesh is pulled into position by flexible wire threads spaced every 2 inches over the entire mesh surface.

Since the front mesh has a 2:1 stretch ratio and is attached on a bias at each gore interface to the adjacent gore, there is a small shear force introduced at the interface. This shear force is maintained by a sewn wire seam on the front mesh. The load introduced into the wire seam is resisted at the rib tip standoff. The wire seam is stopped 6 inches before the rib root and a zig-zag stitch is used to create an elastic membrane to the rib root. This effect is required to prevent the introduction of a bimetallic differential expansion between the wire seam and the rib. The shear force along the gore interfaces on the back mesh is reacted by attachment to the T-bars.

A 1.5-inch rib tip standoff height was selected for the front mesh as a result of an analysis using the tension values described above. This height is necessary to prevent the front and rear mesh from touching as they are pulled together by the ties in the shaping process.

The ribs are constructed from 6061-T6 aluminum alloy for strength and thermal requirements. The rib diameter of 1.5 inches was based on considerations of deployed resonant frequency, launch stress, and weight. The resulting deployed resonant frequency of 8.3 Hz is sufficiently high to prevent dynamic coupling of the deployed antenna with orbital excitations from the attitude control system or with other large flexible structures such as solar panels or the antenna support booms. The ribs have a variable wall thickness. The midsection thickness of 0.013 inch is linearly tapered to 0.009 inch at the rib root and 0.007 inch at the rib tip. Tapering in this fashion produces an efficient, lightweight structure by matching the rib strength to the moment profile imposed on each rib in the maximum stress condition. Figure 3.1-8 illustrates this profile, which results in the restrained stowed condition. The resulting rib design weighs 0.325 pound per rib and totals 3.9 pounds for the 12 ribs.

Thermal control of transverse rib temperature gradients is accomplished by three layers of a multilayer insulation blanket using three layers of nylon net to separate each film. Thermal analyses (see Paragraph 4.3) of the reflector in the orbital environment indicate this thermal control method is sufficient to meet the required orbital surface tolerance and pointing requirements under worst-case orbital conditions.

The ribs are formed to a shape such that application of the mesh tension loads produces the required parabolic rib curvature. The required rib preshape is illustrated in Figure 3.1-9. This required shape is determined by a computer program which considers the forces resulting from application of the mesh and intercostals to arrive at the correct rib shape. Following forming, the ribs are chemically milled to the required wall thickness and tolerance. Tolerance on rib thickness is critical when dealing with the extremely thin wall conditions. The rib thickness is verified using an ultrasonic instrument for thickness measurements. The holes required for midpoint restraint stems are drilled. After fabrication, the ribs are stored in a clean environment and require white glove handling.
Figure 3.1-7. Front Mesh Attachment
Figure 3.1-8. Loading Condition for Stowed Ribs
Figure 3.1-9. Sketch of Optimum Rib Shape
The rib pivot arms are considered an integral part of the rib structure. These pivot arms are constructed as castings from K01 aluminum alloy and are bonded into the end of each rib. This alloy was selected due to its high yield strength and good elongation characteristics. Since the flexural portion of the pivot arm acts as a spring to maintain preload against the rib stops and ensures accurate positioning of the deployed ribs, it is important that yielding does not occur. The dimensions of the flexural portion of the pivot arm are determined from consideration of the stress in the arm due to gravity, preload, and travel allowance for adjustment. The deflection of the pivot arm is sufficient to allow final adjustment of the rib position without removing the preload. Figure 3.1-10 is a view of the pivot arm detailed design. Figure 3.1-11 shows the fabricated pivot arm casting.

3.2 Feed Support Structure

The feed support element is the primary structural member of the stowed antenna. The base diameter of the feed support was selected from a trade-off between electrical performance, stiffness, and weight considerations. A conical structure was chosen because of inherent structural efficiency of this geometry. Past analyses have shown that a truss type support structure is not weight effective in this application due to the high length to small base diameter ratio.

The base of the feed cone is designed to simply unbolt from the hub structure, thus allowing alternate cone and feed designs to be attached. Removal of the cone also allows access to the deployment system, RF feed lines and microwave components within the cone.

The cone is manufactured from 6061 aluminum sheet which is rolled and joined along a vertical seam. After forming, the wall thickness is etched to 0.020 inch for the lower half and 0.015 inch in the upper section. Figure 3.2-1 shows the finished support cone. A stiffener ring is utilized in the cone midsection to support the rib-to-cone restraint system. The hub section is machined from a continuous piece of 6061-T6 aluminum stock. The hub walls are held to 0.050-inch thickness with local stiffening rings, rib ports, and base flange machined into the integral structure. At each rib port, bearing blocks are precisely machined into the surface to locate and support the rib pivot bearings. Figure 3.2-2 shows the finished hub structure. The upper portion of the support cone attaches to a dielectric radome in the shape of an ogive. The ogive geometry was selected due to its high electrical efficiency in the Ku-band region. Figure 3.2-3 shows the fabricated radome and the upper conical section used to attach the rib tips and feed brackets. The dielectric walls are constructed from two skins, 0.010 of an inch thick, high modulus "S" glass and epoxy resin with a 3/8-inch thick, phenolic honeycomb core. The sandwich construction was used because it gave high stiffness to weight and a very low RF loss. Figure 3.2-4 shows the fully assembled feed support system.
Figure 3.1-11. Pivot Arm Casting
Figure 3.2-1. Fabricate Conical Feed Support
Figure 3.2-2. Fabricate Hub Structure
Figure 3.2-3. Ogive Radome and Fabrication Mold
Figure 3.2-4. Conical Support and Ogive Radome Provides High Stowed Stiffness with Minimal RF Blockage and Radome Loss
3.3 Mechanical Deployment System (MDS)

The Mechanical Deployment System (MDS) function is to provide a controlled deployment of the reflector from the stowed to the fully deployed position. This controlled deployment eliminates the transfer of any deployment forces to the spacecraft and also prevents impact loading of the rib structures, thus assuring that the preset parabolic surface is not distorted by the deployment action.

The MDS is located inside the lower section of the feed support cone assembly. Figure 3.3-1 illustrates the mechanism design. The MDS consists of a disc-shaped carriage mounted to the moving section of a recirculating ball nut on a ball screw shaft. Connected between the carriage and the 12 ribs are 12 links that transmit the required force and motion to deploy the individual ribs. Rotation of the ball screw moves the carriage and attached links which, in turn, produces the simultaneous rotation of each rib about its bearing. As the carrier moves 4.25 inches along the screw shaft, the ribs are rotated a total of 68° from their stowed to their fully deployed position. This travel requires approximately 55 seconds. When fully deployed, each connecting link is under 38 pounds compression. This loading holds each rib tightly against an accurately preset stop. The flexural section of the rib pivot arm (located between the rib pivot point and the linkage bearings) acts as a cantilever spring and deflects approximately 0.038 inch due to the 38-pound compression loading. This compliance provides a method for eliminating the effects of minor differences in link adjustments on the final rib position. It also allows for differential expansion and contraction between the various members without resulting in any appreciable movement of the rigid portion of the rib pivot arm.

Latching in the deployed condition is accomplished by driving the ball-nut carrier and linkages through an over center condition (relative to the pivot arms). In this condition the mesh tension forces, rib loads, spring motor, and pivot arm preload all force the carrier against a mechanical stop. Any external loads, such as vibration loads, only serve to further increase the loading of the carrier against the mechanical stop. This toggle action eliminates the requirement for further latching devices in the deployed condition (e.g., a mechanical brake or one-way clutch) thereby improving reliability. A back driving torque of approximately 8-inch pounds to the ball screw is required to back drive the mechanism through the latching toggle action to restow the antenna.

A secondary advantage of this toggle latching is convenience during ground testing and handling. The antenna can be remotely stowed during ground testing by reversing the current to the electric motors.

The MDS utilizes redundant energy drive systems to rotate the ball screw within the ball nut carrier. The primary drive energy is a constant torque (2.5 inch pound) spring motor. A secondary advantage of the spring motor is that it also provides a preload on the mechanism in the stowed position which helps to eliminate any joint looseness in this area. The redundant backup drive system for a flight model version of the design consists of two miniature torque motors driven through a 60:1 ratio high efficiency gear system. For convenience and economy, these motors are replaced on the present ground test model by a 400-cycle, three-phase, ac motor and
Figure 3.3-1.  MDS Mechanism Design
(Sheet 2 of 2)
gear system. The torque motors normally function as dynamic brakes, controlling the deployment rate and requiring no electrical power. If called upon to deliver power (by the deployment control unit) the motors can increase the torque to the ball screw by as much as a factor of five.

Figure 3.3-2 shows the required ball-screw torque in inch-pounds as a function of the number of ball-screw revolutions for both the zero gravity and the face-down gravity conditions. The maximum deployment torque required in the face-down gravity position is approximately 1.8 inch-pounds at 25 revolutions of the ball-screw and this torque requirement is due to the force required to stretch the mesh to the proper tension condition. In zero gravity, only 1.3 inch-pounds are required at this maximum torque.

The constant torque spring motor provides a 2.5 inch-pound torque to the ball screw and thus exceeds the required face-down gravity torque by 40.0 percent and the zero gravity torque by 92 percent. The total deployment torque available is 15.5 inch-pounds and exceeds the face-down gravity requirements by 860 percent and the zero gravity requirements by over 1,000 percent.

All rib and linkage bearings are designed with simple, parallel redundant bearings. This design greatly reduces the probability of any bearing exhibiting undesirable friction changes. In the event of a high friction condition, the deployment system is designed to transfer the full deployment force to the lagging member and overcome the increased friction.

Dry film lubricants are used on the various sliding and rolling surfaces in the MDS. Two basic types of dry film lubricants are used. These consist of transfer film lubricants used in the Bartemp special retainer bearings, and bonded or plated films used on journal shafts and the ball screw. The use of these dry film lubrication techniques allows the deployment mechanism to be operated in space with unsealed components.

The techniques of thin film lubrication involve a hard solid surface covered by a thin film of softer material possessing lower shear strength. The hard underlying substrate acts to support the load and limit the area of contact.

The lubricant system must be compatible with extensive ground testing in an ambient environment in addition to operating in the orbital environment. All of the lubricants used have been previously tested in air and provide satisfactory life in air as well as in a vacuum.

Table 3.3 details the lubricants used. Lubeco 905 is a chemically-bonded, completely inorganic solid dry film made up of molybdenum disulfide and graphite particles of controlled size. The exact chemical binder is vendor proprietary. Lubeco 905 was successfully used on moving mechanical parts of the Surveyor Camera equipment. This lubricant was also used on a previous 12.5-foot diameter test model antenna which was tested under solar-vacuum conditions.

Hi-T-Lube consists of an initial substrate deposition of gold with a film overcoat. The film uses a phenolic binder to adhere the impregnated MoS2 and graphite. The film coatings are applied in the 0.0003 to 0.0005 inch thickness range. Hi-T-Lube was also used on the
Figure 3.3-2. Deployment Torque Requirements
<table>
<thead>
<tr>
<th>Item/Location</th>
<th>Quantity</th>
<th>Material</th>
<th>Lubricant (Vendor)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Pivot Arm Shafts</td>
<td>12</td>
<td>303 Stainless Steel</td>
<td>Hi-T-Lube (General Magnaplate Corp.)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Lubeco 905 (Lubeco Inc.)</td>
</tr>
<tr>
<td>2. Rod End Bearings</td>
<td>24</td>
<td>440C Stainless Steel</td>
<td>Lubeco 905 (Lubeco Inc.)</td>
</tr>
<tr>
<td>3. Rod End Shafts</td>
<td>24</td>
<td>416 Stainless Steel</td>
<td>Hi-T-Lube</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Lubeco 905 (Lubeco Inc.)</td>
</tr>
<tr>
<td>4. Upper Ball Screw Bearing</td>
<td>1</td>
<td>440C Stainless Steel</td>
<td>Hi-T-Lube</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Lubeco 905 (Lubeco Inc.)</td>
</tr>
<tr>
<td>5. Spring Motor Reels</td>
<td>2</td>
<td>6061-T6 Aluminum</td>
<td>Tufram (General Magnaplate Corp.)</td>
</tr>
<tr>
<td>6. Spring Motor Take-Up</td>
<td>2</td>
<td>440C Stainless Steel</td>
<td>Bartemp (Barden Corp.)</td>
</tr>
<tr>
<td>7. Ball Screw and Nut Returns</td>
<td>1</td>
<td>440C Stainless Steel</td>
<td>Hi-T-Lube</td>
</tr>
<tr>
<td>8. Carrier Antirotation Bearings</td>
<td>2</td>
<td>440C Stainless Steel</td>
<td>Bartemp</td>
</tr>
<tr>
<td>9. Gear Train Bearings</td>
<td>4</td>
<td>440C Stainless Steel</td>
<td>Bartemp</td>
</tr>
<tr>
<td>10. Gear System</td>
<td>4</td>
<td>440C Stainless Steel</td>
<td>Hi-T-Lube</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Lubeco 905 (Lubeco Inc.)</td>
</tr>
<tr>
<td>11. Electric Motor Brushes</td>
<td>4</td>
<td>Composite</td>
<td>Silver/Graphite (Inland)</td>
</tr>
<tr>
<td>12. Upper Restraint Cable Ferrules and Cable Guide</td>
<td>12</td>
<td>6061-T6 Aluminum</td>
<td>Tufram (General Magnaplate Corp.)</td>
</tr>
<tr>
<td>13. Thrust Washers and Shaft Spacers</td>
<td>24</td>
<td>Duroid 5813</td>
<td>Composite MoS2, Teflon, Fiberglass (Rogers Corp.)</td>
</tr>
</tbody>
</table>
previous 12.5-foot diameter antenna and this lubricant was flight and ground vacuum tested for the LEM ball nut-screw actuator.

The spring motor reels (and the guide ferrules of the rib tip restraint system) are coated by the Tufram process. This process consists of converting a controlled depth of the surface to aluminum oxide and then impregnating the ceramic surface with TFE particles less than 1 micron in diameter. The combined effect gives a resilient surface having a very favorable coefficient of friction.

3.4 Launch Restraint Design

The launch restraint system serves a dual purpose. First, the restraint system forces the stowed antenna structure to act as a single, stiff, structural element, thereby increasing the stowed resonant frequency of the antenna. Second, the restraint system design is utilized to effectively reduce stresses developed by launch loads in critical areas. Two restraint systems, one at the rib midpoint and one at the rib tip, are utilized to accomplish the above functions.

Each rib is supported at its midpoint in the stowed condition by the midpoint restraint system (see Figures 3.4-1 and 3.4-2). This restraint system is comprised of 12 spars emanating radially outward from the midsection of the feed support cone to a circular hoop. As each rib is stowed, a metal pin protruding from the rib seats into a small conical socket on the hoop. A preload of 15.8 pounds is developed at this point by deflecting the rib tips inward after each pin is seated. This preload assures that no separation of the pin-and-socket joint will occur during the maximum dynamic loading. The pins and sockets are protected from wear and cold welding by plating with Type III hard anodic coating. This system provides rib stability as well as a direct load path from the ribs to the feed support cone.

The midpoint restraint system is entirely passive in performing its function, with no motion involved. Being constructed of dielectric material, its presence does not measurably affect the RF performance of the antenna. The material selected for the radial spars and hoop is a fiberglass and epoxy laminate with undirectional glass fibers. This midpoint restraint system design has been shown by test to produce a 45 percent increase in the stowed antenna resonant frequency with respect to a design without such a restraint.

The upper restraint system provides rib tip restraint and maintenance of the stowed rib preload by a tensioned cable system. An aluminum plug on the tip of each rib contains an accurately machined conical socket (Figure 3.4-3). This socket seats over a mating aluminum cone protruding from the upper restraint ring (Figure 3.4-3). The upper restraint ring is attached to the outer cone of the feed structure. The restraint is illustrated in Figure 3.4-4. When these two parts are mated and held in position by the restraining cable, a moment type connection is achieved. The angles and dimensions of the mating conical parts are chosen to provide resistance to both translational and rotational motion of the ribs while allowing the ribs to easily disengage for deployment when the restraining cable is released.
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Figure 3.4-1. Midpoint Restraint System
Figure 3.4-2. Midpoint Restraint System
Figure 3.4-3. Rib Tip Restraint Socket and Mating Cone on Feed Support System
- PROVIDES STOWED PRELOAD AND MOMENT CONSTRAINT OF RIBS
- DUAL REDUNDANT PYROTECHNICS
- CAPTIVATED RESTRAINT CABLE
- DEPLOYMENT RELIABILITY: 0.999

Figure 3.4-4. Upper Restraint System Details
To seat the rib tip against the mating cone a preload force of 15 pounds is required. This preload is provided by the tensioned cable around the rib tips. Development of this preload also provides the required midpoint restraint preload.

The restraining cable does not directly contact the rib tips but is threaded through ferrules on the ends of a series of 12 leaf springs. These ferrules seat against the rib tips. The opposite end of the leaf springs are attached to the upper restraint ring. The cable passes through the ferrules and then through a pair of pyrotechnic guillotine cutters. The cable ends terminate in a cable crimp. When the cable is cut, the leaf springs return to their unloaded shape and this action lifts the cable free of the rib tips. The cable slips through the ferrules until the springs are fully extended, and then remains captivated inside the ferrules. The ferrules utilize a hard anodic coating with a proprietary impregnated Teflon coating. This dry film lubrication method provides lubrication for cable sliding while preventing cold welding. With the cable and ferrules now out of the way, the ribs are free to be deployed by the mechanical deployment system.
SECTION 4.0

REFLECTOR PERFORMANCE RESULTS AND PROJECTIONS
4.0 REFLECTOR PERFORMANCE RESULTS AND PROJECTIONS

This section presents measured test results on the reflector and includes analytical projections for orbital performance.

4.1 Weight and Surface Error Budgets

The projected and actual weight and surface error budgets are shown in Tables 4.1-1 and 4.1-2, respectively.

The actual weight increased from the projected weight at CDR by 3.5 pounds from 22.75 pounds to 26.25 pounds. This was due mainly to the use of a nonflight deployment motor (0.75 pound) and 2 mil silver-coated Teflon for the outer layer of the MLI blankets.

The surface error budget for the worst-case orbital condition is shown in Table 4.1-2. The error sources are described in the following paragraphs.

The manufacturing error consisting of mesh attachment, adjustment, and bulge error is the measured value of this error source. Components of this source are a small error associated with the mesh seam along each rib due to the inability to practically achieve a perfect joint; the inherent reverse bulge effect between adjacent mesh tie points as well as a slight "dimpling" of the mesh in the immediate vicinity of each tie point; and one's ability to physically adjust the reflector contour with the mesh ties and adjustable rib standoffs.

The gravity deflection error occurs in orbit as the gravity force is removed from the surface. Upon removal of the gravity force, the mesh surface will assume an equilibrium position different from that in the gravity field. Preliminary efforts to determine the quantity of this error indicate that, if no compensation is built in, the magnitude could be as much as 0.023-inch rms for the present design. By setting each gore in a horizontal position where the gravity effects are partially nullified, the effect of this error can be reduced by 75 percent or more. The 0.006-inch contribution listed in the budget reflects such a value.

The thermal error shown is the worst-case distortion projected by thermal analyses (see Paragraph 4.3).

Table 4.1-3 presents the measured surface error data on the reflector. Two significant results are indicated. First, examination of the first and third measured surface error values shown illustrates that a highly repeatable surface is achieved and maintained over multiple deployments. Second, a comparison of the first and second values in the table bounds the gravity distortion effects on the reflector. The first value of 0.020-inch rms was measured by rotating the reflector past the horizontal sweep template. Thus, gravity effects are partially nullified. The second value of 0.032-inch rms was measured by rotating the sweep template around the reflector with the reflector in the face-side condition. This value thus includes the maximum, or worst-case, effects of gravity distortion. One is therefore assured that the orbital surface error before thermal distortions are included must be less than the measured 0.032 value.
### Table 4.1-1. Antenna Weight

<table>
<thead>
<tr>
<th>Element</th>
<th>Weight, Pounds</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Feed Support System</strong></td>
<td></td>
</tr>
<tr>
<td>Hub</td>
<td>2.8</td>
</tr>
<tr>
<td>Cone</td>
<td>3.6</td>
</tr>
<tr>
<td>Ogive</td>
<td>1.0</td>
</tr>
<tr>
<td><strong>Rib Assembly</strong></td>
<td>7.0</td>
</tr>
<tr>
<td>Ribs</td>
<td>4.0</td>
</tr>
<tr>
<td>Midpoint Restraint Pins and Local Reinforcement</td>
<td>0.5</td>
</tr>
<tr>
<td>Standoffs</td>
<td>0.2</td>
</tr>
<tr>
<td>Pivot Arms</td>
<td>1.6</td>
</tr>
<tr>
<td>Rib Tip Restraint</td>
<td>0.7</td>
</tr>
<tr>
<td><strong>Mesh Gore Assemblies</strong></td>
<td>1.7</td>
</tr>
<tr>
<td>Front Gore Assembly</td>
<td>1.2</td>
</tr>
<tr>
<td>Back Gore Assembly</td>
<td>0.2</td>
</tr>
<tr>
<td>Tie Wires</td>
<td>0.1</td>
</tr>
<tr>
<td>Intercostals</td>
<td>0.2</td>
</tr>
<tr>
<td><strong>Mechanical Deployment System (MDS)</strong></td>
<td>2.9</td>
</tr>
<tr>
<td>Hoop and Spar Assembly</td>
<td>1.0</td>
</tr>
<tr>
<td>Top Restraint Ring, Cones, and Hardware</td>
<td>0.6</td>
</tr>
<tr>
<td>Cable, Cutter, Spring, Ferrules, and Pyrotechnics</td>
<td>0.4</td>
</tr>
<tr>
<td><strong>Thermal Control</strong></td>
<td>0.9</td>
</tr>
<tr>
<td>Rib Insulation</td>
<td>0.5</td>
</tr>
<tr>
<td>Cone/Hub Insulation</td>
<td>0.4</td>
</tr>
<tr>
<td><strong>Motor Wire and Harness</strong></td>
<td>0.3</td>
</tr>
<tr>
<td><strong>Feed</strong></td>
<td>0.55</td>
</tr>
<tr>
<td><strong>Total Weight</strong></td>
<td>22.75</td>
</tr>
</tbody>
</table>

*Actual* Weight: 26.25 pounds
Table 4.1-2. Surface Error Budget for Worst-Case Orbital Conditions

<table>
<thead>
<tr>
<th>Error Source</th>
<th>Magnitude, Inches</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal Distortion</td>
<td>0.008</td>
</tr>
<tr>
<td>Manufacturing (mesh attachment, adjustment, and bulge)</td>
<td>0.020</td>
</tr>
<tr>
<td>Gravity Error</td>
<td>0.006</td>
</tr>
<tr>
<td>Total RMS Error</td>
<td>0.022</td>
</tr>
<tr>
<td>Measurement Error Effects on Total RMS Error</td>
<td>±0.001</td>
</tr>
</tbody>
</table>

Table 4.1-3. Summary of Surface Error Measurements

<table>
<thead>
<tr>
<th>Test Condition</th>
<th>Surface Error Inches RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Face-side reflector is rotated past horizontal template; gravity effects minimized</td>
<td>0.020</td>
</tr>
<tr>
<td>Template is rotated around face reflector; gravity effects included</td>
<td>0.032</td>
</tr>
<tr>
<td>Face-side reflector is rotated past horizontal template after pyrotechnic firing and ten stow/deploy cycles</td>
<td>0.019</td>
</tr>
</tbody>
</table>
4.2 RF Performance

4.2.1 RF Range Test Results Summary

Range tests were conducted to evaluate the RF performance of the reflector. Range measurements consisted of pattern measurements at 2.1 GHz and 15 GHz, relative gain measurements at 2.1, 13.4, 15.0, and 15.45 GHz, and an absolute gain measurement at 15.0 GHz.

Figure 4.2.1-1 illustrates the test configuration for the relative gain and pattern measurements. The deployable reflector and a standard 12-foot diameter solid reflector are mounted back to back. The solid reflector has a known surface error of 0.007-inch rms. A standard feed was used for the gain measurements by first placing the feed in the solid reflector and then in the deployable reflector. The feed is supported in the solid, or reference, reflector in such a way that the primary blockage is zero and the secondary blockage is minimal (0.05 dB). The deployable reflector was tested with the complete feed cone, midrib restraint assembly, and radome, thus representing an operational condition. No fixturing was utilized to correct for gravity distortions in the deployable reflector and thus a surface error of 0.032-inch rms existed.

The absolute gain of the deployable reflector at 15 GHz was determined by comparison with an NRL design gain standard horn.

Figure 4.2.1-2 summarizes the gain measurement results. Figures 4.2.1-3 and 4.2.1-4 show the deployable reflector patterns at 2.1 GHz and 15.0 GHz.

Complete details of the range test results are given in Appendix B.

4.2.2 Projected Orbital Performance

To project the orbital performance of the reflector, the worst-case orbital surface error, defocus, and pointing error have been combined with a selected feed concept.

The feed concept selected for these calculations employs a pseudomonopulse tracking Cassegrain Ku-band and programmed-tracking apex S-band implementations. The feed arrangement (see Figure 4.2.2-1) utilizes a frequency sensitive dichroic lens subreflector. The feed is configured to mate with the 12.5-foot rib-and-mesh reflector. Table 4.2.2-1 presents efficiency factors for the feed at Ku-band as well as the overall illumination efficiency. Also, the effects of coupler, bandpass filter, rotary joint, waveguide, diplexer and other losses are reflected by the overall line loss efficiency shown in the table.

The worst-case orbital surface error is 0.024-inch rms, and utilizing Figures 4.3.3-6 and 4.3.3-7, the worst-case axial defocusing and pointing error are 0.065 inch and 0.05 milliradian, respectively. For operation at 15 GHz, these produce a reflector efficiency of 87 percent. Combining these with a measured mesh reflectivity of 93 percent gives an overall reflector efficiency of 81 percent. Table 4.2.2-2 presents the combined feed/reflect or overall antenna efficiency.
RF Range Test Configuration

Figure 4.2.1-1
### RELATIVE GAIN

<table>
<thead>
<tr>
<th>FREQUENCY</th>
<th>GAIN DIFFERENCE*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MEASURED</td>
</tr>
<tr>
<td>2.1 GHz</td>
<td>-0.6 dB</td>
</tr>
<tr>
<td>13.4 GHz</td>
<td>-2.4 dB</td>
</tr>
<tr>
<td>15.0 GHz</td>
<td>-2.5 dB</td>
</tr>
<tr>
<td>15.45 GHz</td>
<td>-2.5 dB</td>
</tr>
</tbody>
</table>

### ABSOLUTE GAIN

<table>
<thead>
<tr>
<th>FREQUENCY</th>
<th>GAIN</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.0 GHz</td>
<td>51.5 dB (WITH RESPECT TO GAIN STANDARD)</td>
</tr>
</tbody>
</table>

*GAIN DIFFERENCE IS BETWEEN SOLID REFERENCE REFLECTOR AND DEPLOYABLE REFLECTOR

Figure 4.2.1-2. Gain Measurement Summary
Figure 4.2.1-4. RF Patterns at 2.1 GHz
Figure 4.2.2-1. Tracking Cassegrain Ku-Band, Nontracking Apex S-Band Feed Layout
<table>
<thead>
<tr>
<th>Efficiency Factors</th>
<th>Ku-Band</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Receive</td>
<td>Transmit</td>
<td></td>
</tr>
<tr>
<td>Spillover/Amplitude Taper Efficiency</td>
<td>0.800</td>
<td>0.800</td>
<td></td>
</tr>
<tr>
<td>Primary Phase Efficiency</td>
<td>0.980</td>
<td>0.980</td>
<td></td>
</tr>
<tr>
<td>Blockage Efficiency</td>
<td>0.981</td>
<td>0.981</td>
<td></td>
</tr>
<tr>
<td>Primary Cross-Polarization Efficiency</td>
<td>0.990</td>
<td>0.990</td>
<td></td>
</tr>
<tr>
<td>Secondary Cross-Polarization Efficiency</td>
<td>0.999</td>
<td>0.999</td>
<td></td>
</tr>
<tr>
<td>Dichroic Loss Efficiency</td>
<td>0.940</td>
<td>0.940</td>
<td></td>
</tr>
<tr>
<td><strong>A. Illumination Efficiency</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.715</td>
<td>0.715</td>
<td></td>
</tr>
<tr>
<td>Horn and Polarizer Loss Efficiency</td>
<td>0.978</td>
<td>0.978</td>
<td></td>
</tr>
<tr>
<td>Diplexer Loss Efficiency</td>
<td>0.994</td>
<td>0.994</td>
<td></td>
</tr>
<tr>
<td>Four-Way Power Divider Loss Efficiency</td>
<td>---</td>
<td>0.985</td>
<td></td>
</tr>
<tr>
<td>Comparator Loss Efficiency</td>
<td>0.982</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>Coupler Loss Efficiency</td>
<td>0.937</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>Bandpass Filter Loss Efficiency</td>
<td>0.966</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>Rotary Joint Loss Efficiency</td>
<td>---</td>
<td>0.955</td>
<td></td>
</tr>
<tr>
<td>Waveguide Loss Efficiency</td>
<td>0.946</td>
<td>0.995</td>
<td></td>
</tr>
<tr>
<td>Diplex Loss Efficiency</td>
<td>---</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>Coaxial Cable Loss Efficiency</td>
<td>---</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>Cupped Helix Feed Loss Efficiency</td>
<td>---</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>Mismatch and Axial Ratio Loss Efficiency</td>
<td>0.978</td>
<td>0.978</td>
<td></td>
</tr>
<tr>
<td><strong>B. Line Loss Efficiency</strong></td>
<td>0.799</td>
<td>0.890</td>
<td></td>
</tr>
</tbody>
</table>
Table 4.2.2-2. Worst-Case Orbital Performance for Ku-Band Operation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Receive</th>
<th>Transmit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dual Frequency Feed at Ku-Band</td>
<td>0.715</td>
<td>0.715</td>
</tr>
<tr>
<td>Line-Loss Efficiency</td>
<td>0.799</td>
<td>0.890</td>
</tr>
<tr>
<td>Reflector</td>
<td>0.81</td>
<td>0.81</td>
</tr>
<tr>
<td>Total Efficiency</td>
<td>0.462</td>
<td>0.515</td>
</tr>
</tbody>
</table>

4.3 Thermal Design Performance

This section presents the thermal analyses that were performed to verify the adequacy of the antenna design.

4.3.1 Thermal Performance Parameters

The primary parameters affecting the antenna orbital thermal performance are hub temperature gradients, diametral rib gradients, feed support cone gradients, and the rib and feed cone average temperatures. These variations are induced by changes in the solar incidence angle and shadow patterns. Hub distortions are potentially the major contributor to the thermal contribution to surface error, defocusing, and mispointing because of their amplification by the rib length to give large rib tip movements. The hub gradients are effectively controlled by the incorporation of a multilayer insulation blanket around the hub and feed support cone. The diametral rib gradients are directly proportional to the rib solar absorptivity, $\alpha_s$, and inversely proportional to the diametral thermal conductance. The gradient is therefore minimized by reducing the rib $\alpha_s$ and increasing the wall thickness and thermal conductivity. The feed support cone diametral heat transfer is predominantly by radiation, therefore, the gradients are reduced by incorporating a high infrared emittance interior surface and a multilayer insulation blanket around the exterior.

Thermal analyses were performed to provide sufficient trade-off data for selection of the optimum rib thermal control system. The high surface accuracy required is achieved through thermal control of the antenna rib locations. Though large temperature variations occur in the mesh itself, the mesh spring constant is adequately low to prevent a significant transmission of mesh effects to the rigid ribs. Further, the mesh pretension ratio is such that no "wrinkling" of the mesh occurs due to orbital temperature excursions.

In addition, a thermal analysis was performed for the antenna assembly for a synchronous orbital condition to confirm the operational performance of the antenna thermal control system.
4.3.2 Thermal Analysis Approach

The preliminary thermal analysis was performed using the Antenna Thermal Analyzer Program (ATAP) which performs the following steps:

1. Generates the thermal math model of the antenna including node assignment and distribution
2. Solves for the steady-state temperature distribution for each sun angle and shadow condition
3. Computes the surface distortion caused by the temperature distribution
4. Computes the rms surface accuracy, defocusing, and mispointing of the best-fit paraboloid generated by the deflected rib coordinates.

Since the thermal distortion analysis was performed on this antenna, additional development has led to a thermoelastic distortion model which includes the mesh surfaces using pretensioned, orthotropic membrane elements. Mesh membrane distortions have been determined to be a significant contributor to on-orbit surface distortion of other deployable antennas. The solar vacuum testing and associated analysis of the Ku-band antenna will provide definitive data concerning mesh distortions. Mesh plating, pretension, and stiffness properties are available which are consistent with the thermal distortions listed in surface error budgets. Presentation of additional analysis results within the scope of this report is not possible.

4.3.3 Thermal Control Coatings

Several thermal control coating systems were considered for the antenna ribs. These can be classified in three basic categories: rib surface treatment, adhesive backed tapes, and multi-layer insulation (MLI). Figures 4.3.3-1 and 4.3.3-2 present the predicted diametral temperature gradient along the antenna ribs for sun angles of 0° and 180°, respectively, for four configurations. (The rib wall thickness at the hub, midpoint and tip are 0.008, 0.012, and 0.006 inch, respectively.) The surface treatment concept investigated involved polishing the rib exterior to yield a relatively low solar absorptivity ($a_s$). Past experience in polishing of the 6061-T6 aluminum ribs yielded an emissivity of approximately 0.06 and $a_s$ values in the range of 0.18 to 0.23 with 0.21 being a representative value. The polished aluminum thermal control
Figure 4.3.2. Antenna Thermal Model and Sun Angle Reference
Figure 4.3.3.1. Diametral Rib Gradient Versus Rib Position for Four-Rib Thermal Control Coating Systems
Figure 4.3.3-2. Diametral Rib Gradient Versus Rib Position for Four Thermal Control Coating Systems
Flexible, adhesive-backed, metallized FEP Teflon tapes were also evaluated for use on the antenna ribs. The FEP Teflon tape is readily available with either vapor-deposited aluminum or silver as the solar reflective surface. Solar absorptivity values of 0.08 and 0.14 were assumed for the silverized and aluminized tapes, respectively. An emissivity of 0.55 was used for both tapes (indicative of a 0.001-inch Teflon thickness). A close inspection of Figures 4.3.3-1 and 4.3.3-2 reveals the significant interaction between the Teflon-coated ribs and the gold-plated mesh. The differences in the front and back mesh transmissivity ($\tau_F = 0.85$, $\tau_B = 0.95$) causes a significantly greater thermal loading condition on the front portion of the ribs. This has the effect of increasing the front-to-back diametral rib gradient for sun angles yielding forward insolation and decreasing it for rear insolation.

Multilayer insulation (MLI) is the third category of rib thermal control systems mentioned above. Most MLI configurations can be classified into two basic categories:

1. MLI with interlayer separating spacers, and
2. MLI without an interlayer separating spacer

The spacer is normally made of a lightweight, low conductive material and is used to retard the interlayer thermal conduction. MLI with interlayer spacers is normally used where contact pressure between layers may be significant.

The MLI configurations without the interlayer spacers rely on crinkling or dimpling of the metallized film to interrupt the thermal conduction paths. Crinkled mylar blankets exhibit high thermal insulating properties for relatively low weight. The primary disadvantage of crinkled mylar blankets is ensuring that for relatively small diameter cylinders (such as the 1.5-inch diameter ribs) the interlayer contact pressure is not so great as to flatten out the crinkles, thereby allowing significant thermal conduction to occur.

An MLI configuration was selected which incorporated alternating layers of a lightweight nylon tulle and aluminized 1/4-mil mylar. The blanket is constructed by placing a layer of nylon tulle on the surface of the rib, followed by alternating layers of aluminized mylar and nylon tulle. The final outer layer of insulation is silverized Teflon rather than aluminized mylar. The mylar used in the blanket is aluminized on both sides. The number of layers is defined as the number of layers of nylon tulle. The approximate weights per unit area and thicknesses for the MLI blanket materials are listed in Table 4.3.3.

Figure 4.3.3-3 presents the results of thermal tests which have been performed on this MLI configuration on 1.5-inch diameter cylinders. The model used in the data correlation assumed heat transfer across the blanket to be by both radiation and conduction. These MLI performance data were used together with the basic antenna design to produce the diametral rib gradient data of Figure 4.3.3-4 for different numbers of layers of MLI. It is interesting to compare the temperature gradient of Figure 4.3.3-1 for the adhesive-backed silver-coated Teflon (approximately $4^\circ$F at segment No. 1) with the gradient indicated in Figure 4.3.3-4 for one-layer
Table 4.3.3. MLI Material Weights

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness, Inches</th>
<th>Weight, Lbs./Ft.²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nylon Netting</td>
<td>0.0035</td>
<td>2.0 x 10⁻³</td>
</tr>
<tr>
<td>Aluminized Mylar</td>
<td>0.00025</td>
<td>1.79 x 10⁻³</td>
</tr>
<tr>
<td>Silverized Teflon</td>
<td>0.001</td>
<td>11.32 x 10⁻³</td>
</tr>
</tbody>
</table>

MLI (1.2°F). Physically, this represents simply exchanging the adhesive for a single layer of lightweight nylon tulle. This represents greater than a 3:1 reduction in weight.

The rib diametral gradient data presented above are used to indicate the best thermal control coating configuration for the antenna. The rib temperature distributions are included in Appendix C of the CDR Data Package with the ATAP printouts of the orbital surface accuracy.

4.3.4 Conclusions

The results of the analyses presented confirm the adequacy of the thermal design of the antenna assembly for operation in the synchronous equatorial orbit.
Figure 4.3.3-3. MLI Thermal Performance Versus Number of Layers
Figure 4.3.3-4. Diametral Rib Gradient Versus Number of Layers of MLI
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4.4 Structural and Dynamic Analyses

Analyses were performed to support design trade-off studies. Of primary concern is attaining a very lightweight antenna that meets the stowed and deployed frequency requirements and can survive the 25 G lateral launch load.

The Rayleigh Method was used in preliminary analysis to calculate fundamental frequencies at a low cost. Eigenvalue solutions were used for final analysis.

4.4.1 Results and Correlation

The final lightweight antenna design meets all frequency and strength requirements as demonstrated in Tables 4.4.1-1 and 4.4.1-2. Table 4.4.1-3 correlates measured stiffness values with calculated values. Detail test results are given in Appendix B.

To aid in the selection of a rib, a parametric analysis was performed by varying the rib thickness and diameter. From these results and considering stresses and thermal requirements, a 1.5-inch diameter rib was selected having a root wall thickness of 0.008 inch, a midpoint wall thickness of 0.012 inch and a tip wall thickness of 0.006 inch.

The selected rib was analyzed more accurately for frequencies by performing an eigenvalue solution and considering the rib parabolic shape and the pivot arm and hub compliance.

A load analysis was performed for the mechanical deployment system for each degree of motion during face-side or face-down deployment in a 1 G field.

Calculations were made for the optimum rib shape that would tend to offset the mesh bulge effects and the zero-G effects of space.

A detail computer model was assembled for the MDS. It included the lower half of the ribs and the lower eight inches of the support cone and hub. A lateral loading of 25 G and a longitudinal loading of 35 G were applied. Stresses due to these launch loads were calculated throughout the MDS and found to be less than 2500 psi limit.

The calculated antenna center of gravity is on the boresight axis and is located 30.29 inches above the base.

4.4.2 Stowed Antenna Dynamic Analysis

4.4.2.1 Description of Computer Model

The nodal topology of the stowed antenna model is shown in Figure 4.4.2.1. This cantilevered antenna was fixed at its base. Each of the 12 ribs was modeled with six straight
Table 4.4.1-1. Comparison of Fundamental Frequencies, Hz

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Axis</th>
<th>Requirement</th>
<th>Calculated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stowed Antenna</td>
<td>Torsional</td>
<td>15.</td>
<td>29.4</td>
</tr>
<tr>
<td>Stowed Antenna</td>
<td>Lateral</td>
<td>40.</td>
<td>55.6</td>
</tr>
<tr>
<td>Stowed Antenna</td>
<td>Longitudinal</td>
<td>90.</td>
<td>141.8</td>
</tr>
<tr>
<td>Deployed Antenna</td>
<td>Lateral</td>
<td>4.</td>
<td>7.02</td>
</tr>
<tr>
<td>Deployed Antenna</td>
<td>Torsional</td>
<td>4.</td>
<td>7.01</td>
</tr>
<tr>
<td>Stowed MDS</td>
<td>Lateral</td>
<td>100.</td>
<td>*648.</td>
</tr>
<tr>
<td>Stowed MDS</td>
<td>Longitudinal</td>
<td>100.</td>
<td>*556.</td>
</tr>
</tbody>
</table>

*Values look too high. See discussion in Appendix D. Section D4.0.

Table 4.4.1-2. Physical Stress Margins of Safety, MS

<table>
<thead>
<tr>
<th>Element</th>
<th>MS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rib</td>
<td>0.31</td>
</tr>
<tr>
<td>Cone, Node 1</td>
<td>1.44</td>
</tr>
<tr>
<td>Cone, Node 2</td>
<td>1.86</td>
</tr>
<tr>
<td>MDS Carrier</td>
<td>0.14</td>
</tr>
<tr>
<td>MDS Push-Rod</td>
<td>1.78</td>
</tr>
<tr>
<td>MDS Ball Screw</td>
<td>1.36</td>
</tr>
<tr>
<td>Pivot Arm</td>
<td>2.45</td>
</tr>
</tbody>
</table>
Table 4.4.1-3. Correlation of Analysis and Test Values for Reflector Stiffness

<table>
<thead>
<tr>
<th>TEST CONFIGURATION</th>
<th>MEASURED VALUE</th>
<th>PREDICTED VALUE*</th>
</tr>
</thead>
<tbody>
<tr>
<td>STOWED, LATERAL AXIS</td>
<td>57.0 Hz</td>
<td>56.8 Hz</td>
</tr>
<tr>
<td>STOWED, LONGITUDINAL AXIS</td>
<td>185.0 Hz</td>
<td>141.8 Hz</td>
</tr>
<tr>
<td>DEPLOYED, LONGITUDINAL AXIS</td>
<td>8.2 Hz</td>
<td>7.0 Hz</td>
</tr>
</tbody>
</table>

*PREDICTED VALUES AT CRITICAL DESIGN REVIEW

CONCLUSIONS:

- ANTENNA IS SUFFICIENTLY STIFF TO BE TREATED AS A COMPONENT AND QUALIFIED SEPARATE FROM SPACECRAFT.
Figure 4.4.2.1. Computer Model of Stowed Antenna Showing Nodal Topology
line beam elements. Each rib was connected at its base by a pinned joint to the antenna hub. The midpoints of the ribs were connected to the support cone by a hoop and spar restraint system. The midpoint restraint is fixed to the rib and ball connected at the spar ring. The rib tips were moment connected about two axes to the top ring with short tip-restraint members that provide the correct amount of eccentricity and no torsional restraint about its axis. The support cone and ogive assembly was modeled as a fourteen member tapered beam. Section property calculations for the support cone and ogive took into account the conical shape, thus, providing effective areas and moments of inertia for each section. In reducing the cone and ogive to a line it was necessary to add rigid members at the midpoint and at the top, e.g., nodes 5-64 and 15-16. Rigid members at the top are fixed at node 15 and ball connected at the top ring.

The hub is 0.050 inch thick up to the pivot pins which are 3.5 inches above the base. The support cone is 0.020 inch thick up to the midpoint and 0.015 inch thick from the midpoint to the neck. The ogive is 0.031 inch thick at the neck and the remaining two-thirds is 0.021 inch thick. Material for the ogive is S-glass having a modulus of elasticity of $3.0 \times 10^6$. The upper cone is 0.021 inch thick S-glass. The rib wall thickness is 0.008 ±0.001 inch at root, increasing to 0.012 ±0.001 inch at the midpoint and decreasing to 0.006 ±0.001 inch at the tip. The ribs, hub, and support cone are all made from 6061-T6 aluminum.

The thermal control on the support cone and hub is black anodize on the interior and 14 layers of mylar, 15 layers of nylon net, and one layer of silverized Teflon on the exterior lower eight inches. Five layers of MLI are used on remainder of cone. The ogive and upper cone thermal control is obtained with white paint on its exterior. The thermal control for the ribs consist of two layers of mylar, three layers of nylon net, and one layer of silverized Teflon. The mass of these items was included in the analyses.

Mesh was conservatively assumed to be 100 percent effective as a mass in the stowed and deployed antenna models.

### 4.4.2.2 Stowed Antenna Analytical Method

Final dynamic analyses were performed using an eigenvalue solution for the antenna. For the stowed antenna an inverse iteration method was used to extract the lowest four frequencies. For the deployed rib, the HQR algorithm was used to solve for all eigenvalues.

The stowed antenna lateral mode shape was used to determine internal loads, deflections and stresses. Knowing that the maximum response is 25 G and that the vibration is harmonic, the acceleration relates to deflection from $G = \frac{1}{1.12} X$. The solved value of $X$ divided by the normalized deflection of 1.0 inch produces a factor which can be multiplied by the eigenmode solution having internal loads.

Preliminary analyses and trade-off studies were performed using the Rayleigh Method to calculate the fundamental frequencies. In this method, it is assumed that the lowest mode shape is the same as obtained by applying a 1 G field to the model. Deflections at all nodes are
calculated using the STARDYNE computer program. The lowest frequency is then calculated from the expression

\[
f = 3.13 \sqrt{\frac{\sum F_i \Delta x_i}{\sum F_i \left( \Delta x_i^2 + \Delta y_i^2 + \Delta z_i^2 \right)}}
\]

Where:

- \( F_i \) = gravity weights that are lumped at nodes \( i \)
- \( \Delta_i \) = deflections in \( x, y, \) and \( z \) directions at corresponding nodes \( i \)

Validity of the Rayleigh Method was verified in prior analyses and tests. A comparison of results with the eigenvalue solution is presented in the next subsection.

4.4.2.3 Stowed Antenna Results

The computer printout of the input and a portion of the results is presented in Section D1.0 of Appendix D of the CDR data package. The primary result is the fundamental frequencies for the stowed antenna which are 29.4, 55.6 and 141.8 Hz for the torsional, lateral, and longitudinal axes, respectively.

Appendix D1.0 of the CDR data package contains additional results on internal loads, stresses, and deflections. This data was used with acceleration load factors to size members and determine the required preload at the rib midpoint, Reference Sections D7.0 and D8.0 of the CDR data package.

Results of the stowed antenna lateral and longitudinal fundamental frequencies as calculated by the Rayleigh Method are presented in Sections D1.3 and D1.4 of Appendix D of the CDR data package. The eigenvalue solutions are presented in Section D1.5 of the CDR data package. The identical model was used in both Rayleigh and Eigenvalue Method solutions. Each method has its advantages. Though the Rayleigh Method can be used to calculate the fundamental frequency with less machine time, the eigenvalue solution is more accurate; especially on mode shapes and stresses. Whereas the Rayleigh Method only provides the lowest frequency, the eigenvalue solution yields the first five natural frequencies.

The Rayleigh Method results in a fundamental lateral frequency of 56.76 Hz. The eigenvalue solution value is 55.61 Hz.

Figure 4.4.2.3 shows the sensitivity of the stowed lateral frequency to additional (in excess of 0.55 pound) weight at the top of the antenna.
Figure 4.4.2.3. The Final Design Antenna Can Support an Extra Payload of 7.5 Pounds
4.4.3 Deployed Rib

4.4.3.1 Parametric Analysis

Previous analyses and test correlation have revealed that the fundamental frequency of the deployed antenna can be calculated within four percent by using a one rib model. This indicates that the mesh spring rate is relatively low and the mesh stiffness can be ignored to obtain approximate results. This is also a valid assumption in the present design because the ribs are relatively stiff compared to the mesh. The four percent accuracy on frequency applies to the final detailed rib model which includes a pivot arm and a portion of the hub. In this section the presumed accuracy is approximately 15 percent while in Paragraph 4.4.3.2 the presumed accuracy is approximately five percent for the fundamental lateral frequency and 10 percent for the fundamental torsional frequency.

Analyses were made to enable selection of a deployed rib based upon meeting a minimum frequency requirement while minimizing weight and tip deflection. Rib diameters of 1.0, 1.5, and 2.0 inches were analyzed. Rib wall thickness was varied from 0.004 to 0.016 inch in 0.002 inch increments. Because the primary stresses are from preloading the rib, they are a maximum at the rib midpoint and a minimum near the tip and root. The rib thickness was also allowed to be a maximum in the center.

The model consisted of 11 nodes connecting 10 segments. Node 1 at the tip was free and Node 11 at the root was fixed. The arc length of the rib was used but the model was a straight beam. Further details on the model and applied weights and results may be found in Section D2.0 of Appendix D of the CDR data package. A portion of the results is presented in Figures 4.4.3-1 through 4.4.3-3.

The rib parametric analysis results show that none of the 1.0 inch diameter ribs meet the frequency requirements. The 1.5-inch diameter ribs meet frequency requirements when thickness is greater than 0.006. All of the 2.0-inch diameter ribs exceed the frequency requirement.

Analysis indicated that preload stress requires a rib midpoint wall thickness of \( t_m = 0.012 \) inch. The data used to plot Figure 4.4.3-2 shows that when the tip and root thicknesses are 0.006 the frequency reduces 14 percent while the weight reduces 25 percent. Thus, it is efficient to have a thickness taper of approximately two to one from midpoint to tip or root.

Figure 4.4.3-3 indicates the degree of frequency-to-weight effectiveness. This chart must be tempered with absolute weight, frequency, stress, and thermal requirements. Figure 4.4.3-3 also indicates that the larger diameter thinner walled tubes are best from a frequency or stiffness viewpoint. This is contrary to thermal requirements which are ideal for small diameter thick walled tubes. Moreover, stress buckling must be investigated when using large D/t ratios.
Figure 4.4.3-1. None of 1.0-Inch Diameter Ribs Meet the 4 Hz Requirement But 1.5-Inch Diameter Is Satisfactory When Thicker Than 0.006 Inch
NOTES: 1. TAPER RATIO = RIB WALL THICKNESS AT MIDPOINT, $t_m'$, OVER THICKNESS AT TIP OR ROOT
2. MINIMUM FREQUENCY REQUIREMENT IS 4 Hz.

Figure 4.4.3-2. Variation of Rib Frequency and Weight Versus Taper Ratio for a Deployed 12.5-Foot Diameter Antenna
Figure 4.4.3-3. Variation of Quality Factor Versus Diameter for Ribs of a Taper Ratio = 2
Of the analyzed ribs there are a number of candidates that appear satisfactory. Preliminary thermal analysis shows that a 1.50 diameter rib with a constant wall thickness of 0.010 inch is marginally satisfactory.

Therefore, giving consideration to stress, frequency, thermal, weight, cost, and low deflections, a rib size was selected. The selected rib is 1.50 inches diameter with a minimum thickness of 0.008 at the root, 0.012 at the midpoint, and 0.006 at the tip. Using a tolerance of ±0.0010 inch the above nominal thicknesses would all increase 0.001 inch.

4.4.3.2 Detailed Rib Analysis

The selected rib was modeled for a STARDYNE eigenvalue run. The parabolic rib shape was now considered and a pivot arm was connected to the rib at the pivot pin. A sketch of the model and the geometry and other details are presented in Section D6.0 of Appendix D. The rib has 11 nodes and 10 beam segments, the pivot arm had 11 nodes and 11 beams and one plate element. Effective areas and moments of inertia were calculated considering the thickness taper.

The fundamental frequencies in the torsional and lateral axes are 6.97 and 6.91 Hz. The torsional mode shape is out-of-plane bending of the rib about the z axis of the pivot pin. The lateral mode shape is in-plane bending of the rib about the y axis. A summary of frequencies and a comparison between computer models for the structure is shown in Table 4.4.3.2.

Table 4.4.3.2. Summary of Lower Frequencies

<table>
<thead>
<tr>
<th>Mode</th>
<th>Frequency, Hz</th>
<th>Model 1 No HUB</th>
<th>Model 2 With HUB</th>
</tr>
</thead>
<tbody>
<tr>
<td>First Lateral</td>
<td>7.02</td>
<td>6.91</td>
<td></td>
</tr>
<tr>
<td>First Torsional</td>
<td>7.02</td>
<td>6.97</td>
<td></td>
</tr>
<tr>
<td>Second Lateral</td>
<td>44.0</td>
<td>43.1</td>
<td></td>
</tr>
<tr>
<td>Second Torsional</td>
<td>43.9</td>
<td>43.7</td>
<td></td>
</tr>
<tr>
<td>Third Lateral</td>
<td>136</td>
<td>132</td>
<td></td>
</tr>
<tr>
<td>Third Torsional</td>
<td>137</td>
<td>137</td>
<td></td>
</tr>
</tbody>
</table>
4.4.4 MDS Load Analysis

Forces and torques in the MDS were calculated for antenna deployment in a face-down position and for deployment in a face-side position. These loads were calculated for each 1° increment of deployment. A summary of the maximum limit loads is presented in Table 4.4.4. The complete load calculations are presented in Section D3.0 of Appendix D of the CDR Data Package.

<table>
<thead>
<tr>
<th>a. Face-Down Condition</th>
<th>Push Rod</th>
<th>Ball Screw</th>
<th>Ball Screw</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angle (a), Degrees</td>
<td>Force</td>
<td>Force</td>
<td>Torque</td>
</tr>
<tr>
<td>49</td>
<td>10.55</td>
<td>81.49</td>
<td>1.44</td>
</tr>
<tr>
<td>74</td>
<td>13.67</td>
<td>4.5</td>
<td>0.081</td>
</tr>
</tbody>
</table>

b. Face-Side Condition

<table>
<thead>
<tr>
<th>Angle (a), Degrees</th>
<th>Push Rod Force</th>
<th>Carrier Moment</th>
<th>Ball Screw Moment</th>
<th>Ball Screw Stress</th>
<th>Ball Screw Deflection</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>16.43</td>
<td>510</td>
<td>319</td>
<td>70,000</td>
<td>0.00005</td>
</tr>
</tbody>
</table>

Moments were taken about the rib pivot point. The rib weight of 0.6548 pound was concentrated at its CG which has a radius arm of 41.79 inches. Reacting this moment is a push rod force acting on a moment arm of \(a\) \(\sin(a + \beta)\). See Figure 4.4.4 for a sketch of the geometry. This approach is approximately two percent conservative because it excludes the counter-balancing effect of the carrier and push rod weights on their moment arms.

4.4.5 Preload Requirements

Appendix D, Section 7.0 of the CDR Data Package, shows the derivation of preload requirements at the rib midpoint and at the rib tip.

To avoid chatter during vibration at 25 G response it is necessary to preload the rib midpoint with 15.84 pounds. This is accomplished by installing the rib so that it must be deflected 1.604 inches at its tip during final assembly.
Figure 4.4.4. Geometry of MDS Used in Load Analysis
4.4.6 Stress Analysis

Rib and Support Cone Detail Stress Analysis is included in Appendix D, Section 8.0, of the CDR Data Package.

4.5 Deployment Reliability

An analysis was performed to determine the probability of proper deployment of the antenna in the orbital environment. Proper deployment is herein defined as release of the ribs by the launch restraint system and subsequent operation of the mechanical deployment system (MDS) which results in a tensioning of the mesh surface to the required levels. The approach taken in the analysis was to evaluate the probability of the restraint system release and MDS operation separately, then these values were combined to yield the probability of successful deployment.

4.5.1 MDS Analysis

The results of tests conducted in the design and development phase of a previous program were used to construct a lower bound on the probability of successful operation of the MDS. Succinctly, the MDS was cycled 400 times, under various conditions, to determine what failure modes, if any, would show up. The extensive testing did not produce any failures. The testing can be thought of as representing 400 Bernoulli trials during which 400 successes were observed.

Let

\[ p = \text{probability of successful operation of the MDS on a single trial} \]

then the maximum likelihood estimator for \( p \) is

\[ \hat{p} = \frac{X_o}{\eta} \]  

(1)

where \( X_o = \text{number of successes} \)

and \( \eta = \text{total number of trials} \).

Using the results of the tests then

\[ \hat{p} = 1, \]

which says that the best point estimate for the true probability of success \( p \) is \( \hat{p} = 1 \). A more revealing statistic at this point is the lower bound on the true probability of success \( (p) \). The arguments leading up to and development of the following lower bound can be found in
References 1 and 2. A 95 percent Lower Bound (LB) on the parameter $p$ is given by the following:

$$\text{LB} = \frac{X_0}{X_0 + (\eta - X_0 + 1) F_{0.95} (2 (\eta - X_0 + 1), 2 X_0)}$$

where $F_{0.95} (2 (\eta - X_0 + 1), 2 X_0)$ is a random variable with the variance ratio distribution and is a function of two parameters (degrees of freedom).

Substituting in the above equation for $X_0 = 400$ and $\eta = 400$ and using tables for the cumulative $F$ distribution\(^\text{2}\)

$$\text{LB} = 0.993.$$ 

Based on the test results we are 95 percent sure that the true probability of successful operation of the MDS is no smaller than 0.993.

4.5.2 Restraint Release Analysis

The problem is one of determining the reliability associated with the deployment of the antenna ribs where each rib is being restrained. The ground rules are that:

1. All 12 ribs must be pulled free.

2. The scope of this analysis is as appears in Figure 4.5.2-1.

3. All system elements exterior to this scope are assumed to function properly.

Approach

The approach consisted of determining the probabilities associated with the successful operation of the pair of redundant guillotines and the freeing of each of the 12 antenna ribs (see Figure 4.5.2-1).

Solution Technique

The probability of successfully cutting the cable by means of the pair of guillotines is

$$\text{PG} = 1 - (1 - \text{pg})^2 \quad (2)$$

\(^1\text{Hald, A., 1952, Statistical Theory with Engineering Applications, John Wiley and Sons, New York}\)

\(^2\text{Brownlee, K. A., 1960, Statistical Theory and Methodology in Science and Engineering, John Wiley and Sons, New York}\)
Figure 4.5.2-1. Simplified Model for Antenna Deployment
where \( pg \) = the probability that a single guillotine will successfully cut the cable and PG is the desired probability. The values of \( pg \) used in the analysis were

\[
pg = 0.99, \text{ conservative estimate} \\
0.9999, \text{ vendor quoted estimate}
\]

The probability that each rib would be free if the cable were cut, depends on the forces acting to pull each rib from the restraining mechanism. There are two components of force acting to free each rib - a force due to preload and a force due to the torque motors. The forces due to preload and torque motors are random variables which are assumed to be normally distributed. This assumption is based on engineering judgement as opposed to mathematical convenience. It is further assumed that each of the 12 ribs is identical from a freeing and restraining force viewpoint.

Let \( x_1 \) be the amount of force on each rib due to preload where \( x_1 \) is a random variable assumed to be normally distributed with mean \( \mu_1 \), and standard deviation \( \sigma_1 \). The probability that the preload force will be greater than the restraining force \( (k) \) is

\[
Pr \{x_1 < k\} = \{1 - Pr \, x_1 \leq k\}
\]

or in terms of the standard cumulative normal

\[
Pr \{x_1 > k\} = 1 \Phi \left( \frac{k - \mu_1}{\sigma_1} \right)
\]

(3)

Based on design values and engineering estimates \( \mu_1 \) was determined to be 5.15 pounds and the three Sigma limits were ±1.50 pounds which implies \( \sigma_1 = 0.5 \) pound. The value of \( k \) (restraint force) was not easily quantifiable, ergo \( k \) was treated as a parameter and allowed to range over 0 to 200 percent of \( \mu_1 \).

The amount of freeing force \( (x_2) \) acting on each rib due to the torque motors was assumed to be normally distributed with the mean \( \mu_2 = 2.75 \) pounds and standard deviation \( \sigma_2 = 0.2750 \) pound determined by design values and engineering judgement. The combined forces \( (x_1 + x_2) \) will act to free each rib, hence

\[
Pr \{x_1 + x_2 > k\} = 1 - Pr \{x_1 + x_2 \leq k\}
\]

or in terms of the cumulative unit normal

\[
Pr \{x > k\} = 1 - \Phi \left( \frac{k - \mu}{\sigma} \right)
\]

(4)

where \( x = x_1 + x_2 \) and is a random variable normally distributed with \( \mu = \mu_1 + \mu_2 \) and \( \sigma = \sqrt{(\sigma_1^2 + \sigma_2^2)}^{1/2} \). Performing the indicated operation yields \( \mu = 7.90 \) and \( \sigma = 0.5706 \).
Since each rib can be freed if either the preload or the combined preload plus torque motor force is greater than the restraining force computations were carried out to gain insight into the effect of restraint force on the freeing force with and without the torque motor. Using Equation (3) for preload force only, let

\[ P_i = \{ Pr( X_i > k) \} \]

where \( P_i \) is the probability that the freeing force on the \( i \)th rib will be greater than the restraint force.

Then

\[ P = P_g \prod_{i=1}^{18} P_i \]  

(5)

where \( P_g \) is defined by Equation (2) and \( P \) is the Probability that the cable will be cut and all 12 ribs will be released.

When the introduction of the freeing force due to the torque motor and assuming statistical independence

\[ P_i = 1 - Pr\{ x_i \leq k \} \cdot Pr\{ x \leq k \} \]

(6)

Hence, substituting Equation (6) for \( P_i \) in Equation (5) will yield the probability that the cable will be cut and all 12 ribs will be released when both the preload and torque motor force are considered.

Results

Computations were carried out with \( P_g = 0.9999 \) (i.e., \( pg = 0.99 \)) and \( P_g = 0.999999 \) (i.e., \( pg = 9999 \)) and for values of \( k = 0, 10, \ldots, 200 \) percent of \( \mu_1 \) under both the preload only and preload plus torque motor freeing force. These computations in essence involved the operations depicted by Equation (5). Extreme precautions were taken so as not to introduce round-off or truncation errors in the computations. The numerical integration of the unit normal density, for example, was executed using the Hewlett-Packard Calculator with 100 subdivisions per integration. This allowed for the computation of very small probabilities (i.e., in the tails of the unit normal density) which are not readily available in table form. The final results are shown in graphic form in Figure 4.5.2-2. The curves marked preload force correspond to removing the block titled "Force Due to Preload and Motor" from Figure 4.5.2-1 which in essence removes a redundant success path. The set of curves marked preload + torque motor force corresponds to the situation enclosed by the dotted region in Figure 4.5.2-1. For the preload force only condition and \( P_g = 0.9999 \), the probability of freeing all the ribs (\( P \)) is virtually 0.9999 for a restraint force less than 50 percent of \( \mu = 5.15 \). The addition of the force due to the torque motor will allow a \( k \) of approximately 90 percent or less to be overcome with probability = 0.9999. The curves can be used to determine the probability that a given restraint force can be overcome by the forces acting to free the ribs. For example, if \( k = 5.12 \) pounds (100 percent of \( \mu_1 \)) then \( P = 0.50 \) (not shown on graph) for the preload force only but when the force due to the torque motor is considered, \( P = 0.9998 \) when \( P_g = 0.9999 \).
Figure 4.5.2-2. Probability of Antenna Deployment (P) Versus Restraint Force (K)
Conclusions

The present design with redundant guillotines and preload and torque motor forces acting to free the antenna ribs, possesses a probability of deploying greater than .999. This conclusion assumes a priori that all other events necessary for antenna deployment will occur with probability one.

4.5.3 Probability of Successful Deployment

From the previous section, $P$ was conservatively estimated at 0.9999 where

$$P = \text{the probability that the cable will be cut and all 12 ribs will be released.}$$

Combining this estimate with the results for the MDS from Paragraph 4.5.1 yields

$$P_s = 0.9999 \times 0.9926 = 0.9925$$

Where $P_s$ is the probability of successful operation of the MDS and deployment of the antenna ribs.

Conclusion

Based on the above analyses, the probability of successful deployment of the antenna is estimated conservatively at 0.9925.
SECTION 5.0
APPLICATIONS STUDIES TASK
The objective of the Applications Studies Task was to investigate the applicability of the 12.5-foot deployable reflector to the requirements of the Tracking and Data Relay Satellite (TDRS) Program. To accomplish this investigation, the following subtasks were conducted:

- Establish baseline system parameters
- Select and analyze two practical feed concepts
- Perform typical link analyses
- Establish pointing error budgets and perform servo analyses
- Develop relationship of reflector weight and surface accuracy as a function of antenna diameter

The following paragraphs describe the results of these activities. However, the applicability of the 12.5-foot reflector design to the TDRS Program is, undoubtedly, best demonstrated by the fact that the reflector design (with only slight modifications) has been cited as the selected baseline design by both contractors in the recently completed TDRSS Definition Phase Studies (see References 2 and 3 and Figure 5.0).

5.1 Baseline Systems Parameters Definition

The first subtask of the Applications Studies Task was the definition of the baseline system parameters on the basis of NASA furnished data. This data was received and evaluated with respect to the antenna system. This section includes a summary of the NASA data, link tables, and an assessment of user satellite antenna gains required to support various data bandwidths for a range of TDRS Ku-band and S-band sizes.

The pertinent antenna parameters may be classified as RF or mechanical. The RF parameters (performance) are fixed by link analyses and required link performance. The mechanical parameters are developed from the selected pointing philosophy, required tracking accuracy, and TDRS and user spacecraft ephemeris and attitude accuracies. The antenna RF parameters supplied by NASA are:

- Transmit Frequency \(13.4 \rightarrow 14.2\) GHz
- Receive Frequency \(14.4 \rightarrow 15.35\) GHz
- Bandwidth \(20\) MHz
- Receiver Sensitivity (G/T) \(\geq 10\) dB/K (Boresight)
Figure 5.0. TDRS Baseline Configuration
- Effective Radiated Power 40 dBW
- Power Output 20 watts
- Transmit Losses 2.0 dB
- Pointing Loss \( \leq 1.0 \) dB

Assuming that solid state Ku-band receivers will be used on the TDRS, the noise temperature will be approximately 1000\(^\circ\)K or 30 dB\(^{\circ}\)K. The minimum antenna gain required, assuming 1 dB circuit losses, is therefore 41 dB and the effective radiated power is 52 dBw with a 20 watt RF source and 2.0 dB losses. The 42 dB gain corresponds to an antenna diameter of approximately 3 feet. As illustrated in Table 5.1, a 3-foot dish provides sufficient margin to support a 20 Mb link to the ground. A conservative noise temperature for a ground based receiving system is 500\(^\circ\)K and the 28 dB\(^{\circ}\)K. The G/T shown in Table 5.1 reflects such a temperature. For completeness, the links corresponding to a range of TDRS antennas are shown for both the TDRS ground and TDRS user satellite links in Table 5.1, although the 3-foot reflector would probably be dedicated to the ground link.

The parameter values shown in Table 5.1 represent gross estimates and this table is included to illustrate the difficulty of maintaining a 20 Mb link between the TDRS and the user satellites.

The NASA supplied user satellite parameters are:

- Antenna Gain 16 dB
- Transmitter Power 6 dBW
- Transmitter Losses 2 dB
- Pointing Loss \( \leq 1.0 \) dB
- Receiving Temperature (assumed) 30 dB\(^{\circ}\)K

Radiation's assumptions which are reflected in this table are:

- TDRS Receiver Noise Temperature 30 dB\(^{\circ}\)K
- User Satellite Noise Temperature 30 dB\(^{\circ}\)K
- Ground Station Noise Temperature 27 dB\(^{\circ}\)K
### Table 5.1. Ku-Band TDRS Link Tables

<table>
<thead>
<tr>
<th>Dish Diameter</th>
<th>Down-Link</th>
<th>Link -</th>
<th>3'</th>
<th>6'</th>
<th>12'</th>
<th>20'</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Gnd</td>
<td>User</td>
<td>Gnd</td>
<td>User</td>
<td>Gnd</td>
<td>User</td>
</tr>
<tr>
<td>Antenna Gain (dB)</td>
<td>39.5</td>
<td>39.5</td>
<td>45.5</td>
<td>45.5</td>
<td>51.5</td>
<td>51.5</td>
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<tr>
<td>Transmitter Power (20 watts) (dBw)</td>
<td>13.0</td>
<td>13.0</td>
<td>13.0</td>
<td>13.0</td>
<td>13.0</td>
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<tr>
<td>Transmitting Circuit Losses (dB)</td>
<td>1.0</td>
<td>1.0</td>
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<td>1.0</td>
<td>1.0</td>
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<tr>
<td>Transmitter EIRP (dB)</td>
<td>51.5</td>
<td>51.5</td>
<td>57.5</td>
<td>57.5</td>
<td>63.5</td>
<td>63.5</td>
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<tr>
<td>Space Loss (dB)</td>
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<td>Receiver Antenna Gain (dB)</td>
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<td>16.0</td>
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<td>Receiver Temperature (dB °K)</td>
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<tr>
<td>Receiver G/Ts dB/°K</td>
<td>+28.0</td>
<td>-15.0</td>
<td>+28.0</td>
<td>-15.0</td>
<td>+28.0</td>
<td>-15.0</td>
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<tr>
<td>P/KT (dB/Hz)</td>
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<td>57.2</td>
<td>106.84</td>
<td>63.2</td>
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<td>69.2</td>
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<td>Margin @ ZOMB and Eb/No = 9.6</td>
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<td>User Dish Rqd.</td>
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<td>4'</td>
<td>35.4 dB</td>
<td>2'</td>
<td>29.4 dB</td>
<td>1'</td>
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</table>

<table>
<thead>
<tr>
<th>Dish Diameter</th>
<th>Up-Link</th>
<th>Link -</th>
<th>3'</th>
<th>6'</th>
<th>12'</th>
<th>20'</th>
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<td>User</td>
<td>Gnd</td>
<td>User</td>
<td>Gnd</td>
<td>User</td>
</tr>
<tr>
<td>Transmitter Antenna Gain (dB)</td>
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<td>17.0</td>
<td>57.0</td>
<td>17.0</td>
<td>57.0</td>
<td>17.0</td>
</tr>
<tr>
<td>Transmitter Power (dBw)</td>
<td>10.0</td>
<td>6.0</td>
<td>10.0</td>
<td>6.0</td>
<td>10.0</td>
<td>6.0</td>
</tr>
<tr>
<td>Transmitting Circuit Losses (dB)</td>
<td>1.0</td>
<td>3.0</td>
<td>1.0</td>
<td>3.0</td>
<td>1.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Transmitter EIRP (dBw)</td>
<td>66.0</td>
<td>20.0</td>
<td>66.0</td>
<td>20.0</td>
<td>66.0</td>
<td>20.0</td>
</tr>
<tr>
<td>Space Loss (dB)</td>
<td>208.18</td>
<td>208.82</td>
<td>208.18</td>
<td>208.82</td>
<td>208.18</td>
<td>208.82</td>
</tr>
<tr>
<td>Receiver Antenna Gain (dB)</td>
<td>40.5</td>
<td>40.5</td>
<td>46.5</td>
<td>46.5</td>
<td>52.5</td>
<td>52.5</td>
</tr>
<tr>
<td>Receiver Temperature (dB °K)</td>
<td>30.0</td>
<td>30.0</td>
<td>30.0</td>
<td>30.0</td>
<td>30.0</td>
<td>30.0</td>
</tr>
<tr>
<td>Receiver Losses (dB)</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Receiver G/Ts (dB °K)</td>
<td>9.5</td>
<td>9.5</td>
<td>15.5</td>
<td>15.5</td>
<td>21.5</td>
<td>21.5</td>
</tr>
</tbody>
</table>
Table 5.1. Ku-Band TDRS Link Tables (Continued)

<table>
<thead>
<tr>
<th>Dish Diameter</th>
<th>3'</th>
<th>6'</th>
<th>12'</th>
<th>20'</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Gnd</td>
<td>User</td>
<td>Gnd</td>
<td>User</td>
</tr>
<tr>
<td>P/KT dB/Hz</td>
<td>95.92</td>
<td>59.28</td>
<td>101.92</td>
<td>65.28</td>
</tr>
<tr>
<td>Margin @ 20 MB and Eb/No = 9.6 dB</td>
<td>13.32</td>
<td>-23.32</td>
<td>19.32</td>
<td>-17.32</td>
</tr>
<tr>
<td>User Dish Rqd.</td>
<td>39.32-2.5'</td>
<td>33.32-1.25'</td>
<td>27.32-7.5&quot;</td>
<td>27.82</td>
</tr>
</tbody>
</table>

15.0 GC Dish Diameter
Up-Link Link -
- Ground Station Maximum Space Loss at 15 GHz 208 dB
  (Assumes 65° longitude separation and Wallops Island ground station latitude)

- User Satellite Maximum Space Loss at 15 GHz 209 dB
  (Assumes 3000 mile altitude orbit and a 5° cutoff angle)

- Required Bit Error Rate $10^{-5}$

Because of the negative link margins for the TDRS User Satellite Links, Figure 5.1-1 was developed to illustrate the bit rate that can be supported with the specified 16 dB gain user satellite antenna for a range of TDRS antenna diameters as well as the additional channel capacity resulting from increased user satellite antenna gain. Because the TDRS antenna system will support many users it is probably advantageous to place most of the link gain requirements on that antenna rather than on the users.

In a similar manner, the possible support of user satellites at S-band frequencies is shown parametrically in Figure 5.1-2. The user satellites are baselined with a 1.5-foot dish, a 10 watt power amplifier and a 500°K noise temperature. The supportable bit rate is shown as the TDRS antenna diameter is increased from 3 feet to 20 feet and the user satellite antenna diameter is increased from 1.5 feet to 6 feet. As in the previous link analysis, the link parameters values represent preliminary estimates and assumptions, and the actual link tolerances are probably in the neighborhood of ±3 to 6 dB. The assumptions made to develop Figure 5.1-2 are:

- TDRS S-band Noise Temperature 500°K (27 dB-°K)
- User Satellite S-band Noise Temperature 500°K
- TDRS S-band Power Output 40 watts
- User Satellite S-band Power Output (Expandable to 40 watts) 10 watts
- Maximum User Satellite Antenna Diameter 6 feet
- Required $E_b/N_o$ (Corresponding to $10^{-5}$ Bit Error Rate) 9.6 dB
Figure 5.1-1. Supportable Bit Rate at Ku-Band as Function of Antenna Diameters
Figure 5.1-2. Supportable Bit Rate at S-Band as Function of Antenna Diameters
5.2 RF Feed Analysis

Two antenna feed concepts have been selected and analyzed which are compatible with the established baseline parameters. Both concepts provide for dual-frequency operation, at Ku- and S-band, and have the following basic characteristics:

- Compatible with 12.5-foot rib-and-mesh reflector
- Single beam direction at a given time determined by reflector steering
- Full duplex operation
- Self-tracking at Ku-band
- Programmed tracking at S-band
- Circular polarization

The analysis was extended to include dual-frequency operation with the cognizance of the NASA Contract Technical Officer. The decision was based on indications that this operation is compatible with and required in the anticipated operation of the TDRS.

The basic characteristics indicated for the selected feed concepts are based on the baseline parameters and other constraints. Although some effort is being expended by NASA to develop feed/reflect concepts which allow multiple frequency, multiple beam and tracking operations simultaneously in a single dish, concepts of this nature were beyond the scope of this program. Hence, only concepts which allow boresight beams and steering by movements of the dish are considered. Full duplex operation, simultaneously receiving and transmitting in the antenna, can be obtained by,

a. Transmitting and receiving in either one of the bands
b. Transmitting in one band and receiving in the other

In most cases, effective use of the latter is obtained only when transmission occurs at S-band frequencies and reception at Ku-band. This allows the narrow Ku-band beam to be utilized for tracking.

The tracking requirement of a 12.5-foot antenna is fundamentally a function of the frequency of operation and the attendant beam width. At S-band frequencies the half-power beam width is relatively large at approximately 2.5°; therefore, a programmed tracking mode is accurate and reliable enough and probably cost-effective for this band. On the other hand, the 3 dB beam width for the Ku-band frequencies is on the order of 0.4° indicating the probable need for self-tracking for the Ku-band. Consequently, concepts having these tracking characteristics have been selected.
Possible applicable self-tracking schemes include analog and digital monopulse implementations and step-track implementations. Both schemes are used in the two concepts presented in this section.

Inasmuch as all requirements for the TDRS system are not fully defined at this time, the two concepts selected for analysis cannot be considered optimum configurations. They are, however, important candidate types meeting the requirements as known and therefore allow meaningful modeling of the system for performance of the overall applications study and in particular, the pointing study task. In addition, the two concepts offer enough contrast to give insight over a relatively broad range of variation in operational requirements of the system. For example, the concepts allow for programmed, monopulse, and step tracking, and right- and left-hand circular polarization are available including like and orthogonal polarization for the receive and transmit signals of a given band. The concepts employ up-to-date, yet proven, techniques for obtaining the required performance for the TDRS antenna.

In the following paragraphs full descriptions of the two selected feed concepts are presented along with analytical projections of gain and efficiency budgets for each.

5.2.1 Monopulse Tracking Cassegrain Ku-Band/Programmed Tracking Apex S-Band Feed

A dual frequency feed concept is described in this paragraph employing pseudo-monopulse tracking Cassegrain Ku-band and programmed-tracking apex S-band implementations. A frequency sensitive dichroic lens subreflector is used in the configuration. The feed is configured to mate with a 12.5-foot rib-and-mesh reflector.

Description

The feed system consists of the components shown in the block diagram, Figure 5.2.1-1, and the sketch of the feed layout, Figure 5.2.1-2. These include an apex-mounted S-band cupped helix antenna which illuminates the 12.5-foot reflector through a frequency-sensitive or dichroic subreflector. The dichroic subreflector operates in the transmissive mode at the S-band frequencies and reflective mode at Ku-band frequencies. The cupped helix provides either right- or left-hand circular polarization for both transmit and receive channels depending on the winding direction of the helix. A low-loss cable interconnects the cupped helix and diplexer required for separating the receive and transmit channels. The received signals are amplified in a preamplifier, probably a tunnel diode or uncooled preamp. Both S-band channels are transmitted through rotary joints on the x-y mount. In the system four identical noncontacting, rotary joints are used, each having a center section of circular waveguide choke-flange coupled through the joint. The S-band channel is concentric to the circular waveguide. The design provides separation of the transmit and receive channels to opposite sides of the gimbal system to maintain good isolation.

The dichroic lens or subreflector is an important component in the concept. This type of subreflector has been developed and demonstrated by test on several programs to exhibit
Figure 5.2.1-1. Tracking Cassegrain Ku-Band, Nontracking Apex S-Band Feed
Figure 5.2.1-2. Tracking Cassegrain Ku-Band, Nontracking Apex S-Band Feed Layout
no greater than 0.3 dB loss in the reflective band (Ku-band) and less than 0.1 dB loss in the transmissive band (S-band). The design is amenable to subreflector shaping (as opposed to maintaining a conventional hyperboloid) to achieve greater spillover/amplitude taper ($\eta_{sp}$, $\eta_{at}$) efficiency. Spillover/amplitude taper efficiencies in excess of 80 percent have been measured with this technique.

The Ku-band system features the 13-wavelength diameter, dichroic, shaped subreflector mentioned above and a single channel (pseudomonopulse) tracking waveguide circuit in which the received sum channel is modulated sequentially by the x- and y-axis error signals via an electronic scanner. The error signals are subsequently demodulated at the receiver and used for pointing the antenna.

As shown in the block diagram, the transmit signal is coupled through the rotary joints to a power splitter and then to orthomode transducers (duplexers) which serve to maintain about 20 dB isolation between the transmit and receive signals presented to the comparator. This isolation mainly results from the orthogonality of the two polarizations of the receive and transmit signals. An additional 80 to 100 dB of isolation can be provided in the bandstop filter located ahead of the preamplifier. The transmit signals are properly polarized, that is right- or left-hand circular, and then presented to the four-part choked, or corrugated, horn feed.

The received signals present in the four channels are passed through the polarizers and diplexers and presented to the comparator. The comparator develops a sum channel comprised of the sum of the four received signals, and two difference channels corresponding to the difference between the signals in the x and y directions. The scanner sequentially gates the difference channels onto the sum channel via the coupler which consequently modulates the sum channel by the error, or difference, signal. After bandpass filtering the modulated received signal is amplified in a preamplifier, typically a parametric amplifier, and presented at the output connector through the rotary joints.

Several variations on this general concept are possible. For example, the preamplifier may not be necessary in the final configuration, the rotary joints may be replaced by flexible cables especially at S-band frequencies, full monopulse requiring three channels with three receivers may be used instead of the pseudomonopulse, and only two up-down channels (one at S-band and one at Ku-band) may be desired with the result that the duplexers and diplexers may be deleted from the diagram. However, the configuration presented is a likely candidate and will be analyzed in the following section.

**Gain and Efficiency Budgets**

In Table 5.2.1 budgets for both S-band and Ku-band receive and transmit channel gain and efficiency are presented. The values presented include all elements of the antenna including the rotary joints for the x-y gimbal.
Table 5.2.1

<table>
<thead>
<tr>
<th>Efficiency Factors</th>
<th>S-Band</th>
<th>Ku-Band</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rec</td>
<td>Xmit</td>
</tr>
<tr>
<td>Spillover/Amplitude Taper Efficiency</td>
<td>.650</td>
<td>.650</td>
</tr>
<tr>
<td>Primary Phase Efficiency</td>
<td>.970</td>
<td>.970</td>
</tr>
<tr>
<td>Blockage Efficiency</td>
<td>.957</td>
<td>.957</td>
</tr>
<tr>
<td>Primary Cross-Polarization Efficiency</td>
<td>.998</td>
<td>.998</td>
</tr>
<tr>
<td>Secondary Cross-Polarization Efficiency</td>
<td>.978</td>
<td>.978</td>
</tr>
<tr>
<td>Dichroic Loss Efficiency</td>
<td>.980</td>
<td>.980</td>
</tr>
<tr>
<td>A. Illumination Efficiency</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface Tolerance Efficiency</td>
<td>.999</td>
<td>.999</td>
</tr>
<tr>
<td>RF Reflectivity</td>
<td>.995</td>
<td>.995</td>
</tr>
<tr>
<td>B. Reflector Efficiency</td>
<td>.994</td>
<td>.994</td>
</tr>
<tr>
<td>Horn and Polarizer Loss Efficiency</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diplexer Loss Efficiency</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Four-Way Power Divider Loss Efficiency</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Comparator Loss Efficiency</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coupler Loss Efficiency</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bandpass Filter Loss Efficiency</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rotary Joint Loss Efficiency</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Waveguide Loss Efficiency</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diplexer Loss Efficiency</td>
<td>.933</td>
<td>.933</td>
</tr>
<tr>
<td>Coaxial Cable Loss Efficiency</td>
<td>.938</td>
<td>.938</td>
</tr>
<tr>
<td>Cupped Helix Feed Loss Efficiency</td>
<td>.995</td>
<td>.995</td>
</tr>
<tr>
<td>Mismatch and Axial Ratio Loss Efficiency</td>
<td>.970</td>
<td>.970</td>
</tr>
<tr>
<td>C. Loss Efficiency</td>
<td>.845</td>
<td>.826</td>
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<tr>
<td>Overall Efficiency (A x B x C)</td>
<td>.485</td>
<td>.474</td>
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<tr>
<td>Midband Gain (dB)</td>
<td>35.2</td>
<td>35.8</td>
</tr>
<tr>
<td>Half-Power Beam Width (Degrees)</td>
<td>2.64</td>
<td>2.42</td>
</tr>
</tbody>
</table>
5.2.2 Nested Ku-Band and S-Band Apex Feed

A dual frequency feed concept is described in this section employing apex-mounted Ku-band and S-band nested feeds. Single channels are implemented for both bands. The feed is configured to mate with a 12.5-foot rib- and mesh-reflector.

Description

The feed system consists of the components shown in the block diagram of Figure 5.2.2-1 and the sketch of the feed layout, Figure 5.2.2-2. The Ku-band horn is mounted within the S-band coaxial-cavity feed at the apex. The four ports of the S-band feed are phased and summed in a hybrid and balun network to provide a single channel which may be right- or left-hand circular polarized. A diplexer separates the received signal from the transmitted signal allowing a preamplifier to be placed in the receive channel ahead of the long coaxial cable run and the rotary joints. The transmitted signal is also passed through the rotary joints and low-loss coaxial cable. The rotary joints for this concept are identical to those described for the other feed concept.

The Ku-band system is similarly configured. A choked horn and polarizer is connected to a waveguide diplexer where the transmit and receive signals are separated. Right- or left-hand polarization may be obtained. A preamplifier is provided ahead of the rotary joints and waveguide runs.

It is intended in this concept that self-tracking in the Ku-band be accomplished through the use of a step-tracking technique. Such a technique has been extensively studied at Radiation and utilized in ground antenna systems. The technique consists basically of sensing the change in received signal amplitude which occurs when the antenna is steered in small increments, both in the x and y direction, and developing the necessary tracking signals. Stepping algorithms can be developed for maximizing the tracking capability under the expected operational constraints.

Several variations on this basic configuration are also possible. Orthogonal transmit and receive polarizations may be obtained at Ku-band by providing a waveguide diplexer at the output of the horn and polarizer, and at S-band by simply taking both polarizations from the 3-dB hybrid instead of terminating the unused one. However, this involves doubling the number of cables and waveguide leading to the feed, therefore, increasing the feed blockage losses. The preamplifier may not be necessary in the final configuration and the rotary joints may possibly be replaced by flexible cables. The configuration described above will be considered in the following section where its gain and efficiency budgets are presented.

Gain and Efficiency Budgets

Table 5.2.2 presents a tabulation of the gain efficiency budgets for the nested Ku- and S-band apex feed system described above. The performance of the transmit and receive channels for both frequency bands is detailed.
Figure 5.2.2-1. Nested Ku- and S-Band Apex Feed
Table 5.2.2

<table>
<thead>
<tr>
<th>Efficiency Factor</th>
<th>S-Band</th>
<th>Ku-Band</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rec</td>
<td>Xmit</td>
</tr>
<tr>
<td>Spillover/Amplitude Taper Efficiency</td>
<td>.680</td>
<td>.680</td>
</tr>
<tr>
<td>Primary Phase Efficiency</td>
<td>.970</td>
<td>.970</td>
</tr>
<tr>
<td>Blockage Efficiency</td>
<td>.957</td>
<td>.957</td>
</tr>
<tr>
<td>Primary Cross-Polarization Efficiency</td>
<td>.998</td>
<td>.998</td>
</tr>
<tr>
<td>Secondary Cross-Polarization Efficiency</td>
<td>.978</td>
<td>.978</td>
</tr>
<tr>
<td>A. Illumination Efficiency</td>
<td>.616</td>
<td>.616</td>
</tr>
<tr>
<td>Surface Tolerance Efficiency</td>
<td>.999</td>
<td>.999</td>
</tr>
<tr>
<td>RF Reflectivity</td>
<td>.995</td>
<td>.995</td>
</tr>
<tr>
<td>B. Reflector Efficiency</td>
<td>.994</td>
<td>.994</td>
</tr>
<tr>
<td>Feed Loss Efficiency</td>
<td>.991</td>
<td>.991</td>
</tr>
<tr>
<td>Diplexer Loss Efficiency</td>
<td>.933</td>
<td>.933</td>
</tr>
<tr>
<td>Waveguide Loss Efficiency</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Coaxial Cable Loss Efficiency</td>
<td>.938</td>
<td>.938</td>
</tr>
<tr>
<td>Rotary Joint Loss Efficiency</td>
<td>---</td>
<td>.978</td>
</tr>
<tr>
<td>Phasing Network Loss Efficiency</td>
<td>.912</td>
<td>.912</td>
</tr>
<tr>
<td>Mismatch and Axial Ratio Loss Efficiency</td>
<td>.960</td>
<td>.960</td>
</tr>
<tr>
<td>C. Loss Efficiency</td>
<td>.759</td>
<td>.743</td>
</tr>
<tr>
<td>Overall Efficiency (A x B x C)</td>
<td>.465</td>
<td>.455</td>
</tr>
<tr>
<td>Midband Gain (dB)</td>
<td>35.0</td>
<td>35.7</td>
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<tr>
<td>Half-Power Beamwidth (degrees)</td>
<td>2.64</td>
<td>2.42</td>
</tr>
</tbody>
</table>
Figure 5.2.2-2. Nested Ku- and S-Band Apex Feed Layout
5.3 Pointing Mechanism Study

This section describes a candidate gimbal design approach for a dual-frequency, dual-tracking, S- and Ku-band antenna system. The dual frequency system utilizes a 12.5-foot diameter antenna with open loop (or program) tracking in S-band and closed loop (pseudomono-pulse) tracking in Ku-band. The gimbal design utilizes the TDRS location and ephemeris patterns to minimize the "keyhole" problem and thus simplify the design. The design requirements and the candidate design and its associated control and torquing devices are described in the following paragraphs.

5.3.1 Design Performance Considerations

5.3.1.1 Viewing Angle Requirements

Figure 5.3.1.1 shows the kinematic information relating to the TDRS performance. The maximum viewing angle at 10,000 km (5400 nmi) is 24° from nadir and represents a total field of view cone of 48°. An x-y gimbal configuration, with the axes of rotation at right angles to one another and to the nominal LOS, is preferred for these viewing requirements. Such an x-y mount totally eliminates the "keyhole" problem and does not require unlimited angular freedom. This is an important feature since it eliminates the requirement for slip rings to provide gimbal control signals and power on the outer gimbal on the antenna.

5.3.1.2 Antenna Rates

The basic angular rates linking the TDRS to the user spacecraft are low (on the order of 0.75 radian per hour). Conditions which can increase these rates are slewing and improper choice of the gimbal configuration. Slewing is required when the antenna must sign off one satellite and acquire another. Since the minimum potential communication time to a user satellite is approximately 37 minutes, rapid slewing is not of great importance. A reasonable slew rate is about 0.1 radian per second. This rate allows the entire field of view to be scanned in 10 seconds.

An unknown in the determination of the maximum drive rates is the angular motion of the TDRS spacecraft and the deflections in the antenna support structure. These rates are assumed to be less than the 0.1 radian per second allowed for slewing.

5.3.1.3 Antenna Accelerations

An evaluation of the antenna accelerations and their effects was made based on an antenna inertia of 1.5 foot/pound/second² and a peak acceleration during slew of 0.1 radian/second². These values yield a peak torque requirement of 0.15 foot/pound or 1.8 inches/pound. Coulomb friction is estimated to add 1.0 inch/pound to this torque requirement. The inertial torque
Figure 5.3.1.1. Tracking Data Relay Satellite Kinematic Information
should have negligible effect on support structure bending. This is significant in that support structure bending is therefore almost exclusively a function of the spacecraft motion.

5.3.1.4 Drive Requirements

The gimbal drive requirements were based on the following parameters:

Maximum Torque: \(2.5 \text{ inches/pound}\)

Maximum Velocity: \(0.1 \text{ radian/second}\)

The use of a gear train is favored for this combination of torque and speed. The drive may be provided by a dc motor, an ac motor, or a stepper motor. The characteristics of these approaches are shown in Table 5.3.1.4.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>DC Motor</th>
<th>AC Motor</th>
<th>Stepper</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td>5</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Weight</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Motor</td>
<td>2.3</td>
<td>2.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Tach</td>
<td>2.3</td>
<td>2.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Gear Train</td>
<td>4.0</td>
<td>7.0</td>
<td>6.0</td>
</tr>
<tr>
<td>Total</td>
<td>8.6</td>
<td>9.0</td>
<td>9.0</td>
</tr>
<tr>
<td>Gear Ratio</td>
<td>40:1</td>
<td>4500:1</td>
<td>1500:1</td>
</tr>
</tbody>
</table>

The life of the motor brushes in the dc motor and the life of the ac motor and stepper motor gear train are on the order of 5 years in currently available hardware (from firms making space qualified hardware). Since it is entirely likely that a failure may occur in this time span, redundancy should be given some consideration. The prime wear points on the dc motor are the brushes, and any rotation of the motor causes wear, even if the motor is not operating. A method of achieving redundancy in any of these configurations is a differential gear and brake arrangement.
5.3.1.5 **Antenna Pointing**

The antenna must be pointed prior to acquisition. The transmission $3\sigma$ pointing requirements for a 6.5-foot diameter dish are $0.33^\circ$ at 15 GHz. The acquisition $3\sigma$ pointing requirements are somewhat wider at $0.5^\circ$. In order to point the antenna within the accuracy requirements, errors such as TDRSS position and attitude uncertainty, user satellite position uncertainty, and support structure deflection must be held under strict control. Providing these errors can be held to less than the pointing requirement, then some form of angular position transducer may be used to point the antenna.

Potentiometers, synchros, shaft encoders, and stepper motors may be used to perform this function. Potentiometers are easily implemented, however, wear characteristics limit their useful life to about two years in this application. Also, the angular accuracy of potentiometer systems is limited to about $0.3^\circ$ ($1\sigma$). Synchros offer good accuracy and wear is limited to low power slip rings. The primary disadvantage of synchro systems is the electronic complexity required for digital-to-synchro conversion.

Optical encoders are currently the most accurate shaft position transducers and have no mechanical wear problem. The primary problem with optical encoders is light source life and, in general, the light source must be turned off when the antenna is not in a pointing mode. In this way, it is possible to achieve a useful life of 5 years. Stepper motors may be used to point antennas in that each step is angularly precise. The design used for the drive requirements portion of this section has a step size of $0.03^\circ$ while maintaining a slew rate capability of greater than $6^\circ$ per second. The disadvantages of stepper motors is their poor efficiency and interaction with structural resonance which exist in the zero to 200 pulse per second stepping range.

5.3.1.6 **Unaided Acquisition**

The normalized receiving and tracking gain curves for candidate antennas are shown in Figure 5.3.1.6. This figure shows that the acquisition beam width is about 30 percent wider than the $3\ dB$ receiving beam width. The pointing requirements for the antenna are shown in Table 5.3.1.6-1. The acquisition half angle is the peak error which may occur. It should be noted that a $2^\circ$ TDRSS attitude uncertainty will not be adequate for this approach. A TDRSS attitude uncertainty of $0.1^\circ$ peak will allow the system to be pointed accurately with a budget of $0.182^\circ$ for a 12-foot dish.

<table>
<thead>
<tr>
<th>Table 5.3.1.6-1. Dish and Pointing Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gain</td>
</tr>
<tr>
<td>12-Foot Dish</td>
</tr>
<tr>
<td>53 dB</td>
</tr>
<tr>
<td>$15\ GHz$</td>
</tr>
<tr>
<td>$3\ dB$ Beam Width</td>
</tr>
<tr>
<td>$0.32^\circ$</td>
</tr>
<tr>
<td>Acquisition Half Angle</td>
</tr>
<tr>
<td>$0.208^\circ$</td>
</tr>
</tbody>
</table>

125 of 356
Figure 5.3.1.6. Normalized Receiving and Acquisition Curves
A candidate budget for the 12-foot dish pointing system would be:

User Uncertainty 0.100° (Ephemeris)
TDRSS Position Uncertainty 0.050°
Antenna Deflections and Servo 0.140°
RSS 0.182°

Total servo uncertainties can be held to 0.086° (peak) with a 13-bit encoder or a synchro with 5 minutes (peak) error. Both of these devices are well within the state-of-the-art with the synchro having the edge for long life space use.

A remaining consideration is the control power necessary for the 12-foot dish. True, the inertia of the antenna approximates between the square and the cube of the diameter, however, the inertia loads are insignificant at the angular rates considered for the TDRSS as shown in Tables 5.3.1.6-2 and 5.3.1.6-3. It should also be kept in mind that the frictional loads on the antenna system are on the order of 5 to 10 ounces/inch.

Table 5.3.1.6-2. TDRSS Operation

<table>
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<tr>
<th>Orbital Altitude</th>
<th>100 nmi</th>
<th>250 nmi</th>
<th>500 nmi</th>
</tr>
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<tr>
<td>TDRSS Viewing Angle</td>
<td>17.86°</td>
<td>18.60°</td>
<td>19.90°</td>
</tr>
<tr>
<td>TDRSS Acquisition Angle</td>
<td>8.82°</td>
<td>8.93°</td>
<td>9.03°</td>
</tr>
<tr>
<td>Single TDRSS Availability</td>
<td>48.5%</td>
<td>54.0%</td>
<td>58.4%</td>
</tr>
<tr>
<td>Maximum TDRSS Rate</td>
<td>0.00626°/sec</td>
<td>0.00618°/sec</td>
<td>0.00567°/sec</td>
</tr>
<tr>
<td>Approximate Maximum Acceleration</td>
<td>$5.85 \times 10^{-6}$°/sec$^2$</td>
<td>$5.15 \times 10^{-6}$°/sec$^2$</td>
<td>$4.64 \times 10^{-6}$°/sec$^2$</td>
</tr>
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Table 5.3.1.6-3. Antenna Torque Loads

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<tr>
<td>Inertia</td>
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<tr>
<td>Acceleration</td>
</tr>
<tr>
<td>Torque</td>
</tr>
</tbody>
</table>
S-Band Aided Acquisition

A second method of acquisition using S-band in place of the Ku-band for acquisition has good overall qualities as shown in Table 5.3.1.6-4.

Table 5.3.1.6-4. S-Band Dish and Pointing Parameters

<table>
<thead>
<tr>
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<th>12-Foot Dish</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gain</td>
<td>37.4 dB</td>
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<tr>
<td>3 dB Beam Width</td>
<td>1.92° 2.5 GHz</td>
</tr>
<tr>
<td>Acquisition Half Angle</td>
<td>1.25°</td>
</tr>
</tbody>
</table>

The 12-foot antenna requires TDRSS uncertainties on the order of 1° and defocusing will be required to broaden the acquisition half angle to greater than 2.25°. This defocusing is easily accomplished at the 37.4 dB gain level.

5.3.2 Description of Candidate Design

One candidate design for the TDRSS antenna is a stepper motor (such as Kearfott or MPC) in a braked differential configuration. This approach offers minimum electronic complexity at the expense of increased power. Figures 5.3.2-1 through 5.3.2-4 show block diagrams for both the servo approach and the stepper motor (open loop) approach. Figure 5.3.2-5 shows the proposed x-y gimbal configuration. If the stepper motor is used redundantly in this configuration, an overall weight for the gimbal structure of 6 pounds is projected.

An accompanying dual redundant electronics package is required to provide the necessary drive and is preferably mounted back on the spacecraft proper. The weight of this unit is approximately 7.5 pounds. The unit controls both the x and y axes.

The power for the stepper motor approach is 8 watts to drive each motor, 4 watts to release the differential brake, and 4 watts dissipation in the electronics. This results in a total power requirement of 24 watts.

The slewing requirements of the antenna introduce a maximum momentum transfer to the spacecraft of 0.15 foot/pound/second for a maximum of 10 seconds (at which time a canceling momentum impulse occurs). In a passive spacecraft with a moment of inertia of 230 feet/pound/second² this represents an angular offset of 0.3°.

The stepper motor approach allows the antenna to be stopped and effectively braked when the power is removed from the drive mechanism.
Figure 5.3.2-1. Block Diagram for Antenna Servo in the Tracking Mode

\[ S_1 = \text{PSEUDOMONOPULSE ERROR SIGNAL} \]
Figure 5.3.2-2. Block Diagram for Antenna Servo in the Pointing Mode

\[ S_2 = \text{EXTERNALLY GENERATED POINTING COMMAND} \]
$S_1 = \text{Pseudomonopulse Error Signal}$

Figure 5.3.2-2. Block Diagram for Stepper Motor in Tracking Mode
$S_2 = \text{EXTERNALLY GENERATED POINTING COMMAND}$
Figure 5.3.2-5. Gimbal Configuration
5.4 Reflectors Weight and Surface Accuracy

Based on the measured results achieved on the present program, weight and surface error values were developed for reflectors from six (6) to thirty (30) feet in diameter.

Figure 5.4-1 presents rms surface error as a function of reflector diameter for reflectors up to 30 feet in diameter. The surface error values shown represent the total rms surface error for the orbital condition. These values are based on analyses of the thermal and gravity associated errors and an extrapolation of the manufacturing error based on rib stiffness, mesh stiffness, and number of ribs.

Figure 5.4-2 presents weight as a function of reflector diameter for the double mesh design. The weight values shown represent an extrapolation of the present 12.5-foot diameter design to the larger and smaller diameters.
Figure 5.4-2. Antenna Weight (Excluding Feed) as a Function of Reflector Diameter
SECTION 6.0
CONCLUSIONS AND RECOMMENDATIONS
6.0 CONCLUSIONS AND RECOMMENDATIONS

This program has demonstrated that the "rib-dominated" rib-and-mesh deployable reflector design concept is a viable approach for mission applications requiring deployable reflectors. The "double mesh" technique allows the achievement of surface accuracies consistent with Ku-band operation with lightweight (previous technology would have resulted in a reflector weight of no less than twice that achieved).

The test program conducted (RF, deployment, surface accuracy, and vibration) has resulted in a nearly "flight-qualified" design. The solar-thermal-vacuum tests planned by NASA after the reflector delivery will essentially complete the qualification. The high stiffness exhibited by the design in both the stowed and deployed conditions allows users to procure the reflector as a component, thereby reducing both analysis and test costs on applicable programs. The applicability of the design is demonstrated by its selection as the baseline design by both contractors in the recently completed TDRSS Definition Phase Studies (see References 2 and 3) and Figure 6.0.
Figure 6.0. TDRS Baseline Configuration
REFERENCES


APPENDIX A

DETAIL FABRICATION DRAWINGS
## INDEX OF ENGINEERING DRAWINGS

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<td>MDS Assy (3 Sheets)</td>
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<td>Washer</td>
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(Place holder)
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1. ALL OVER UNLESS OTHERWISE SPECIFIED.
2. MARK SHAFT 314001 PER MIL STD 519D.
3. MATERIAL 6061-T6.
4. FINISH SURFACE A ONLY, COAT WITH 0012001
   THE "TFRM" BY GENERAL MAGNAPLAT CORP.
   ALL OTHER AREAS TO BE CHEMICAL FILM PER
   MIL-C-53441 TYPE I, GRADE B, CLASS I.

S-MATL: AL ALLOI.)
4 FINISH: SURFACE A' ONLY, COAT WITH 0012001
   THE "TFRM" BY GENERAL MAGNAPLAT CORP.
   ALL OTHER AREAS TO BE CHEMICAL FILM PER
   MIL-C-53441 TYPE I, GRADE B, CLASS I.
REPROducIBILITY OF THE
ORIGINAL PAGE IS POOR

NOTES:
1. MARK 9407.534091-1 PER MIL-STD-130
(MAG OR TAG).
2. ALL SURFACES.
4. FINISH SURFACE A ONLY, COAT WITH 0.0012IN THICK
"TUFRAM" BY GENERAL MAGNAPLATE CORP.
ALL OTHER AREAS TO BE CHEMICAL FILM PER
MIL-C-5541 TYPE-I, GRADE-B, CLASS-1.

SURFACE A

DIA

.025 TIP

.025 REF

.02 TIP

.02 REF

NO.6-32UNC-28
3.38 DEEP

ENGRAV DEV

FOLDOUT FRAME 2

FOLDOUT FRAME 1
NOTES:
1. MARK 9417-420820-1 PER MIL-STD-130

OMIT FINISH ON THESE SURFACES.

ENGRG DEV'

RADIATION INCORPORATED
9417-420820

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MATERIAL:
Aluminum, per specifications.

FINISH:
AODIZE, per MIL-A-8625 TYPE III CL 1.

QUANTITY REQUIRED:
- 1050

SCALE:
1:1
## Notes:

1. MARK 91417-308389-1 PER MIL-STD-130 (BAG)

2. MAKE FROM PIC DESIGN CAT NO. AS-7, TO BE STRAIGHT WITHIN .001 PER IN. TO BE .18750 T.O. 90 DEG. AND MADE FROM TYPE 303 CRES. CLEAN PASSIVATED.

3. EN. C.O. SHALL BE LUBRICATED WITH LUBEEO # 905 IN ACCORDANCE WITH PAD DWG. NO. 307610.

4. DIMENSION APPLIES AFTER COATING PER NOTE 3.

---

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- **Date:** 12/10/71
- **Rev:** B
- **Code:** 91417
- **Sheet:** 1
- **Scale:** 1/2" = 1'-0"
- **Note:** This is a mechanical drawing.
NOTES:
1. MARK 91417 308396 PER MIL-STD-130 (Bag)
   2. RT/SPB DUROC-ROGERS
      CORP, ROGERS, CONN.

DRAFTS:

A'ORS
9/1-3 6 ACONE

REVISIONS

ZONE LTR DESCRIPTION DATE APPROVED

1.00 A2

PART NO. QTM A QTM B
308396-1 0.50 0.50
308396-2 0.50 0.50
308396-3 0.50 0.50
308396-4 0.50 0.50

QUALITY

AUTHOR

MANUFACTURER

TITLE

RADIATION INCORPORATED,
511 S. CANTON ST., ROCHESTER, N. Y.

WASHER

MATE

ASSAM

APPLICATION

0-0.7A

SIL 4-1-7A

SHEET

158 of 356
NOTES:
1- MARK 91417-308384-1 PER MIL-STD-130.
2- MTRL: LAMINATED SHIM STOCK PER
   MIL-S-22499 COMPOSITION-1, TYPE-1,
   CLASS-1.

125 DIA

-090

50 DIA

SHIM - TAKE-UP SHAFT

B 91417 308384
NOTES:
1. MARK 91417-308383-1 PER MIL-STD-308, BAG.
2. MAT: STAINLESS STEEL TYPE 303.
3. FINISH PASSIVATE PER QQ-P-35.

DESCRIPTION
ITEM: SHAFT - TAKE-UP DRUM

LIST OF MATERIALS OR PARTS LIST

- 4-40 UNC-3A x .7 DEEP x .18
### NOTES:

1. **MARK**: 421196-001 PER MIL-STD-180, (S/A or TAG).
4. **LIST OF PARTS**

#### SECTION A-A

- **TUBE, COMPRESSION ROD**
- **FINISH**

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<td>TUBE, COMPRESSION ROD</td>
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NOTES:

1. MARK 91417 308388-001 PER MIL-STD-130, (BAG OR TAG).
   - MATL: SIMILAR TO NEW HAMPSHIRE BALL BEARINGS INC., PART NO. M-2.
   - FINISH: SPHERICAL SURFACE OF BALL TO BE LUBRICATED WITH LUBECO #505 IN ACCORDANCE WITH RADIATION DWG 307610.

NO. 3-5G UNF-3A REF

ENGINE DVL DWG

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SCALE 2:1

DRAWN: 9/11/72
CHECKED: C. J. Kelly
APPROVED: 9/11/72
**Notes:**
1. **Mark 9417 308390-1** per MIL-STD-130 (Bag)
2. **Matl.: 0924-4000 Stainless Steel** Type 416 Per QQ-S-764A
3. Pin O.D. to be lubricated with Lubeco M-905 in accordance with Radiation Dwg. 3074G.
4. **Dimension Applies After Coating Per Note 3.**

**List of Materials or Parts List**

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**Remarks:**
- **Rev.:** 1

**Revisions:**

- **Mark:** 19417 308390-1 per MIL-STD-130 (Bag)
- **Material:** 0924-4000 Stainless Steel Type 416 Per QQ-S-764A
- **Pin O.D.** to be lubricated with Lubeco M-905 in accordance with Radiation Dwg. 3074G.
- **Dimension Applies After Coating Per Note 3.**
NOTES:
1. MARK 9; MIL-4211891 PER MIL-STD-130.
2. BRAZE PER MIL-B-7883.
3. FINISH: CHEM. FILM PER MIL-C-5541, TYPE 1, GRADE C, CLASS I.
4. HEAT TREAT TO T4 CONDITION PER MIL-H-6088.
NOTES
1. MARK 91417-308386-1 PER MIL-STD-130.
2. MATL: .010 WALL AL ALY TUBING 6061-T6
NOTES:
1. MARK 91417-308398-1 PER MIL-STD-430 (BAG).
2. MATL: LAMINATED SHIM STOCK PER MIL-S-22499 COMP. 1, TYPE 1, CLASS I.
NOTES:
1.- MARK 91417-4211861
PER MIL STD 130 (TG2)
2.- BRAZE PER MIL-B-7833.
3.- FINISH: CHEM FILM PER
MIL-C-5541 TYPE I,
GRADE C, CLASS 1.
4.- HEAT TREAT TO CON-
DITION T4 PER MIL-
N-6086.

MATERIALS:
1. AL ALY ROD
   6061-T6
2. AL ALY TUBE
   .375 DIA .020 WALL
   6061-T6
3. AL ALY HEX
   6061-T6

DIMENSIONS:
- .03 x .45°
- .375 DIA
- .03
- 5.674 REF
- 4-40 UNC-3B
- 4.4000
- 5.624

END OF DETAIL
2 MATL: MAKE 2 SHAFTS FROM
PIC CATALOG NO. AI-10, PIC DESIGN
CORP, RIDGEFIELD, CONN.

.117 ± .0015
 Dia. Typ

.115 ± .015
 TYP

.012 ± .002
 TYP

.230

.290

.030

.1245
 Dia. Ref

10

ENGRG. DEV

NOTES
1) MARK 91417-308373-1 PER
MIL-STD-130 (BAG)

2) MATL: MAKE 2 SHAFTS FROM
PIC CATALOG NO. AI-10, PIC DESIGN
CORP, RIDGEFIELD, CONN.
NOTES:

1. MARK 91417 308387-001
   PER MIL-STD-130 (BA4)
   MATL: AL ALLOY ROUND
   G001-T6 PER QQ-A-200
   FINISH: COAT INSIDE SURFACE
   ONLY WITH "TUFRAM" BY
   GENERAL MAGNAPLATE CO.

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FINISH: COAT INSIDE SURFACE ONLY WITH "TUFRAM" BY GENERAL MAGNAPLATE CO.
NOTES:
1. MATL: SST TYPE 410 PER QQ-S-766
   .008 THK
   CLASS 3
2. FINISH: PASSIVATE PER QQ-P-35
3. HEAT TREAT TO 180,000 PSI MIN
   TENSILE ULTIMATE PER MIL-H-6875.
4. MARK 91417-308372-1 PER MIL-ST-130
   (TAG)

---

SCZ II

LIST OF MATERIALS OR PARTS LIST

198 of 356
NOTES:
2. MATL: AL ALLOY 6061-T651.

- 5/16-18UNC-18

- .50 HEX STOCK

- .374 & .373 DIA.

- .06

- .35
NOTES:

1. MATERIAL: 5/16 HEX SS TYPE 440 PER QQ-S-742.

2. FINISH: PASSIVATE PER QQ-P-35.

3. UNDERCUT TO MINOR DIA OF THD.

4. MARK 91417-308369-1 PER MIL-STD-1505(BAG)

   NO. 0-80 UNC-2A
   NO. 4-40 UNC-2A
   1.06 REF
   0.032 ± 0.005
   0.075 MAX
   0.092 ± 0.002
   0.025 MAX
   0.050
   0.041
   ENGRG DEV

LIST OF MATERIALS OR PARTS LIST

STAND-OFF

PART OR IDENTIFYING NO.

MATERIAL OR DESCRIPTION

RADIATION INCORPORATED

91417
308369
NOTES:

1. MATERIAL: 3/16 DIA SS TYPE 303 PER QQ-S-763

2. FINISH: PASSIVATE PER QQ-P-35.

3. MARK 91417-308370-1 PER MIL-STD-130 (BAG)

DIA REF

.030 R

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.042 ± .005

ENERGY DEV.
**Title:** ENGRG DEV D'76

**Drawing Number:** 309061

**Notes:**

1. MARK 91417-309061-1 PER MIL-STD-130(BK)
2. MATERIAL: AL ALLOY 6061-T6

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- **Date:** 1/14
- ** Approach:** 1/14
- **Approver:** 1/14

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- **Title:** ENGRG DEV D'76
- **Drawing Number:** 309061
- **Date:** 1/14
- **Approver:** 1/14
- **Scale:** 1/4" = 1'0"
NOTES:

1. M4721: 410 EPOXY BOARD .117-.132 THICK.

2. PRIME & PAINT PER T741

3. .070 DIA. HOLE & SURFACE INDICATED TO BE FREE OF PRIMER & PAINT - (NOTE-2).

4. MARK 91417-309059 PER MIL-STD-130. (BAE)

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2. MATE AL ALLOY 6061-T6.

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**Application**

- Drawing title: STANDOFF
- Drawing scale: 2:1

---

**Scale**: 2:1

**Sheet**: 1 of 1
FINAL

TEST PLAN AND PROCEDURES REPORT

FOR

ADVANCED APPLICATIONS FLIGHT EXPERIMENT

NAS1-11444

SEQUENCE NUMBER: 4314-01

PREPARED FOR

LANGLEY RESEARCH CENTER

PREPARED BY

RADIATION
A DIVISION OF HARRIS-INTERTYPE
P.O. BOX 37
MELBOURNE, FLORIDA 32901

9 FEBRUARY 1973

PREPARED BY:

W. E. Marbry
Test Engineer

APPROVED BY:

C. E. Warren
Program Manager

APPROVED BY:

L. A. Baugher
Quality Engineer

RAD 7902

215 of 356
APPENDIX B

TEST PLAN AND PROCEDURES WITH TEST RESULTS

1.0 INTRODUCTION

This Test Plan and Procedure describes the testing program for the 12.5-foot diameter antenna produced during the Advanced Applications Flight Experiment Program.

1.1 Purpose

The purpose of this test plan is to define a meaningful and efficient evaluation and test program for the deployable antenna. The major objectives of this program are:

1. To determine the various physical and operational characteristics of the deployable antenna and

2. To provide test data for correlation with the analyses performed during this program

1.2 Scope

The scope of this document is to detail the overall test program for the 12.5-foot diameter deployable antenna. Included in this plan is a description of parameters to be measured, the test objectives, test methods, required facilities and equipment, and data to be recorded.

2.0 APPLICABLE DOCUMENTS

Applicable documents to the test plan development are:

a. Statement of Work, dated 15 December 1971

b. Program Plan for Advanced Applications Flight Experiment Program, dated 17 May 1972

c. Drawing 615283, Antenna Assembly
3.0 VIBRATION TEST

3.1 Test Objective

The primary purpose of this test is to measure the resonant frequencies and response accelerations of the 12.5-foot diameter model antenna in various stowed and deployed configurations.

3.2 Facilities and Instrumentation

The fixtures shall be designed to restrict the motion of the base of the antenna to the specified input. Crosstalk shall not exceed 50 percent of the input and variation of the input across the antenna base shall not exceed a ratio of 2 to 1. Lowest fundamental frequency for the stowed antenna fixtures shall exceed 500 Hz, and for the deployed antenna the frequency shall exceed 50 Hz. These criteria have been verified by tests with a heavier antenna.

Five Endevco Model 2222B, or equivalent, accelerometers will be attached to the antenna at the locations shown in Figures 3.2-1 through 3.2-3. All accelerometer data shall be recorded on magnetic tape. The test setups are shown in Figures 3.2-4 and 3.2-5.

3.3 Test Procedure

3.3.1 Low-Level Sinusoidal Vibration, Stowed Antenna

3.3.1.1 Lateral Axis

a. Sweep the bandwidth from 10 to 300 Hz in the lateral axis at the rate of one octave per minute using a 0.15 G<sub>rms</sub> sinusoidal input while recording the output from accelerometers at the locations shown in Figure 3.2-1.

b. Dwell at up to three selected frequencies as determined by analysis and test data from the sinusoidal sweeps. Input level shall be 0.15 G<sub>rms</sub>. Read accelerations and phase angles from the five accelerometers.

3.3.1.2 Longitudinal Axis

Conduct a low-level sinusoidal vibration as described in Paragraph 3.3.1.1a, on the stowed antenna in the longitudinal axis. Record the output of accelerometers at the locations as shown in Figure 3.2-2.
Figure 3.2-1. Accelerometer Locations for the Low-Level Sine Test in the Lateral Axis for the Stowed Antenna
Figure 3.2-2. Accelerometer Locations for the Low-Level Sine Test in the Longitudinal Axis for the Stowed Antenna
Figure 3.2-3. Accelerometer Locations for the Low-Level Sine Test in the Longitudinal Axis for the Deployable Antenna
Figure 3.2-4. Setup for Lateral Axis Vibration, Stowed Antenna

1. DRIVE BAR T-6798
2. 6" ADAPTER T-7033
3. ADAPTER 614669G1
4. TEAM BEARINGS
Figure 3.2-5. Setup for Longitudinal Axis Vibration, Stowed or Deployed Antenna
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3.3.2 Low-Level Sinusoidal Vibration, Deployed Antenna, Longitudinal Axis

Sweep the bandwidth from 40 to 5 Hz at a rate of one octave per minute using a 0.15 G_{rms} input while recording the output of accelerometers at the locations shown in Figure 3.2-3.

3.3.3 Mechanical Inspection

At the completion of each test, the antenna shall be visually inspected for any degradation. After all tests are completed, the antenna shall be visually inspected in more detail. Findings are reported in the test record.

3.4 Measurements and Tolerances

All measurements shall be made with calibrated instruments. The maximum allowable tolerances for test conditions shall be as follows:

a. Vibration amplitude

Sinusoidal: ±10%

b. Vibration Frequency

±2% or 1 Hz, whichever is greater

3.5 Test Record

As a minimum, the data obtained during testing shall be presented in the test report as follows:

1. Plots of response acceleration versus frequency for all accelerometer measurements taken for the 0.15 G_{rms} input test

2. Table showing G_{rms} response and relative phase angle for selected accelerometers for resonant dwell tests using a 0.15 G_{rms} input

AAFE Vibration Test Summary

Lateral Axis, Stowed Antenna

The fundamental frequency of the stowed antenna in the lateral axis was 57.0 Hz. The mode shape was lateral bending of the entire antenna. The second resonant frequency occurred at 93.1 Hz and the mode shape was the first bending mode of the stowed ribs. The third resonant
frequency was 245.0 Hz and was the second lateral bending mode of the entire antenna. Figures 3.5-2 through 3.5-6 are acceleration versus frequency plots of the five instrumentation accelerometers.

**Longitudinal Axis, Stowed Antenna**

There were two primary resonances in the longitudinal axis. The first resonance occurred at 96 Hz and was a rib cage mode combining longitudinal translation (Z-axis) of the rib cage and bending of the ribs. The second resonance was 195 Hz and was the longitudinal mode of the feed support cone-ogive structure. Figures 3.5-7 through 3.5-13 are the acceleration versus frequency plots of the instrumentation accelerometers.

**Longitudinal Axis, Deployed Antenna**

In the deployed test, there was only one major resonance in the frequency band tested. This was the fundamental bending node of the rib-and-mesh assembly in the longitudinal axis and occurred at a frequency of 8.3 Hz. Figures 3.5-14 through 3.5-19 show the acceleration versus frequency plots of the instrumentation accelerometer.

**Post Test Inspection**

A complete inspection of the antenna after the completion of all testing showed no signs of any degradations of any parts.
4.0 SURFACE ACCURACY MEASUREMENT TEST

4.1 Test Objectives

The objective of this test is to measure the surface accuracy and deployment repeatability of the deployable antenna using a precise sweep template, and compute the rms surface error. This test is also a demonstration of deployment kinematics of the antenna.

4.2 Test Method

The antenna surface measurement configuration is shown in Figure 4.2. The sweep template consists of an accurately machined track along which a movable micrometer can be positioned. This feature allows any point on the reflector surface to be measured.

Using the sweep template, the surface error of the reflector can be accurately measured. However, some uncertainties exist in predicting the surface error which the reflector would exhibit in a zero-g environment, due to the sag of the mesh between the ribs.

Two techniques for measurement of surface accuracy have been defined for use on the deployable antenna in order to minimize the uncertainty of the gravity error. In both techniques a total of 225 points on the mesh surface are measured, and the surface error is calculated using the paraboloid computer program (Appendix I).

In the first technique, the antenna is placed in a face-side orientation, with the sweep template extending horizontally outward from the antenna axis. The sweep template remains stationary in this position during the entire measurement procedure. Different points on the reflector are measured by rotating the antenna about its central axis until the point to be measured is in the plane of the sweep template. The micrometer is then moved along the template to coincide with the desired point. Using this method, the mesh in the vicinity of the point being measured at any given time is in a vertical plane. In this configuration, the gravity effect on the mesh is reduced, and the surface error calculated from these measurements is an approximation of the actual zero-g error.

In the second technique, the antenna is oriented in a face-side position as in the first technique. However, during the measurement process, the antenna is held stationary while measurements are made by rotating the template about the antenna axis. After all the desired points have been measured in this way, the antenna is then rotated exactly 180° about its central axis. The same points which were measured during the first sweep are then measured a second time, again with the reflector held stationary and the sweep template rotated about its axis. The deviation of each point is averaged for the two readings, and the surface error is computed using the average position of each point.
Figure 4.2. Surface Measurement Tooling
The surface error determined by the second technique is expected to provide an upper bound for surface error in a zero-g environment. It contains certain additional errors, such as hysteresis in the ribs and effects of the nonlinearity of the mesh spring rate, which result from measuring the reflector in the two opposite orientations. Past experience has shown these effects to be very small.

As part of the surface accuracy measurement test, the antenna is deployed once by activating the pyrotechnic cable cutter. The antenna is refolded and deployed nine more times using the MDS motor drive. Surface accuracy measurements are performed after the first deployment and then after the nine additional deployments.

4.3 Test Procedure

4.3.1 Test Preparation

Mark the antenna surface at each of the 225 points to be measured. There shall be nine points equally spaced along each of 25 equally spaced radial lines. The marking is accomplished by using either tiny pieces of adhesive-backed tape or by using ink dots.

Install the antenna on the mounting fixture. Deploy the antenna by activating the pyrotechnic cable cutting device.

Attach the sweep template to the antenna in the proper measurement configuration.

4.3.2 Surface Accuracy Test Number 1

Position the antenna in a face-side orientation. Position the sweep template such that it extends horizontally outward from the antenna axis.

Using the sweep template, measure the deviation from the theoretical paraboloid of each of the 225 points marked on the reflector surface. During this test the sweep template remains in a horizontal position. The antenna is rotated about its central axis to bring the desired points into the plane of the sweep template. Record the deviation of each point in the data sheet. Input the data to the paraboloid computer program and record the calculated surface error on the data sheet.

4.3.3 Surface Accuracy Test Number 2

Position the antenna in a face-side orientation. Record the angular position of the support fixture turntable.
With the antenna left stationary in this orientation, rotate the sweep template about the antenna axis and measure each of the 250 points marked on the reflector. Record the data on the data sheet.

Rotate the antenna 180° about its axis. Record the angular position of the support fixture turntable. With the antenna left stationary in this orientation, rotate the sweep template about the antenna axis and measure each of the 225 points again. Record the second readings on the data sheet.

Compute the average of the two readings for each of the 225 points. Record these results on the data sheet. Input these results into the paraboloid computer program and record the calculated surface error on the data sheet.

4.3.4 Surface Accuracy Test Number 3

With the sweep template removed, refold and deploy the antenna nine times ending with the antenna in the deployed configuration.

Attach the sweep template to the antenna in the proper measurement configuration.

Position the antenna in a face-side orientation. Position the sweep template such that it extends horizontally outward from the antenna axis.

Using the sweep template, measure the deviation from the theoretical paraboloid of each of the 225 points marked on the reflector surface. During this test the sweep template remains in a horizontal position. The antenna is rotated about its central axis to bring the desired points into the plane of the sweep template. Record the deviation of each point in the data sheet. Input the data to the paraboloid computer program and record the calculated surface error on the data sheet.
VIBRATION TEST DATA
ACCELERATION VS. FREQUENCY

PROJECT: 1080
TEST ARTICLE: A1E2 A712AA
RUN NO.: 2
TEST DATE: 12-8-73
OPERATOR: L.C

INPUT AXIS: X
INPUT LEVEL: 15
ACCEL. LOCATION: X
ACCEL. SER. NO.: A/B/C
ACCEL. SENSITIVE AXIS: X

Figure 3.5-2
VIBRATION TEST DATA
ACCELERATION VS. FREQUENCY

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<td>C ± 3%</td>
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**Figure 3.5-7**

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**Table:**

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**Graph:**

- Y-axis: Amplitude (in arbitrary units)
- X-axis: Frequency (Hz)
- Grid lines for visualization

---
VIBRATION TEST DATA
ACCELERATION VS. FREQUENCY

PROJECT 1080
TEST ARTICLE ANF4 Antenna
INPUT AXIS 2
RUN NO. 5
TEST DATE 18-8-73
OPERATOR TEC

INPUT LEVEL 71C
ACCEL. LOCATION 2 7
ACCEL. LOCATION ACCEL. SER. NO. PCC6
ACCEL. SENSITIVE AXIS 3

Figure 3.5-9
VIBRATION TEST DATA
ACCELERATION VS. FREQUENCY

PROJECT 1080
TEST ARTICLE BASE ANTENA
RUN NO. 5
TEST DATE 12-8-73
OPERATOR TEC.

INPUT AXIS Z
INPUT LEVEL 21 Gs
ACCEL. LOCATION 42
ACCEL. SER. NO. KR 70
ACCEL. SENSITIVE AXIS Z

FREQUENCY Hz

0.01 0.02 0.05 0.10 0.20 0.50 1.0 2.0 5.0 10.0

0 10 20 30 40

DECIBELS

0.01 0.02 0.05 0.10 0.20 0.50 1.0 2.0 5.0 10.0

0 10 20 30 40

ACCELERATION g

Figure 3.5-11
Figure 3.5-14
VIBRATION TEST DATA
ACCELERATION VS. FREQUENCY

PROJECT 1080
TEST ARTICLE AP1L ANTENNA
RUN NO. 6
TEST DATE 12-8-73
OPERATOR TEC

INPUT AXIS Z
INPUT LEVEL 2110
ACCEL. LOCATION Z
ACCEL. SER. NO. A423
ACCEL. SENSITIVE AXIS X

ACCELERATION - Pk

FREQUENCY Hz

DECIBELS

Figure 3.5-15
VIBRATION TEST DATA
ACCELERATION VS. FREQUENCY

PROJECT 1084
TEST ARTICLE N/A
INPUT AXIS Z
INPUT LEVEL 10
ACCEL. LOCATION X
ACCEL. SER. NO. TCY4
ACCEL. SENSITIVE AXIS Y

TEST NUMBER 6
TEST DATE 12-8-73
RUN NO. 6
OPERATOR TEC

Figure 3.5-17
VIBRATION TEST DATA
ACCELERATION VS. FREQUENCY

PROJECT 1080
TEST ARTICLE 0912 ANTIPHP
RUN NO. 6
TEST DATE 12-8-73
OPERATOR TAC

INPUT AXIS Z
INPUT LEVEL -316 db
ACCEL. LOCATION 22
ACCEL. SER. NO. XA 76
ACCEL. SENSITIVE AXIS Z

ACCELERATION

FREQUENCY Hz

Figure 3.5-18
VIBRATION TEST DATA
ACCELERATION VS. FREQUENCY

PROJECT 1080
TEST ARTICLE NAME A
RUN NO. 6
TEST DATE 12-8-73
OPERATOR TEC

INPUT AXIS
INPUT LEVEL 21.6 dB
ACCEL. LOCATION S2
ACCEL. SER. NO. 7624
ACCEL. SENSITIVE AXIS

FREQUENCY Hz
ACCELERATION

Figure 3.5+19
## Test Record

### Surface Accuracy Test No. 1

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#### Computer Results

Surface Error: 0.0203-inch rms
PARABOILIS PROGRAM

THIS PROGRAM COMPUTES THE PARABOILIS FROM A GIVEN SET OF DATA POINTS.

STRUCTURES SECTION
RADATION DIVISION
HARRIS INTERTYPE INC.
MELBOURNE, FLORIDA

REVISION DATE OF THIS PROGRAM, AUG 73
BEST-FIT PARABOLOID FOR 150 INCH ANTENNA

4.4.1.1 MEASUREMENT AND SURFACE DEVIATION
DX = .00521 INCHES
DY = .08564 INCHES
DZ = .01117 INCHES

FOCAL LENGTH OF BEST FIT PARABOLOID = 62.2070 INCHES

RMS WITH RESPECT TO BEST FIT PARABOLOID = .026283 INCHES
4.4.2 Surface Accuracy Test No. 2

### 4.4.2.1 First Angular Position of Turntable

0 degrees.

### 4.4.2.2 Sweep No. 1 Measurement Data

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### 4.4.2.3 Computer Results

Surface Error: 0.0258 inches rms.

260 of 356
23 of 43
188 of 7
This program computes the best-fit paraboloid from a given set of data points.

Structures Section
Radiation Division
Harris Intertype Inc.
Melbourne, Florida

Revision date of this program: Aug-73
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\[ DY = -1.23237 \text{ INCHES} \]
\[ DZ = -0.00307 \text{ INCHES} \]

FOCAL LENGTH OF BEST FIT PARABOLOID = 62.3226 INCHES

RMS WITH RESPECT TO BEST FIT PARABOLOID = 0.025799 INCHES
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180 Degrees

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ANGLE OF ROTATION, ABOUT Z AXIS = 0.0305
OFF AXIS ANGLE, ABOUT ROTATED X AXIS = 0.04036
VALUES DX, DY, DZ LOCATE THE VERTEX OF THE BEST FIT PARABOLOID
IN THE ROTATED COORDINATE SYSTEM.
DX = ±0.676 INCHES
DY = ±0.993 INCHES
DZ = ±0.0066 INCHES

FOCAL LENGTH OF BEST FIT PARABOLOID = 62.3173 INCHES

RMS WITH RESPECT TO BEST FIT PARABOLOID = .031608 INCHES
### Average Measurements of Sweep #1 and Sweep #2

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### Computer Results

Surface Error: _______ inches rms.
PARABOLOID PROGRAM

This program computes the best-fit paraboloid from a given set of data points.

structures section
radiation division
harris intertype inc.
melbourne, florida

revision date of this program, aug 73
BEST-FIT PARAROID FOR 150 INCH ANTENNA
AVERAGE OF MORNING AND AFTERNOON REFLECTIONS
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Number of Iterations = 24

Angle of Rotation, about Z axis = +2.759.570359123+000 radians
Off-axis angle, about rotated X axis = +7.848.502929301+000 radians
Values of x, y, z locate the vertex of the best fit paraboloid in the rotated coordinate system.
\[ k_1 = 0.02157 \text{ INCHES} \]
\[ k_2 = 0.02370 \text{ INCHES} \]
\[ k_3 = 0.00116 \text{ INCHES} \]

Focal Length of Best Fit Paraboloid = 62.3226 INCHES

RMS with respect to Best Fit Paraboloid = 0.021219 INCHES
### 4.4.3 Surface Accuracy Test No. 3

#### 4.4.3.1 Measurement Data

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#### 4.4.3.2 Computer Results

Surface Error: 0.019-inch rms
PARABOLOID PROGRAM

This program computes the best-fit paraboloid from a given set of data points.

STRUCTURES SECTION
RADIATION DIVISION
HARRIS INTERTYPE INC.,
MELBOURNE, FLORIDA

REVISION DATE OF THIS PROGRAM, AUG-73
BEST FIT PARABOLOID FOR 150 INCH ANTENNA
SURFACE ACCURACY TEST NUMBER 3
### Joint Deviation from the Best Fit Paraboloid (Inches)

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<tr>
<td>53</td>
<td>0.01615</td>
</tr>
<tr>
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<td>0.00919</td>
</tr>
<tr>
<td>55</td>
<td>0.04902</td>
</tr>
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</table>
Number of iterations = 10

Angle of rotation, about Z axis = -1.532783920943400 radians
Off axis angle, about rotated X axis = 0.1934403837911002 radians
Values of x, y, and z locate the vertex of the best fit paraboloid
in the rotated coordinate system.
Focal length of best fit paraboloid = 62.1693 inches

RMS with respect to best fit paraboloid = 0.01054 inches
<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Model No.</th>
<th>Serial No.</th>
<th>Cal. Exp. Date</th>
</tr>
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<td>Starrett</td>
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<td></td>
<td>4-29-74</td>
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</tbody>
</table>
COMMENTS:

* Approved all except 4.4.3 Test Number 3 (Results not available)
5.0 RF EVALUATION TEST

5.1 Test Objective

The purpose of this test is to evaluate the RF performance of the 12.5-foot diameter deployable antenna. This is done in three separate procedures. First, the gain of the deployable antenna with a feed installed is compared with the gain of the same feed in a standard solid metal parabola with a known and relatively small surface tolerance and the same diameter and focal length. Second, a feed with a known phase center is placed at the designed focal point of the parabola, and the gain difference is measured between this feed position and the feed position obtained by electrical testing. Third, the far field radiation patterns of the dish are measured and compared with the far field radiation patterns of the standard parabola. These three measurements are performed at 15 GHz.

5.2 Instrumentation

The model deployable antenna and standard antenna are mounted back-to-back 15 feet above ground on a pedestal which may be remotely adjusted in azimuth and elevation.

For a given test frequency, the three types of measurements, gain comparison, focusing, and patterns can be performed with a single set of test equipment. The list of equipment to be used is shown below:

<table>
<thead>
<tr>
<th>Function</th>
<th>15.0 GHz</th>
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</thead>
<tbody>
<tr>
<td>Signal Generator</td>
<td>HP-628A</td>
</tr>
<tr>
<td>Source Feed</td>
<td>Radiation</td>
</tr>
<tr>
<td>Transmit Reflector</td>
<td>Andrews 6 foot</td>
</tr>
<tr>
<td>Mixer</td>
<td>SA-13A-12</td>
</tr>
<tr>
<td>Receiver</td>
<td>SA-1600</td>
</tr>
<tr>
<td>Pattern Recorder</td>
<td>SA-1540</td>
</tr>
<tr>
<td>Precision Attenuator</td>
<td>HP-P382A</td>
</tr>
<tr>
<td>Frequency Meter</td>
<td>PRD 536</td>
</tr>
<tr>
<td>Reference Antenna</td>
<td>(Advanced) Structures/12 feet</td>
</tr>
</tbody>
</table>
5.3 Gain Comparison Test

The objective of this test is: 1) to determine the rms surface error of the model deployable parabola, and 2) to compare the gain of the entire deployable antenna assembly with the predicted gain of the reference antenna. Both measurements are based upon the measured gain difference between the deployable antenna assembly and a reference antenna assembly. The reference antenna has an accurate surface (0.007 inch rms) so that the loss due to surface phase error is small and accurately known. The reference antenna feed is supported in such a way that its primary blockage is zero and its secondary blockage is minimal. This feed support configuration allows the reference antenna gain to be accurately calculated so that it serves as a gain standard for gain measurements on the deployable antenna assembly. The deployable antenna is tested with the complete feed cone, midrib restraint assembly, and feed support in position, hence, fully representing an operational state.

5.3.1 Surface Accuracy Measurement by Relative RF Gain

The secondary gain of a paraboloidal antenna is degraded by surface error in the shape of the reflector. When the errors have a Gaussian distribution and a correlation interval which is large with respect to a wavelength, the loss due to surface error is:

\[ \eta_{\phi_s} = e^{-\left( \frac{4\pi \varepsilon^2}{\lambda} \right)^2} \]

Solving for \( \varepsilon \):

\[ \varepsilon = \frac{\lambda}{4\pi} \left( -\log \eta_{\phi_s} \right)^{1/2}, \text{ or} \]

\[ \varepsilon = 0.23 \frac{\lambda}{4\pi} \left( -10 \log \eta_{\phi_s} \right)^{1/2} \]

The surface phase error \( \eta_{\phi_s} \) is isolated and measured to compute \( G \). This error is determined by measuring the difference in gain between the deployable antenna and the reference antenna. This difference in gain is modified by measured or predicted values for all other differences between the two antennas other than surface error. This gives an rms surface error (in inches) of:

\[ \varepsilon = 0.0144 \left( |\Delta G| + \sum_{k=1}^{n} (10 \log \eta_k) \right)^{1/2} \]

when \( f = 15 \text{ GHz} \)
The factors $\eta_k$ are given below.

<table>
<thead>
<tr>
<th>$k$</th>
<th>Factor</th>
<th>$10 \log \eta_k$</th>
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</thead>
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<tr>
<td>1.</td>
<td>Diameter Difference</td>
<td>+0.35 dB</td>
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<tr>
<td>2.</td>
<td>Ogive Blockage</td>
<td>-0.45</td>
</tr>
<tr>
<td>3.</td>
<td>Midrib Restraint Assembly</td>
<td>-0.60 dB</td>
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<tr>
<td>4.</td>
<td>Scalloped Area Loss</td>
<td>-0.45</td>
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<td>5.</td>
<td>Mesh Loss</td>
<td>-0.30 dB</td>
</tr>
<tr>
<td>6.</td>
<td>Reference Reflector Feed Support Blockage</td>
<td>+0.05</td>
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<tr>
<td>7.</td>
<td>Deployable Reflector Center Blockage</td>
<td>-0.55 dB</td>
</tr>
<tr>
<td>8.</td>
<td>Reference Reflector rms</td>
<td>+0.05 dB</td>
</tr>
</tbody>
</table>

$\sum 10 \log \eta_k = -1.9 \text{ dB}$

The derivation of the above terms is given in detail below.

1. **Diameter Difference**
   
   $= 10 \log \left( \frac{(12.5 \text{ feet})}{(12.0 \text{ feet})^2} \right) = +0.35 \text{ dB}$.

2. **Ogive Blockage**
   
   $= -0.45 \text{ dB}$ by substitution measurements in the standard reflector.

3. **Midrib Restraint Assembly Blockage**
   
   $= -0.6 \text{ dB}$ by substitution measurements in the standard reflector.

4. **Scalloped Area Loss**
   
   $= 10 \log (1 - 0.10) = -0.45$ by computation from measured geometry of mesh intercostal.
5. **Mesh Loss**
   
   \[ \text{Mesh Loss} = -0.3 \text{ from measured flat panel tests.} \]

6. **Reference Reflector Feed Support Blockage**
   
   \[ \text{blockage} = +0.05 \text{ dB from calculation similar to 7.0 below.} \]

7. **Center Blockage of Deployable**
   
   \[
   \text{loss} = 10 \log \left[ 1 - \frac{(A_{\text{center}})}{(A_{\text{reflector}})} \left( \frac{(1)}{(\eta_{at})} \right)^2 \right]^2
   \]
   
   \[ \text{loss} = -0.55 \text{ dB} \]

8. **Reference Reflector rms**
   
   \[ \epsilon = 0.007 \text{ in. rms} \]
   
   \[ \text{the rms loss} = 10 \log \left[ \frac{4\pi \epsilon}{\lambda} \right]^2 \]
   
   \[ = +0.05 \text{ dB} \]

---

5.3.2 **Determination of Relative Gain**

The gain of the deployable antenna assembly with representative feed in place is determined by comparison with the reference reflector. The gain of the reference antenna may be predicted accurately because the normal losses due to surface error and primary blockage are small in this case. This makes it a good standard for measurement of absolute gain. Because it is about the same size as the deployable antenna, ground reflections have a negligible effect on a gain comparison measurement between the two antennas.

The following table lists the factors used to compute the gain of the reference reflector.

<table>
<thead>
<tr>
<th>Factor</th>
<th>(-10 \log \eta)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\eta_{sp}) (\eta_{at})</td>
<td>1.5</td>
</tr>
<tr>
<td>(\eta_b)</td>
<td>0.05</td>
</tr>
</tbody>
</table>

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The gain of the deployable by this method is the measured value of $\Delta G$ from Paragraph 5.3.5, subtracted from this reference reflector gain.

$$G_{\text{deployable}} = G_{\text{standard}} - \Delta G$$

$$\Delta G = 53.4 - 2.5 \text{ dB}$$

$$G_{\text{deployable}} = 50.9 \text{ dB}$$

This is the gain by comparison to the computed gain of the reference reflector in 1 G gravity. The on orbit gain is greater because the surface accuracy is a more accurate paraboloid on orbit where the distortions of gravity are not a factor.

### 5.3.3 Measurement Technique

The antenna feed for both the deployable antenna assembly and the reference antenna is a flared horn designed for equal 10 dB edge tapered illumination over the entire circumference of the reflector. Figures 5.3.3-1 and 5.3.3-2 are E- and H- plane cuts through this pattern. This feed is representative of the feed which would be used in a flight application. The same feed, reflection isolator, and mixer, and mixer-receiver cable are used in both reflector assemblies, so that no variations in these components affect the accuracy of the gain comparison. The reflection isolator absorbs power reflected from the mixer so that it is not reradiated by the feed horn. This eliminates the possibility that feed VSWR due to vertex reflections might interact with the VSWR of the mixer.

Each of the two reflectors has its own three-dimensional focusing adjustment mechanism with a mounting interface for the feed horn-isolator-mixer assembly. The feed is focused in each reflector axially for minimum null depths and radially for equal side lobes. The feed may then be substituted from one reflector to the other in minimum time. This substitution
is done five times; each time the peak of the antenna beam is pointed at the boresight source. A rotary vane precision attenuator is used as a standard against which to measure the difference in received power levels. The range geometry is shown in Figure 5.3.3-3.

5.3.4 Test Procedures

The following procedure will be used to measure delta gain, \( \Delta G \).

1. With the measure configuration shown in Figure 5.3.2, set approximately 3 dB of attenuation in the precision attenuator. Orient the boresight antenna to the vertical polarization position.

2. Set the generator at 15.0 GHz.

3. Focus both antennas for maximum gain.

4. With the waveguide horn feed in the deployable reflector, orient the antenna so that the peak of the main beam is aligned on boresight.

5. Establish a reference level of the antenna output signal on the pattern recorder.

6. Remove the waveguide horn feed and install the feed in the standard reflector.

7. Orient the antenna so that the peak of the main beam is aligned on boresight.

8. Establish a reference level of the antenna output signal on the pattern recorder.

9. Adjust the precision attenuator until the two reference levels are coincident.

10. The amount of attenuation change in the precision attenuator is \( \Delta G \).

11. Repeat this procedure until three measurements of \( \Delta G \) are recorded.

5.3.5 Test Record

\[
\begin{align*}
\text{Frequency (GHz)} & \quad 15.0 \\
+ \sum_{k=1}^{N} 10 \log \eta_k & \quad -1.90 \\
\Delta G & \quad 2.41
\end{align*}
\]
Figure 5.3.3-3. Measurement Configuration
<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>15.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta G_2$</td>
<td>2.58</td>
</tr>
<tr>
<td>$\Delta G_3$</td>
<td>2.45</td>
</tr>
<tr>
<td>$\Delta G_4$</td>
<td>2.53</td>
</tr>
<tr>
<td>$\Delta G_5$</td>
<td>2.50</td>
</tr>
<tr>
<td>$\Delta G_{\text{average}}$</td>
<td>2.49</td>
</tr>
<tr>
<td>$-10 \log \eta_{\phi s}$</td>
<td>0.60 dB</td>
</tr>
<tr>
<td>$\epsilon$</td>
<td>0.011 inch rms</td>
</tr>
</tbody>
</table>

5.3.6 **Error Analysis**

The accuracy of the terms $\Sigma 10 \log \eta_k$ and $\Delta G$ above determine the accuracy of the measured value of $\epsilon$. The most probable value of $\eta_{\phi s}$ based on estimates of the accuracy of the individual terms $\eta_k$ and $\Delta G$ is as follows:

<table>
<thead>
<tr>
<th>K Factor</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Diameter Difference</td>
<td>$\pm 0.0$ dB</td>
</tr>
<tr>
<td>2. Ogive Blockage</td>
<td>$\pm 0.15$</td>
</tr>
<tr>
<td>3. Midrib Restraint Assembly</td>
<td>$\pm 0.20$</td>
</tr>
<tr>
<td>4. Scalloped Area Loss</td>
<td>$\pm 0.0$</td>
</tr>
<tr>
<td>5. Mesh Loss</td>
<td>$\pm 0.10$</td>
</tr>
<tr>
<td>6. Reference Reflector Feed Support Blockage</td>
<td>$\pm 0.05$</td>
</tr>
<tr>
<td>7. Deployable Reflector Center Blockage</td>
<td>$\pm 0.15$</td>
</tr>
<tr>
<td>8. Reference Reflector rms</td>
<td>$\pm 0.0$</td>
</tr>
<tr>
<td>Measured value of $\Delta G$</td>
<td>$\pm 0.15$ dB</td>
</tr>
</tbody>
</table>
The square root of the sum of the squares of the above values is 0.35 dB. The most probable value of surface phase loss then lies in the range of 0.60 ±0.35 dB

This corresponds to rms surface accuracies from 0.007 to 0.014 inches based on the use of Ruze's equation for the calculation. It should be noted, however, that it is widely recognized that this equation is typically pessimistic for calculation loss from rms surface accuracy. Comparisons between calculations made using ray tracing pattern computing programs and the use of Ruze's equation often show loss factors of two to three times less with the ray tracing technique. Therefore, if compensations are made in proportion to these factors, then the calculated rms surface error based on RF measurements is more consistent with the 0.025 inch rms measured in the program.

5.4 Focusing Accuracy Test

5.4.1 Test Method

This measurement determines how much gain loss the model deployable antenna suffers due to uncertainty about the location of its focal point. The technique is to locate the feed at the predicted focal point of the deployable antenna and make a gain measurement, using the standard parabola as a reference. Then the feed is focused electrically for deepest nulls and best side-lobe balance. A second gain measurement is made at this point. The gain increase is a measure of the inaccuracy in phase center location and its effect on the antenna's performance. A block diagram of the test configuration is shown in Figure 5.4.1-1. The procedure used to locate the predicted best fit focal point of the parabola is shown in Figure 5.4.1-2. The location of the best electrical focus as determined by running patterns and focusing for best nulls and the location of the best fit paraboloid focal point as computed for best rms surface error are shown in Figure A-7 in the Appendix.

5.4.2 Test Procedure

The following test procedure is used to evaluate the feasibility of positioning the feed at the analytically determined focal point of the deployable antenna.

1. Set up the test equipment as shown in Figure 5.4.1-1.

2. Set approximately 3 dB of attenuation in the precision attenuator.
Figure 5.4.1-1. Block Diagram of Antenna Focusing Measurements
Figure 5.4.1-2. Procedure for Locating Predicted Best Fit Focal Point
3. Set the signal generator to 15.0 GHz.

4. Orient the boresight antenna to the vertical polarization position.

5. Focus the standard reflector by balancing the side-lobe levels and the null depths. Use the standard feed.

6. Focus the deployable antenna model by balancing the side-lobe levels and the null depths. Use the feed with the known phase center.

7. Point the standard reflector on boresight and set a reference level of the received signal power on the recorder.

8. Point the deployable reflector on boresight and set a reference level of the received signal power on the recorder.

9. Adjust the precision attenuator until the two reference levels are coincident. The amount of attenuation change is $\Delta G_1$.

10. Reposition the feed in the deployable reflector until its phase center is coincident with the analytically determined focal point.

11. Position the deployable reflector such that the received signal power is maximized.

12. With the antenna in this position, set a reference level of the received signal power on the recorder.

13. Point the standard reflector on boresight and set a reference level of the received signal power on the recorder.

14. Adjust the precision attenuator until the two reference levels are coincident. The amount of attenuation change is $G_2$.

15. Subtract $G_1$ from $G_2$ to determine the amount of gain difference due to setting the feed at the analytically determined focal point.

5.4.3 Test Record

<table>
<thead>
<tr>
<th></th>
<th>Number 1</th>
<th>Number 2</th>
<th>Number 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G_{\text{mechanical focus}} - G_{\text{standard}}$</td>
<td>7.5 dB</td>
<td>7.3 dB</td>
<td>7.5 dB</td>
</tr>
<tr>
<td>$G_{\text{electrical focus}} - G_{\text{standard}}$</td>
<td>2.5</td>
<td>2.5</td>
<td>2.3</td>
</tr>
<tr>
<td></td>
<td>Number 1</td>
<td>Number 2</td>
<td>Number 3</td>
</tr>
<tr>
<td>------------------------</td>
<td>----------</td>
<td>----------</td>
<td>----------</td>
</tr>
<tr>
<td>$G_{\text{electrical focus}} - G_{\text{mechanical focus}}$</td>
<td>5.0</td>
<td>4.8</td>
<td>5.2</td>
</tr>
<tr>
<td>Average $G_{\text{electrical focus}} - G_{\text{mechanical focus}}$</td>
<td>5.0 dB</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

5.5 Pattern Measurement

5.5.1 Test Method

To expedite this test, the antenna patterns are recorded during the antenna focusing measurement procedure. The test equipment and test facility required for the focusing measurements are also required to record antenna patterns.

The procedures described in Paragraph 5.4.2 of the antenna focusing measurement procedure are followed to the point where the test feed has been focused electrically in the deployable antenna model.

The focused antenna is then pointed on boresight. With the antenna pattern recorder synchronized to the rotation of the turntable, the turntable is rotated approximately $\pm10^\circ$ in azimuth around boresight with the pen of the recorder in the down position.

5.5.2 Test Procedures

Follow the procedure described in Paragraph 5.4.2 to the point where the test feed has been focused electrically in the deployable antenna model, then proceed with the following steps:

1. Orient the antenna at $-90^\circ$ in azimuth.
2. Place the pen of the antenna pattern recorder in the down position.
3. Rotate the antenna in azimuth to $+90^\circ$.
4. The curve plotted by the antenna pattern recorder as the antenna is rotated from $-10^\circ$ to $+10^\circ$ is the antenna pattern.
5. Perform this measurement at 15.0 GHz where the focusing accuracy test is performed.
5.5.3 Test Record

Attach all patterns taken on the deployable antenna and on the standard antenna. (See Appendix Figures A14, A15, A17.)

5.6 Absolute Gain

5.6.1 Test Objective

The object of this test is to measure the gain of the deployable antenna at 15 GHz.

<table>
<thead>
<tr>
<th>Test Equipment</th>
<th>Type</th>
<th>Serial No.</th>
<th>Calibration Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal Generator</td>
<td>HP-628A</td>
<td>105785</td>
<td>2-14-74</td>
</tr>
<tr>
<td>Transmitter Antenna</td>
<td>6-foot reflector</td>
<td></td>
<td>NCR</td>
</tr>
<tr>
<td></td>
<td>illuminating a 5-foot</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>by 7-foot flat passive</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>reflector</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard Attenuator</td>
<td>HP-P382A</td>
<td>102932</td>
<td>8-8-74</td>
</tr>
<tr>
<td>Mixer</td>
<td>SA-13A-12</td>
<td>218632</td>
<td>NCR</td>
</tr>
<tr>
<td>Standard Gain Horn</td>
<td>NRL-18 MM Band</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Receiver</td>
<td>SA-1600</td>
<td>106350</td>
<td>4-2-74</td>
</tr>
<tr>
<td>Pattern Recorder</td>
<td>SA-1520</td>
<td>105987</td>
<td>4-2-74</td>
</tr>
</tbody>
</table>

5.6.2 Error Analysis

The gain of the deployable antenna will be determined by a comparison with an NRL design gain standard horn. There are three basic sources of uncertainty in this measurement: 1) the uncertainty in on-axis gain of the gain standard horn, 2) the measurement uncertainty in the comparison of the deployable antenna with the gain standard, and 3) power which reaches the gain standard horn from reflections which are not focused by the larger deployable reflector. The first uncertainty is ±0.3 dB peak as described in the NRL report. The second is one percent of the amplitude difference between the standard and the test antenna, or 0.25 dB. The third source of error, power which enters the standard gain horn by way of ground reflections (see Figure 5.6.2-1). The value for A in this model is a function of the transmitter pattern, the receiver pattern, and the reflectivity of the ground. The value for Ø is a function of the length difference between the direct and reflected ray path. The change in this path length difference between the top and bottom of the reflector is 11.8 inches. This range geometry is shown in Figure 5.6.2-2.
Figure 5.6.2-1. Model for Evaluating Ground Reflection Effects
Figure 5.6.2-2. Range Geometry
The ratio \( \frac{E_{\text{reflected}}}{E_{\text{direct}}} = A \) in the above model.

The peaks of the interference pattern measured as the horn is moved across the field represent successive values of \( E \) maximum, and the nulls represent \( E \) minimum. At each transition between peak and null the two above equations are solved for \( E_{\text{direct}} \) and \( E_{\text{reflected}} \), so a total of 72 values of \( E_{\text{direct}} \) are obtained. These are converted back to relative power levels and averaged to obtain the reference power level for the gain measurement.

It is possible to check this value by pointing the large reflector directly at the reflected ray. Measurements of the relative strength of the reflected ray, \( A \) in the model, by these two methods, are in close agreement. Deviations in the smoothed signal level of the standard gain horn limit the accuracy to \( \pm 0.25 \) dB error. Together with the two other errors, the peak error of the gain measurement is \( \pm 0.8 \) dB.

5.6.3 Test Procedure

1. Set up the test equipment.
2. Set the generator at 15 GHz.
3. Focus the antenna by balancing side-lobe levels and null depths.
4. Point the antenna toward the boresight.
5. Set the attenuator at 22 dB and record the level on the chart paper. Repeat for 23, 24, 25 and 26 dB settings of the attenuator.
6. Connect the mixer to the standard gain horn. Record vertical field probe using the standard gain horn.
7. Plot the magnitude of the reflected ray and direct ray as computed using the technique described above.
8. Average the direct ray data points and compare this average with the calibration marks made using the precision attenuator.
9. Record the data on the data sheets.
5.6.4 Absolute Gain Measurement Data Sheet

See Figure 5.6.4.

Frequency 15 GHz
Gain of Gain Standard 24.4 dB
Average Direct Ray Gain Standard Reading 26.5 dB
Attenuator Loss at Zero Setting 0.6 dB
Gain of Test Antenna 51.5 dB
Efficiency of Test Antenna 41%*

NOTE
This efficiency is referenced to a circular aperture with the rib-tip diameter. The efficiency with respect to the mean diameter including scallop area loss is 46 percent.

The model based on simple geometrical optics assumes that only a single reflected ray enters the standard gain horn from the point of specular reflection. Because the relative phase $\phi$ between the direct and reflected rays varies directly as the height up and down the aperture of the large reflector, the standard gain horn sees an interference pattern as it is raised and lowered in front of the large reflector. This interference pattern results from the vector addition of the two signals in the standard gain horn.

The locus of received voltage level at the standard horn is shown below:
The desired reference voltage for gain measurements is $E_{\text{direct}}$, but the only directly observable are $E_{\text{maximum}}$ and $E_{\text{minimum}}$. By solving the two simultaneous equations,

$$E_{\text{direct}} = \frac{E_{\text{maximum}} + E_{\text{minimum}}}{2}$$

$$E_{\text{reflected}} = \frac{E_{\text{maximum}} - E_{\text{minimum}}}{2}$$
5.7  S-Band Pattern and Relative Gain Measurements

Pattern measurements on the deployable antenna and gain comparison between the deployable antenna and the reference antenna are made. The feed horn used is a flared horn with equal E- and H-plane beam widths and 10-11 dB illumination taper from the center to the edge of the reflector. The measurements were conducted at 2.1 GHz. The pattern measurements follow a procedure similar to that described in detail in Paragraph 5.5. The relative gain measurements follow a procedure similar to that described in Paragraph 5.3.

The elevation (E-plane) pattern from the deployable reflector is shown in Figure 5.7-1. The pattern below -6° is affected by ground reflected energy.

The azimuth (H-plane) pattern of the deployable reflector is shown in Figure 5.7-2. The pattern beyond ±120° is affected by range reflections.

The azimuth and elevations of the reference reflector are shown in Figure 5.7-3.

The gain comparison measurements between the deployable antenna and the reference reflector are shown in Figure 5.7-4.

6.0  PHYSICAL PROPERTIES MEASUREMENT

In this test, several physical properties of the antenna are measured.

6.1  Test Objectives

The objective of this test is to measure the weight and packaging envelope size of the deployable antenna.

6.2  Test Procedure

The antenna is first placed on a platform scale and its weight is recorded. For this measurement the antenna is completely assembled, including the restraint cable.

The size of the packaging envelope is determined by measuring the overall height and the overall diameter of the antenna in the stowed configuration.

6.3  Test Record

The data specified above are recorded on the data sheets at the time of the test.
Figure 5.7-4
### Paraboloidal Antenna Efficiency Factors

#### E-plane Right Side

<table>
<thead>
<tr>
<th>Angle (°)</th>
<th>Efficiency</th>
</tr>
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<tbody>
<tr>
<td>00</td>
<td>1.46</td>
</tr>
<tr>
<td>05</td>
<td>2.36</td>
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<tr>
<td>26</td>
<td>3.05</td>
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<tr>
<td>79</td>
<td>4.52</td>
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</table>

#### E-plane Left Side

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<th>Efficiency</th>
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<td>00</td>
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<tr>
<td>30</td>
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<tr>
<td>45</td>
<td>4.92</td>
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</table>

#### F-plan Right Side

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<th>Efficiency</th>
</tr>
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<tbody>
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<tr>
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<td>2.36</td>
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<tr>
<td>26</td>
<td>3.05</td>
</tr>
<tr>
<td>79</td>
<td>4.52</td>
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</table>

#### F-plan Left Side

<table>
<thead>
<tr>
<th>Angle (°)</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>00</td>
<td>1.44</td>
</tr>
<tr>
<td>05</td>
<td>2.51</td>
</tr>
<tr>
<td>30</td>
<td>3.52</td>
</tr>
<tr>
<td>45</td>
<td>4.92</td>
</tr>
</tbody>
</table>

#### Feed Amplitude Pattern

<table>
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<tr>
<th>Angle (°)</th>
<th>Efficiency</th>
</tr>
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<tbody>
<tr>
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<tr>
<td>05</td>
<td>2.36</td>
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<tr>
<td>26</td>
<td>3.05</td>
</tr>
<tr>
<td>79</td>
<td>4.52</td>
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</tbody>
</table>

#### Feed Polarization Efficiency

<table>
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<tbody>
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<tr>
<td>05</td>
<td>2.36</td>
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<td>26</td>
<td>3.05</td>
</tr>
<tr>
<td>79</td>
<td>4.52</td>
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#### Feed Temperature

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<th>Angle (°)</th>
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<tr>
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<td>05</td>
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<td>26</td>
<td>3.05</td>
</tr>
<tr>
<td>79</td>
<td>4.52</td>
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</tbody>
</table>

Figure A3
**Deployable Antenna Relative Gain Measurement**

<table>
<thead>
<tr>
<th>Reference Reflective</th>
<th>TOTAL SPILL, AMP, TAPER, PHASE/CROSS EFFICIENCY</th>
<th>0.00000</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TOTAL SPILL, AMP, TAPER, PHASE EFFICIENCY</td>
<td>0.00000</td>
</tr>
<tr>
<td></td>
<td>TOTAL SPILL, AMP, TAPER EFFICIENCY</td>
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</tr>
<tr>
<td></td>
<td>TOTAL SPILLOVER EFFICIENCY</td>
<td>90.74923</td>
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<tr>
<td></td>
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</tr>
<tr>
<td></td>
<td>TOTAL PHASE EFFICIENCY</td>
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<td></td>
<td>TOTAL CROSS POLARIZATION EFFICIENCY</td>
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<td></td>
<td>TOTAL NOISE TEMPERATURE</td>
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<tr>
<td></td>
<td>TOTAL GMAX(ABSOLUTE)</td>
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<td></td>
<td>TOTAL GMAX (DB)</td>
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</tr>
<tr>
<td></td>
<td>ALABOLOID EDGE ANGLE</td>
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**Figure A4**
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<th>NCUTS</th>
<th>NPTS</th>
<th>NPHASE</th>
<th>NCROSS</th>
<th>IFAP</th>
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<tbody>
<tr>
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**FEED AMPLITUDE PATTERN**

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<th>2.36</th>
<th>3.45</th>
<th>4.52</th>
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</thead>
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<td>20.98</td>
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<td>24.00</td>
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<td>37.03</td>
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**E-PLANE RIGHT SIDE**

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<td>20.82</td>
<td>22.49</td>
<td>24.02</td>
<td>26.06</td>
<td>27.11</td>
<td>29.31</td>
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<td></td>
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**PILL. AMP., TAPER, PHASE, CROSS EFFICIENCY**

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**PILL. AMP., TAPER, PHASE, CROSS EFFICIENCY**

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<th>85.13897</th>
<th>100.00000</th>
<th>1,96020</th>
<th>8,10426</th>
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**PILL. AMP., TAPER, PHASE, CROSS EFFICIENCY**

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**PILL. AMP., TAPER, PHASE, CROSS EFFICIENCY**

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**PILL. AMP., TAPER, PHASE, CROSS EFFICIENCY**

| Plane Left Side | 75.45264 |

Figure A5
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<th>Parameter</th>
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<tr>
<td>Spill, Amp, Taper Efficiency</td>
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<tr>
<td>Spillover Efficiency</td>
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<tr>
<td>Amplitude Taper Efficiency</td>
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<tr>
<td>Phase Efficiency</td>
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<tr>
<td>Cross Polarization Efficiency</td>
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<tr>
<td>Noise Temperature</td>
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<td>Gmax (dB)</td>
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**Feed Amplitude Pattern**

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<th>%</th>
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**Deployable Antenna Relative Gain Measurement**

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<tr>
<td>Total Spill, Amp, Taper, Phase Efficiency</td>
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<td>Total Spill, Amp, Taper Efficiency</td>
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<td>Total Amplitude Taper Efficiency</td>
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<td>Total Noise Temperature</td>
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<tr>
<td>Total Gmax (Absolute)</td>
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<td>Total Gmax (dB)</td>
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<td>Arboloid Edge Angle</td>
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**Figure A6**
FOCAL POINT LOCATION DATA

Location of best electrical focus with respect to design, focal point determined by focusing for best nulls and sidelobe looking balance downrange.

0.49 up
0.14 to right
0.56 in (toward reflector)

Location of focal point predicted by PARABOLOID with respect to design focal point.

0.568 down
0.186 to right
0.230 out (away from reflector)

Location of design focal point with respect to ¼ mounting plate riveted to ogive front surface.

7.96 into ogive (toward reflector)
Figure A17
<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Model No.</th>
<th>Serial No.</th>
<th>Cal. Exp. Date</th>
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<tbody>
<tr>
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APPENDIX C

THE PARABOLOID PROGRAM
APPENDIX C

THE PARABOLOID PROGRAM

The Paraboloid Program was developed to provide a computer technique for the calculation of rms surface accuracy and axis location of parabolic antenna reflectors under arbitrary loadings. A general discussion of the program method is given below.

The input to the program consists basically of the spatial coordinates of points representing the theoretical reflector surface and a set of distortions of these points due to some form of loading. These distortions are obtained directly from STRUDL or SPACE or by measurement, and are used to calculate the spatial location of the deflected or distorted paraboloid. The program then applies statistical techniques to determine a mathematically "best-fit" paraboloid of revolution through the distorted points. This paraboloid is next evaluated to determine the angular location of the axis of revolution, the new location of the paraboloid vertex, and the change in focal length between the theoretical and best-fit paraboloid. Angular values of encoder rotation and feed deflection are inputted to the program and are combined with the above data to yield net values of absolute and encoder corrected azimuth and elevation pointing errors.

Finally, the axial rms deflection of the deflected points is computed with respect to both the best-fit and undistorted parabolic surfaces with and without the area and illumination weighting techniques described below.

The scheme for both area and illumination weighting is to adjust the deviations from the best-fit paraboloid such that the relative difference in area and illumination associated with each joint is taken into account.

Two illumination weighting functions are available in the program. A uniform aperture distribution such as is typical with DIELGUIDE feeds, or the following function:

\[ 0.3 + 0.7 \left( 1 - \left( \frac{R}{R_0} \right)^2 \right)^2 \]

where \( R_0 \) is the radius of the reflector, \( R \) is the radius to the point and the exponent \( P \) characterizes the illumination provided by the particular feed being used.

The projected area associated with each joint is computed and normalized with respect to the total projected area of the reflector for the area weighting factors.

The coordinates of the data points and deflections can be inputted to the program in several ways. The coordinates of the theoretical paraboloid can be inputted along with deflections in either the x, y and z coordinate directions or in the y (axial) direction only. Also the coordinates of the actual distorted points can be inputted to the program.