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Large Space Erectable Antenna Stiffness Requirements

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A key problem in large space erectable antennas is the stiffness requirements that can significantly affect ground testing, thermal distortion, beam pointing, and attitude-control system cost. Without adequate stiffness, ground test of deployment sequence, rf alignment or surface tolerance measurements become difficult, reducing the reliability of large expensive systems. Typically, Earth-based and current space antennas have held a natural frequency above 2 cps. Stiffness is reflected in thermal distortion as a minimum of a depth squared function. With deep-space heat sink and the sun on one side of the large antenna and local shadowing from other spacecraft elements, large thermal excursions are possible. Low-expansion graphite composites have considerably reduced the thermal distortion problem, but as operations are extended to higher frequencies, the antenna distortion again becomes sensitive to thermal affects. As the mass moment of inertia of a large antenna exceeds that of the spacecraft, its stiffness is the critical function of the control system. Extremely "soft" large antennas may require distributed control systems to maintain pointing accuracy. While it is impractical to parametrically solve this multidisciplined problem, this paper discusses the general problem area with respect to the geodetic truss concept solution.

Introduction

As the need for large antennas operating at higher frequencies develop, major initial questions are: to what stiffness do you design? and what are the impacts in antenna design as size and weight constraints cause the natural frequency to decrease? Figure 1 shows the typical pointing accuracy requirements as a function of size and rf operating frequency. Many of the proposed space programs require antennas in the 10-m size for Earth resources to 1 km diameter for the microwave power relay.

Four design criteria must be considered: contour control, thermal distortion, ground test capability, and most critical, pointing capability. Without ample isotropic stiffness, the thermal distortion becomes excessive and the antenna surface tolerance degrades, losing phase, resulting in gain loss and pointing errors. Ground adjustment and test of a whole or parts of an antenna are necessary to ensure performance. Large misalignment losses may readily double the size and weight of an orbital system to perform the same function that an efficient smaller system could accommodate at lower cost. Extremely flexible erectable antennas have been considered in the past ten years, but lose credibility for operational systems when the first time the real surface contour or natural frequency can be tested is in the zero-*g* environment of space.

In a recent study[3] of both space and ground antennas, a summary was assembled of resonant frequencies for antennas in the 0.3- to 183-m range. At the 9-m size, structural frequency ranged from 1.7 cps (ATS erectable antenna) to 11 cps with an average of 4.5 cps. At 18.3 m the average stiffness was 2.2 cps of eleven antennas evaluated. At 24.4- to 30.5-m diameter, the average stiffness held above 2 cps. In the 30.5- to 91.4-m range, the average dropped to 1.2 cps.

Concepts for large space antennas have ranged from static charged, actively stabilized membranes to maypole concepts and long boom systems. A reasonable stiffness, that could be matched into a control system even for the low motion required at synchronous orbit, has been their major problem. Even the precision pointing achieved with the best angular momentum exchange control system becomes a problem as the moment of inertia (MOI) becomes appreciable with respect to the MOI of the "rigid main body." At this point antenna flexibility becomes a significant control system stability consideration (Fig. 2). The stability problem is most readily overcome when the antenna has sufficient stiffness per unit mass to provide natural frequencies that are higher than the vehicle control system frequency. If the frequency separation is great enough, the natural attenuation of the rigid-body dynamics can provide sufficient stability margin. Somewhat less separation can be handled by filtering without appreciably affecting the principal dynamics of the attitude control.

As the first bending mode approaches the control frequency, the nature of the problem changes. Since there is usually more confidence in the control system phase shift at the lower frequencies, the problem is not so much stability of the first mode as incorporating it into the principal dynamics. With real-life hardware there are usually sufficient problems in meeting response time, settling time, dynamic error and

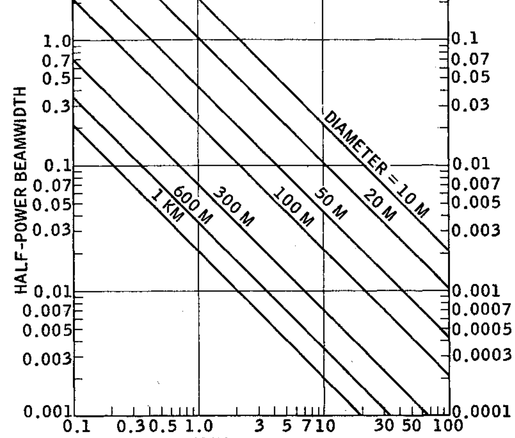

Fig. 1 Pointing accuracy is rigorous for large antennas.

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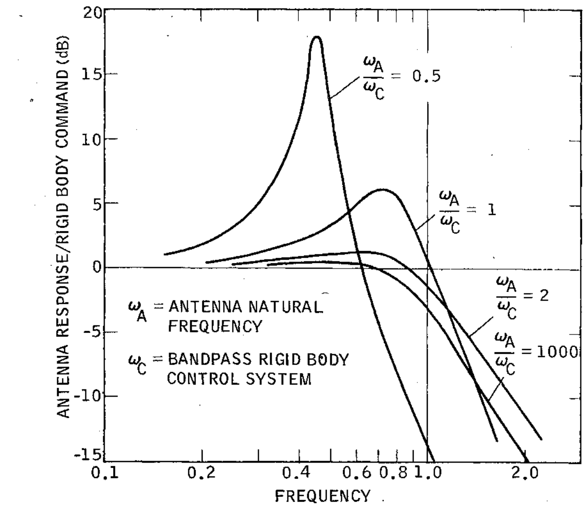


Fig. 2 Antenna response per body command for increasing antenna inertia contribution.

static error requirements without having to accommodate oscillatory terms.

It might be noted that, in theory, filters can be constructed to cancel the offending dynamics, but accuracy in analytical prediction of structural modes is sometimes "less than exact" (as is prediction of 0-g modes from 1-g test data or in large systems that cannot be tested prior to launch). Use of cancellation, therefore, is somewhat of a last resort if all else fails.

One of the space erectable or assembly concepts that has the promise of supplying the isotropic stiffness needed for large systems is the geodetic truss.[1] Figure 3 shows the sizes that can be packaged in the shuttle for deployment as a whole unit up to the 91.4-m size, assembled by units of multiple bay structures, or for the very large systems assembled as tetrahedron elements (the basic units of the geo-truss). By changing the size of the tetrahedrons, a large matrix of varying stiffness antenna substructures can be developed. Figure 4 shows a realistic range of stiffness for the geo-truss concept in the 10-m to 1-km size range (see Table 1).

Due to the low stiffness in the <40 m size, a distributed control system is most probable in which control moment gyros (CMG's) or reaction systems are mounted at the selected truss intersections (spiders). Reasonable stiffness is still required in these "local" stabilized areas so the influence of each controlled area can be effectively integrated into the total antenna control system.

Dynamic Behavior of Geo-Truss Concept

The versatility of the geo-truss design concept is perhaps most significantly exploited in the acquisition of desired natural frequency characteristics. Because the design of a given diameter reflector may be varied in the number of bays or the strut angle, its frequency characteristics may be adjusted within limits to satisfy the particular requirements. Typical characteristics are briefly discussed in the lower size range.

The truss concept provides for a stiff lightweight structure that nominally will possess relatively high natural frequencies. The strength of the truss system permits consideration of side mounted arrangements as well as center or apex mounted schemes. Characteristics for side-mounted reflectors are shown in Figs. 5 and 6. The lowest frequency modes involve localized structural distortion and may be characterized as near-rigid-body distortions about the support points.

The lowest modes are in pitch and yaw and have nearly the same frequency. Increasing the strut angle tends to raise the pitch mode faster than the yaw mode, as shown in Fig. 6. Pitch direction stiffness is influenced by the distance between the upper and lower surface reaction points, so, as the strut angle increases, the effective support stiffness also increases, resulting in higher pitch mode frequencies. Roll modes are substantially higher than pitch and yaw mode frequencies principally because the roll mass moment of inertia at the point of attachment is smaller.

When the reflector is supported at the center three aft spiders, the natural frequencies rise appreciably due to the reduced mass moment of inertia at the attachment point. The structure is now cyclic symmetric and will exhibit multiple eigenvalues. As illustrated in Fig. 7, the lowest frequency modes are those which display near-rigid-body pitch and roll motion. The first modes containing appreciable surface distortion are the astigmatic, or $N=2$ modes (normal

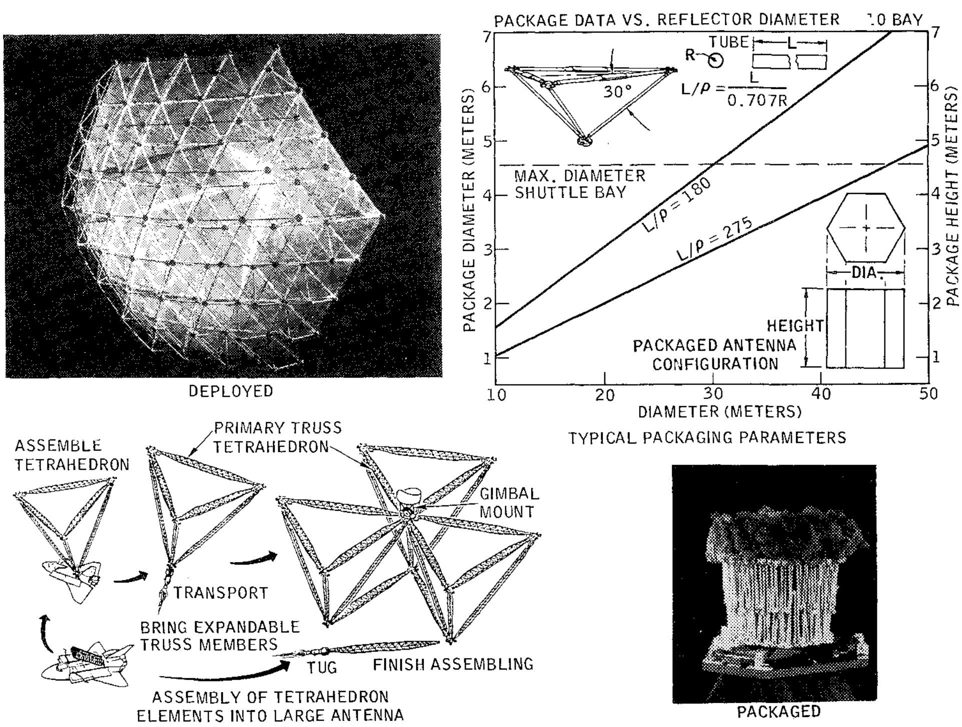


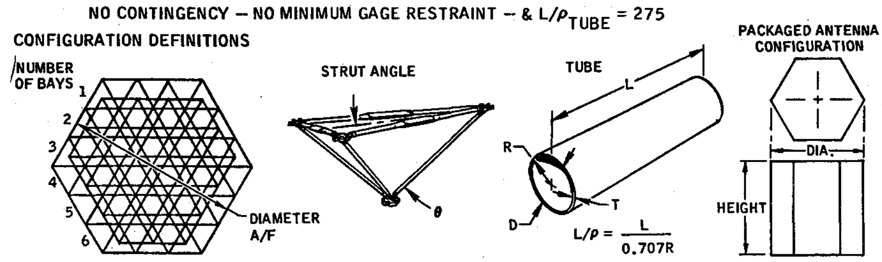
Fig. 3 Geo-truss approach.

Table 1 Variation in stiffness by changing depth of geo-truss structure

GROUND RULES

NO CONTINGENCY – NO MINIMUM GAGE RESTRAINT – & $L/\rho_{TUBE} = 275$

CONFIGURATION DEFINITIONS



Diameter, m	Stut angle θ deg,	No. of days	D/T	Weight, kg	Package Height, cm	Package Diam., cm	Freq., Hz
10	30	8	100	30	102	132	5.33
10	60	8	100	48	122	216	10.64
20	30	8	150	119	204	247	3.63
20	60	8	150	158	224	416	6.85
50	30	10	300	617	493	1215	1.19
50	60	10	300	832	542	1496	2.28
100	30	10	600	2212	990	2450	0.63
100	60	10	600	3042	1084	2970	1.19
300	30	12	1200	19,512	NA	NA	0.58
300	60	12	1200	25,603	NA	NA	1.44
600	30	12	2000	85,033	NA	NA	0.30
600	60	12	2000	114,172	NA	NA	0.75
1000	30	12	2500	282,750	NA	NA	0.19
1000	60	12	2500	390,518	NA	NA	0.47

Note: Apex-mounted to 100 m, free-free above 100 m.

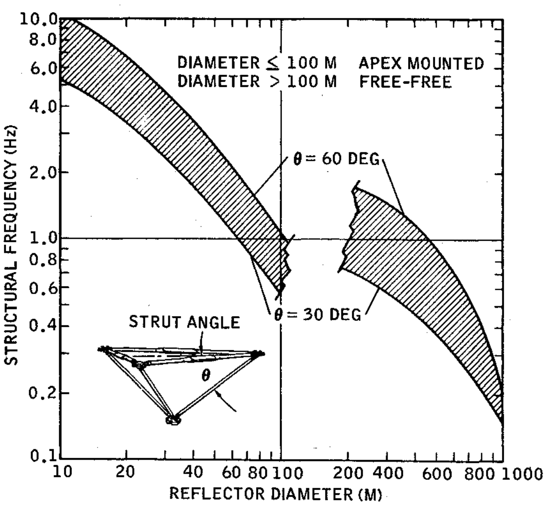


Fig. 4 Geodetic truss parametric stiffness trade study.

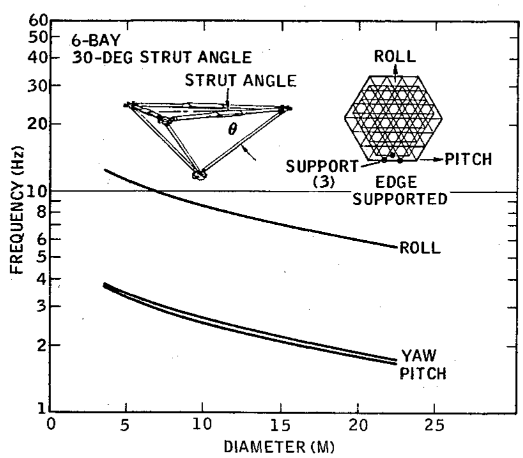


Fig. 5 Natural frequencies vs diameter for edge-mounted reflector.

deflections describe two full sine waves around the periphery).

As the strut angle is varied, as illustrated in Fig. 8, modal frequencies increase gradually. The exception to this trend is the yaw or torsion mode because the increased depth reduces torsional stiffness.

It should be pointed out that the modal characteristics described above are applicable to a hard-mounted reflector truss only. Elastic support systems will lower the natural frequencies of the structure, particularly for the near-rigid-body modes. Where a subreflector is included in the antenna system (e.g. cassegrain) and supported at the focal point by a set of struts rising from the erectable truss structure, the added mass moment of inertia will lower the system frequencies; the presence of the subreflector struts will also cause alteration of mode shapes. Minimum reduction occurs for those modes that are axisymmetric (torsion and spherical aberration).

During operational phases of activity, spacecraft slewing activity may be required to point the antenna. The dynamic response of the antenna to this disturbance is important from several viewpoints including loads, distortions, and impact on antenna performance. These areas have been investigated for an eight-bay geo-truss reflector with subreflector mounted on a spacecraft through three bipod mounts at the rear surface. The center bay of the reflector has been removed to permit proper positioning for the feed.

Rotational accelerations typical of pointing maneuvers were imposed individually upon the rigid spacecraft at its cg, assumed to be 2.55 m aft of the antenna bipod supports.

The response of the antenna was determined by a modal transient analysis of the spacecraft/antenna system. A large number of elastic modes were included in the study; however, examination of the results indicated that only the first few

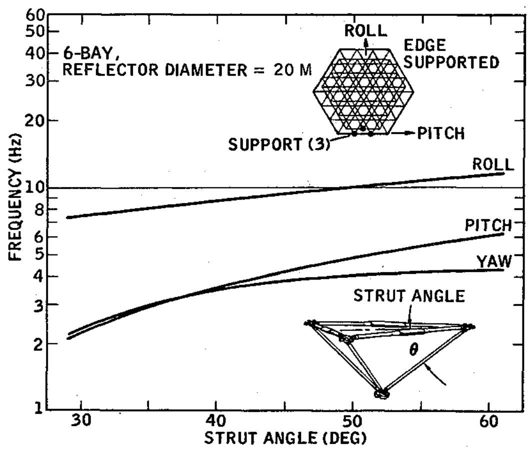


Fig. 6 Natural frequencies vs strut angle for edge-mounted reflector.

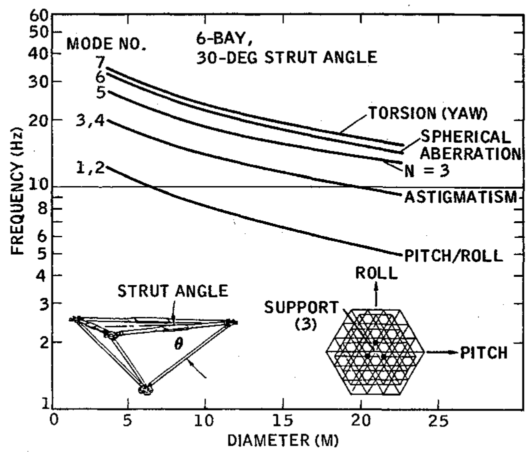


Fig. 7 Natural frequencies vs diameter for apex-mounted reflector.

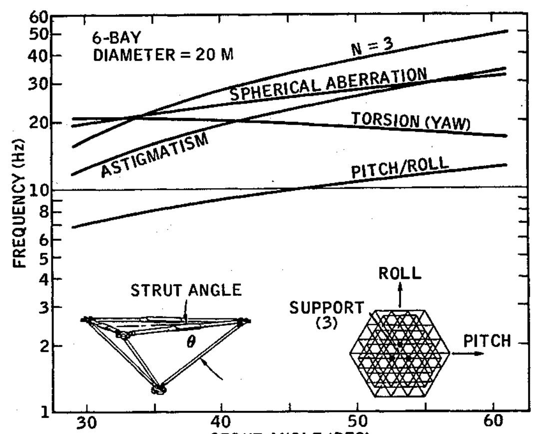


Fig. 8 Natural frequencies vs strut angle for apex-mounted reflector.

modes participated in any significant degree. This characteristic reflects the influence of high stiffness on intrinsic dynamic behavior.

The behavior of the antenna due to the slewing disturbances is illustrated in Figs. 9-11. These responses are measured relative to the rotating rigid motion. Also included are error parameter time histories. The parameters selected include beam pointing with respect to the rigid spacecraft reference frame and path length error.

Table 2 summarizes the beam pointing and defocus maximum and residual error amplitudes. The most severe case is rotation about a transverse axis. Even for that case, residual

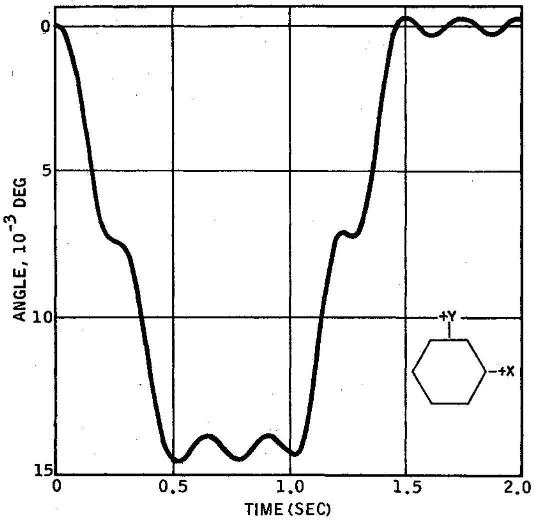


Fig. 9 *x*-Axis beam pointing error—*x*-axis rotation, 20 m size range.

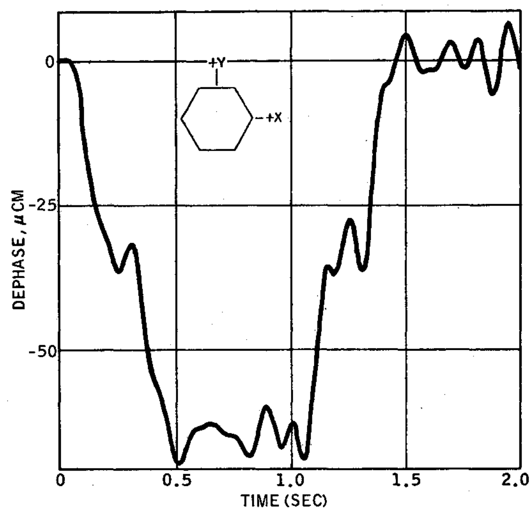


Fig. 10 Dephase—*x*-axis rotation.

error terms are extremely small as a result of the high natural frequency of the geo-truss antenna. Degradation of antenna performance as a result of structural deformation transients following a spacecraft maneuver is minimal and may not result in the need for any settling time before resuming antenna operations.

Ground Testing

Since operational strength requirements for large space structures tend to be relatively low, the tendency is to design extremely flexible systems. Ground testing of such structures is quite difficult because 1-*g* environmental loads can produce major distortions. Within limits, geo-truss reflectors can be rf/performance tested without the necessity of augmenting with strongback devices. At higher frequencies load relief

Table 2 Focal stability parameters

	x-Axis Rotation		*z*-Axis rotation	
Parameter	Maximum	Residual	Maximum	Residual
x-Axis beam error, deg	1.5×10^{-2}	3.7×10^{-4}	3.5×10^{-6}	1.1×10^{-7}
y-Axis beam error, deg	1.2×10^{-4}	2.1×10^{-5}	8.5×10^{-6}	3.1×10^{-7}
Defocus, cm	7.1×10^{-5}	6.4×10^{-6}	17.8×10^{-6}	4.6×10^{-6}

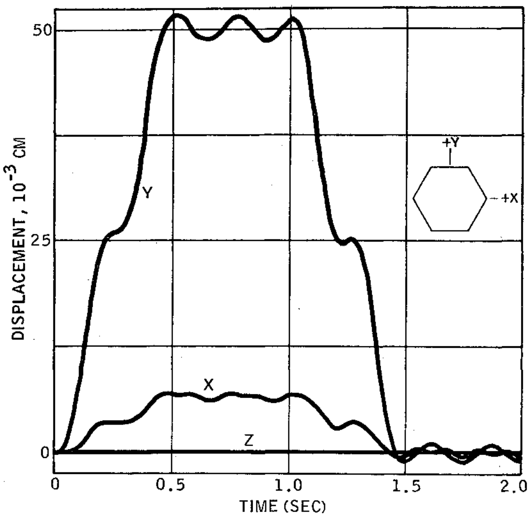


Fig. 11 Displacements of secondary—x-axis rotation.

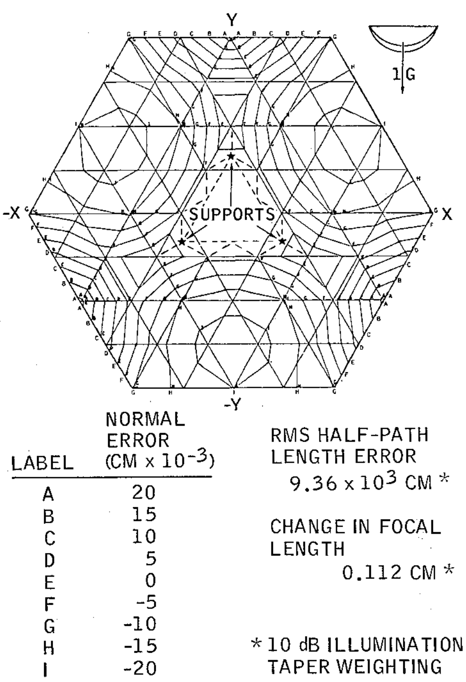


Fig. 12 One-g deflections for three-point support, 15 m reflector.

systems can be ideally attached at the tetrahedron intersections.

In addition, initial manufacturing surface contour errors are minimized and the small surface contour errors due to the 1-g environment are reduced because the stiff geo-truss reflector structure has inherent small 1-g deformations. Predicted 1-g distortions are compensated for during the surface contour adjustment procedure; errors in prediction result in error in the surface figure in the 0-g environment.

Measurement and adjustment of the surface is accomplished in a zero-g simulation test stand. The antenna is supported pointing upward partly by the interface structure which mounts the antenna to the spacecraft, and partly by fine wires attached to the front surface spiders. The wires are attached to negator springs in an overhead framework that carries the local weight of each spider and adjacent tubes.

To determine the accuracy of this approach, i.e., the uncertainty in the surface figure of the reflector in space as a result of g-release prediction error, a finite-element analysis was conducted for the load cases on Earth and in space.

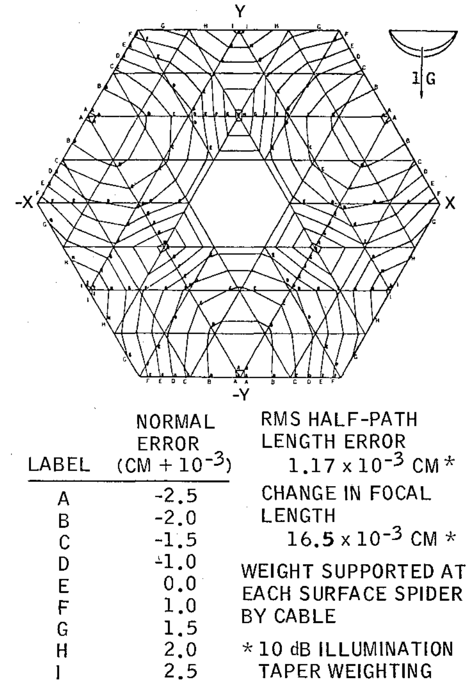


Fig. 13 One-g deflections for three-point support and zero-g simulation support (15 m).

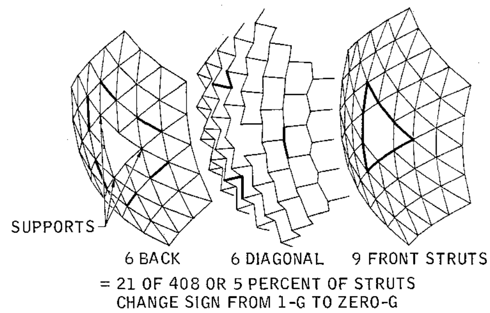


Fig. 14 Normal preload direction reversed in zero-g simulated support (compression to tension).

Figure 12 shows the deformation of the surface of a 15-m diameter reflector as the result of 1-g forces with the reflector mounted on three points and no additional support. Because of the inherent stiffness of the deep truss structure, these deflections are relatively small, the computed values yield an rms normal error of 0.0094 cm and an increase in focal length of 0.113 cm (10 dB taper weighting). The reflector can be adjusted with a bias deformation so that when the 1-g forces are removed, the correct shape results. The residual error depends on the accuracy to which the 1-g sag can be predicted. Prediction accuracy depends on the variation in Et for the struts, where E is the elastic modulus and t is the cured thickness of the graphite[2] strut wall. The Et product can be controlled to $\pm 10\%$ without difficulty. Prediction accuracy also depends on nonelastic deformations resulting from motion in joints at the structural nodes. The bearings used are essentially zero-tolerance devices, however, the cumulative effect of many joints with nonzero tolerance can be significant. The mesh control system and, to a lesser degree, the mesh itself preload the structure so that bearings do not rattle ($\pm 5 \times 10^{-4}$ cm) under normal loads in space.

In the 1-g environment, reflector element weights do overcome the normal preload. With deformation as shown in Fig. 13, 17.7% of the 408 reflector struts have had the preload tension/compression reversed in sign, and could respond nonlinearly in the 1-g environment.

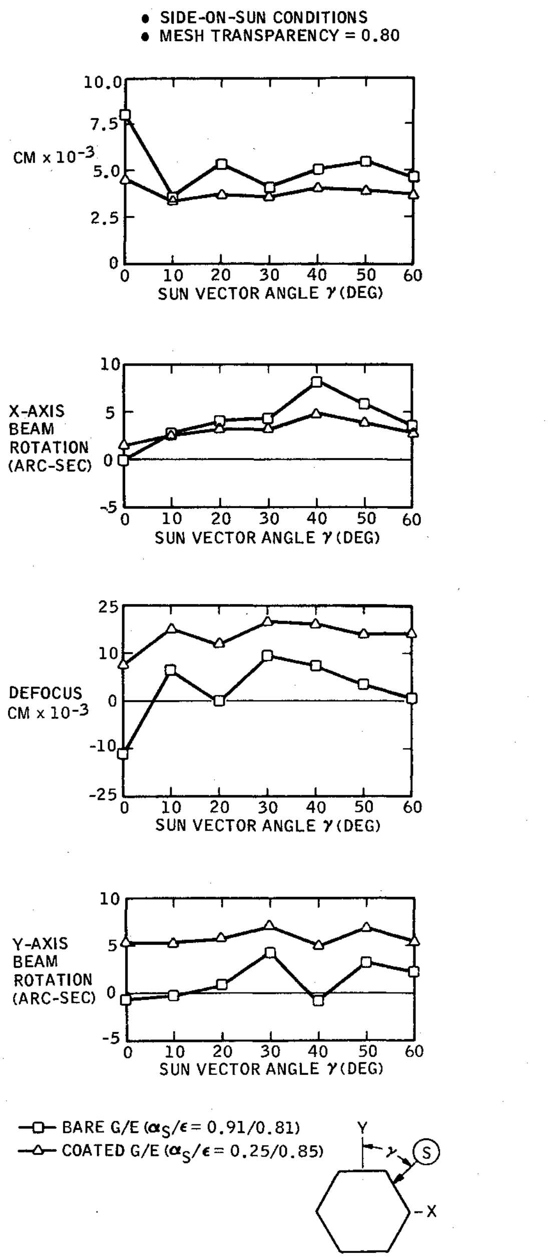
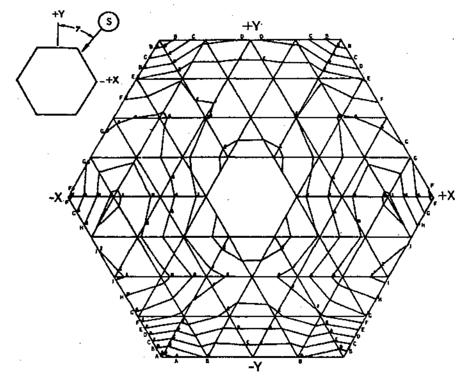


Fig. 15 Effect of surface thermal properties and sun vector orientation on backup structure thermal distortion.

The system has also been simulated with forces applied to each front surface spider as provided by the zero-g suspension system. Figure 14 shows the contours for these conditions. The rms normal error is not 0.00127 cm with focal length decrease of 0.0165 cm. More significantly, only 5% of the struts show load sign reversal (Fig. 14). Simulation of step response equivalent to bearing tolerance (± 0.0005 cm) in a small percentage of struts in the highly redundant truss structure does not lead to a significant change in surface rms.

Thermal Distortion

Large flexible space antennas can experience serious distortions as a result of exposure to thermal environments. High stiffness is desirable to minimize thermal distortions. The high warpage of a thin plate compared to a thick plate over a heat source is a vivid demonstration of the effect of stiffness. The performance of the geo-truss reflector structure has been evaluated through a series of studies for a variety of typical orbiting spacecraft environments.



LABEL	NORMAL ERROR (CM x 10^{-3})
A	-12.5
B	-10.0
C	- 7.5
D	- 5.0
E	- 2.5
F	0.0
G	2.5
H	5.0
I	7.5

- 15-M REFLECTOR (8 BAY)
- SIDE-ON-SUN THERMAL CONDITION, SUN ANGLE = 0 DEG
- MESH TRANSPARENCY = 80%
- COATED GRAPHITE/EPOXY
- SURFACE ERROR = 4.58×10^{-3} CM
- DEFOCUS = 9.65×10^{-3} CM
- BEAM DEFLECTION
  X-ROTATION = 1.3 ARC-SEC
  Y-ROTATION = 5.3 ARC-SEC

Fig. 16 Surface error contour plot—coated graphite/epoxy (backup structure distortions only).

The thermal models simulate each element of the truss structure and include the shadowing of solar energy by the semitransparent reflector mesh surface, all tubular backup structure elements, feed module, and parent vehicle and associated equipment as required. Incident Earth albedo and Earth thermal heating rates on a strut element include only the effects of mesh shadowing. Although shadowing is included, the thermal effects of the mesh, feed, parent vehicle and associated equipment on strut temperatures were neglected.

Distortion results in terms of surface error (rms), defocus, and rf beam deflection for a 15 m diameter configuration as a function of the sun vector γ and orbital altitude are shown in Fig. 15. Variations in all distortion parameters are noted as a function of the orientation of the sun vector. This is attributed to the lower overall structural temperature in the coated configuration. Typical surface error contour plots for the two thermal configurations in the side-on-sun ($\gamma = 0$ deg) orientation is presented in Fig. 16.

Summary

As in ground antennas, in order to point the narrow beams of large antennas it must have reasonable stiffness levels in the 1 to 2 cps range. With very flexible structures the four criteria—pointing accuracy, surface contour, ground testing, and thermal distortion—will significantly impact system performance, reliability, and cost. Even with the distributed control system that may be required in the 300 m to 1 km system range, stiffness is important to develop reasonable areas of influence and to allow proper integration of all elements of the antenna.

Since the integration of a real spacecraft antenna pointing system is a function of a large matrix of variables, it is difficult to project spacecraft cost vs stiffness. But for a given system, a tradeoff analysis should be performed early before the antenna design work has committed the control designer to a difficult task that could have been alleviated earlier by using a stiffer antenna concept.

While the geo-truss concept does not solve all problems, it does have the promise of supplying an isotropic stiffness required for a realistic antenna. It can be readily analyzed with a high degree of confidence with the standard finite element approach. With adequate antenna stiffness, related subsystems (ATC and power) will be simplified, saving weight and cost.

Acknowledgments

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References

[1] Fager, J.A. and Garriott, R., "Large-Aperture Expandable Truss Microwave Antenna," *IEEE Transactions on Antenna & Propagation*, Vol. AP-17, July 1969, pp. 452-458.

[2] Fager, J.A., "Application of Graphite Composites to Future Spacecraft Antennas," *Satellite Communications: Advanced Technologies—Progress in Astronautics and Aeronautics*, Vol. 55, AIAA, New York, 1977.

[3] Pidhanney, D., "Study of Grounds and Space Antennas," Aerospace Corp.