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THE DEVELOPMENT AND TESTING OF THE LENS ANTENNA DEPLOYMENT DEMONSTRATION (LADD) TEST ARTICLE

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ABSTRACT

The USAF Rome Laboratory and NASA Marshall Space Flight Center, through contract to Grumman Corporation, have developed a space-qualifiable test article for the Strategic Defense Initiative Organization to demonstrate the critical structural and mechanical elements of single-axis roll-out membrane deployment for Space Based Radar (SBR) application. The Lens Antenna Deployment Demonstration (LADD) test article, originally designed as a shuttle-attached flight experiment, is a large precision space structure which is representative of operational designs for space-fed lens antennas. Although the flight experiment was cancelled due to funding constraints and major revisions in the Strategic Defense System (SDS) architecture, development of this test article was completed in June 1989. To take full advantage of the existence of this unique structure, a series of ground tests are proposed which include static, dynamic, and thermal measurements in a simulated space environment. An equally important objective of these tests is the verification of the analytical tools used to design and develop large precision space structures.

INTRODUCTION

The development of affordable multi-mission Space-Based Radar (SBR) concepts is strongly dependent upon large space-deployable antenna technologies. For this application two types of antenna concepts are being considered, the corporate-fed array and the space-fed array. Due to satellite prime power limitations and the significant ranges that are involved, large antennas are needed to provide detection and tracking of small targets in the presence of clutter and jamming. These large antennas, however, must satisfy strict mass and stowed-volume constraints imposed by the launch vehicle. The vacuum of space and the zero gravity environment in which these systems will operate enables the deployment of very large, low-mass antennas. The ability of these large low-mass space structures to properly deploy and maintain antenna shape on-orbit is critical to radar performance. Even small deformations in the shape of the antenna can cause path length errors which can result in the loss of antenna gain, increased sidelobe levels, and beam pointing error.

According to J. Ruze [1], distortion by an amount Δ in the surface of a corporate-fed array scanned to an angle θ creates a path length error ϵ defined by the equation

$$\epsilon = \Delta \cos\theta$$

In contrast, a similar distortion in the surface of a space-fed array creates a path length error

$$\epsilon = \Delta \left[\cos\theta - \frac{1}{\sqrt{1 + \left(\frac{r}{2f}\right)^2}} \right]$$

where f is the focal-length-to-diameter ratio (F/D); and r is the radial coordinate from the center of the aperture normalized to unity at the rim. It can be seen in this equation that the second term reduces the path length error. This error compensation significantly decreases the effect of out-of-plane distortions on radar performance for space-fed arrays. The result is that for small scan angles the space-fed array is about one order of magnitude less sensitive to out-of-plane distortion than the corporate-fed array. This result is significant for large antennas, especially considering that performance specifications for typical corporate-fed planar arrays require that flatness be maintained to within 1/10 wavelength (30 mm at L-band, 3 mm at X-band) across the entire array. Figure 1 provides a graphical interpretation of these equations with varying scan angle.

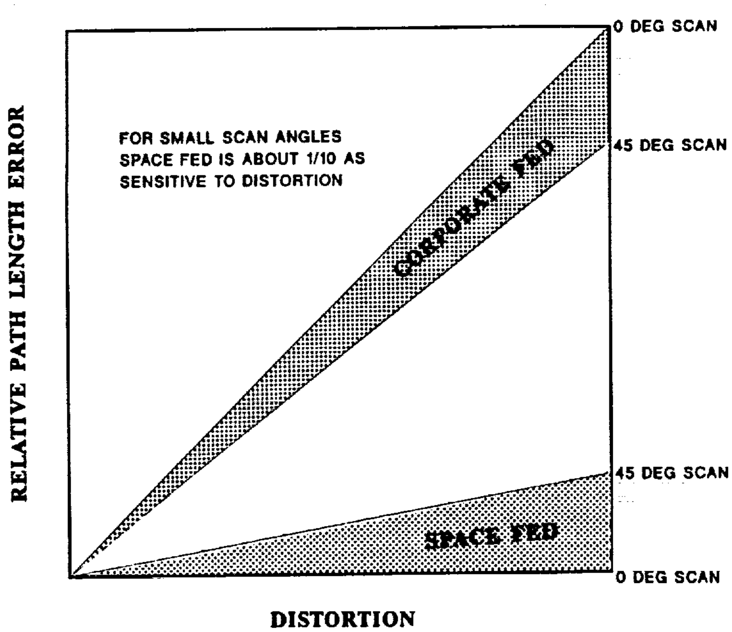

Figure 1. Path length error sensitivity to aperture distortion

The tolerance of the space-fed array to out-of-plane distortion may allow the design of SBR concepts that do not require electrical or mechanical compensation for path length errors to meet performance specifications. Reduced sensitivity to out-of-plane distortion also suggests that less rigid and correspondingly less massive support structures can be utilized. Additionally, the elimination of a constrained feed structure enables concepts to be developed which require fewer connections, allow for simpler deployment schemes, and are more manufacturable.

Figure 2 illustrates a space-fed phased array lens SBR concept deployed on-orbit. The concept depicted employs a single-axis roll-out, or "window shade", deployment scheme developed by Grumman Space Systems Division, Bethpage, NY. Primary components of the system are the RF feed at the end of a continuous-longeron deployable mast and the aperture which is deployed in a plane from the storage drum. Pretension forces in the long direction provide out-of-plane stiffness to the membrane as it is suspended within its space frame. The lightweight membrane supports transceiver modules that are powered by regulated dc through a power distribution system which is an integral part of the membrane structure. Antenna elements are attached to these modules. They receive both beam steering commands and radar signals from the remote feed. The module introduces the necessary phase shifting to steer the beam to the commanded direction and amplifies the radar signal. These in turn are passed to the target side antenna elements for radiation toward the target. The reflected signal is transmitted to the feed in an analogous manner.

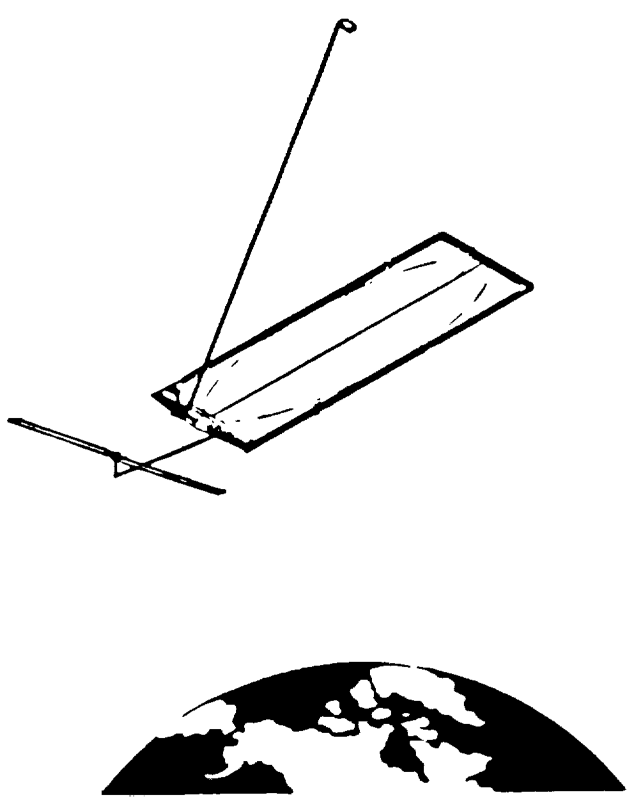

Figure 2. Space-fed phased array lens SBR concept

BACKGROUND

The potential benefits of space-fed arrays for SBR application prompted DOD development and testing of phased array membrane segments to validate concepts and support configuration development. Membrane test articles have been developed and tested in a fixed deployed condition for structural and RF evaluations. Since structures/mechanism validation of membrane deployment and retraction is critical to future system designs, recent efforts have focused on design and analysis of a deployment test article for ground and flight test demonstrations.

In Oct 1985 Rome Laboratory and NASA Marshall Space Flight Center, through contract to Grumman Corporation, initiated the design and fabrication of the LADD test article to perform structural/mechanical tests on-orbit as a shuttle-attached experiment for the Strategic Defense Initiative Organization (SDIO). Planned tests included functional, static flatness, dynamic, and thermodynamic measurements. Following the successful completion of these tests, an active X-band array could be installed in the article for a second flight to demonstrate imaging/discrimination for SDIO mission needs. Although major revisions to the Strategic Defense System (SDS) architecture eliminated space-based radar from the near-term system and therein caused the LADD experiment's shuttle manifest to be canceled, the test article was completed in Jun 89, essentially with a full flight pedigree.

The objective of this effort was to produce a space-fed lens antenna test article that could be used for ground, and shuttle testing in a subsequent phase, in order to demonstrate the structural feasibility and reliability of the single-axis roll-out deployable SBR approach. Now that the construction of the LADD test article is completed, analytical tools for predicting behavior can be verified and an initial indication of structural damping can be determined. Thus, it is now possible to obtain information on various aspects of the mechanical distortion of the membrane. From this measured data the RF performance of the single-axis roll-out deployable SBR can be predicted.

LADD DESCRIPTION

The LADD test article, shown in its stowed configuration in Figure 3 and its deployed configuration in Figure 4, consists of a 2.44 m x 6.10 m (8 ft x 20 ft) X-band phased array membrane, populated with approximately 5000 thermal representations of transceiver modules, that is automatically deployed utilizing a lightweight frame. This configuration is similar to that envisioned for large space-fed phased array SBR concepts which employ the single-axis roll-out aperture deployment technique. The frame is comprised of an end beam, two continuous-longeron canister-deployed side masts, and a storage drum which is supported on trunnions extending from the drum support beam that would also serve as the main spacecraft of a free-flying satellite. In this particular X-band antenna, the transceiver module is a four element subarrayed design: thus an active radar of this size would have about 20,000 radiating patch elements.

The membrane is fabricated as four .61 m (2 ft) wide panels that extend from the storage drum to the end beam. The two central panels are connected during deployment by an automatic seaming device that would be required in a large satellite which is folded to fit within the shroud of a launch vehicle. The outer strips are connected to the adjacent membrane through permanent, but very compliant interpanel splices. These connections provide RF isolation from one side of the membrane to the other.

It should be noted that as a shuttle-attached payload, the LADD test article was designed with considerably high margins of safety than would be required in a free-flying satellite. Therefore, as a structural frame the LADD test article is somewhat stiffer than a typical satellite.

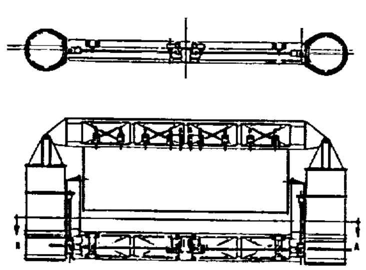

Figure 3. Stowed LADD test article

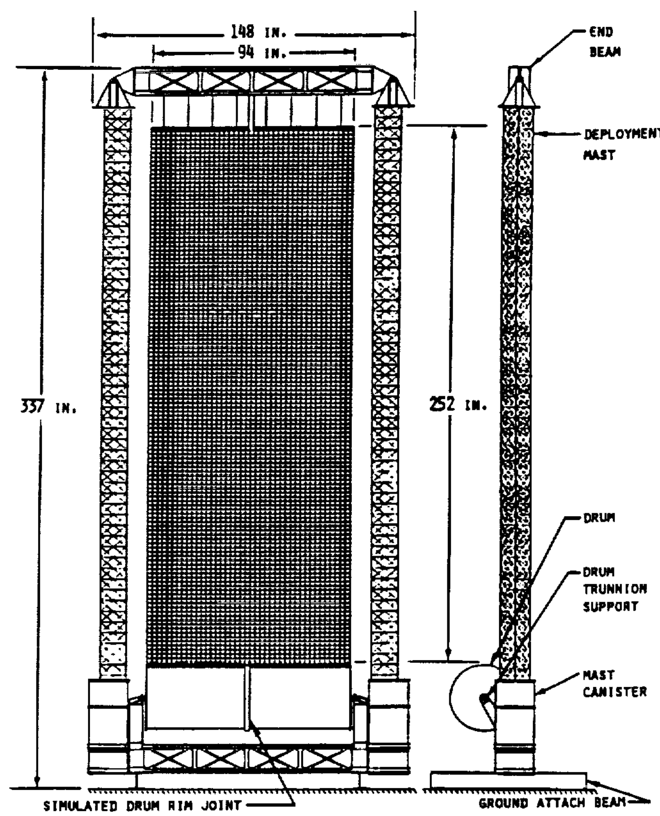

Figure 4. Deployed LADD test article

TEST PROGRAM

The LADD test article belongs to a class commonly referred to as large precision space structures. These structures typically have low spatial density, modes of vibration well under 1 Hz, many closely spaced modes, and interaction between the structure's dynamic behavior and the performance of the operational system. Since the LADD test article was originally designed as a shuttle-attached space experiment and is representative of operational designs for SBR, it provides a unique test opportunity to address issues of concern relating to this class of structure. Specific areas of interest include testing of large flexible space structures in a gravity environment, modeling and analysis of low-mass pretensioned membranes, and system identification. To address these issues, a series of ground tests are proposed which includes static, dynamic, and thermal measurements in a simulated space environment.

Static tests will include multiple deployments of the LADD test article with corresponding membrane flatness and tension measurements taken after each deployment. These tests will establish the repeatability of the membrane static shape. To date, the LADD test article has been cycled through more than 100 deployments and retractions.

Thermal tests will include differential heating and deployment/retraction at temperature extremes. Membrane flatness, membrane tension, and membrane structure temperature measurements will be taken in each test case. The differential heating tests will establish the ability of the LADD test article to maintain required membrane flatness in and out of periods of solar illumination and eclipse while on-orbit. The thermal tests at the expected temperature extremes will establish the performance of the deployment mechanisms as a whole at those operating points.

Dynamic testing will be performed to determine the structural modal properties. Test results will be used to validate the analytical model, which will in turn be used to perform transient response analyses to predict the behavior of the structure in the presence of on-orbit disturbances.

All tests will be performed in a vacuum chamber with radiative heating and cooling capability. A non-contact displacement measurement system will be used to quantify the flatness of the LADD test article membrane during static tests. Photogrammetry techniques are being considered for this purpose. Both photogrammetry and multiplexed laser vibrometer system techniques are being considered for measuring vibration at numerous points on the membrane during modal tests. Conventional accelerometers will be used to measure vibration at points on the structure other than the membrane. The tension in the membrane will be measured using load cells. Thermocouples and calorimeters will be used to measure the temperature and heat flux during thermal tests.

An equally important objective of this test program is the verification of the analytical tools used to design and develop large precision space structures, such as the LADD test article. Testing of the LADD test article provides an opportunity to compare predicted behavior with actual test data to verify those analytical tools. A successful test program coupled with a detailed, comprehensive modeling effort will evaluate the ability of existing analytical methods to predict behavior of new designs.

A modeling effort was carried out by Grumman Space Systems Division under terms of the original LADD contract. This analysis considered the LADD test article attached to the shuttle in a microgravity environment. Although details of that modeling effort are considered proprietary, it can be said that the procedures and tools used are considered standard by the industry. Good correlation was obtained between the finite element formulation and numerical solution of the characteristic equation derived from thin plate vibration theory for the membrane. The first five natural frequencies predicted by the finite element model are listed in Table 1. Figure 5a illustrates the finite element model and the corresponding mode shapes for the first five natural frequencies are illustrated in Figures 5b-f.

Table 1. Predicted natural frequencies of shuttle-attached LADD test article

Mode	Frequency (Hz)
1	0.205
2	0.270
3	0.307
4	0.312
5	0.325

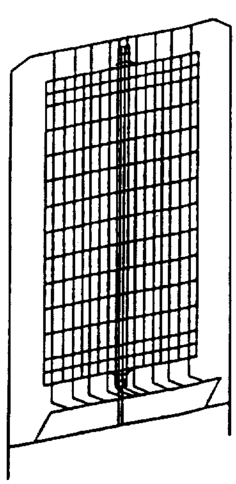

Figure 5a. LADD finite element model (772 elements)

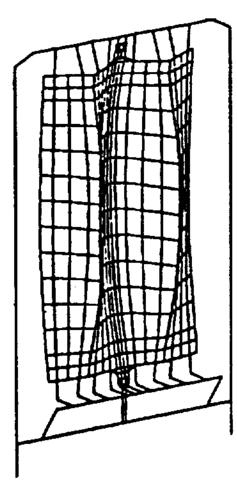

Figure 5b. Mode 1

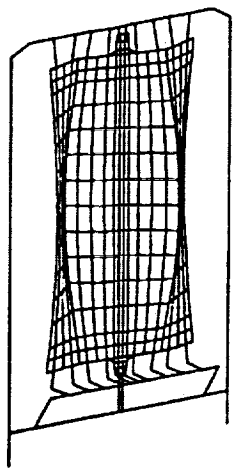

Figure 5c. Mode 2

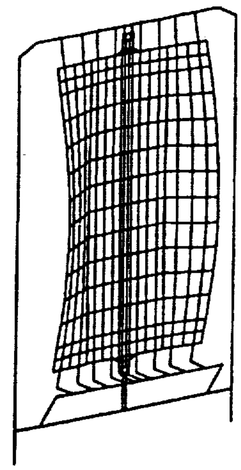

Figure 5d. Mode 3

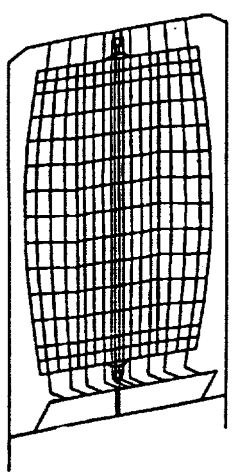

Figure 5e. Mode 4

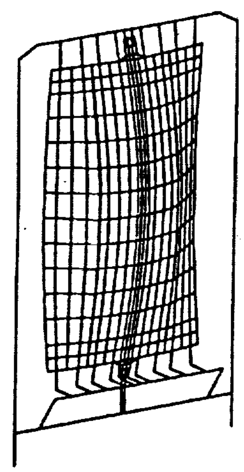

Figure 5f. Mode 5

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2. Grumman Space Systems Division, "Membrane Deployment/Retraction Test Article Design Study", Final Report, Jun 1986, Contract No. NAS 8-36113.

3. Grumman Space Systems Division, "Lens Antenna Deployment Demonstration Critical Design Review", Report No. 31.18, Nov 1987, Contract No. NAS 8-36621.