THE DEVELOPMENT OF INFLATABLE ARRAY ANTENNAS

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Abstract

The deployable array antenna using an inflatable or thin-membrane structure has been identified as one of the enabling technologies to achieve low-mass, high packaging efficiency, low cost, and reliable deployment for future NASA/JPL spaceborne high-gain and large aperture antennas. Array antennas, when compared to parabolic reflectors, although suffering from limited bandwidth performance, offer wide-angle beam scanning capability and a more reliable flat "natural" aperture. To demonstrate the feasibility and capability of this low-mass array technology, three antenna concepts using inflatable and thin-membrane structures were initiated in 1997 at JPL and several breadboard units have been successfully developed. These three concepts are (1) the inflatable phased array, (2) the inflatable reflectarray, and (3) frame-supported thin-membrane array antenna. All three concepts utilize the printed microstrip antenna technology. Although all three concepts will be briefly presented, this paper will discuss in more detail of the recent development of the second concept. The first concept of inflatable phased arrays that have been constructed are 3 to 5-meter size L-band dual-polarized synthetic aperture radar (SAR) arrays for Earth remote sensing application. They all consist of a rectangular configuration with inflatable cylindrical tubes that support and tension a multi-layer thin-membrane radiating aperture with microstrip patches and microstrip power divider lines. For the second concept, an inflatable reflectarray was developed for future deep-space telecom applications. It is a 3m Ka-band inflatable reflectarray (1.8 kg/m^2). This reflectarray uses inflated torus tubes to support and tension a flat-membrane reflectarray surface. The reflectarray surface emulates a curved parabolic reflecting surface. However, because of its flat surface being a "natural surface", it is much easier to achieve and more reliable to maintain the required surface tolerance than that of a curved parabola during long space flight. For the third concept, an L-band dual-polarized SAR array with a 5m x 3m aperture and 2.5 kg/m^2 of mass has recently been demonstrated. It consists of seven foldable panels each having a rectangular frame that supports a two-layer thin-membrane microstrip subarray aperture. Each frame is made of light-weight graphite composite material. The chief advantage of this deployable "frame" concept is that each frame is able to rigidly support an appropriate number of T/R modules and phase shifters to achieve the desired power distribution and beam scanning. Several technology challenges, such as the development of rigidizable inflatable tubes, a controlled deployment mechanism, thin-membrane thermal effects, a low-mass inflation system, membrane mounted T/R modules, means to counter surface tolerance issues, etc. are being investigated and will be discussed in the presentation. With foreseeable success in the development of these challenging areas, the inflatable/thin-membrane array antennas could be mature enough in a few years for actual space flight.

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Introduction

JPL/NASA's Earth remote sensing and deep-space exploration programs have increasing demand for spacecraft high-gain and large aperture antennas. At the same time, however, low mass and small stowage volume are emphasized on these antennas in order to reduce payload weight and size and thus reduce launch cost. To meet these goals, large-aperture antennas must be deployable. One deployable concept using an inflatable parabolic reflector [1] was introduced about two decades ago and was demonstrated in a recent space shuttle experiment [2]. However, the full implementation of this concept is still hampered by the inability to achieve and maintain the required surface accuracy. Even with a rigidizable membrane and an inflatable support structure, it is believed that it will be difficult to maintain the desired surface accuracy of a large parabolic aperture for the duration of a long space flight. To mitigate the difficulty associated with curved surfaces, a new class of planar array technology is being developed [3,4]. It is believed that it will be significantly simpler to maintain the required surface tolerance of a flat "natural" surface, such as a planar

array, than a curved "non-natural" surface, such as a parabolic reflector. In addition, a planar array offers the possibility of wide-angle beam scanning, which cannot be easily achieved by a parabolic reflector.

At JPL, three inflatable planar array antennas have recently been developed [5]. Most of the RF capabilities and a portion of the mechanical capabilities of these antennas have been demonstrated for space application. These three antennas are the 3.3m x 1.0m L-band SAR array for Earth remote sensing application, the 3.0m-diamater Ka-band reflectarray for deep-space telecom application and the 5m x 3m L-band frame-supported thin-membrane array for Earth remote sensing. The RF design and the aperture membrane surface of these antennas were developed at JPL, while the development of the inflatable structures and the antenna integration were mostly accomplished by ILC Dover, Inc., L'Garde Corp. and Composite Optics, Inc. These antennas demonstrated that inflatable/thin-membrane arrays are feasible across the microwave and millimeter-wave spectrums. Further developments of these antennas are deemed necessary, in particular, in the area of qualifying the inflatable structures for space environment usage.

Antenna Description and Performance

All three inflatable antennas are constructed and deployed in a similar fashion. Each antenna is basically constructed from an inflatable tubular frame that supports and tensions a multi-layer thin-membrane RF radiating surface with many printed microstrip patch elements. All three antennas are deployed by a "roll out" mechanism as a carpet is rolled out. The folding mechanism is not used here to avoid forming large creases on the printed patch elements and transmission lines. Any large crease may significantly degrade the RF performance. All three antennas were developed as breadboards for the purpose of initial technology demonstration to assure that the inflated thin membrane can indeed yield proper RF performance. Several technologies remain to be developed in the future to allow these antennas to be used in the space environment. The detailed description and performance of these antennas are separately presented in the following subsections.

L-Band SAR Arrays:

Antenna Description -- The inflatable L-band SAR array, having an aperture size of 3.3m x 1.0m, is a technology demonstration model with 1/3 the size of the future full size (10m x 3m) array. Two such inflatable arrays were recently developed: one by ILC Dover, Inc. and the other by L'Garde Corp. Both antennas' concepts and electrical designs were accomplished at JPL, while the inflatable structures were developed by the two companies. The ILC Dover unit is shown in Fig. 1, and the L'Garde unit is given in Fig. 2. Both units are very similar and each basically is

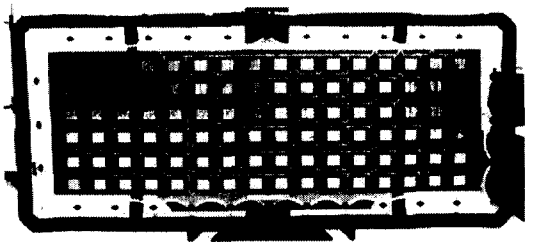

Figure 1. Inflatable L-band SAR array developed by JPL/ILC Dover Inc.

Figure 2. Inflatable L-band SAR array developed by JPL/L'Garde Corp.

a rectangular frame of inflatable tubes that support and tension a three-layer thin-membrane radiating surface with microstrip patches and transmission lines. The inflatable tube of the ILC Dover unit has a diameter of 13 cm and is made of 0.25mm-thick urethane coated Kevlar material. The L'Garde's inflatable tube has a diameter of 9 cm and is made of 0.08mm-thick rigidizable stretched aluminum material. The rigidizable tube is used to avoid the need of constant air pressure and the concern of air leakage due to space debris damage. The three membrane layers are separated 1.27 cm between the top radiator layer and the middle ground-plane layer and 0.635 cm between the middle layer and the bottom transmission-line layer. The connection between these membranes and the inflated tubular frame is made by a series of catenary attachment points and tension cords. The required spacings between the three membranes are maintained by the tension of the catenary cords, the honeycomb spacing panels and bars, and small spacing blocks at each of the catenary points. The membrane material used is a thin film of 5-micron-thick copper cladding on a 0.13-mm-thick Kapton dielectric material.

Antenna test results -- The L'Garde unit achieved a total antenna mass of 11 kg with an average mass

density of 3.3 kg/m^2. The ILC Dover unit has a slightly higher mass. The surface flatness of the L'Garde unit was measured to be ± 0.28 mm and is better than the requirement of ± 0.8 mm. The ILC Dover's surface flatness was measured to be ± 0.7 mm. Both antenna units achieved bandwidths slightly wider than the required 80 MHz, and achieved port isolation between the two orthogonal polarizations of greater than 40 dB within the required bandwidth. The radiation pattern of the ILC Dover unit measured in one principal plane at 1.25 GHz is given in Figs. 3. Sidelobe levels of –14 dB in the azimuth plane and –12 dB in the elevation plane are reasonable for this uniform distributed array. The cross-pol level of less than –20 dB within the main beam region is also considered acceptable for this radar application. Pattern measured at frequencies from 1.21 GHz to 1.29 GHz are very similar to those shown in Figs. 3 without significant degradation.

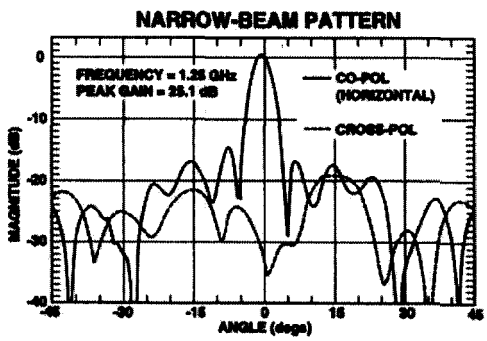

Figure 3. Measured pattern of the inflatable SAR array along the aperture's long dimension.

The measured peak gain of ILC Dover's unit is 25.2 dB at 1.25 GHz, which corresponds to an aperture efficiency of 52%. L'Garde's unit has a peak gain of 26.7 dB and an aperture efficiency of 74%. The better efficiency of L'Garde's unit is the result of better surface tolerance and more precise membrane spacing. Nevertheless, both units are considered quite good as they are the first demonstration models ever developed.

Ka-Band 3-m Reflectarray:

Antenna description -- A photograph of the inflatable Ka-band reflectarray antenna with a 3-m-diameter aperture is shown in Fig. 4. This antenna was co-developed by JPL and ILC Dover, Inc. It consists of a horse-shoe shaped inflatable tube that supports and tensions the 3-m aperture membrane. The tube, 25 cm in diameter, is made of urethane coated Kevlar and is inflated to 3.0 psi pressure, which translates to about 90 psi of tension force to the aperture membrane. The inflatable tube is connected to the aperture membrane at 16 catenary points with spring-loaded tension cords. Each connecting point has displacement adjustment capability in the x, y, z directions so that the circumference of the circular aperture membrane can be made into a single plane orthogonal to the feed horn axis. The single-layer aperture membrane is a 5-mil (0.13 mm) thick Uplex^{TM} dielectric material (a brand of polyimide) with both sides clad with 5-micron thick copper. The copper on one side was etched to form approximately 200,000 microstrip patch elements while the copper on the other side is un-etched and serves as the ground plane for the patch elements. Portion of the microstrip elements are shown in Fig. 5. The elements use variable rotation technique [6] to provide the needed electrical phases. The inflatable tripod tubes, asymmetrically located on the top portion of the horse-shoe structure, are used to support a Ka-band corrugated feed horn. The horse-shoe-shaped main tube structure and the asymmetrically connected tripod tubes are uniquely designed in geometry to avoid membrane damage and flatness deviation when the deflated antenna structure is rolled up.

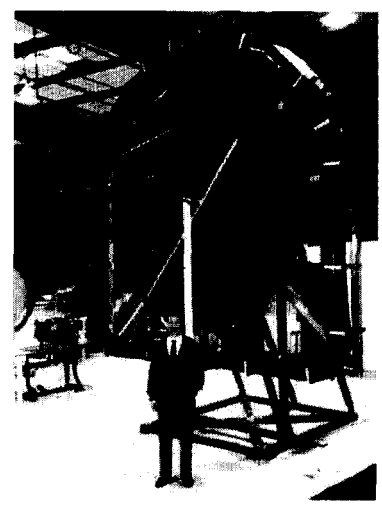

Figure 4. 3m Ka-band inflatable reflectarray

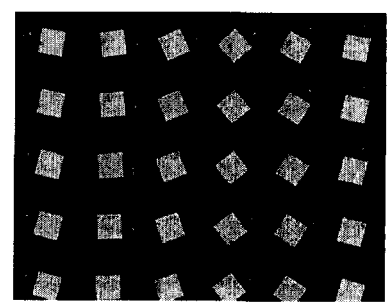

Figure 5. Reflectarray elements with variable angular rotation technique printed on 0.13mm thick Kapton-like substrate

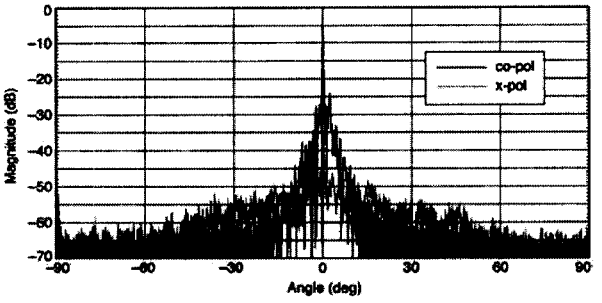

Figure 6. Measured radiation pattern of the 3m Ka-band inflatable reflectarray

Antenna test results – The antenna's RF tests were performed at the in-door compact range of Composite Optics, Inc. (COI), where up-to-10m size antenna can be tested. A typical elevation pattern of the antenna is given in Fig. 6 where a 0.22° beamwidth was measured. The sidelobe level is –30 dB or lower below the main beam peak, and the cross-pol level is –40 dB or lower. All patch elements are circularly polarized and are identical in dimensions. Their angular rotations are different and are designed to provide correct phase delays to achieve a co-phasal aperture distribution. The antenna gain was measured versus frequency. The results show that the antenna is tuned at the desired frequency of 32.0 GHz with a –3 dB bandwidth of 550 MHz. A peak gain of 54.4 dBic was measured. This measured antenna gain indicates an aperture efficiency of 30%, which is away from the expected 40%. This relatively lower efficiency was the result of large element resistive loss due to the poor loss-tangent material of Kapton used, large feed struts blockage, and non-optimal feed illumination. The phase delay line that attached to each patch element has certain amount of impedance mis-match to the patch and, thus, sending some amount of RF power to form undesirable cross-pol energy and resulting in poor radiation efficiency. It is quite certain that future development can improve the efficiency to the expected 40% or higher. The measured surface flatness data of the antenna aperture shows a RMS value of 0.2mm, while the required surface RMS value is 0.5mm. This good surface flatness is also reflected by the well-formed far-field pattern with expected main beamwidth and low sidelobe level. Although the aperture efficiency was not as expected, the achievement of excellent membrane flatness indicates that inflatable array antenna at Ka-band is now feasible.

Improved Ka-Band 3m Reflectarray:

The above Ka-band 3m inflatable reflectarray was build for primarily laboratory demonstration of its RF performance only. Since than, a second model was developed to demonstrate its mechanical integrity. There are two major differences. One is that the second model has its inflatable reflectarray surface deployed without the deployment of a tripod-supported feed. The offset feed is fixed on the spacecraft bus as illustrated in Fig. 7, where the inflatable surface, shown in Fig. 8, can be rolled up and down as a movie screen. The second major difference is that the inflatable tubes are made of rigidizable aluminum tube reinforced internally by using carpenter tapes as shown in Fig. 9. Once the tubes are inflated in space, the aluminum membrane will soon rigidize itself and the inflation gas is no longer needed. In addition, in the event that the tubes are penetrated by small space debris, they will remain rigid to provide proper support for the reflectarray membranes. The carpenter tapes are used as reinforcement to provide additional axial load as well as some orthogonal load to each tube.

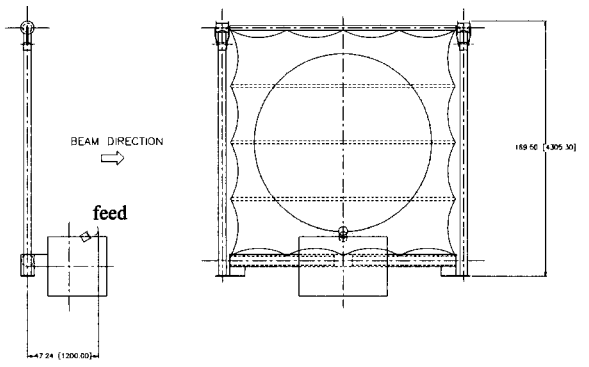

Figure 7. Offset-fed inflatable reflectarray configuration.

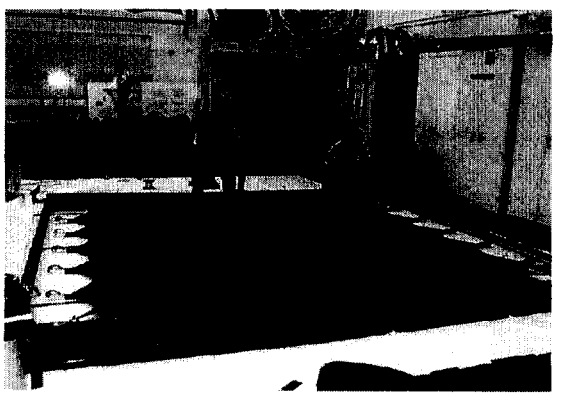

Figure 8. 3m reflectarray surface deployable by two rigidizable inflatable tubes (shown on the right and left of the photo).

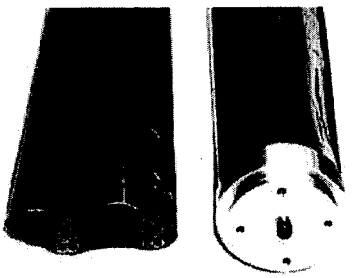

Figure 9. Rigidizable inflatable aluminum tubes reinforced by carpenter tapes.

Frame-Supported Thin-Membrane Array:

The required aperture size for this SAR antenna is 10m x 3m. This complete array antenna would consist of 14 foldable panels that are made deployable by using the carpenter-tape hinges. No inflatable structure is involved here. Prior to deployment, these panels could be folded up to form a relatively small stowed volume of 2.85m x 0.7m x 0.9m. In this development effort, instead of the full-size array, only a half array with 7 panels were fabricated and tested [7]. This half array, shown in a photo in Fig. 10, has a total radiating aperture of 5m x 2.85m. Each panel of this half array, sketched in Fig. 11, is a rectangular rigid frame that supports a two-layer, thin-membrane, L-band subarray aperture. The rigid frame is made of very low-mass graphite composite material with honeycomb core and graphite epoxy face sheets (developed by Composite Optics, Inc.). In each framed aperture, it has an aperture size of 2.85m x 0.71m and 14 rows of microstrip patch radiators with each row consisting of two 1x2 series-fed dual-polarized subarrays. The spacing between any two adjacent rows is 0.8 free-space-wavelength at the center operating frequency of 1.25 GHz. The spacing between adjacent patches in the horizontal direction is 0.74 free-space-wavelength. Each 1x2 subarray, as shown in Fig. 11, can be connected to T/R modules that may be rigidly mounted onto the frame. The chief advantage of this "frame" concept is that each frame is able to rigidly support an appropriate number of T/R modules and phase shifters for achieving the desired beam scan. With this particular design, the complete array is able to scan its beam to ±20° in the vertical direction and a few degrees in the horizontal direction. In this development, however, T/R modules and phase shifters were not used and all the 1x2 subarrays were connected together behind the ground plane via coax cables and discrete power dividers. For the two-layer thin-membrane structure, as shown in the photo in Fig. 12, the top layer has all the radiating patches and microstrip transmission lines, while the bottom layer serves as the ground plane. Both layers are made of 5-micron-thick copper deposited on 0.05mm-thick Kapton membrane. The two layers are separated 1.3cm apart for the purpose of achieving the required 80 MHz RF bandwidth.

To deploy the foldable panels, the novel but simple "carpenter tape" hinges were used. Fig. 13 shows the carpenter tape hinge in its deployed and folded positions. Each hinge is comprised of two tape stacks with their concave side facing inward. Each of the stacks may have one to four layers of tapes. The tape hinge has two distinct performance regimes: When folded, they exhibit non-linear behavior, with the ability to store significant amounts of energy in the tape deformation, which is released upon deployment. When latched after deployment, it acts as a rather stiff composite beam (linear behavior) to support the panels.

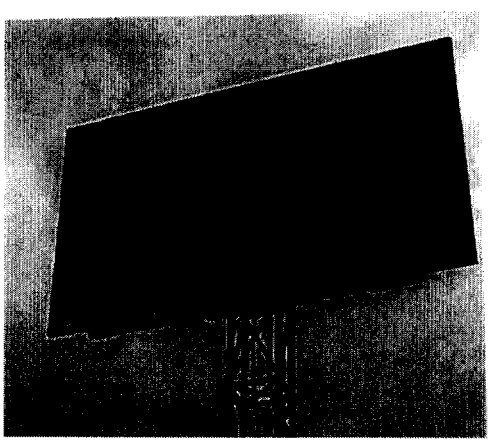

Figure 10. Photo of the half-size array with 7 foldable panels.

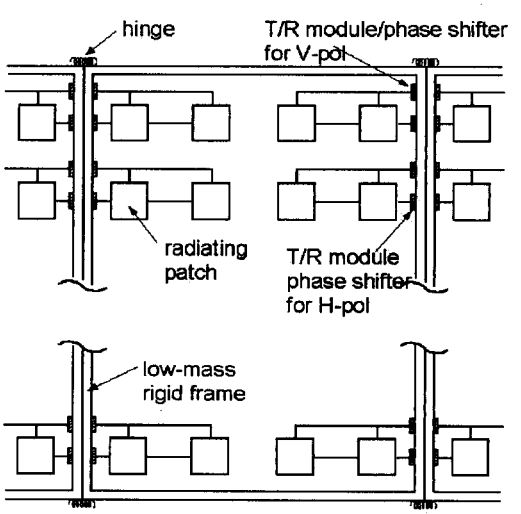

Figure 11. Sketch of each panel's major components.

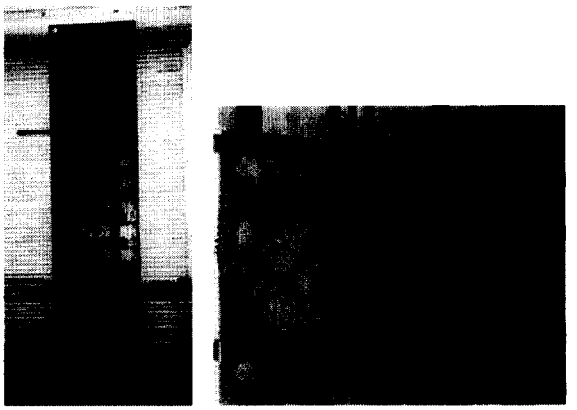

Figure 12. Photo of a single panel and a close-up view of the two-layer membranes.

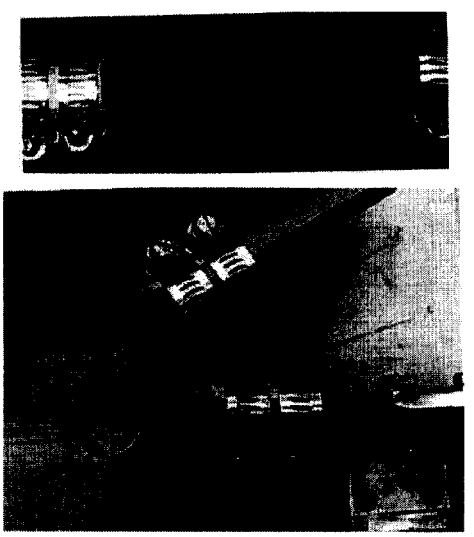

Figure 13. The "carpenter tape" hinge

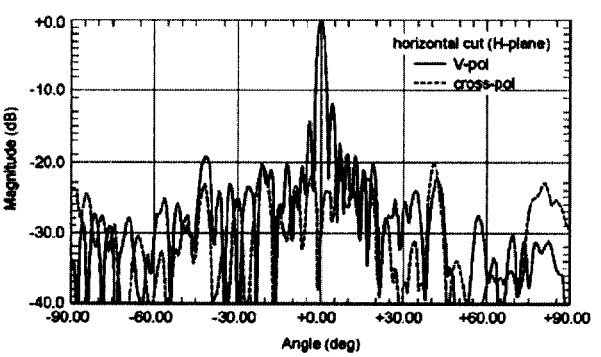

Figure 14. Vertical polarization pattern measured in the horizontal cut of Fig. 10.

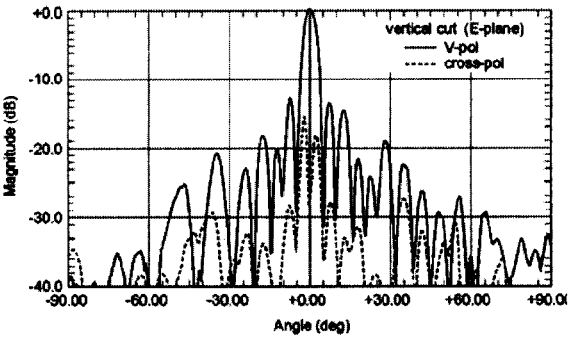

Figure 15. Vertical polarization pattern measured in the vertical cut of Fig. 10.

Performance results: The half-size (5m x 2.85m) breadboard array antenna, shown in Figure 10, was measured for its radiation characteristics at an outdoor far-field range. The typical measured patterns at 1.25 GHz for the vertically polarized array in both the E and H-plane cuts are shown in Figs. 14 and 15, respectively. The peak sidelobe is about –12 dB, which is close to that expected for a uniformly distributed array. The cross-pol lobes are mostly below –20 dB in the H-plane pattern, but are showing –15 dB level in the E-plane. For SAR application, reduction of this –15 dB cross-pol radiation to –20 dB level is needed in future development of this array. The measured -3dB beamwidths in the E-plane and H-plane directions are 4.47° and 2.44°, respectively, which are very close to those expected for a uniformly distributed aperture of 2.85m x 5m. The input return losses measured at the inputs of the 1x2 subarray are below the required –10 dB level over a bandwidth of ±40 MHz centered at 1.25 GHz. The measure array efficiency (not including the losses of the coax cables and discrete power dividers) is 85%, which is considered quite good.

Thermal Analysis of the 3m Inflatable Reflectarray

The most critical structural component of the 3m inflatable reflectarray antenna, as shown in Fig. 8, are the two STR aluminum laminate inflatable/self-rigidizable booms [8]. Due to other mechanical reasons, these two booms cannot be thermally protected with thermal blankets and will undergo thermal distortions in space. This section presents results of a study on structural integrity of these booms under space thermal environments, as well as the effects of thermal distortion of the booms to surface deviation of the RF membrane [9].

The in-space structural integrity of these booms is first investigated. After in-space deployment of the antenna, the two Spring-Tape-Reinforced (STR) booms, shown

in Fig.9, are continuously loaded by axial forces that react to the tension in the RF membrane. The two booms will also bow due to the circumferentially uneven thermal expansions. This leads to significant reductions in the buckling capabilities of the booms. The Earth orbit's thermal load condition was used to calculate the temperature distributions and gradients of a single boom as shown in Fig. 16. The bending of the boom introduced by temperature gradients was determined consequently. Buckling capability of the bended boom was subsequently calculated to be 916 N. The baseline STR boom is capable to take the required load, which is 156 N. Since the Earth application has the most severe thermal environment among all near-term mission applications, it was concluded that the STR booms with current design and configuration is structurally strong enough for both Earth and deep-space applications in terms of buckling capability.

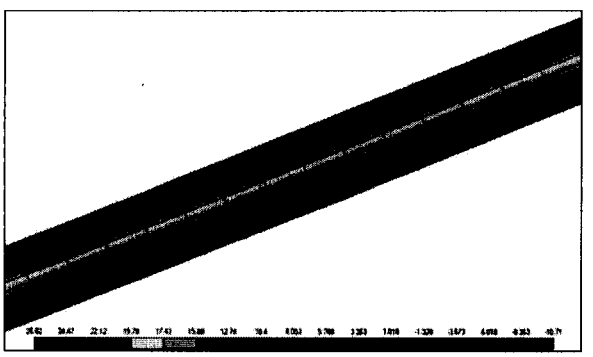

Figure 16. Close-up view of temperature distribution of the 3.5m inflatable boom.

The thermally introduced deviation of the RF membrane is also investigated by this study. The case in which the antenna membrane aperture directly faces the sun is identified as the worst situation because at that moment the inflatable antenna structure has the least moment of inertia to resist the thermal loads. During a typical Earth orbiting mission, the RF membrane deviations of the antenna, as illustrated in Fig. 17, equipped with baseline STR booms was first analyzed. The membrane tilt angle is calculated to be 0.758 degree, which is three times larger than the antenna beam-width (0.22 degree). This large tilt angle will lead to unacceptable degradation of RF performance and must be reduced. There are several ways to remedy this undesirable situation, including: 1) replacing steel spring tapes of the boom with composite spring tapes, since composite material is less sensitive to temperature change, 2) mechanically adapting the feed position to the membrane, and 3) electronically feed adapting by using an array of feeds with phase compensation technique. However, replacing steel spring tapes of the boom with composite spring tapes is the most feasible and simplest way. To validate this, two antennas, one with the baseline STR booms and the other with booms that have their steel spring tapes replaced by composite tapes were analyzed for thermal environments of the Earth, Mars, and Jupiter orbits. It is concluded from the results of these analyses that the current booms with steel tapes are not acceptable for Earth missions, but are acceptable for Mars and Jupiter missions. On the other hand, the boom design with composite spring tapes is acceptable for all Earth, Mars, and Jupiter missions.

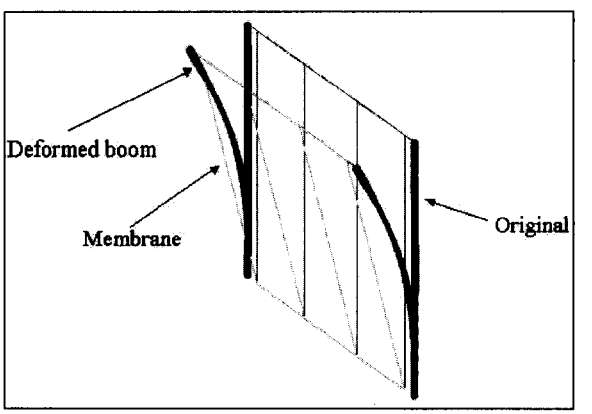

Figure 10. Bending of the membrane aperture due to thermally deformed booms

Future Challenges

The basic structure of an inflatable/thin-membrane array is a multilayer planar aperture surface that is supported and tensioned, through a catenary system, by several inflated tubular elements or a rigid frame. In order to successfully develop an inflatable array antenna at any frequency throughout the microwave and millimeter-wave spectrums and with any aperture size from a few meters to tens of meters, several technical challenges must be addressed and resolved. These challenges are listed below.

- Membrane flatness and separation
- Tube rigidization technique
- Controlled deployment
- Space qualified RF usable membrane materials
- Packaging efficiency
- Membrane mountable T/R modules
- Mathematical modeling and simulation of static and dynamic space environmental effects

Conclusions

Several inflatable/thin-membrane array antennas have been developed at the microwave frequencies of L-band

and X-band, as well as at the millimeter-wave frequency of Ka-band. These antennas were developed to demonstrate that the inflatable array technology is feasible in reducing the mass and stowage volume of future spacecraft's high-gain and large-aperture antennas. To realize the inflatable array technology for space application, several challenges in the mechanical area remain to be resolved. The development of inflatable structure rigidization methods, controlled deployment techniques, space survivable membrane materials, and accurate mathematical structure analysis tools are necessary if successful space application is to be achieved.

Acknowledgements

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