The Development of Inflatable Array Antennas

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Abstract

Three inflatable array antennas recently developed for spacecraft applications are a 3.3m x 1.0m L-band synthetic aperture radar (SAR) array, a 1.0m-diameter X-band telecom reflectarray, and a 3m-diameter Ka-band telecom reflectarray. All three antennas are similar in construction and each consists of an inflatable tubular frame that supports and tensions a multi-layer thin-membrane RF radiating surface with printed microstrip patches. These antennas demonstrated that inflatable arrays are feasible across the microwave and millimeter-wave spectrums. Further development of these antennas are deemed necessary, in particular, in the area of qualifying the inflatable structures for space environment usage.

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. 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 in space 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. 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 [5] for Earth remote sensing application, the 1.0m-diamater X-band reflectarray [6] and the 3m-diameter Ka-band reflectarray [7] for deep-space telecom application. 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 accomplished by ILC Dover, Inc. and L'Garde Corp.

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. 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 Array

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. The ILC Dover unit is shown in Fig. 1, and

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the L'Garde unit is given in Fig. 2. Both units are very similar and each basically is a rectangular frame of inflatable tubes that support and tension a three-layer thin-membrane radiating surface with microstrip patches and transmission lines. A portion of the RF design of the three layers is shown in Fig. 3. 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.

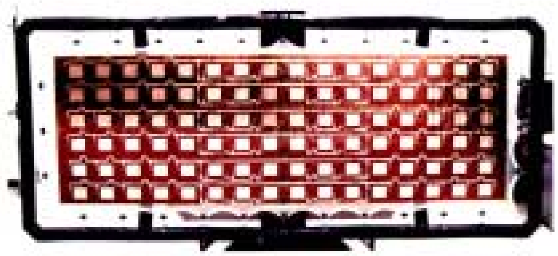

Figure 1. Inflatable L-band SAR array developed by JPL/ILC Dover Inc.

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

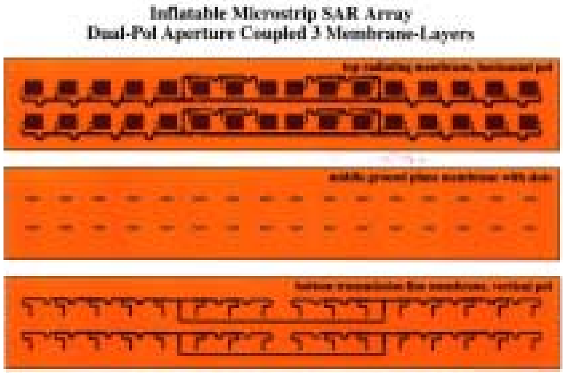

Figure 3. RF designs of the three membrane layers

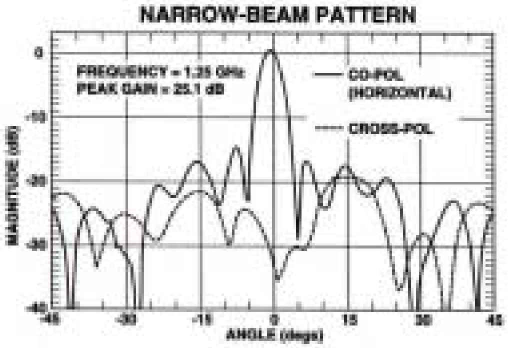

Figure 4. Measured pattern of the inflatable SAR array along the aperture's long dimension.

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. 4. Sidelobe levels of –14 dB is expected for that of a uniformly 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. 4 without significant degradation. 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 built.

X-Band 1-m Reflectarray

Antenna description -- The inflatable X-band reflectarray antenna [6], shown in Fig. 5, has an inflated torus tube that supports and tensions the one-meter-diameter two-layer-membrane reflectarray surface. The antenna's overall RF system and the aperture membrane surface were designed at JPL, while the inflatable structure and antenna integration were developed by ILC Dover, Inc. The inflated tripod tubes are attached to the torus as struts to support a feed horn. The inflatable tubes are made of 0.25mm-thick urethane coated Kevlar material and the reflectarray membrane material is made of 5-micron-thick copper cladding on 0.05mm-thick Kapton. There are a total of two membrane layers separated by 1.3 mm. The top copper layer was etched to produce approximately 1,000 isolated microstrip patches, while the un-etched bottom layer serves as the ground plane. Many small foam discs (7 mm diameter) are placed between the two membranes as means of maintaining the required uniform membrane spacing.

Antenna test results -- This inflatable antenna structure achieved a mass of 1.2 kg, which excludes the mass of the inflation system and the feed horn. With future development, it is believed that the mass of the inflation system for this particular antenna size can be on the order of 0.5 kg. A measured antenna elevation pattern at 8.3 GHz is given in Fig. 6 where the peak sidelobe level (-19 dB) and peak cross-pol level (-19 dB) are both acceptable to the communication system. However, the peak sidelobe of –19 dB is higher than the expected –25 dB. This is primarily due to the blockage effects of the feed and feed support struts. The main beam of the antenna has a –3 dB beamwidth of 2.4° which is expected from a circular aperture of 1m diameter. The antenna also achieved the expected –1 dB gain-bandwidth of 250 MHz (about 3%). The measured peak gain at 8.3 GHz is 33.7 dBi which implies an antenna efficiency of 37%. The expected efficiency from an X-band 1m aperture should be about 50%. The relatively poor efficiency achieved by this inflatable reflectarray is primarily due to design and manufacturing inexperience in building this first demonstration model. Imperfect separation between membranes, feed and strut blockage, surface roughness, leakage radiation from phase delay lines are all contributors to the inefficiency. All these errors are believed to be correctable for future models.

Figure 5. 1m X-band inflatable reflectarray

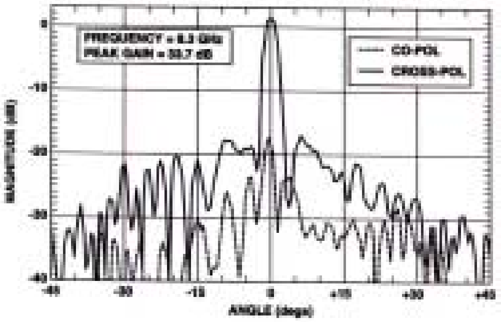

Figure 6. Measured radiation pattern of the inflatable X-band 1m reflectarray

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. 7. This antenna, similar to the above X-band reflectarray, 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. 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.

Antenna test results – The antenna's RF tests were performed at the in-door compact range of Composite Optics, Inc. (COI). A typical elevation pattern of the antenna is given in Fig. 8 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 [8] 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 700 MHz. A peak gain of 54 dBic was measured, which indicates an aperture efficiency of 30%. This efficiency, although is not the expected 40%, is considered quite acceptable for this first unit of large Ka-band inflatable antenna. In addition, the achievement of excellent membrane flatness indicates that inflatable array antenna at Ka-band is now feasible.

Figure 7. 3m Ka-band inflatable reflectarray

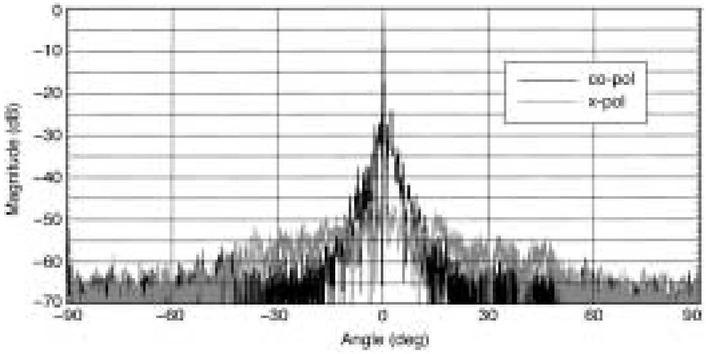

Figure 8. Measured radiation pattern of the 3m Ka-band inflatable reflectarray

Conclusion and Future Challenges

Three inflatable 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. In order to successfully develop an inflatable array antenna for space application at any frequency throughout the microwave and millimeter-wave spectrums and with any aperture size from several meters to tens of meters, several technical challenges must be addressed and resolved. These challenges, to be discussed in the conference, are listed as follows: membrane flatness and separation, inflatable tube rigidization techniques, controlled deployment, packaging efficiency, membrane mountable T/R modules, and mathematical simulation of static, dynamic and thermal space environmental effects.

Acknowledgment

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