Experimental and Analytical Studies of a Large In-Space Deployable Dual-Band Membrane Reflectarray Antenna

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An 8-m-diameter 8.4-GHz/32-GHz (X-/Ka-band) reflectarray antenna, as well as the associated technologies, is being developed for deep-space communication applications. Membrane implementation and the in-space deployable antenna frame are two challenging mechanical aspects of this antenna. A 1.5-m by 1.5-m breadboard and a 3-m-diameter X-/Ka-band radio frequency functional reflectarray antenna have been fabricated to develop technologies associated with the membrane implementation. To investigate the technologies associated with the deployable antenna frame, a 2.2-m sub-scale breadboard and a 3-m by 10-m breadboard were fabricated, and the deployment process was successfully demonstrated by these two breadboards at different scale levels. The design of an 8-m-diameter reflectarray antenna with current state-of-the-art, extremely thin membrane materials has also been accomplished, and results are encouraging.

I. Introduction

Since the late 1990s, the Jet Propulsion Laboratory has been developing deployable reflectarray antenna technologies for in-space communications and science applications [1–7].[4] The key aspect of a reflectarray antenna is that the system of printed metallic shapes not only behaves as a frequency-selective surface (FSS) but also modifies the phase of the local radio frequency (RF) energy by appropriately rotating the circularly polarized reflectarray elements [8,9]. Thus, the reflectarray can compensate for path-length differences from the feed. In this way, a flat surface instead of a parabolically shaped surface can be utilized as a reflective medium. Furthermore, since the reflectarray uses FSS, the antenna can, in principle, be operated at multiple widely spaced frequencies by placing the same number of reflectarray layers adjacent to each other. For this to work, the uppermost layers of FSS must act as bandpass filters for succeeding layers.

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[4] *Design, Fabrication, and Integration of a 1 Meter X-Band (8.4 GHz) Inflatable Microstrip Reflectarray Low Mass Technology Demonstrator*, Final Report of ILC Dover Inc. (internal document), Frederica, Delaware, August 1997.

The research described in this publication was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

NASA missions often use both 8.4 GHz (X-band) and 32 GHz (Ka-band) as communication links, so this combination of two frequencies was chosen as the target of our specific development activities. A three-layer membrane approach has the layer nearest the feed reflect X-band RF with etched copper reflectarray ring elements; the second layer reflects Ka-band RF; and the third layer is the ground plane. Figure 1 illustrates two thin-membrane layers with X- and Ka-band annular ring elements. The middle-layer Ka-band ring elements will re-radiate the incident field from the feed without significant blockage from the top-layer X-band reflectarray ring elements. The ultimate target of the current program is to develop an X-/Ka-band dual-frequency antenna with an aperture diameter of approximately 8 m. There are two challenging mechanical aspects of the 8-m dual-frequency reflectarray antenna: the first one is the implementation of precisely aligned and adequately flat multiple-layer membranes, and the second one is the in-space deployable antenna frame technology. Two tasks have been performed to develop the associated technologies.

The first task is to implement membranes. Technologies for implementing membranes include catenaries for proper membrane tensioning, flatness testing, a spacing system for precisely separating the layers, and a multi-layer membrane fabrication process. To develop these technologies, a 3-m-diameter X-/Ka-band dual-frequency reflectarray antenna has been designed and fabricated. This antenna is the stepping-stone for the 8-m-aperture antenna. The 3-m reflectarray is an RF functional test article.

The second task is to develop a deployable frame for the 8-m reflectarray antenna. The packaging scheme for this antenna involves rolling up the membranes in one direction after z-folding them in the other direction. The goal is to stow the entire antenna within the launch fairing of a Delta II launch vehicle. To investigate the technologies associated with this goal, a 2.2-m sub-scale breadboard was fabricated, and the deployment process was demonstrated. Following the successful development of the 2.2-m sub-scale breadboard, a 3-m by 10-m breadboard was also designed and fabricated. This larger test article is deployed using a gravity-compensation fixture so that the deployment process can be investigated and verified on the ground. The last study discussed by this article is the design of an 8-m-diameter reflectarray antenna that uses current state-of-the-art, extremely thin membrane materials.

II. Membrane Implementation

A. Membrane Tensioning, Flatness, and Spacing

The RF components of this antenna are flat membranes with hundreds of thousand of copper patches. In order to maintain the membrane's flatness, a catenary system is employed by the reflectarray design. This catenary system implements a physical connection between the membrane and the supporting structure.

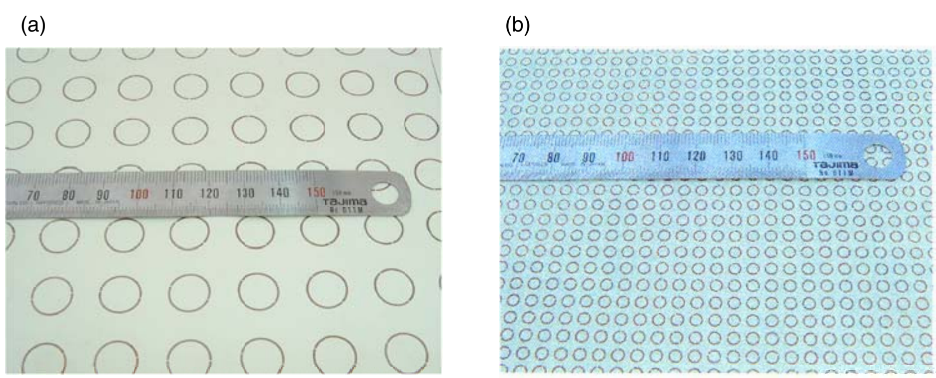


Fig. 1. The two thin-membrane layers with (a) X-band and (b) Ka-band annular ring elements.

The inflatable reflectarray antenna consists of three layers of membrane: ground layer, Ka-band layer, and X-band layer. The separation between the ground layer and the Ka-band is 1.6 ± 0.16 mm, and the separation between the Ka-band and the X-band layer is 3.2 ± 0.32 mm. The membrane flatness requirement is 0.17 mm root-mean-square (rms). Both flatness and spacing between layers are vital for the RF performance of the 8-m inflatable reflectarray antenna. In order to meet these requirements, a 1.5-m by 1.5-m breadboard (as shown in Fig. 2) has been assembled. This breadboard has been used to develop a connecting system that connects the membrane to the deployable frame, maintains constant stress distribution on the membrane while the whole antenna experiences a harsh space temperature environment, and ensures the membrane surface flatness. This breadboard has also been used to develop a reliable and feasible spacing system that guarantees a uniform spacing between the membrane layers across the entire antenna membrane area.

A test was performed on the 1.5-m by 1.5-m breadboard. The test was carried out using a V-Stars photogrammetry system with a Pro-Spot projector and a multiple theodolite system, as shown in Fig. 2. The rms of this breadboard was experimentally determined to be 0.127 mm, to a best-fit plane. This result is very encouraging and significant. It indicates that, after going through several years of technology developments with many tries and tests as well as analyses, we are able to fabricate a membrane system that includes membrane strip seaming technology, catenary analysis, and implementation technology, as well as constant force spring tensioning technology.

The spacing throughout the membranes for an 8-m-diameter antenna cannot be guaranteed by providing the adequate precision spacing only along the perimeter of the membranes. One of the reasons is that static has been observed among the membranes, which pulls them together. To ensure that the spacing is maintained across the membranes, various types of spacer techniques have been tested, and the most suitable spacing system has been developed [7]. Membrane spacings of the 1.5-m by 1.5-m breadboard were measured and are presented in Table 1. The measurements are all well within the ± 10 percent tolerance.

B. Multi-Layer Membrane Manufacturing Process

Another challenge is the multi-layer membrane spacer implementation process. A feasible manufacturing process that allows us to place spacers between membrane layers has been successfully developed and tested on the 1.5-m and 3-m breadboards. The assembling system consists of three incrementally sized frames. Each frame fits into another, with the frame for the ground layer being the largest. Before any spacers are adhered to the membranes, each layer is tensioned onto its individual frame, making sure

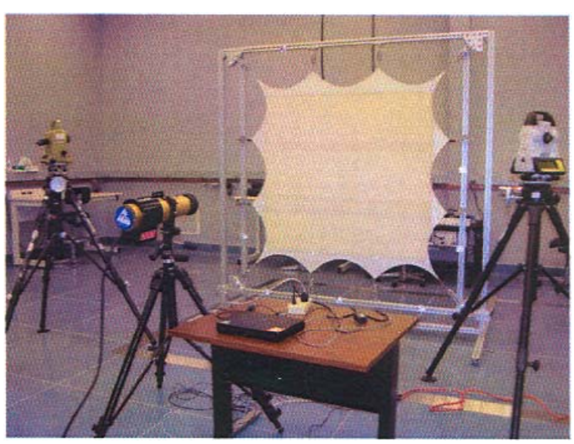


Fig. 2. Membrane flatness test setup for the 1.5-m by 1.5-m breadboard.

Table 1. 1.5-m by 1.5-m breadboard membrane-spacing measurement results.

Hole no.	X- to Ka-band, mm	Ka-band to ground, mm
1	3.2040	1.6194
2	3.2652	1.5858
3	3.2388	1.6107
4	3.2226	1.5513
5	3.2169	1.5579
6	3.2388	1.5315
7	3.2643	1.6461
8	3.3120	1.6056
9	3.3060	1.5603
10	3.2685	1.5555

that the catenary perimeter between layers is aligned. After the three membranes are aligned, the frames are separated to facilitate the adhering of the spacers. The frames are then carefully put back together, and the membranes are connected by double-sided spacers. Figure 3 shows the 3-m membranes being assembled.

C. 3-m X-/Ka-Band Reflectarray

To experimentally study the RF performance of the reflectarray, a 3-m RF functional reflectarray breadboard has been developed. The etched copper rings used for both frequencies form a circle with a diameter of 3 m. The spacing and manufacturing process previously mentioned were implemented and verified on this model. The 3-m antenna needs only to be rolled to fit into a launch vehicle. Since it doesn't need to be folded, cross-bars were used instead of double catenary. The frame was made of aluminum for its machinability and low cost.

Constant force springs are used to tension the membranes. These springs keep the membranes tensioned properly even if the membranes have some expansion or contraction while experiencing a very harsh in-space thermal environment. Brackets, shown in Fig. 4, were designed to hold the constant force springs, and these brackets are attached to the panels. Each bracket holds three constant force springs, one for each layer of membrane. There is a precision plate at the end of the bracket that keeps the catenary cables separated by a distance equal to the membrane spacing. The brackets also incorporate a release pin that is used to hold the constant force springs until the antenna frame is fully deployed.

The main part of the antenna frame is called the flat panel. The flat panel is 0.2 m wide, 3.18 mm thick, and 4.2 m long. The brackets that hold the constant force springs are attached to this panel. Around the flat panel is a cylindrical shell so that the membranes can be rolled up for packaging. This cylindrical shell is composed of two half-shells that both attach to the flat panel to form a complete cylinder. The complete cylinder has a diameter of 0.2 m. The shells have multiple cutouts so the brackets and constant force springs can be accessible in case minor adjustments are needed. Figure 5 shows the antenna frame.

Carbon fiber composite cross-bars are attached behind the ground layer to tension the membrane laterally. The brackets used for tensioning the membranes are bonded to these cross-bars at their free ends. Inflatable booms are used to connect the two flat panels together. An external frame made from

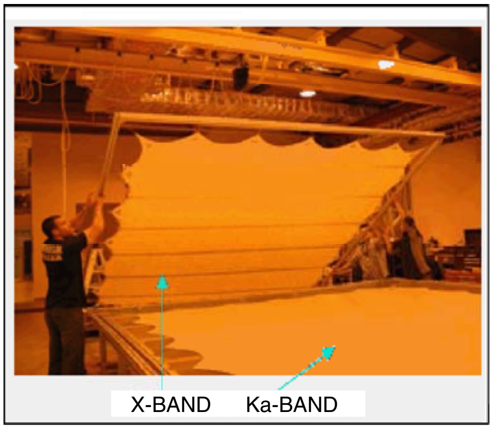


Fig. 3. Assemble multi-layers of membranes.

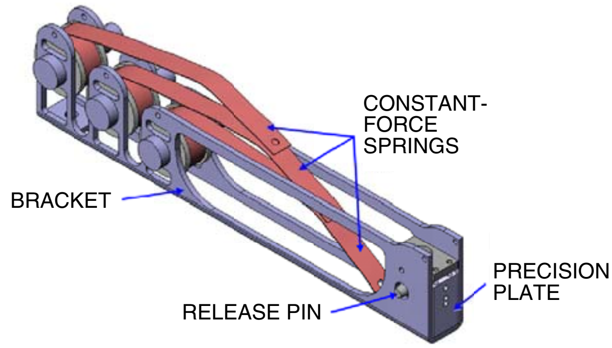


Fig. 4. Constant-force spring bracket assembly.

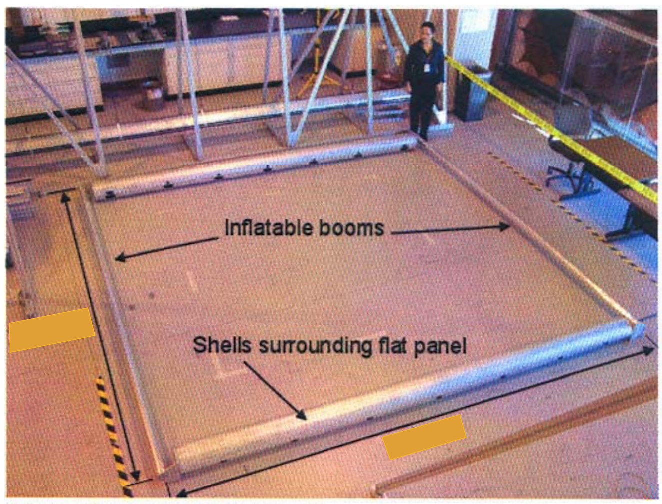


Fig. 5. The inflation deployable frame for the 3-m X-/Ka-band reflectarrray antenna.

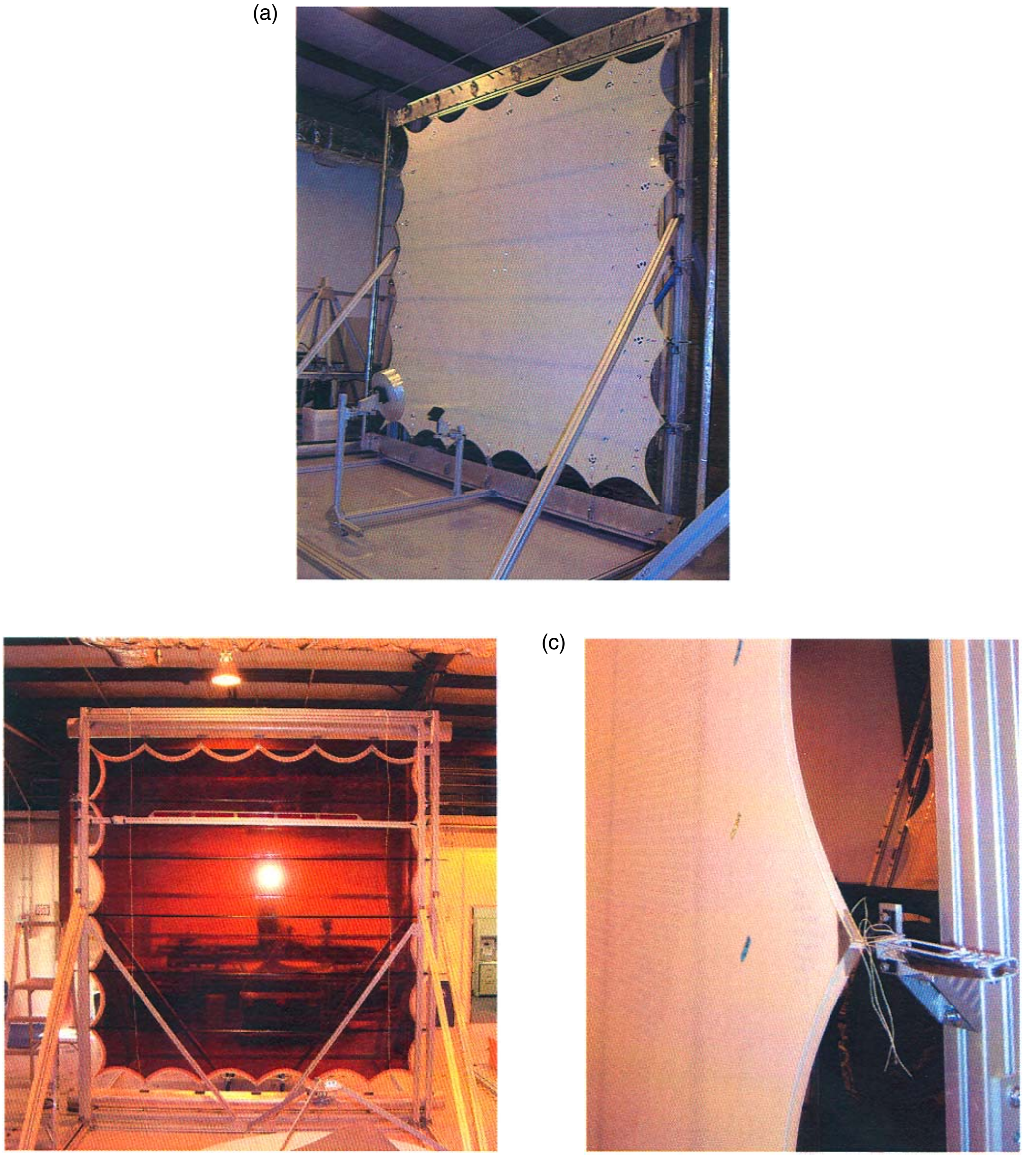
Bosch extrusions was built to support the reflectarray for RF testing. Figure 6 gives the isometric view, back view, and close-up view of the 3-m dual-frequency reflectarray antenna. It can be seen from these pictures that a nearly perfectly flat surface has been achieved. This antenna has been assembled and is waiting for RF testing.

III. Deployable Antenna Frame

A. Architecture of the Frame

Another challenging major task is to develop an in-space deployable frame to support the 8-m-diameter FSS membranes. Figure 7 is a schematic view of the 8-m reflectarray design. To accommodate the folding of the frame, this design employs double catenary. The double catenary system of this antenna consists of an outer catenary that tensions the inner catenary, which is connected directly to the membrane. After the inner catenary is designed [10], θ_i (as indicated in Fig. 8) and the corresponding outer cable forces, T_i, are determined by Eqs. (1) and (2):

(a)



(b)

(c)

Fig. 6. The 3-m-diameter X-/Ka-band RF functional reflectarray antenna: (a) isometric view, (b) back view, and (c) close-up view.

$$\theta_i = \text{atan}\left[\frac{\left(F + T_{i-1} \cdot \sin(\theta_{i-1})\right)}{T_{i-1} \cdot \cos(\theta_{i-1})}\right] \tag{1}$$

$$T_i = \frac{T_{i-1} \cdot \cos(\theta_{i-1})}{\cos(\theta_i)} \tag{2}$$

where F is the force applied by the inner catenary at that location. One of the driving factors in determining θ_i and T_i is how much force an inflatable boom can withstand. Another driving factor in determining θ_i and T_i is the space available in a launch vehicle.

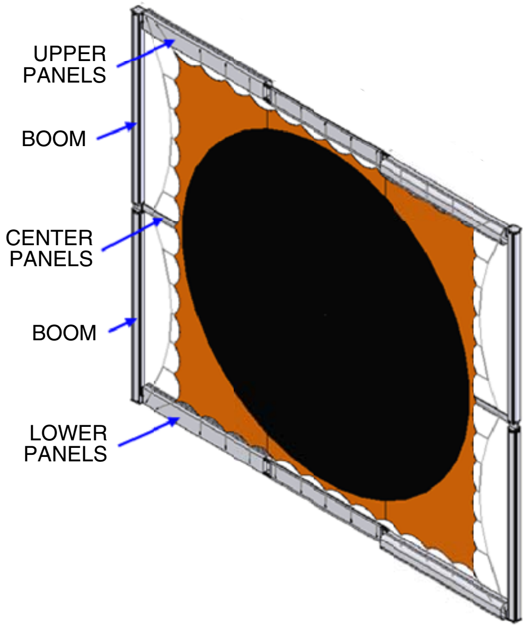


Fig. 7. Schematic view of the 8-m reflectarray design.

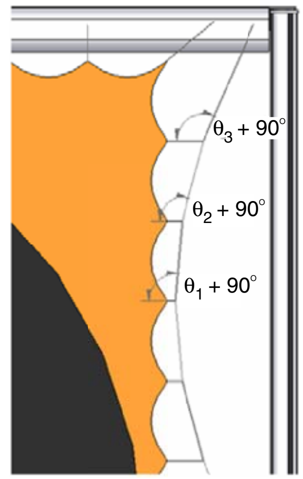


Fig. 8. Angles of the outer catenary.

The design of the frame uses a membrane thickness of 50 μm, which is readily available. The size, stiffness, and ultimately the mass of the frame are dependent on the catenary forces, which are a function of the thickness of the membranes. Using a 50-μm membrane requires the use of 0.24-m-diameter booms. These booms are able to support 1780 N of compression. The frame design is driven by the size of the booms and catenary loads.

The catenary analysis for this thickness of membrane shows that the catenary height and loads will be very large over a full 10-m span. To solve this problem, a center panel was designed that cut each boom size and catenary height in half. This means that there are four total outer catenaries along with four booms as shown in Fig. 7.

Figure 9 shows the packaged antenna system, which can fit into a box that is 4.4 m by 2.08 m by 1.63 m. A Delta II launch vehicle can accommodate this packaged antenna as well as the associated spacecraft, feed, and sub-reflector.

The deployment of the antenna starts with each boom unrolling outward from the center panel. Once the booms are fully deployed, the center panels along with the upper and lower panels unfold in a z-like manner. Six hinges are used for the unfolding. Alignment pins that utilize magnets are used to ensure the alignment and to have sufficient bending stiffness. Once the hinges are locked into place, the next step is to tension the membrane by releasing the pins that hold the constant force springs. The last step is the deployment of the feed and sub-reflector system. Figure 10 illustrates the deployment process.

B. 2.2-m Sub-Scale Breadboard

As a stepping-stone of the 8-m deployable antenna frame development, a 2.2-m sub-scale breadboard has been fabricated and deployment tested. To have a smooth deployment, a structure as seen in Fig. 11 was designed and assembled to support the breadboard and eliminate gravitational effects during the deployment. It is crucial to the success of the deployment that the breadboard be leveled and aligned properly. The bending loads on the breadboard hinges must be minimized during the deployment process to have a successful deployment.

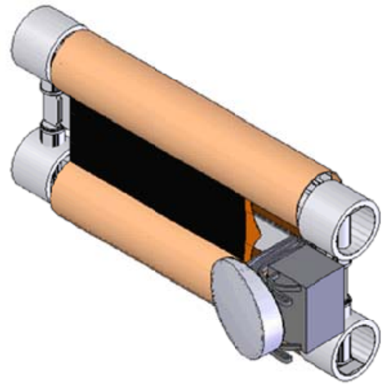


Fig. 9. Packaging scheme.

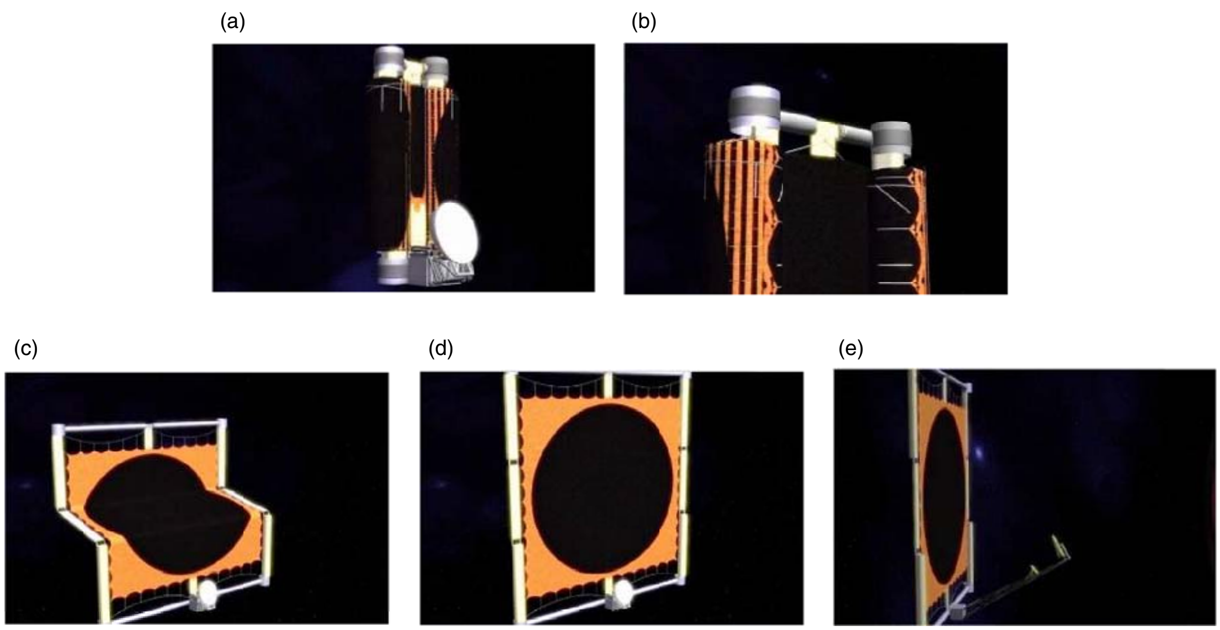


Fig. 10. The deployment process: (a) the packaged system, (b) unrolling, (c) unfolding, (d) membrane tensioning, and (e) the fully deployed antenna.

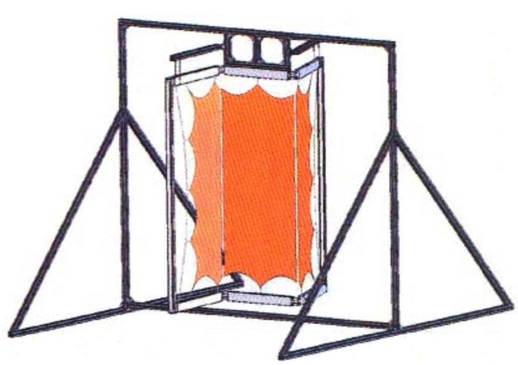


Fig. 11. Schematic of the 2.2-m breadboard deployment test setup.

The deployment process is composed of two steps. The first step is the unrolling of the inflatable/self-rigidizable boom. The second step is the unfolding of the hinges. To unroll the antenna, a pulley system is used to counter the weight of the antenna. This ensures that the inflation of the booms controls the unrolling process of the deployment. In order for the gravity-compensation structure to support the unfolding of the antenna, low-friction ball-bearing hinges are used on two free-swinging arms. The two outer sections of the antenna are attached to these free-swinging arms with cables, while the center section is rigidly fixed to the gravity-compensation structure.

The deployment process starts from the unrolling of inflatable/self-rigidizable booms by slowly adding air to inflate the booms. The pulley system, as well as the Velcro that is attached to the booms, allows the air flow to control the speed of the boom inflation deployment. For the spring tape reinforced (STR) aluminum laminate inflatable/self-rigidizable boom developed by this study, no pressure is needed after the boom is fully deployed.

The second step of the deployment is the unfolding, which is driven by elastic memory composite (EMC) hinges. The EMC hinge was developed by Composite Technology Development (CTD). It contains shape-memory polymer resin and embeds redundant electrical heaters, which allow for a low-shock, controlled deployment upon heating and become a rigid structure after deployment [11]. The 2.2-m sub-scale breadboard is shown in Fig. 12.

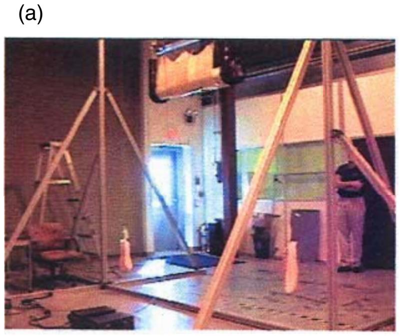
C. 10-m by 3-m Breadboard

To verify the deployment at a large scale, a 10-m by 3-m breadboard was developed. The 3-m height was dictated by the laboratory space. The lengths of the panels were the same as the full-sized design, but the booms were cut shorter. The breadboard represents the middle panel and the lower panel. Since the design is symmetric, only two booms are needed to test the system instead of four. If a larger facility becomes available, then a full-scale model can be tested by simply manufacturing longer booms.

The panels were designed so they could support three membranes of 50-μm thickness each. Figure 13 shows the hinge and alignment pins used for deployment. The hinge was supplied by Foster-Miller Inc. The hinge relies on stored elastic energy to deploy and has built-in viscous damping to minimize the deployment impact. The booms are 0.24 m in diameter so they will be able to support the catenary loads. The frame is made of aluminum due to the budget constraint and for easy machining. If a full-scale model is tested in the future, it would be made from composite materials to reduce the weight.

Just like for the 2.2-m breadboard, a gravity-compensation structure is essential for conducting the deployment test. Figure 14 shows the structure with the deployable frame attached. This gravity-compensation system needs to support the frame during the unfolding process as well as during the unrolling. The unfolding has been successfully demonstrated. Future work will involve the deployment of the booms as well as the integration of three membranes properly spaced and tensioned.

(a)



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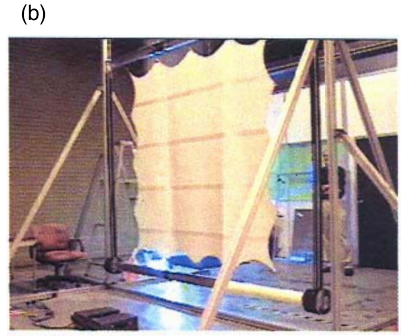

Fig. 12. The 2.2-m subscale breadboard: (a) packaged and (b) deployed (the membrane has not been tensioned yet).

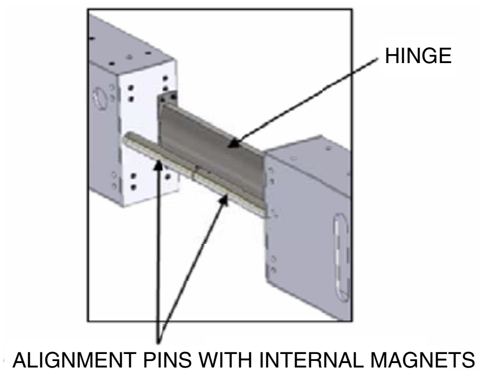

Fig. 13. Aluminum panels with hinges and alignment pins.

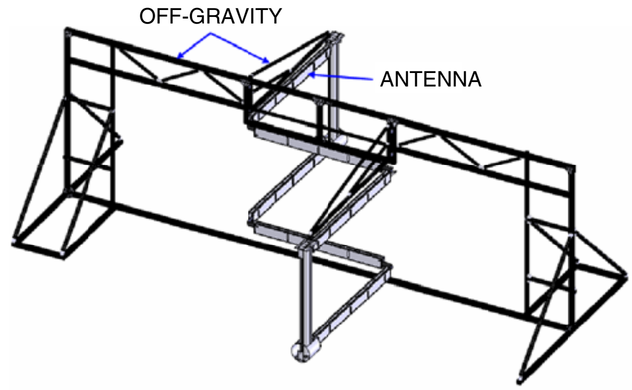

Fig. 14. Schematic of the 10-m by 3-m antenna frame and the gravity compensation system.

During the design, the total mass of the 10-m by 3-m antenna frame was estimated to be 352.2 kg, and Table 2 gives the estimated mass breakdown. The actual mass of the frame weighed 355.6 kg—that is, about 1 percent heavier than the estimated mass.

D. Mass Estimation of the 8-m-Diameter Antenna Using a 50-μm Membrane

The same approach used for the mass estimation of the 10-m by 3-m antenna has also been used to estimate the mass of the 8-m-diameter reflectarray antenna with the design that was given in Fig. 7. The membrane thickness is 50 μm. All panels are sandwich panels that are composed of 3.2-mm-thick Nomex honeycombs and 1.6-mm-thick T300/934 carbon compost facing sheets. Table 3 presents the mass breakdown of the 8-m-diameter antenna with 50-μm membrane.

The area density of the 8-m-diameter X-/Ka-band reflectarray using 50 μm membrane is estimated to be 2.54 kg/m^2. This area density includes all the components shown in Fig. 7. Other elements, such as the sub-reflector, feed, feed-supporting truss, inflation system, and launch constraining devices, are not included.

IV. An 8-m-Diameter Reflectarray Design Case with an Extremely Thin Membrane

New technology currently being developed will allow for the membrane thickness to be extremely thin, down to about 2.5 μm. This means the forces needed to tension the membranes as well as the loads applied to the deployable antenna frame by the catenary will be significantly reduced. As a result of that, the strength of the deployable antenna frame and, accordingly, the weight of the deployable antenna frame can also significantly decrease. The required boom diameter will consequently be much smaller. With smaller booms, the deployable antenna frame can be designed to be extremely light. Also, the center panel can be eliminated because the catenary angle does not need to be very steep in order to reduce the loads loaded to the inflatable/self-rigidizable booms. In addition, the development of the spacing technique will eliminate the need for brackets to hold three different constant force springs at the catenary connection points. Instead, one constant force spring can be used at each point, and the spacers will be responsible for maintaining the spacing requirement between membranes. Finally, structural components of the frame will be made out of light-weight composite materials. All of these features allow for a very low antenna area density that makes this antenna competitive with other antennas of similar size and functionality.

Table 2. Mass breakdown of the 10-m by 3-m antenna frame.

Component	Mass, kg
Outer panels (×4)	238.74
Inner panels (×2)	98.94
Booms (×2)	9.07
Hinges (×4)	1.80
Hinge end plate (×8)	3.66
Total mass	352.21

Table 3. Mass breakdown and area density of the 8-m-diameter antenna with 50-μm membrane.

Component	Mass, kg
Membranes (×3)	4.34
Mandrels (×4)	15.44
Outer panels (×4)	31.24
Inner panels (×2)	18.70
Outer shells (×4)	19.61
Complete center panel (×1)	9.37
Booms (×4)	5.61
Hinges (×6)	2.04
Total mass	106.34
Mass + 20% contingency	127.61
Parameter	**Value**
Functional area	50.27 m^2
Area density	2.54 kg/m^2

A. Design

It was determined by the catenary analysis that a 76-mm-diameter boom will be able to support the loads of the catenary with a factor of safety of 5.0. It is important to keep the diameter of the booms to a minimum. As the boom diameter increases, the diameter of the mandrel used to roll the booms also increases. Since the booms and the membranes will be rolling simultaneously, the three panels that fold together must have a circumference equal to (or slightly less than) that of a mandrel. Consequently, the small mandrel size implies the small size of the entire antenna frame. With a 76-mm boom diameter, one design point was to choose the circumference of the mandrels to be 0.64 m. This leads to the main structure of the three panels being 0.17-m high and 0.043-m wide composite rectangular tubes. The outer panels will have semicircular shells that have an arc length of 0.19 m. When the three panels are z-folded together, they will form a shape, shown in Fig. 15, similar to a cylinder and will have a circumference of 0.63 m. This is 5.8 mm smaller than that of the mandrel to allow the membrane to be rolled slightly looser than the booms, which is essential to ensure a smooth deployment.

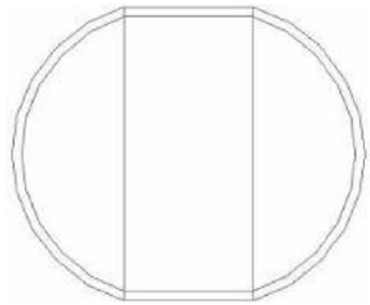

Fig. 15. Cross-section of the panels after folding.

A preliminary design and some design analysis have been conducted, and Fig. 16 shows a drawing of the design. The mass estimation has also been performed, and Table 4 gives the mass breakdown of this design.

Since this mass estimation is very preliminary, a 50 percent contingency has been employed for area density calculation. All the development discussed in this section has brought the area density of this design down to 0.67 kg/m^2. However, this area density includes only the 8-m-diameter reflector. The sub-reflector, feed, feed supporting truss, inflation system, launch constraint devices, etc., need to be included if a more sophisticated mass estimation is performed. Optimization of the structure will allow for further mass reduction.

B. Dynamic Analysis

Along with the strength analyses that have been performed for major components to ensure the integrity of the deployable antenna frame, a dynamic analysis has also been conducted to verify the stiffness of the antenna frame. A finite-element model of the deployable antenna frame was assembled in the pre-/post-processing software FEMAP and analyzed using the finite-element software NASTRAN. The first step of this analysis is to perform a nonlinear static analysis to obtain the differential stiffness of the antenna frame introduced by tensioning the membranes. The differential stiffness is the stiffness deviation from the original structural stiffness due to stress. The second step of this analysis is to combine the differential stiffness with the original structural stiffness and to perform a modal analysis. The first three resonant frequencies are calculated to be 0.112, 0.362 and 0.577 Hz, respectively, with the corresponding mode shapes shown in Fig. 17. Although membrane differential stiffness and membrane modes were

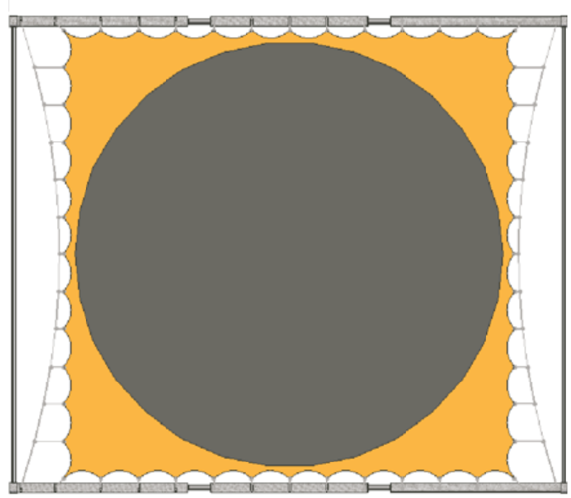

Fig. 16. Design with thin membranes implemented.

Table 4. Mass breakdown and area density of the 8-m-diameter antenna with 2.5-μm membrane.

Component	Mass, kg
Membranes ($\times$3)	0.578
Mandrels ($\times$2)	0.451
Outer panels ($\times$4)	10.218
Inner panels ($\times$2)	4.606
Outer shells ($\times$4)	2.842
Booms ($\times$2)	1.876
Hinges ($\times$4)	1.363
Hinge end plate ($\times$8)	0.656
Total mass	22.590
Mass + 50% contingency	33.885
Parameter	**Value**
Functional area	50.265 m^2
Area density	0.674 kg/m^2

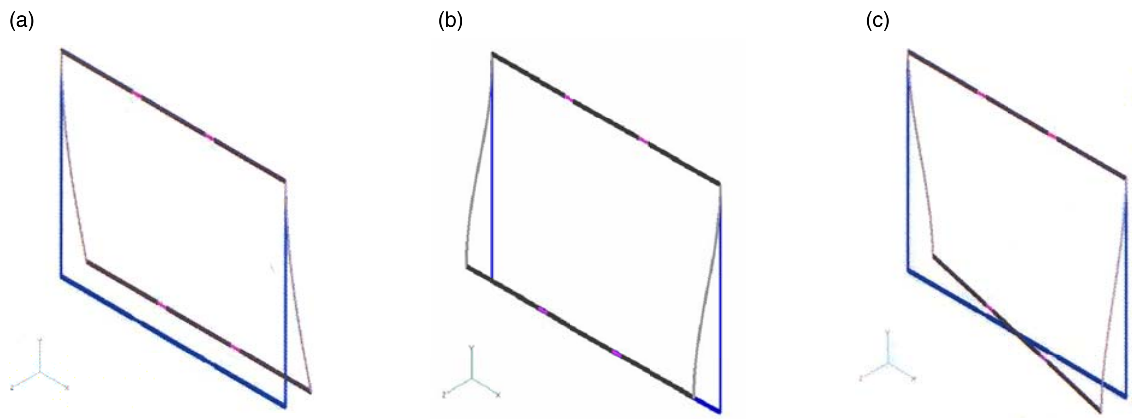

Fig. 17. Mode shapes of the antenna frame: (a) first mode shape, (b) second mode shape, and (c) third mode shape.

not analyzed since their mass participation is very small, their equivalent mass was taken into account when performing the resonant frequency analysis for the deployable antenna frame.

V. Conclusions

An 8-m-diameter X-/Ka-band reflectarray antenna, as well as the associated technologies, is being developed for deep-space communication applications. This antenna offers the advantages of a large aperture, high RF frequency, being lightweight, and high packaging efficiency. There are two challenging mechanical aspects of this 8-m dual-frequency reflectarray antenna: the first one is the implementation of precisely aligned and adequately flat multiple-layer membranes, and the second one is the in-space deployable support-frame technology.

To develop the associated membrane implementation technologies, two sub-scale breadboards have been assembled. The first breadboard is 1.5 m by 1.5 m, and the second one is a 3-m-diameter X-/Ka-band RF functional reflectarray antenna. With the help of these sub-scale breadboards, most of the challenging membrane problems—which include membrane sheet bonding; double catenary for membrane tensioning; membrane flatness testing and maintenance; a high-precision multi-layer membrane spacing system; a multi-layer membrane fabrication process; and antenna system manufacturing—have been overcome on the sub-scale level. A future task for the membrane implementation is to scale up these technologies from sub-scale to full scale.

The second task of this study is to develop a deployable frame for the 8-m reflectarray antenna. To investigate the technologies associated with this task, a 2.2-m sub-scale breadboard and a 3-m by 10-m breadboard were fabricated and tested. The deployment process was successfully demonstrated by these two breadboards at different scale levels.

Because the architecture of the reflectarray antenna has been demonstrated in a laboratory environment by several sub-scale engineering models and the inflatable/self-rigidizable boom technology has been tested in the vacuum/thermal chamber [7], the current technology readiness level (TRL) level of this technology is 4 and higher. Future tasks for the deployable antenna frame include scaling up from sub-scale to full scale, reducing weight, and increasing the TRL of the reflectarray antenna technology.

The design of an 8-m-diameter reflectarray antenna with current state-of-the-art, extremely thin membrane materials has also been performed by this study. As a result of this design study, the area density of the X-/Ka-band reflectarray antenna (excluding the sub-reflector, feed, feed supporting truss, inflation system, and launch constraining devices) can be as low as 0.67 kg/m^2. This result provides a good rationale for the development of this technology.

Acknowledgments

The authors wish to thank Faramaz Davarian and Jim Lesh of JPL for their encouragement, guidance, support, and help. The authors want to acknowledge Daniel Polo, Jose Luis Perez, Julieta Morales, Sam Szeto, and Vinh Bach, all of California State University at Los Angeles, and Nicholas Voelker of the University of Washington for their contributions to both experimental and analytical aspects of this study.

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