In-space Deployable Reflectarray Antenna: Current and Future

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Technologies associated with a 10-m diameter X/Ka-band dual-frequency reflectarray antenna have been developed for deep space communication applications. The membrane implementation and in-space deployable antenna frame are two challenging mechanical aspects of this antenna. To address these mechanical aspects, two tasks have been performed. The first task is the development of a 3-m diameter X/Ka dual frequency reflectarray antenna which serves as a stepping-stone to the 10-m aperture antenna membrane implementation. The membrane implementation technologies includes: seaming, catenary, spacing, and multi-layer assembly process. The second task is to develop a deployable frame for the 10-m reflectarray antenna. To investigate the technologies associated with the deployable antenna frame, a 2.2-m sub-scale breadboard and a 3x10-m breadboard were fabricated and the deployment process was successfully demonstrated by these two breadboards at different scale levels. In addition, the paper discusses a couple of future reflectarray antenna developing directions which include using extremely thin membrane materials and using micro MEMS actuators to implement the large angle beam scanning capability.

I. Introduction

Since the late 1990s Jet Propulsion Laboratory has been developing deployable reflectarray antenna technologies for in-space communications and science applications[1-8]. 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 RF energy by appropriately rotating the circularly polarized reflectarray elements[9]. Thus, the reflectarray can compensate for path-length differences from the feed. In this way a flat surface can be utilized as a reflective medium instead of a parabolically shaped surface. Furthermore, since the reflectarray uses FSS, the antenna can, in principal, be operated at multiple widely spaced frequencies by placing reflectarray layers adjacent to each other. For this to work, the uppermost layers of FSS must act as band-pass filters for succeeding layers.

NASA missions often use both X and Ka band as communication links, so this combination of two frequencies was chosen as the target of our specific development activity. A three-layer membrane approach has the layer nearest the feed to 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. 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 dual-frequency antenna with an aperture diameter of approximately 10 meters. There are two challenging mechanical aspects for the 10-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. Two tasks have been performed to develop the associated technologies.

The first task is the development of a 3-m diameter X/Ka dual frequency reflectarray antenna. This antenna is the stepping-stone to the 10-m aperture antenna. The 3-m reflectarray is a functioning RF test article that is mounted in a fixed frame. Section II of this paper will discuss how etched membrane strips are seamed together and tensioned to achieve the accuracy of the spacing between the FSS layers. Membrane implementation technologies that will be

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discussed also include: catenaries for proper membrane tensioning, a spacing system for precisely separating the layers and a multi-layer membrane fabrication process.

The second task is to develop a deployable frame for the 10-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 be able to stow the entire antenna within the 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 successfully demonstrated. The paper will discuss the developments of this prior 2.2-m breadboard and the results of the 3x10-m breadboard activity. This larger test article was deployed using a gravity compensation fixture so that the deployment process can be investigated and verified on the ground.

Section IV of this paper will discuss a couple future developing directions for this study which include the design case study of a 10-m X/Ka-band dual-frequency reflectarray antenna using extremely thin membranes and the implementation of large angle beam scanning capability using micro MEMS actuators.

II. Dual Frequency Membrane Development

The dual frequency inflatable reflectarray antenna consists of 2 frequency selective surface (FSS) membrane layers, Ka-Band and X-Band with thin annular ring elements and a ground layer[10]. The separation between the ground layer and the Ka-Band is 1.6 mm plus/minus ten percent and the separation between the Ka-Band and the X-band layer is 3.2 mm plus/minus ten percent. The spacing between layers is vital for the RF performance of the 10-meter diameter inflatable reflectarray antenna. In order to meet these requirements, a 3-m diameter RF functional breadboard has been assembled. This breadboard has been used to develop a membrane strip seaming process and a catenary system which provides an adequate way to uniformly tension the membrane. This breadboard has also been used to develop a reliable and feasible spacing system that guarantees a consistent spacing between the membrane layers across the entire antenna membrane area.

A. Seaming Process

A membrane strip seaming process is essential to manufacture large membrane layers since a current manufacturing method for etching large membranes is not available. The current largest etched membrane strip is about 60 inches by 18 inches and it would require 16 of these strips to manufacture a 3-m diameter membrane as illustrated in Fig. 1. Prior to implementing the seaming process, the etched membrane strips are precisely aligned using pre-determined alignment marks and temporarily taped using removable tape to preserve the performance of the 3-m diameter functional area.

Figure 1. Membrane strips layout for a 3-m diameter functional area membrane

The implementation of the seaming process begins by methodically turning the temporarily taped membrane strips over with a large diameter mandrel to prevent any permanent wrinkling. This will expose the non-etched surface of the membrane strips where the seams can be placed. Two inches wide bands of the same membrane material were used as the permanent seams. The adhering agent used after a thorough research is a 2 part 3M Scotch-Weld epoxy (Adhesive 2216B/A Gray) which has a 24 hours curing time to furnish ample time for any required detail work such as removing trapped air bubbles. A thin layer, no thicker than 5 mils (0.127 mm), of the adhering agent was used to maintain the seamed sections flexible enough to roll onto a minimum of 6 inches diameter mandrel without causing any delaminating or cracking of the seams.

B. Catenary Process

A set of membrane strips seamed together becomes the radio frequency (RF) component of the antenna which is called a FSS membrane. For optimal antenna performance the FSS membrane with hundreds of thousand of etched copper rings needs to preserve a RMS flatness of 0.17 mm. In order to maintain the membrane's flatness, a catenary system is employed. The catenary system implements a physical connection between the membrane and the deployable frame which maintains a constant stress distribution on the membrane assuring the membrane surface flatness[11].

The catenary design is generated using a program developed in MathCAD where the key parameters are the membrane stress, membrane perimeter dimensions, pulling force and number of catenary spans. Special jigs were designed using the acquired catenary equation from the MathCAD code and manufactured to facilitate the outlining, cutting and forming of the catenary. The forming of the catenary was accomplished by using Kapton tubing and flaps which are made by cutting slits every 1/4 inch (6.35 mm) along the perimeter of the catenary curvature as illustrated in Fig. 2. The tubing used is an off the shelf high performance polyimide tubing from Micro Lumen. The catenary system process is completed as the following three steps; stringing, catenary vertices reinforcement and attaching of eyelets are carried out (Fig. 2).

Figure 2. Catenary vertex showing flaps, catenary vertex reinforcement and eyelet

C. Spacing Process

The dual frequency inflatable reflectarray antenna as aforementioned consists of Ka-Band and X-Band FSS membrane layers as well as a ground layer, where the separation between the ground layer and the Ka-Band is 1.6 mm and the separation between the Ka-Band and the X-band layer is 3.2 mm. In order to meet these requirements, RF transparent precision foam spacers are methodically adhered throughout the membranes as illustrated in Fig. 3. The catenary vertices were also populated with foam spacers to avoid any layer to layer misalignment during packaging and deployment respectively.

Figure 3. Precision foam spacers layout

To ensure that the spacing is consistently maintained between the FSS membranes layers across the entire antenna, the spacing of the 3-meter diameter breadboard were measured using over one hundred strategically selected locations. The measurements of these selected locations for the Ka-Band and X-band were within their respective required tolerance. The average of the measurements for the Ka-Band and X-band were calculated to be 1.67 mm and 3.23 mm respectively.

D. Multi Layer Fabrication Process

Each membrane layer is manufactured independently. To fabricate a multi layer antenna, all the membrane layers must preserve the catenary vertex alignment between layers throughout the catenary perimeter. To facilitate the alignment of all the catenary vertices, all membrane layers are fabricated using equal perimeter dimensions. Also during the assembly, incrementally sized frames are used to maintain all the catenary vertices aligned. The assembling frames are designed so that the smaller frame fits inside the larger frame thus allowing for the membrane layers to stack up as shown in Fig. 4.

Figure 4. Assembling of multi layer membranes

Before any spacers are adhered to the membranes, each layer is tensioned onto its individual frame. The frames are brought together to ensure that the alignment of the catenary vertices between layers is preserved. Once the membrane layers are aligned several special guiding brackets are attached to each frame which allows the removing and reposition of the frames without changing the catenary vertex alignment between layers. To facilitate the adhering of the RF transparent precision foam spacers, the frames are temporarily separated. The frames are then carefully put back together consequentially adhering all membrane layers together via the foam spacers. Figure 4 shows the 3-m functional area breadboard being assembled.

III. 10-m Reflectarray Antenna Deployable Frame

A. 2.2-m Breadboard Deployment

A subscale breadboard was necessary to develop and advance several innovative and critical components and concepts before moving on to the full-scale 10-meter antenna. This breadboard design is a 2.2-meter square membrane supported by an inflatable/self-rigidizable structure as shown in Fig. 5. The 2.2-meter breadboard was used to test the unfolding and unrolling process which is necessary for the deployment of the 10-meter antenna. A double catenary system, used to tension the membranes, was also tested to verify that it can be implemented in the 10-meter antenna.

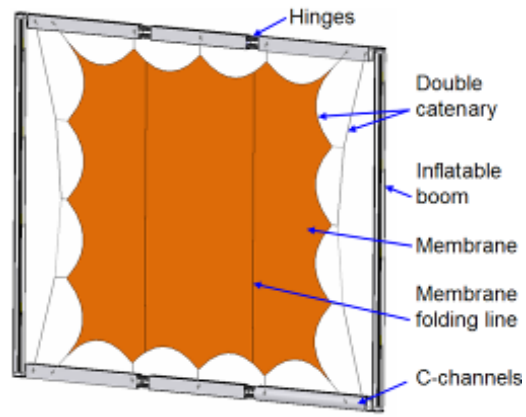


Figure 5. The 2.2-m breadboard design

The membrane and double catenary system needs to be placed inside a structure that can perform a "Z" fold for packaging but maintain rigidity after deployment. Figure 6 shows such a structure which is made of aluminum c-channels and 4 sets of hinges. The hinges are responsible for driving the deployment as well as providing stiffness once deployed. Since the axes of the hinges were not collinear with the catenary forces, pins were added to prevent the hinges from experiencing large bending moments. These pins also take some of the buckling loads and help with alignment. Magnets can also be added to ensure full deployment and lockout of the hinges.

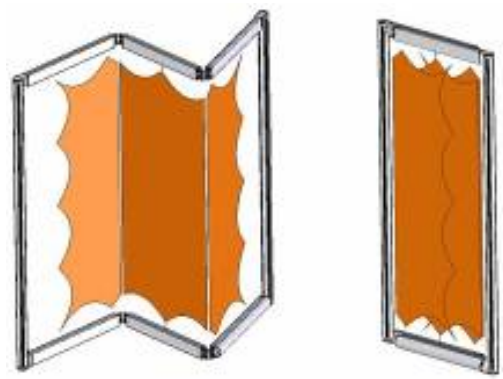


Figure 6. "Z" Fold of antenna structure

There are a total of 20 constant force springs in this design. For simplicity, a thicker single membrane was used instead of three thinner membranes. The thicker membrane still requires the same force to tension it as the thinner membranes combined. This means that single constant force springs can be mounted directly to the c-channels instead of using brackets holding three springs. The cross-section of the panels consists of two c-channels that are connected together as shown in Fig. 7. The plates that connect the two c-channels are also used to attach the hinges, alignment pins, and mandrels for the boom. The bolts used to connect the c-channels are countersunk so they do not interfere with the membrane when it is rolled up. The constant force springs are attached to one of the c-channels so the string that tensions the membrane is in the middle of the two c-channels. Each c-channel has half of a hole drilled into it so when they are connected together a pathway is created for the string that tensions the membrane. The springs are on a bushing which allows them to rotate freely, and the bushings are on a pin attached to the c-channel. A pin is placed in front of each spring to pre-tension it because no tension can be on the membrane while it is unrolling or unfolding. A string is connected from each spring to its corresponding pin. A separate string bypasses the pin and connects the spring to the membrane. After the antenna is fully deployed, a releasing mechanism will disconnect the strings attached to the pins and the membrane will be tensioned.

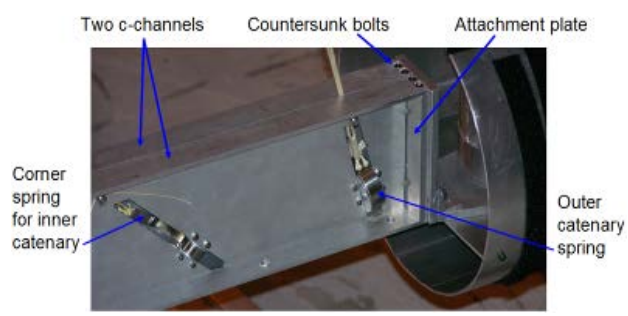


Figure 7. Constant force springs attached to the c-channels

Before the antenna unfolds, it must unroll from its packaged configuration. The inflatable booms are responsible for this part of the deployment. An aluminum mandrel shown in Fig. 8 is used to roll-up the booms[6]. The booms are

attached to the outside of the c-channels with large L-brackets. For the 2.2-m antenna, the mandrels have a diameter of 8 inches (0.2 meters). The membrane also needs to be rolled onto a cylinder-like structure. Since the membrane is rolled up after the z-fold occurs, the three sections of the antenna need to form a cylindrical cross-section after they are folded. To accomplish this, the two outer sections of the antenna form half cylinders while the center section is flat. These sections do not form a perfect cylinder as shown in Fig. 9 but they provide a smooth surface to roll the membrane on. The circumference of the folded sections is slightly smaller than the circumference of the mandrels which is necessary for smooth deployment. Foam is used to create the cylindrical surface for the membrane to be rolled on. The edge of the foam is placed on the inside edge of the appropriate c-channel and runs along its entire length. The foam is cut to a width that will create the right curvature for the membrane to be rolled around.

A gravity compensation system (GCS) is needed for the antenna to deploy successfully. The hinges cannot take large bending loads so the weight of the antenna needs to be supported by the GCS. The structure in Fig. 10 is used to support the antenna during deployment. To unroll the antenna, a pulley system is used to counter the weight of the antenna. This ensures that the boom inflation controls the unrolling process of the deployment. In order for the GCS to be able to perform a z-fold, low-friction ball bearing hinges are used to attach 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 GCS. The hinges on the antenna drive the unfolding because the free swinging arm hinges are passive.

The deployment starts with slowly increasing air pressure to inflate the booms. The Velcro on the booms along with the pulley system allows for the air flow to control the speed of the deployment[12]. Once the booms are completely deployed and

Figure 8. Mandrel for rolling booms

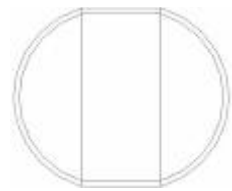


Figure 9. Cross-section of C-channels after Z-folding

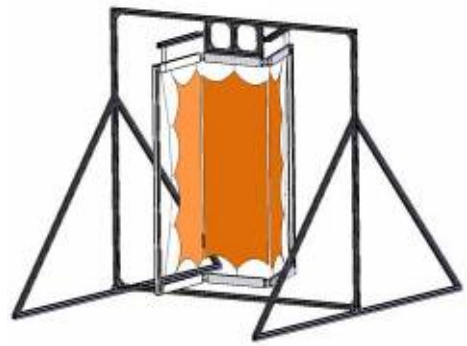
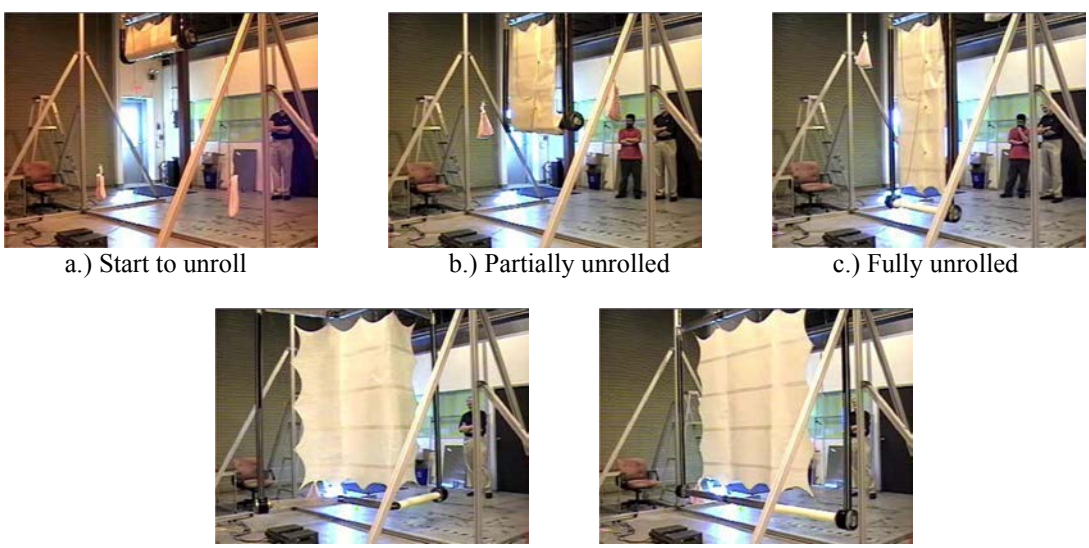


Figure 10. Architecture of the GCS



a.) Start to unroll b.) Partially unrolled c.) Fully unrolled

d.) Partially unfolded e.) Fully deployed

Figure 11. Deployment demonstration of 2.2-m breadboard

rigidized, the air is turned off and the hoses are disconnected. The pulleys and counterweights are removed before the antenna is unfolded. Next, the quick release pins are released and the hinges deploy the antenna. The strings that were attached to the pins can now be pulled in order to release the springs and tension the membrane. At this point the deployment is complete with a tensioned membrane. The sequential steps are shown in Fig. 11.

B. 10x3-Meter Breadboard Deployment

To verify the deployment at a large scale, a 10x3-meter breadboard was developed. The 3-meter height was restricted by the lab space. The lengths and the cross-sections of the panels are the same as the full size design but the booms were cut shorter.

The panels were designed so they could support three membranes of 2 mils (51 microns) thickness each. Figure 12 shows the hinge and alignment pins used for deployment. The hinge was provided courtesy of Foster-Miller Inc (FMI). The hinge relies on stored elastic energy to deploy and incorporates viscous damping to minimize the deployment impact. The booms are 9.5 inches (0.241 meters) 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. A future full-scale model could be made from composite materials to reduce the weight.

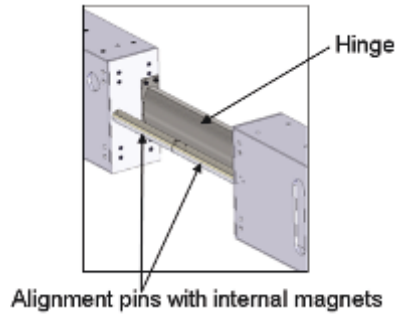


Figure 12. Aluminum panels with hinge and alignment pins

Just like for the 2.2-meter breadboard, a gravity compensation structure (GCS) is essential for conducting the deployment test. Figure 13 shows the structure with the deployable frame attached. This gravity compensation system needs to support the frame during the unfolding process as well as the unrolling. The GCS has moving components that support the moving panels of the deploying antenna. The moving components are called swing arms as shown in Fig. 13. The swing arms are attached to the GCS via hinges. Each swing arm has two hinges that connect it to the GCS. These hinges are passive because the deployment is driven by the FMI hinges. For an antenna with large inertia such as this one, it is imperative that these passive hinges utilize low friction bearings.

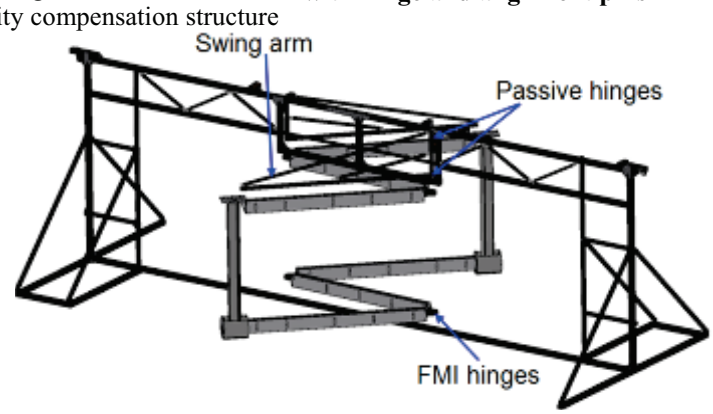


Figure 13. 10x3 m frame attached to GCS

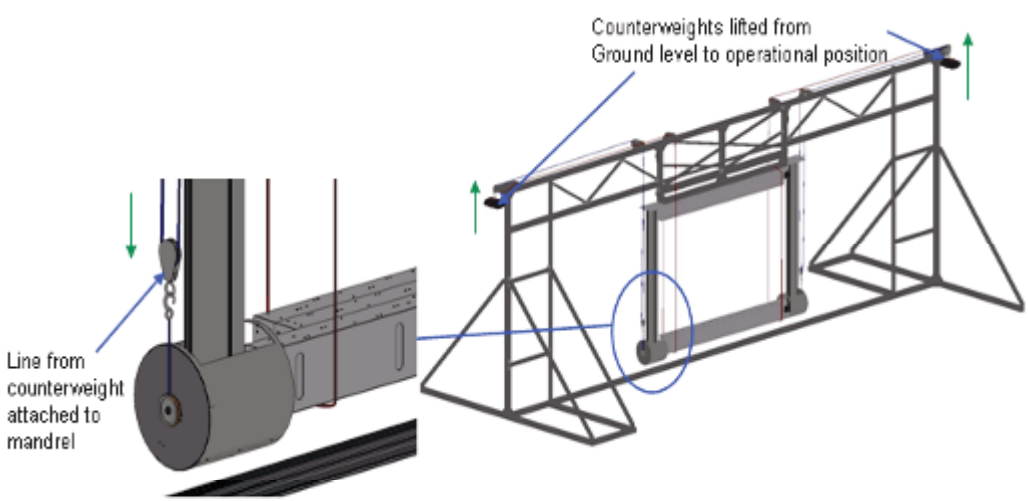


Figure 14. Antenna folded and attached to GCS

The GCS also supports the unrolling process. The unrolling process is the same for the 10x3-meter as it is for the 2.2-meter breadboard design. The system is composed of pulleys, ropes, and counterweights that offload the lower portion of the frame throughout the unrolling process. Pulleys are used to connect the center of the mandrels to the counterweights via Vectran rope. The setup is shown in Fig. 14.

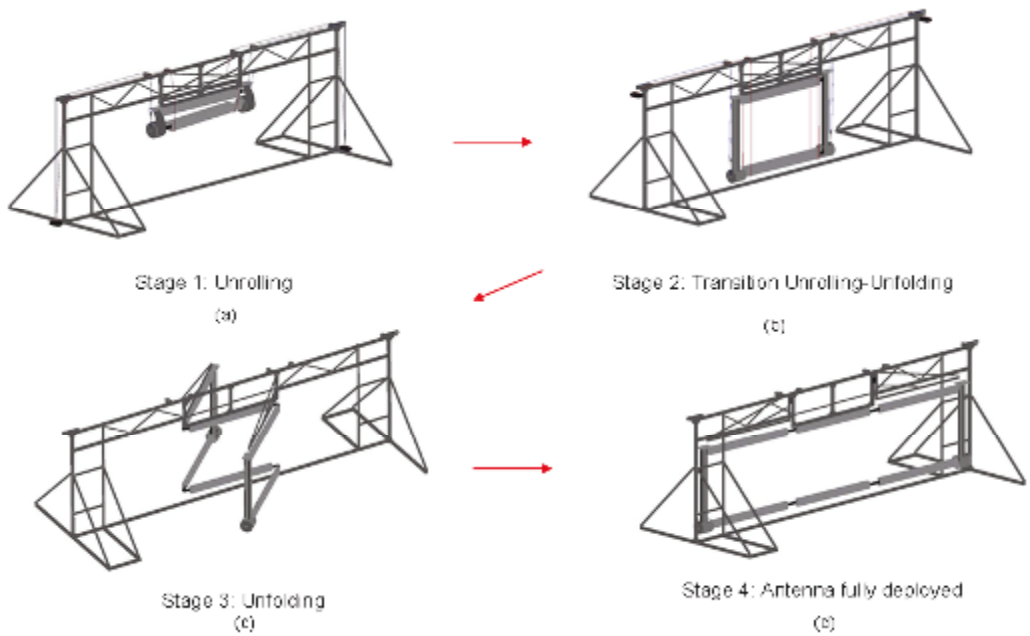
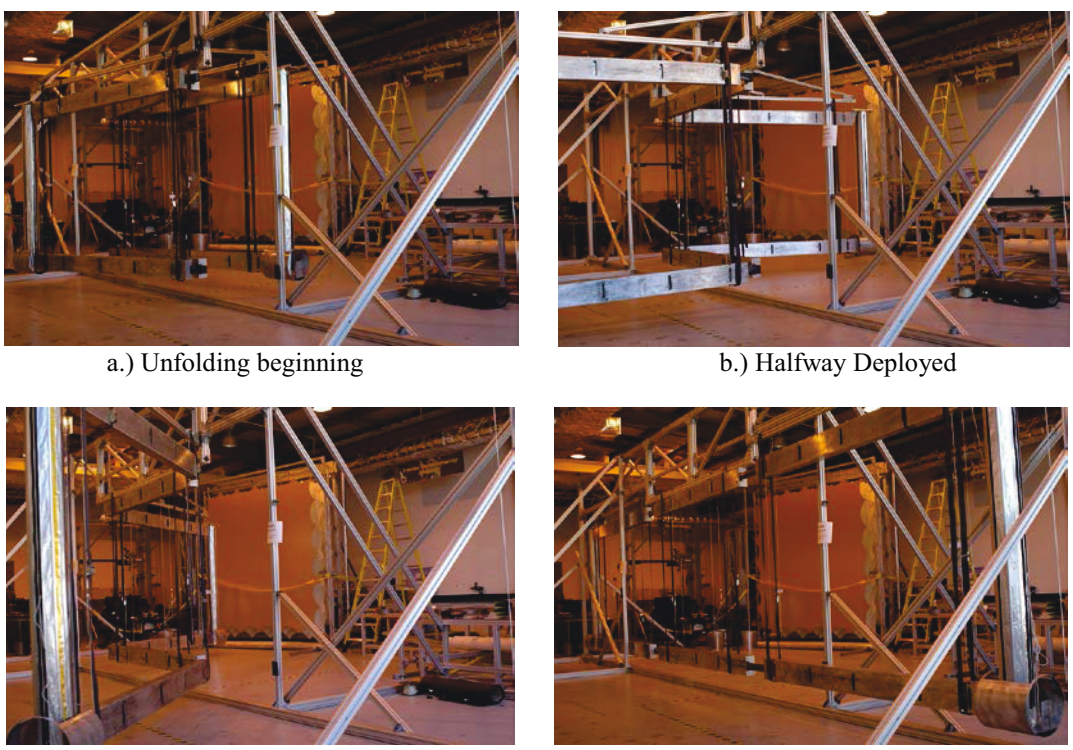


Figure 15. Deployment sequence



a.) Unfolding beginning

b.) Halfway Deployed

c.) Unfolding continued

d.) Fully deployed

Figure 16. 10x3-m unfolding demonstration

The deployment process as described below can be seen in Fig. 15. When the antenna is completely packaged, the frame is rolled-up and the counterweights are at the ground level as shown in Fig 15(a). Also, the booms are fully deflated and rolled around the mandrels. A pipeline coming from a pressurized air source is connected to a valve located at the top of each boom. Then, the pressure inside of the booms reaches 20.68 kPa +/- 3.45 kPa (3 psi +/- 0.5 psi) and the unrolling process begins. The panels are lowered until the booms are unrolled to their maximum length as shown in Fig. 15(b). The second stage of the deployment process is a transition from unrolling to unfolding. The mandrels are released from the cable that is attached to the counterweights so the panels can freely unfold. Also, the pins that hold the panels together are removed and the unfolding stage starts. Once the pins are removed, the outer panels start to unfold separately as shown in Fig. 15(c). The deployment of the panels is driven by the stored energy of the FMI hinges. The frame is fully deployed when the hinges on both sides completely lock back into their original shape as shown in Fig. 15(d). The unfolding process has been successfully demonstrated as shown in Fig. 16.

IV. Further Developing Directions

A. Design Case with Extremely Thin Membrane

New technology currently being developed will allow for the membrane thickness to be extremely thin, down to about 2 microns. 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, the strength of the deployable antenna frame and, accordingly, the weight of the deployable antenna frame can also be significantly decreased. The required boom diameter will consequently be much smaller. With smaller booms the deployable antenna frame can be designed extremely light. Also the center panel, shown in Fig. 17 can be eliminated because the catenary angle does not need to be very steep in order to reduce the loads applied 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[8]. 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.

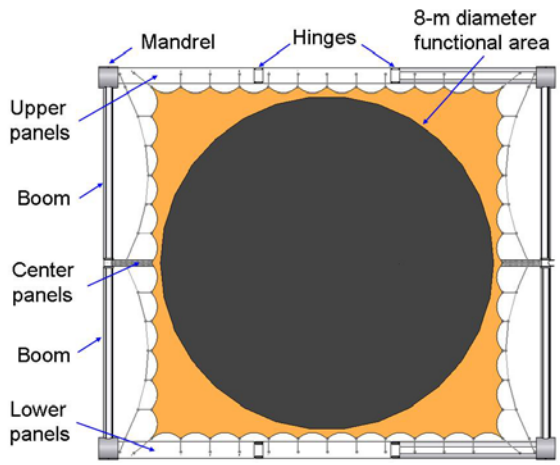


Figure 17. Assembling of multi layer membranes.

To estimate the areal density of a dual-frequency 10-m diameter reflectarray made of 2-micro thick membranes, a preliminary design and analysis has been conducted[13]. The first step of this preliminary design and analysis is to find the new loads necessary to tension three layers of 2-micron membrane. It was determined by the catenary analysis that a 3 inch (76.2 mm) diameter boom will be able to support the loads of the catenary with a Factor of Safety of 5.0. Using 3 inch (76.2 mm) diameter booms instead of 9.5 inch (0.24 meters) diameter booms is crucial in lowering the mass of the antenna. 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. So the small mandrel size implies the small size of the entire antenna frame. With a 3 inch (76.2 mm) boom diameter, one design point is to choose the circumference of the mandrels to be 0.64 meters. From previous studies a 3 inch (76.2 mm) boom, requires about an 8 inch (0.2 meter) diameter mandrel minimum to allow the boom to transition smoothly into the rolling phase[4,6].

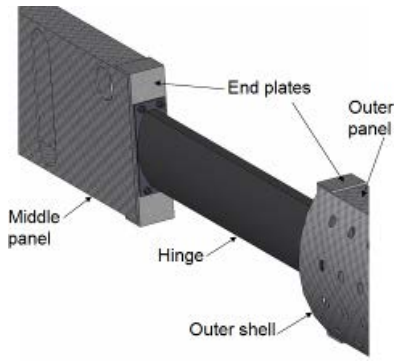


Figure 18. Assembly of panels and hinge.

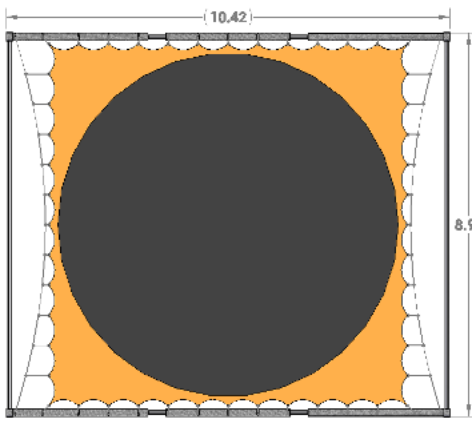


Figure 19. Design with thin membranes implemented.

Table 1. Mass breakdown for thin membrane design.

Component	Mass (kg)
Membranes (x3)	0.578
Mandrels (x2)	0.451
Outer Panels (x4)	10.218
Inner Panels (x2)	4.606
Outer Shells (x4)	2.842
Booms (x2)	1.876
Hinges (x4)	1.363
Hinge End Plate (x8)	0.656
Total Mass (kg)	22.590

Table 2. Area density calculation for thin membrane design

Total Mass (kg)	22.590
Mass + 50% contingency (kg)	33.885
Functional Area (m^2)	50.265
Area Density (kg/m^2)	0.674

The mandrel size leads to the main structure of the 3 panels being 6.75 inches (0.17 meters) high and 1.68 inches (0.04 meters) wide composite rectangular tubes. The outside edges are 1/16 inches (1.59 mm) thick and made from T300/934 Carbon/Epoxy composite. The thicker edge is made from two face sheets of 1/16 inch (1.59 mm) composite and a 1/8 in (3.18 mm) Nomex Honeycomb Core sandwiched between them. This surface is thicker because it is where the constant force springs are mounted to tension the membranes. The surface opposite of the springs has a pattern of cutouts that help lighten the structure. Each outer panel is 3.18 meters long while each center panel is 2.92 meters long.

The outer panels will have semicircular shells that have an arc length of 0.19 meters. These shells are used so the membrane will have a cylindrical surface to wrap around when stowed. This was demonstrated in the 2.2-m breadboard test using foam. The shells are made from the same material as the outer panels and also have cutouts in order to reduce their mass. The outer shell can be seen in Fig. 18.

End plates are connected to the end of the outer and middle panels in order to attach the hinges. These end plates are also made from carbon composite and can be seen in Fig. 18. The end plates are attached to the outer panels by epoxy and the hinges are attached to the end plates by bolts.

When the three panels are z-folded together they will form a shape as previously shown in Fig. 9. This shape is similar to a cylinder and will have a circumference of 0.63 meters. This is 5.84 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.

This preliminary design has been conducted and Fig. 19 shows the overall antenna design with some major dimensions. The mass estimation has also been performed and Table 1 gives the mass breakdown of this design.

Since this mass estimation is very preliminary, a 50% contingency has been employed for the area density calculation and is shown in Table 2. 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 only includes the 10-m membrane and support structure. Sub-reflector, feed, feed supporting truss, inflation system, launch constrain devices, and etc. need to be included if a more sophisticated mass estimation is to be performed.

B. Large Angle Beam Scanning with MEMS Actuator

One of the further developing directions for the reflectarray antenna is the wide-angle (up to ±50º) beam scanning capability for advanced deployable large antennas by combining the reflectarray technology with Micro Electro Mechanical System (MEMS) actuator technology. Large and high-performance communication and radar antennas with wide-angle scanning capability are highly demanded for future space missions. The large aperture can detect with increased resolution while the scanning beam can significantly increase the coverage area. This technology will provide the lowest-cost, most-simple and most reliable phased array system. Figure 20 illustrates the schematic of this technology.

The “reflectarray” principle makes this technology possible. The reflectarray uses passive patch elements that efficiently reflect RF

within a certain bandwidth when organized in a geometric pattern. By properly rotating the elements of a circularly polarized reflectarray, the phases of the elements can be adjusted to compensate for the different phase delays incurred in the different wave paths from the feed to the reflectarray elements[9]. MEMS miniature angular stepper actuator can then be used under each circularly polarized element of a reflectarray to achieve wide-angle beam scanning capability. By implementing miniature angular stepper actuators under all passive RF patch elements to actively rotate them in unison, the re-radiated RF can be steered in both elevation and azimuth directions with excellent RF scan performance. The maximum range of element rotation that is required is only about ±180º, and can be executed in relatively coarse steps. It has the potential to outperform the costly, complex and massive Electronically-Scanned Array's (ESA's) state-of-the-art while yielding better antenna performance at frequencies and power levels.

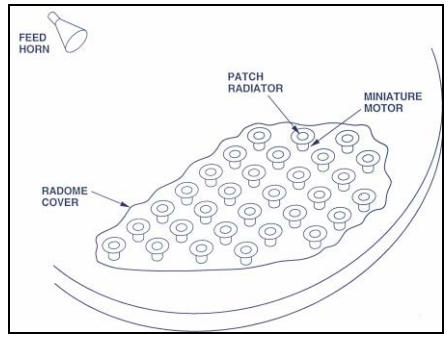


Figure 20. Schematic view of the wide-angle beam scanning

The fundamental element of this technology is the miniature angular stepper actuator that needs to be small and light-weight. With the recent advancing of the MEMS, this miniature actuator becomes feasible. Figure 21 shows one of the possible piezoelectric (PZT) micromotor architectures[14] that can potentially be modified for this application. For this architecture, the piezoelectric ceramics are shaped rectangular parallelepipeds, which are polarized in the direction of their thickness. They expand and contract when alternated voltage is applied to them. The elastic cantilever oscillator generates vibration and flexion in synchronization with the expansion and contraction motion of piezoelectric ceramics. Since the cantilever oscillators have flexural vibration, the elliptic movements are excited at the free end of the cantilever oscillators. After the rotor and the stator with cantilever oscillators are assembled, the elliptic movements are transmitted to the rotor, and only the horizontal vibration of elliptic movements generates the rotor rotation in the alternated voltage. The most efficient rotation is achieved when the frequency of the applied voltage equals the resonance frequency of the cantilever oscillator. The stator is made from stainless steel and glued to piezoelectric ceramics. The rotor is made from nickel by electroforming and gilding. The shaft is made from stainless steel. The flat spring has three beam-shaped suspension parts between the center part and the outer part. The flat spring is made from stainless steel by etching process, and three suspensions and center part are etched once more, so that the outer part is thicker than the suspensions and the center part. The micromotor is constructed by piling up the shaft, the stator, the rotor and the flat spring in this order. The center part of the flat spring and the top of the shaft are welded with laser when the micromotor is assembled. The flat spring structure generates contact pressure between the stator and the rotor by bending suspension parts to the rotor. It is also possible to control contact conditions between the stator and the rotor by the choice of the shape and the material of the flat spring structure.

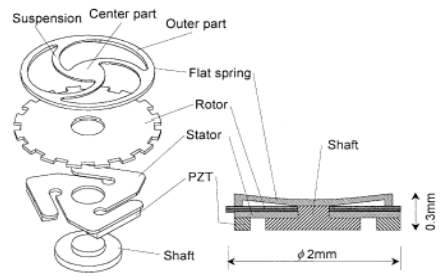


Figure 21. Schematic drawing of new type piezoelectric micromotor.

The size of this PZT micromotor is 2 mm in diameter and 0.3 mm height. Due to the modern technology developed by biomedical engineering society, producing high quality PZT films by the sol-gel process, we may be able to further miniaturize this micro motor. The speed of this type of motor is in the order of milliseconds, which will result in a beam scanning speed of similar magnitude. It is believed that most space-based communications or radars do not require beam scanning speed faster than this.

Many thousands of miniature actuators and RF patches are used to form a reflectarray antenna with beam scanning capability, which Fig. 22 shows a small portion of this reflectarray antenna. The following are several different architectures which can potentially be employed to implement this technology.

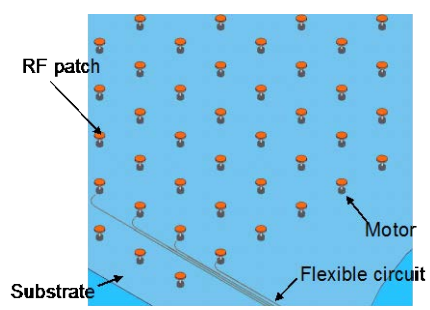


Figure 22. A portion of the reflectarray with miniature actuators and patches.

1. First architecture

Figure 23 illustrates the first architecture of the system assembly where miniature actuators are secured at bottom to the base substrate. Every actuator has a circular ground plane stationary connected to it. A flexible circuit connects two adjacent ground planes. An RF patch on top of its substrate is connected to the shaft of the miniature actuator and rotates with the shaft. Flexible circuits are used to connect miniature actuators to the controller.

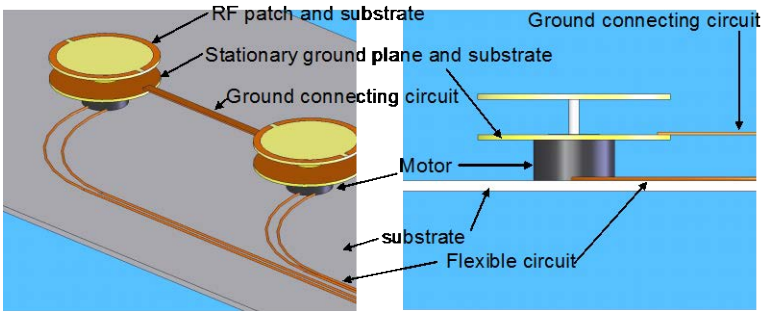


Figure 23. Schematic view of the first system assembly architecture (showing only two miniature actuators with circular ring patch elements).

2. Second architecture

Figure 24 shows the second architecture of the system assembly. Miniature actuators are secured to the bottom side of the ground plane substrate and shafts protrude the ground plane and its substrate. Flexible circuits are placed at the bottom side of the ground plane substrate to connect actuators to the controller. Circular ring patch elements on top of their substrates rotate with shafts.

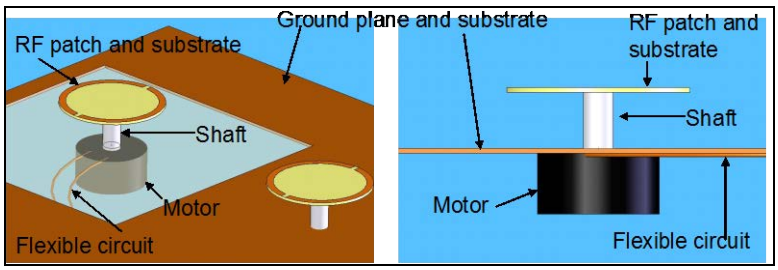


Figure 24. Schematic view of the second system assembly architecture (transparent section is for viewing components underneath ground plane).

3. Third architecture

Figure 25 shows an architecture that requires a miniature actuator with a very small height. The actuator is placed between the RF patch and the ground plane and the spacing between RF patch and ground plane is designed to be 1.6 mm. This architecture offers the smallest system thickness.

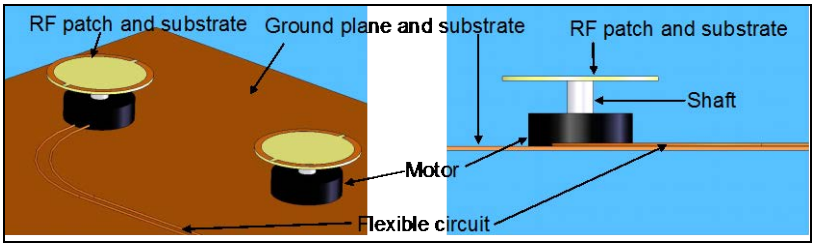


Figure 25. Schematic view of the third system assembly architecture where both RF elements and actuators are above the ground plane.

4. Fourth architecture

Figure 26 shows the fourth architecture where the spacing between the RF patch and the ground plane is reduced to sub-millimeter and form a single thin disc. A sub-millimeter thick substrate is used to separate the RF patch and the ground plane. This architecture offers a high precision spacing between the RF patch and the ground plane but suffer with significantly reduced RF bandwidth.

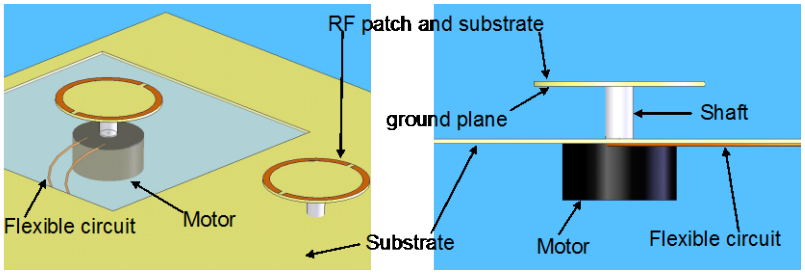


Figure 26. Schematic view of the fourth system assembly architecture (transparent section is for viewing components underneath the substrate).

V. Conclusion

The technologies for a 10-meter diameter multiple-band X/Ka bands frequency reflectarray antenna have been developed for deep space communication applications. This antenna offers large aperture, high RF frequency, lightweight, and high packaging efficiency. During this development there were two major challenging findings in the mechanical aspects of the 10-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 address these challenging findings several sub-scale engineering models have been assembled and their developing technologies have been study. With the help of these sub-scale engineering models, most of the challenging problems which include: double catenary for membrane tensioning, seaming of membrane strips, high precision multi-layer membrane spacing system; multi-layer membrane fabrication process; off-gravity system for studying the deployment process; have been overcome on the sub-scale level. Further study directions which include using extremely thin membrane material to reduce the areal density as well as using micro MEMS actuators to implement the large angle beam scanning capability have also been discussed.

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References

[1]Final Report of ILC Dover Inc., "Design, Fabrication, and Integration of a 1 Meter X-Band (8.4 GHz) Inflatable Microstrip Reflectarray Low Mass Technology Demonstrator", Ref. Contract # 960929, August 1997.

[2]Feria, V. A., Huang, J. and Cadogan, D., "3-Meter Ka-Band Inflatable Microstrip Reflectarray", *ESA AP 2000 Conference*, Davos, Switzerland, April 2000.

[3]Lin, J. K. H., Cadogan, Huang, D. P., J., and Feria, V. A., "An Inflatable Microstrip Reflectarray Concept for Ka-Band Applications", *AIAA 2000-1831, 41st AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Material Conference*, Atlanta, Georgia, April 2000.

[4]Lou, M., and Fang, H., "Development of Inflatable Antenna structures", *Proceedings of the European Conference on Spacecraft Structures, Materials & Mechanical Testing*, Toulouse, France, 11-13 December, 2002.

[5]Fang, H., Lou, M., Huang, J., Quijano, U., and Hsia, L., "Thermal Distortion Analyses of A Three-Meter Inflatable Reflectarray Antenna" *AIAA 2003-1650, will be presented at 44th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference and Exhibit*, Norfolk, Virginia, April 2003.

[6]Fang, H., Lou, M., Huang, J., Hsia, L., and Kerdanyan, G., "Inflatable Structure for A Three-Meter Reflectarray Antenna," *AIAA Journal of Spacecraft and Rockets*, Vol. 41, No. 4, pp. 543-550, July-August 2004.

[7]Fang, H., Lou, M., John H., Hsia, L., Quijano, U., Pelaez, G., Svolopoulos, V., "Development of a 7-Meter Inflatable Reflectarray Antenna," *AIAA 2004-1502, 45th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, Palm Springs, California, April 2004.

[8]Fang, H., Huang, J., Quijano, U., Knarr, K., Perez, J., Hsia, L., "Design and Technologies Development for an Eight-Meter Inflatable Reflectarray Antenna", *AIAA-2006-2230, 47th AIAA/ASME/ ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, Newport, Rhode Island, May 1-4, 2006.

[9]Huang, J., and Pogorzelski, R. J., "A Ka-Band Microstrip Reflectarray with Elements Having Variable Rotation Angles," *IEEE Trans. On Antennas & Propag*. Vol. 46, May 1998, pp. 650-656.

[10]Han, C., Huang, J., and Chang, K., "A high efficiency offset-fed X/Ka-dual-band reflectarray using thin membranes," *IEEE Trans. Antennas Propagat.*, vol. 53, pp. 2792-2798, Sep. 2005.

[11]Fang, H., Lou, M., Hsia, L., and Leung, P., "Catenary system for Membranes structures", *AIAA 2001-1342, presented at 42nd AIAA/ASME/ASCE/AHS/ ASC Structures, Structural Dynamics, and Materials Conference and Exhibit*, Seattle, WA, 16-19 April 2001.

[12]Salama, M., Fang, H., and Lou, M., "Resistive Deployment of Inflatable Structures Using Velcro," *AIAA Journal of Spacecraft and Rockets*, Vol. 39, No. 5, pp. 711-716, September-October 2002.

[13]Kevin Knarr, "Development and Ground Verification for an In-Space Large Deployable Antenna," *Master Thesis, Department of Mechanical Engineering, California State University at Los Angeles,* June 2007

[14]Suzuki, Y., Tani, K., and Sakuhara, T., "Development of a New Type Piezoelectric Micromotor," *Sensors and Actuators*, 2000, Vol. 83, pp.244–248.