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THE DEVELOPMENT OF LARGE INFLATABLE ANTENNA FOR DEEP-SPACE COMMUNICATIONS

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ABSTRACT

NASA/JPL's deep-space exploration program has been placing emphasis on reducing the mass and stowage volume of its spacecraft's high-gain and large-aperture antennas. To achieve these goals, the concept of deployable flat reflectarray antenna using an inflatable/thin-membrane structure was introduced at JPL several years ago. A reflectarray is a flat array antenna space-fed by a low-gain feed located at its focal point in a fashion similar to that of a parabolic reflector. The reflectarray's elements, using microstrip technology, can be printed onto a flat thin-membrane surface and are each uniquely designed to compensate for the different phase delays due to different path lengths from the feed. Although the reflectarray suffers from limited bandwidth (typically < 10%), it offers a more reliably deployed and maintained flat "natural" surface. A recent hardware development at JPL has demonstrated that a 0.2mm rms surface tolerance (1/50th of a wavelength) was achieved on a 3-meter Ka-band inflatable reflectarray. Another recent development, to combat the reflectarray's narrow band characteristic, demonstrated that dual-band performance, such as X- and Ka-bands, with an aperture efficiency of above 50 percent is achievable by the reflectarray antenna.

To mechanically deploy the antenna, the reflectarray's thin membrane aperture surface is supported, tensioned and deployed by an inflatable tubular structure. There are several critical elements and challenging issues associated with the inflatable tube structure. First, the inflatable tube must be made rigidizable so that, once the tube is fully deployed in space, it rigidizes itself and the inflation system is no longer needed. In addition, if the tube is penetrated by small space debris, the tube will maintain its rigidity and not cause deformation to the antenna structure. To support large apertures (e.g. 10m or beyond) without causing any buckling to the small-diameter inflatable tube during vibration, the tube, in addition to rigidization, is also reinforced by circumferential thin blades, as well as axial blades. Second, a controlled deployment mechanism, such as by using Velcro strips, must also be implemented into the system so that, for very large structures, the long inflatable tubes can be deployed in a time-controlled fashion and not get tangled with each other. Third, the thermal analysis is another critical element and must be performed for the tube design in order to assure that the inflated tube, under extreme space thermal conditions, will not deform significantly. Finally, the dynamic vibration analysis must also be performed on the inflatable structure. This will investigate the response of the structure due to excitation introduced by the spacecraft maneuvering and thus determine any necessary damping.

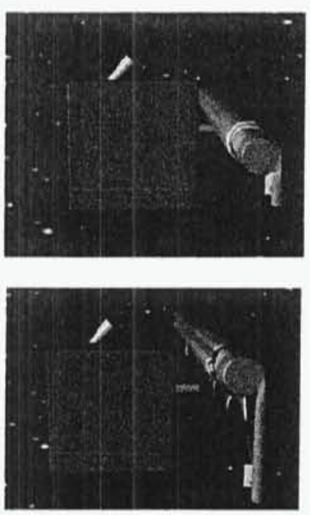
Several reflectarray antennas have been developed at JPL to demonstrate the technology. These include an earlier 1-meter X-band inflatable reflectarray, a 3-meter Ka-band inflatable reflectarray, a half-meter dual-band (X and Ka) reflectarray, and the current on-going 10-meter inflatable structure development. The detailed RF and mechanical descriptions of these antennas, as well as their performances, will be presented during the conference.

INTRODUCTION

With the advancing of space sciences, larger and larger apertures with very low launching masses and volumes are demanded by space scientists for future missions. Space inflatable technologies will revolutionize future space structures and make satisfaction of these demands possible. Inflatable structures used as supporting structures have been extensively investigated recently[1]. Major challenges include controlled deployment, space rigidization, dynamic modeling and simulation, etc. This paper will discuss the mechanical design and development of an inflatable Ka-band (32 GHz) reflectarray antenna[2]. The Radio Frequency (RF) component of this type of antenna is a flat membrane with hundreds of thousands of copper patches. The membrane is supported by an inflatable/self-rigidizable frame structure. Booms of the inflatable/self-rigidizable structure can be flattened. The flattened booms are will be difficult to protect thermally from extremely cold temperature in space. Vibration of the feed supporting struts is another drawback of this design. RF blockage introduced by feed supporting struts is also a drawback of this design. On the other hand, space rigidization is necessary for future real space missions. This configuration cannot easily accommodate currently available rigidization technologies.

INFLATABLE/SELF-RIGIDIZABLE REFLECTARRAY ANTENNA

In order to increase the readiness level for space application, a design trade study for the three-meter inflatable reflectarray antenna has then been conducted[7]. The "movie screen with offset feed array" was identified to be the best candidate for the reflectarray antenna structure. Based on the results of the design trade study, a new inflatable/self-rigidizable "movie screen" reflectarray antenna has been developed. The feed of this unit is offset located on the spacecraft and the reflectarray surface is deployed up by two inflatable booms. Figure 3 demonstrates the deployment process of the "movie screen" antenna. The inflation deployment process only involves the unrolling and pressurization of two inflatable booms. Compared to other mechanically deployed antennas, many fewer moving parts are employed by the inflatable structure. Fewer parts not only means less weight and less development cost, it also implies better deployment reliability.



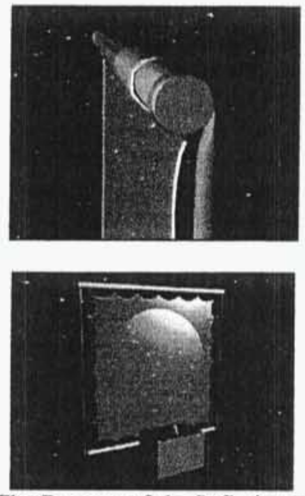


Figure 3. The Process of the Inflation Deployment

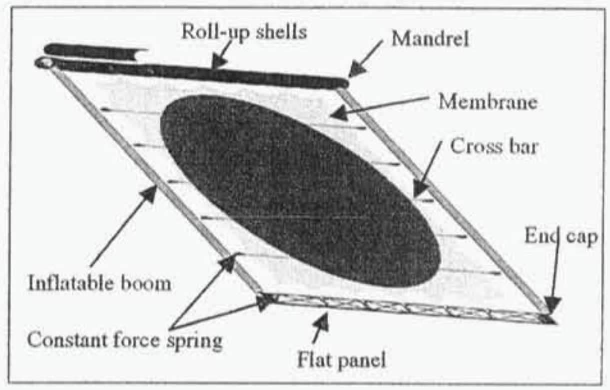


Figure 4. Schematic of the "Movie Screen" Inflatable Reflectarray Antenna

Figure 4 is the schematic of the "movie screen" inflatable reflectarray antenna. Major components include inflatable booms, RF membrane, flat panels, roll-up shells, cross bars, constant force springs, mandrels, end caps, catenary systems, etc. Detailed design consideration of each component will be discussed in the following.

a) Inflatable/self-rigidizable boom technology

There is a major advantage of the "movie screen" antenna over the "horse-shoe" antenna. The "movie screen" antenna employed inflatable/self-rigidizable technology while the "horse-shoe" antenna only used inflatable technology without the rigidization.

Technically, the word "inflatable" means the structure is deployed by pressurization. After a structure is deployed, pressure still has to be kept inside the structure to maintain the rigidity of the structure. Due to the material imperfections and/or small damages caused by micro-meteoroids, small leaks are unavoidable. Large amount of make-up gas has to be carried to the space for a long-term mission, which is very costly or even not feasible at all.

With the development of space inflatable technologies, space rigidization is becoming a major research topic. Space rigidization in inflatable/rigidizable structure implies that a structure is rigidized upon the completion of its inflation deployment.

A new inflatable/self-rigidizable method, namely the Spring Tape Reinforced (STR) aluminum laminate boom, has been developed by this research for the "movie screen" antenna[8]. Compared to other rigidization technologies, the STR aluminum laminate boom automatically rigidizes after it is deployed with no space power, no curing agent, and no rigidization system required. Therefore, it is called self-rigidizable technology. Figure 5 is the buckling test set up of an STR aluminum laminate boom. Figure 6 is a picture of a 5-meter long STR aluminum laminate boom, which is rolled up on a 6.5 inch diameter mandrel. A typical STR boom consists of a tube that is formed with aluminum laminate. Four spring tapes are attached to the inside wall of the tube in axial direction. At this time, the commercially available stainless steel measuring tapes, commonly known as carpenter tapes, are used. With a wall thickness less than 0.1 mm, an STR boom can be easily flattened, rolled-up (or folded-up), and deployed by a relatively low inflation pressure. The buckling capability of an STR aluminum laminate boom is significantly improved mainly due to the high modulus of elasticity and curved cross-sectional profile of the spring tapes. The length of a STR boom can consequently be significantly increased. It should be pointed out that spring tapes are very effective in resisting inward buckling and the aluminum laminate wall is very stable in resisting outward buckling. Therefore, these two components effectively complement each other in resisting local crippling of the boom. In addition, unlike the non-reinforced aluminum laminate booms, an STR aluminum laminate boom relies on the reinforcing tapes, not pre-strain induced by high internal pressure, to attain its post-deployment stiffness. The required inflation pressure for an STR aluminum laminate boom is relatively low. Several 5-meter long, 7.6-centimeter diameter booms have been assembled and tested. The weight of each boom is only 0.9 kilogram. The axial buckling load carrying capability of this kind of boom can reach 74 kilograms (with pin-pin boundary conditions).

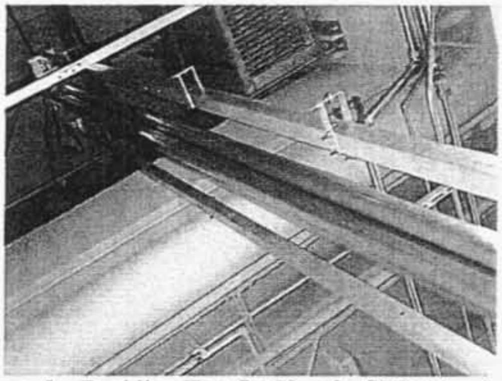


Figure 5. Buckling Test Set Up of a STR Aluminum Laminate Boom

Figure 6. A 5-Meter Long STR Aluminum Laminate Boom Rolled Up on a 6.5 Inches Diameter Mandrel

b) RF membrane

The most important component of the antenna is the RF membrane. The large circular portion of the membrane carries RF patches (approximately 200,000 patches). Figure 7 gives the close-up view of the RF patches. Membrane around the RF section is used to connect the RF area to the catenary system, which is attached to the supporting structure by constant force springs. The whole supporting structure is only designed to hold the membrane, to stretch the membrane, to avoid wrinkles on the membrane, and to keep the flatness of the membrane.

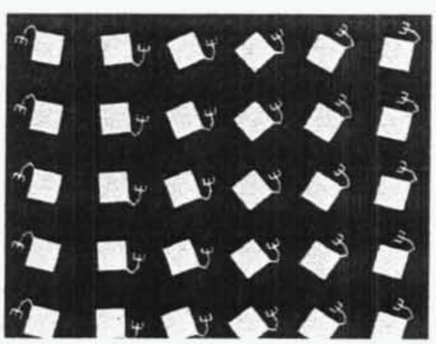


Figure 7. Close-up of the RF Patches

Because of the unavailability of large-size membrane material, the RF aperture is assembled from seven-strips of membranes. Each membrane strip consists of 5-mil thick Kapton with 5 micrometer copper completely cover one side to serve as ground plane and many etched square patches (also 5-micrometer copper) on the other side to serve as reflectarray elements. Originally we used two-inch width double-sided adhesive tape to join two strips and the double-sided adhesive tape was coved by a four-inch width Kapton adhesive tape. However, creeps were observed along the seams one year after the assembling of the membrane. Creeps degraded the accuracy of the dimension and geometry, which can significantly impact the antenna performance.

In order to resolve the creeping problem, a new method was developed to bind the seven strips of membrane together. This method uses flexible epoxy, which made the membrane stronger with no creeping and kept the geometry intact. According to the results from the seam tests, the flexible epoxy adhesive chosen is 3M Scotch-weld two-part Epoxy adhesive (2216 B/A Gray). Adhesive is applied to the bounding area of the membrane and this area is then patched by four-inch width copper coated Kapton strip. The reason for using copper coated Kapton instead of clear Kapton is that it is easier to find adhesive to bind two metallic surfaces than to bind a metallic surface with Kapton.

c) Catenary system

A catenary system, which is composed of tensioning cord around the membrane, is used to attach the membrane to the structure and to uniformly tension it. Based on the required stress density (90 psi), the curvature of the catenary is calculated as a parabolic curve[9]. Tubing is attached to the edges of the membrane. A string inside the tubing is used to connect the membrane to the supporting structure. The string can freely slide inside the tubing. Figure 8 shows the catenary system. The tensioning cord is pulled by constant-force springs, which are connected either to cross bars or to flat panels.

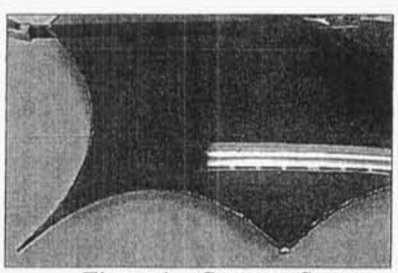


Figure 8. Catenary System

d) Constant force springs

The string of the catenary system is connected to 24 constant force springs (10 on cross bars and 14 on flat panels). Since a constant force spring provides a constant pulling force, the tension on the membrane does not depend on the elongation of the spring, the elongation of the springs does not have to be accurately adjusted. The use of the constant force springs is not only convenient but also necessary. When the antenna experiences substantial temperature changes in the space, the supporting structure and the membrane will expand or contract differently. Because of the constant force springs, stress distribution in the membrane will not be affected by temperature changes in the space. These springs are used to insure the stress distribution required for the membrane. Figure 9 shows how a constant force spring is attached to a flat panel.

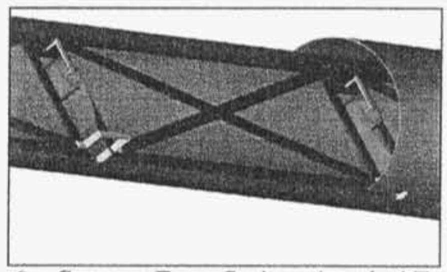


Figure 9. Constant Force Springs Attached To a Flat Panel

e) Flat panel

Two flat panels are used at two ends of the antenna. They are made of carbon fiber material and the material has been removed as much as possible to minimize the weight. Figure 10 shows the picture of a flat panel attached by constant force springs. Flat panels are located inside the roll-up shells. Flat panels have two functions. The first one is to provide attachment points for constant force springs. The second one is to resist bending loads created by constant force springs.

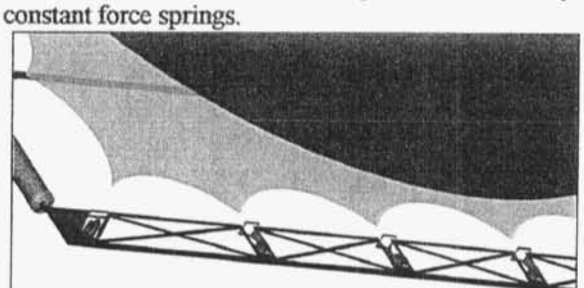


Figure 10. Flat Panel Attached By Constant Force Springs

f) Roll-up shells

Flat panels are covered by roll-up shells and figure 4 shows the roll-up shells. The carbon fiber roll-up shells have two functions. One is to provide a surface for the RF membrane to be tightly rolled upon, so the thin membrane will be able to survive the launching impact. These shells also act as structural members to provide bending and compression stiffness.

g) Cross bars

Due to the reason that inflatable booms cannot take much bending loads, cross bars are employed as compression members to stretch the RF membrane. Each cross bar is made of carbon fiber tubing with an aluminum bracket at each end of the cross bar. Figure 11 shows how a constant force spring is installed on the aluminum bracket and connected to the cross bar. Cross bars can be rolled up onto roll-up shells with the membrane.

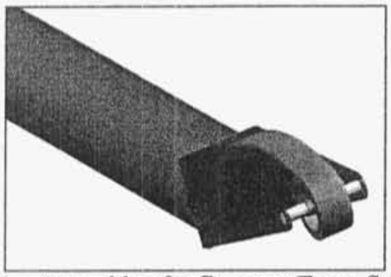


Figure 11. Assembly of a Constant Force Spring and a Bracket to the Cross Bar

h) Mandrels

Mandrels have two functions. The first one is to connect inflatable booms to flat panels and roll-up shells. Figure 12 shows how a mandrel is connected to an inflatable/self-rigidizable boom and a flat panel.

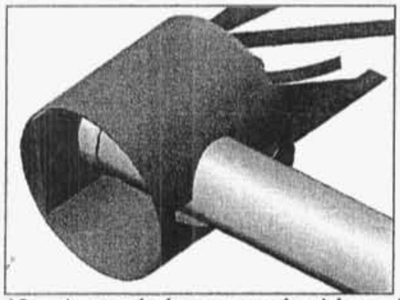


Figure 12. A mandrel connected with an inflatable boom and a flat panel

The second function is to provide circular surfaces for inflatable booms to roll up. It is found[8] that the axial buckling capability of an inflatable/rigidizable boom after it is deployed is associated with the diameter of the mandrel while it is packaged. A mandrel is necessary to maintain the diameter of the bundle to avoid the boom damage caused by the packaging.

i) End caps

End caps serve two purposes, they are used to connect the booms to the structure and keep pressure inside inflatable/self-rigidizable booms during the deployment. Each end cap is composed of outer cap, inner cap, and o-rings. Both inner cap and outer cap are machined out of aluminum. Inner cap and outer cap are pulled together by a single bolt, which causes the o-rings to expand in the radial direction and press the boom skin against the walls of the outer cap. The end caps have been tested up to 25 psi and they remained airtight. Figure 13 demonstrate how an end cap is assembled to the boom.

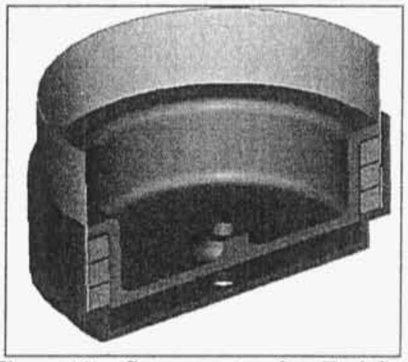


Figure 13. Components of an End Cap

j) Launch constraining system

During the launch, the antenna has to withstand high acceleration, vibration, and acoustic impact. In order for the antenna to survive the launch, a constraining system is essential to hold the packaged antenna. The launch constraining system is composed of two half-circle lightweight shells. When these two shells are closed, the packaged antenna is constrained. After these two shells open up, the antenna can freely deploy. Figures 14 demonstrates how this launch constraining system works.

Figure 14. Schematic of the launch constraining system

DYNAMIC ANALYSIS

The structure of the antenna is relatively large and flimsy. The dynamic characteristics of the inflatable/self-rigidizable structure have been questioned. In order to investigate the response of the structure to the excitation introduced by the spacecraft maneuvering, a finite element model has been made and the dynamic response analysis has been conducted. The membrane itself has very little out-of-plane bending stiffness. The out-of-plane stiffness of the membrane is from the pretensioning. It is a function of the membrane stress distribution and is called differential stiffness. Therefore, the dynamic response analysis of a membrane structure has three steps[10]. The first step is the static analysis to obtain the stress distribution, the second step is the modal analysis, and the third step is the response analysis.

A finite element model with 568 nodes and 622 elements was assembled. The finite element software NASTRAN was used for the analysis. First of all, static analysis was performed to simulate the tensioning of the membrane and to obtain the differential stiffness. Stress distributions both in x direction (from left to right of the membrane) and y direction (from bottom to top of the membrane) were calculated and they were within the range of +/- 1 psi of the 90 psi (90 psi is design goal). Modal analysis, incorporating differential stiffness induced by pretension of the membrane, was also performed. Figure 15 gives the first mode shape of the antenna.

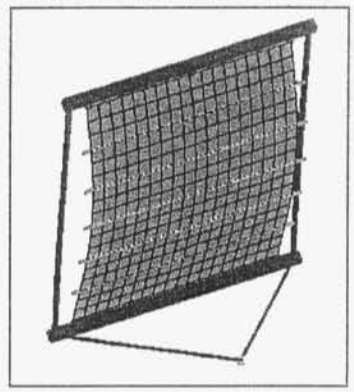


Figure 15. First Mode Shape

After the modal analysis, transient analysis was conducted. 1% critical damping, which was reduced from dynamic test result of the inflatable/self-rigidizable boom, was used for the analysis. 0.1-G step-function disturbance (lasting for two seconds) from spacecraft attitude control was used as the excitation force. Figure 16 gives the responses of the membrane center as well as the spacecraft. It is concluded that the disturbance from spacecraft attitude control can induce displacement of up to 0.065 centimeter at the center of the membrane. 0.065 centimeter is about 0.07 of the wavelength and can cause 0.2 dB gain loss. It can also be concluded from Figure 16 is that the membrane motion will decay (i.e., be damped out) to less than 0.025 centimeter (0.027 wavelength; near-zero gain loss) in 18 seconds.

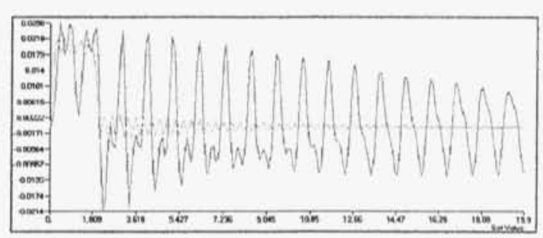


Figure 16. Transient Analysis Results

DEMONSTRATION OF THE DEPLOYMENT

One of the most important tasks of this study is to use the engineering model to demonstrate the deployment process of this configuration. Figures 17 and 18 are pictures of the antenna in stowed configuration (without the launching constraining system).

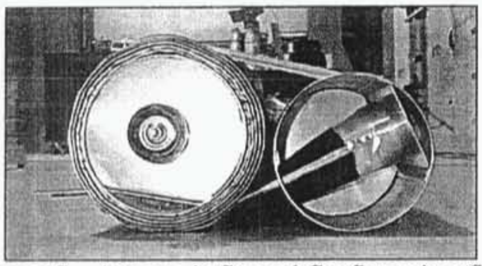


Figure 17. Antenna in Stowed Configuration (Side View)

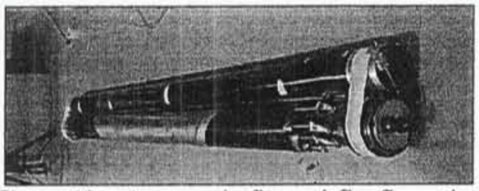


Figure 18. Antenna in Stowed Configuration

When the antenna is in its deployed configuration, the membrane is stretched by constant force springs that lengthen about two inches. However, springs are not lengthened when the antenna is packaged. During the deployment, inflatable booms would have to stretch springs to their extended length before booms are fully deployed if a pre-holding system were not provided. Because the inflation pressure is very low (less than 5 psi), inflatable/self-rigidizable booms are unable to take loads before they are fully deployed. These spring loads on the booms during the deployment process prevent the success of the deployment. Therefore, a constant force spring pre-holding system has been developed to guarantee a successful deployment.

This system is composed of two major components corresponding to two flat panels. There are two flat panels, one is stationary and another one is rotating during the deployment. The first component is a controllable string. While the antenna is in stowed configuration, all constant force springs attached to the stationary flat panel are lengthened and held by this string. As a result, these spring forces are disconnected from the membrane and inflatable booms can be deployed without any spring forces.

Every spring on the flat panel, which is rotating during the deployment, is held in position by a string attached to a locking pin. Figure 19 shows the schematic of this mechanism. The pin is placed in two brackets. The pin is pulled toward the walls of brackets by the string and is held in place by friction. When the membrane stretches the spring, the load on the pin as well as the friction force are removed. The locking pin is pulled out by a small locking spring. The locking spring has to be a soft spring so the pin cannot be self-removed when it is held in place by the friction force.

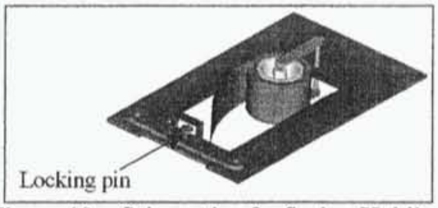


Figure 19. Schematic of a Spring Holding Mechanism

After the booms are fully deployed, the controllable string attached to the stationary springs is released and spring forces are loaded on to the membrane. This starts the membrane moving toward the stationary flat panel and stretches the springs on the rotating flat panel. Consequently, locking pins on the rotating flat panel are triggered and popped out. Constant force springs on both flat panels are thus loaded directly to the membrane.

In order to have a smooth deployment, a structure was designed and built to support the antenna and eliminate some of the gravitational effects during deployment. This supporting structure is composed of two tracks and five pairs of moving arms as shown in figure 20. Every moving mandrel is attached by a roller and the roller rotates on the track to eliminate resistance during the deployment as demonstrated by figure 21. Five pairs of arms were originally in a lower position. During the deployment, each pair of arms opens up to support one of the cross bars right after that cross bar separated from the bundle. Arms are actuated by pneumatic cylinders.

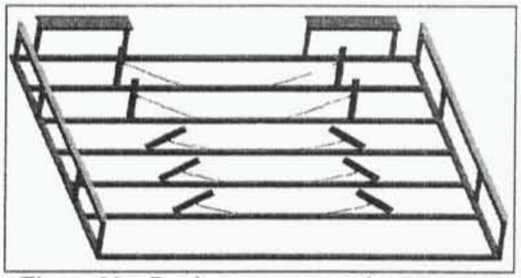


Figure 20. Deployment supporting structure

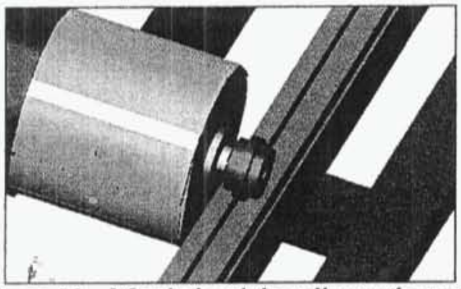


Figure 21. Mandrel and the roller on the track

Several deployment tests were successfully conducted and figures 22 show the process of the deployment, from packaged to fully deployed.

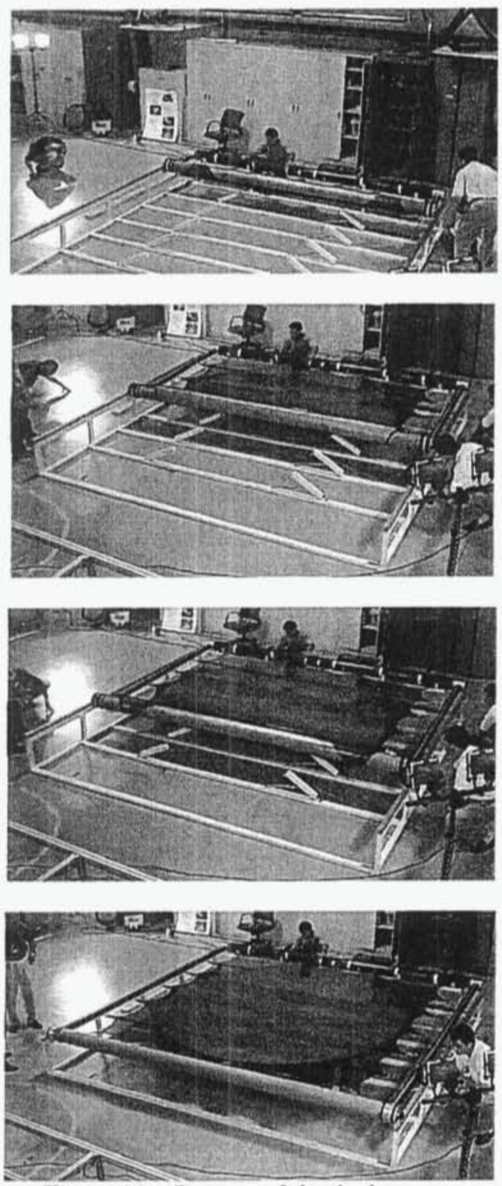


Figure 22. Process of the deployment

LARGE ANTENNA WITH A 10M BOOM

Currently, a 7 to 10-meter-aperture inflatable X/Ka dual-band reflectarray is being developed. The X-band is intended for robust uplink control and command signals, while the Ka-band is for high data rate downlink transmission. Smaller antenna models (0.5-meter) have recently demonstrated that X/Ka dual-band reflectarray with thin membranes is technologically feasible [11] by using annular rings as elements. This is illustrated in Fig. 23 where the large X-band rings are placed on top of the small Ka-band rings. Both ring elements are printed on 0.13mm-thick membrane materials.

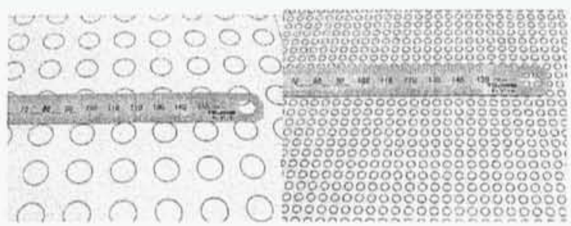


Figure 23. Reflectarray ring elements on thin membranes, X-band rings on the left and Ka-band rings on the right

Another on-going technology development is a 10-m long inflatable boom. In order to support and tension the large 7 to 10m membrane aperture, inflatable booms much stronger than the previous 3m structure are needed. This 10m boom, as illustrated in Fig. 24, using similar stretchable aluminum technology, has a diameter of 25cm and uses both axial and circumferential reinforced tapes. This boom, which is still being developed, will undergo vibration, buckling, and thermal tests to assess its strength.

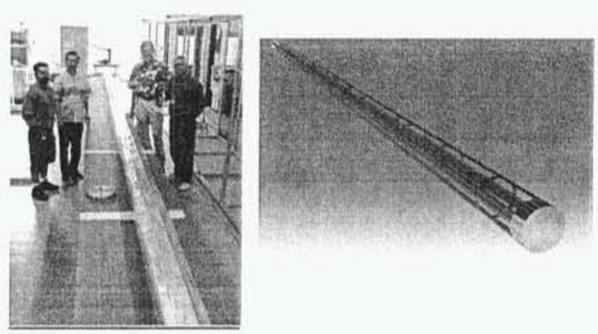


Figure 24. 10m-long inflatable boom with axial and circumferential reinforced tapes

FUTURE TASKS

In order to make the inflatable/self-rigidizable reflectarray antenna ready for space missions, several tasks remain to be accomplished. A few important tasks that have been planed for the near future are briefly discussed below.

The first task is the structural thermal distortion investigation. The space thermal environment is very harsh and could distort the inflatable structure. Consequently, it could degrade the flatness of the FR membrane. Therefore, the structural thermal distortion needs to be studied. The second task is studying the effects of damping on antenna's dynamic responses to spacecraft maneuvering. The sensitivities of damping locations will be investigated and extra damping will be applied to those most effective places. The third task is performing in-space deployment dynamics analysis. Due to the gravity, deployment test of a large inflatable space structure on the Earth is very difficult and costly. Deployment dynamics analysis is therefore a necessary task for a space mission. Certainly, the analysis and test of the 10m inflatable boom and the whole antenna structure also remain to be completed in the near future.

CONCLUSIONS

For a space mission, the launch cost is always a significant portion of the life-cycle cost. Launch cost is usually directly proportional to the launch volume and mass. Space inflatable technology is one of the emerging space technologies that can potentially revolutionize the design and applications of large space structural systems.

This paper presented the development of an inflatable structure for a three-meter Ka-band reflectarray antenna. This development took three stages. The first stage was a one-meter X-band inflatable antenna. The second stage was a three-meter (horse-shoe) Ka-band inflatable antenna. The third stage was a three-meter (movie screen) inflatable/self-rigidizable Ka-band antenna. Detailed design of the "movie screen" antenna as well as functions of each major component have been discussed. Dynamic response analysis of the antenna to the spacecraft maneuvering has been presented. The deployment test has also been exposed. The "movie screen" antenna used an inflatable/self-rigidizable technology so that any small leaks caused by materiel imperfection as well as micrometeoroids impact would not affect the membrane performance and inflation air is no longer needed once the antenna is inflated. Future remaining important tasks for the development of the inflatable reflectarray antenna have also been discussed.

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