Testing of an Inflation-Deployed Sub-Tg Rigidized Support Structure for a Planar Membrane Waveguide Antenna

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L'Garde, Langley Research Center, and Georgia Technical Research Institute have accomplished much in the area of planar membrane waveguides. A waveguide offers a method of providing transmit/receive communications for spacecraft. The advantage of the planar membrane waveguide concept, in addition to its lightweight and low packaged volume, is its inherent shape. Relative to parabolic antennas, the requirement to make an accurate doubly curved surface is removed. This paper summarizes the development of a lightweight waveguide structural technology utilizing inflation-deployed sub-Tg rigidization methods to provide a complete gossamer antenna system. The purpose of this investigation was to advance the readiness level of the inflatable planar support structure. This work summarizes the design, analysis, testing, and fabrication of an inflation-deployed rigidized support structure for the waveguide array thus advancing the gossamer antenna system. Work includes breadboard testing of component level struts, stiffness measurements of struts, and deployment testing of a prototype system. Testing included shape and dimensional performance measurements under ambient conditions. Photogrammetry results show a planar surface accuracy of 0.84 mm RMS for the sensing area of the waveguide and 1.50 mm RMS for the structure. The result is an advanced system ready to move to the next phase. The new structural technology will lend itself to a wide range of applications.

I. Introduction

With today's high launch costs and tightening launch opportunities, low payload mass, cost, and packaged volume can determine mission feasibility. L'Garde had developed the core IPSS structure design to alleviate these constrictions and open new opportunities.

The core IPSS structural configuration with low mass and stowage volume is an excellent solution for these several structural applications. New technologies have been developed at L'Garde that show great promise to significantly enhance the already competitive inflatable technology by addressing two key areas -- scalability and deployment control. Using new sub-T_g rigidization material technologies and a novel conical strut deployment technique, we developed an enhanced configuration over previous inflated structures exhibiting improved deployment dynamics and allowing scale-ups for more demanding mission applications. The result is an ultra low mass and low stowage volume design able to enhance the effectiveness and lower the cost of future spacecraft.

The performance requirements for this effort were open ended with "best performance" as the target. The structural strength and natural frequency of the design drives the performance parameters when considering any design. From this, the performance and cost factors emerge. These factors include mass of the system and volume of the packaged system.

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To analyze this configuration L'Garde developed a software tool to size structural components with given design inputs. The inputs of interest are the orbital maneuvering loads, the desired natural frequency, and the power of the system. The outputs are structural safety factors, system mass, center of gravity, and specific power.

Representative booms have been designed, fabricated, and tested in the laboratory environment for several programs at L'Garde. The conical boom is considered by L'Garde as state of the art technology. A laboratory test deployment is shown in Fig. 7. The sequence is shown from fully packaged on the left to deployed on the right.

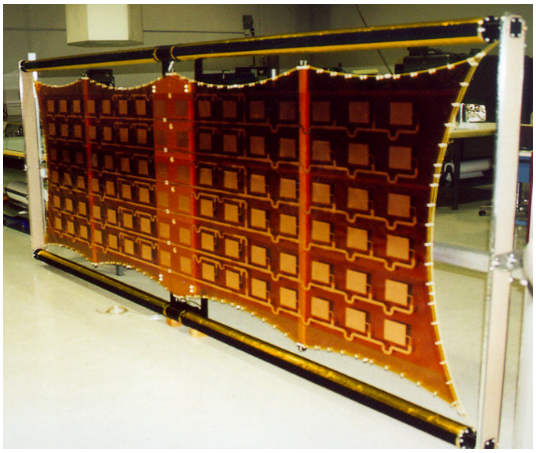

Figure 1. L'Garde's Aluminum Laminate Tube Structure for SAR Membrane Systems

II. Design Evolution

A. Background

The IPSS structural configuration was conceived as an offshoot from the Synthetic Aperture Radar (SAR) program[1] where a roll out aluminum laminate structure was used to tension a planar membrane SAR antenna, see Figure 1. The initial conceptual work for the IPSS was conducted under a SBIR Phase I program, in which a feasibility study was conducted. Subsequently a Phase II effort refined this design, performed FEA and structural calculations, generated detailed drawings, fabricated the hardware and tested the components producing a prototype system. This phase included a successful system deployment at ambient conditions and a successful component test at thermal conditions.

The new IPSS design offers advantages over the SAR roll-out aluminum structure by replacing the aluminum laminate rigidization technology due to it suffering from two weaknesses that limit its applicability. The first is scalability. Tests at L'Garde have shown that the aluminum laminate technology is wall thickness limited due to packaged constraints. Because of this, larger structures that require greater structural strength simply can not provide the necessary structural margin necessary. The second limitation of the aluminum laminate concept is few deployment control options. The best ways to stow aluminum laminate tubes for deployment is "z-folding" or "rolling" which provide little deployment control. For larger configurations, a more controlled deployment is desirable. To address these weaknesses and improve the applicability of the IPSS concept, a sub-T_g rigidizable material with a conical boom deployment technique was utilized.

B. Sub-T_g Rigidization

Sub-T_g or cold rigidization takes advantage of the stiffening of certain materials at specific temperatures to achieve structural strength. Instead of thin aluminum, the material is made up of a specialized composite weave utilizing strong, lightweight fibers impregnated with a specialized L'Garde-developed elastomer. Though called "cold rigidizable," they don't necessarily require cold temperatures. Elastomers can be formulated which rigidize at temperatures tailored to specific mission requirements. Cold rigidized structures can be constructed for a variety of missions, from LEO to deep space.

Cold rigidizable structures are simple and reliable. They are completely passive and in general require only moderate heating to soften the material for deployment. However, since their rigidization depends on temperatures below their T_g, a thorough understanding of the thermal environment is required. Ideally, an elastomer is selected with a glass transition temperature above the equilibrium temperature of the spacecraft during operation. After inflation and deployment, outside the spacecraft's thermal environment, the structure cools and becomes rigid. As an example, for a 1000 km orbit altitude- thermal analysis shows that after a few orbits, the temperature will have fallen to about -60°C. The thermal loadings were obtained from TRASYS[4] and the temperatures were calculated using SINDA.[5] Current matrix T_g formulations include +50C, +20C, 0C, and –20C to meet the peak temperature requirements that would be seen on a variety of missions.

Cold rigidizable materials do not suffer from the scalability issues affecting the aluminum laminate rigidization concept. They are not as limited in thickness and can be deployed and packaged reliably in larger thicknesses. Commonly used structural fabrics are graphite, Kevlar, PBO, and glass. The matrix is a thermoplastic elastomer tailored to be space hazard resistant and become rigid below a designed temperature. The material is completely passive, reversible, and in general requires only moderate heating to soften for deployment if the spacecraft environment is below the composite T_g. This is a low power option to thermosetting plastics.

C. Conical Deployment

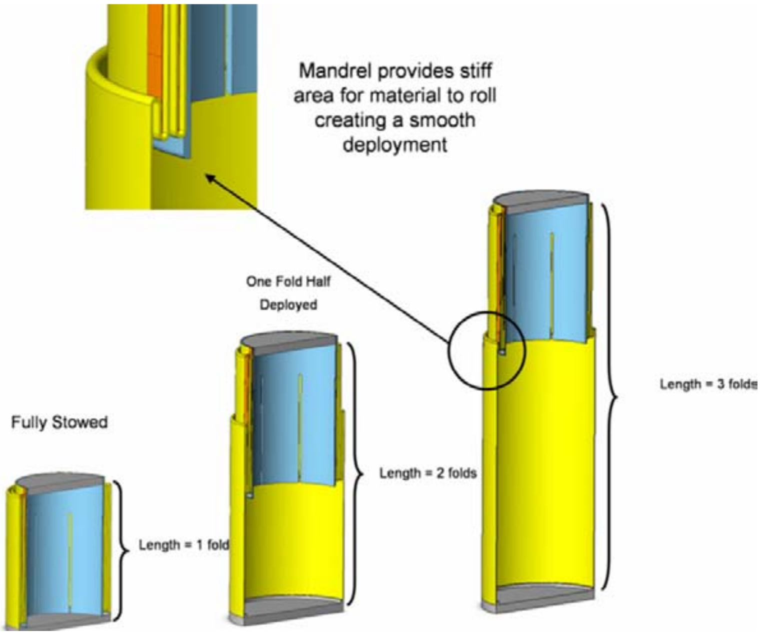

Figure 2. Conical Deployment Sequence

Inflatables are quite robust when it comes to deployment. Properly designed inflatables require minimal control during inflation to reach their final configuration. Mission and spacecraft constraints become the driving requirement for additional control of the inflation and deployment. Figure 2 shows the conical strut packaging and deployment scheme. It uses a unique concentric packaging arrangement about the strut axis and provides a high degree of deployment control. In this method, a tapered tube is packaged in a manner similar to a telescoping tube.[3] L'Garde conceived and patented this method for applications requiring highly controlled struts and is an offshoot from our decoy work in the 70's. Because there is a very low mass associated with the deployment control method, it scales very well both up and down in size and provides excellent packaging efficiency. To deploy the conical strut, inflation gas is introduced at the base. Pressure is exerted against the walls of the tube, the tip, and base end caps. The inflation pressure squeezes the walls against the outer folds and also unfolds and deploys the leading folds.

The typical material used for this technology was tested and yielded excellent results. To predict the performance of the laminate, laboratory tests were conducted on L'Garde's proprietary sub-T_g resin. After subsequent repackaging and deployment, little change was seen in the stiffness of the strut. This allows the same article to be tested and reused for a ground-based qualification program.

III. Current Design Description

A. Structural Design

The IPSS system design is comprised of inflation-deployed struts creating a picture frame structure capable of accepting loads at the corners as shown in Figure . The struts are telescoping, thin-walled, conical tubes that when inflated deploy the IPSS system. The waveguide is a flexible, thin film structure thoroughly described in a previous publication.[1]

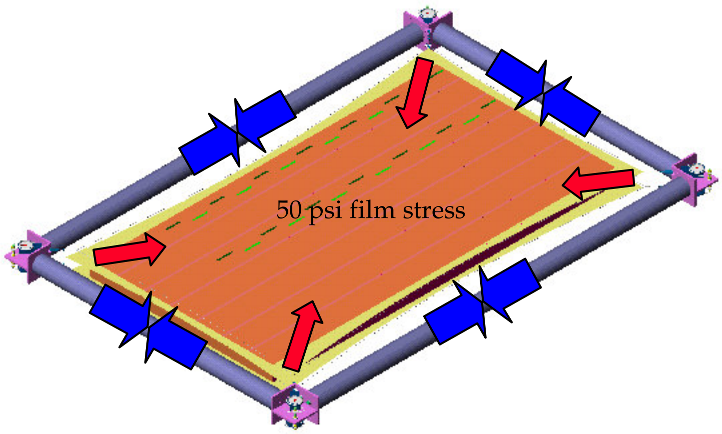

Figure 3. Load Paths for Planar Structure

In the stowed configuration, the struts are nested along their axes with alternating concentric folds as shown in the first picture of Fig. 3. The waveguide is collapsed along the cell length and serpentine folded between the stowed tubes. This stowed configuration, Fig. 4, provides exceptional packaging efficiencies and lends itself to very large aperture stowage.

To deploy the structure the first step is to energize a heater to allow the strut material to become pliable. A control system, either on the spacecraft bus or an onboard timing and control circuit would be used to monitor the strut temperature and control it above the T_g of the composite. The strut is made of a Kevlar® weave impregnated with a sub T_g resin. During deployment, the strut is always enclosed in multilayered insulation (MLI) to reduce the heat needed to make the strut pliable and minimize thermal gradients on orbit during operation.

After reaching deployment temperature, strut inflation begins. The longitudinal struts deploy sequentially as shown in Fig. 5. As the deployment reaches the end of a fold, a tieback release allows the next fold to repeat the sequence. The struts continue to deploy in this sequential fashion until all folds are extended. During deployment and until the struts are rigidized, the strut remains inflated and can carry load both in its partially and fully deployed state. The inflation system that would control the deployment rate for a flight experiment has considerable flight heritage as the L'Garde team has used it on numerous missions. After completing the longitudinal phase the lateral phase is initiated and completed in the same manner.

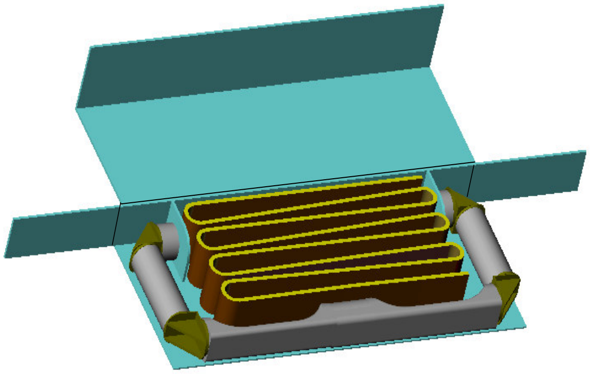
Figure 4. Stowed, the IPSS has a very efficient packing volume enabling large apertures to be utilized.

Finally, once the struts are fully extended and the waveguide is tensioned, the heater is de-energized. The inflation gas remains while the struts cool below their T_g to rigidize. Once rigid, the inflation gas is no longer required for support and is vented through a non-propulsive vent.

The sub-T_g conical struts have a robust capability for dealing with buckling phenomena. Using thicker materials mitigates local buckling effects; using larger diameters mitigates long column buckling effects. This flexibility makes the design fully scalable: other composites and resins tailored for a wide range of glass transition temperatures can be developed to fit the structural needs of a specific mission. Consequently, the free design parameters for the inflatable, rigidizable strut design are not tightly constrained and can be tailored to fit a wide variety of missions.

B. Waveguide Packaging

The first stage of the packaging was conducted on the delicate feed network incorporated onto the array. Small gaps or "hinges" were incorporated into the design in the proper location for folding. The initial folding sequence is shown in Fig. 6(a). The folds along the Waveguide to facilitate the accordion style packaging of the waveguide cells have been initiated and the folding at the hinge locations is clearly evident. Clips are utilized to hold the fold in place near the feed trace hinge lines. To facilitate support for the array during the packaging procedure a simple fixture was developed to support the cell walls during packaging. Chords are tied from the support rod to the hinge support clips to carry the weight of the cell walls during packaging.

Once the cell feed network was stowed and the cell walls were collapsed together, straps were lightly wrapped around the packaged cells to hold them together during the serpentine folding of the array, Fig. 6(b). Note the shunted end of the cells, the opposite end from the feed, are slightly fanning out toward the ends. This was required to reduce the packaging stress on the cell end caps while packaged. At this stage the array is folded back and forth in a serpentine manner to further package the array.

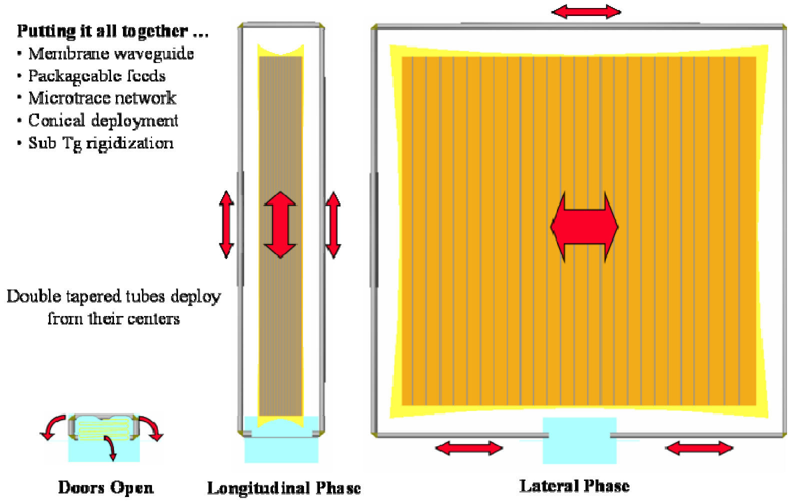

Figure 5. IPSS Deployment Sequence

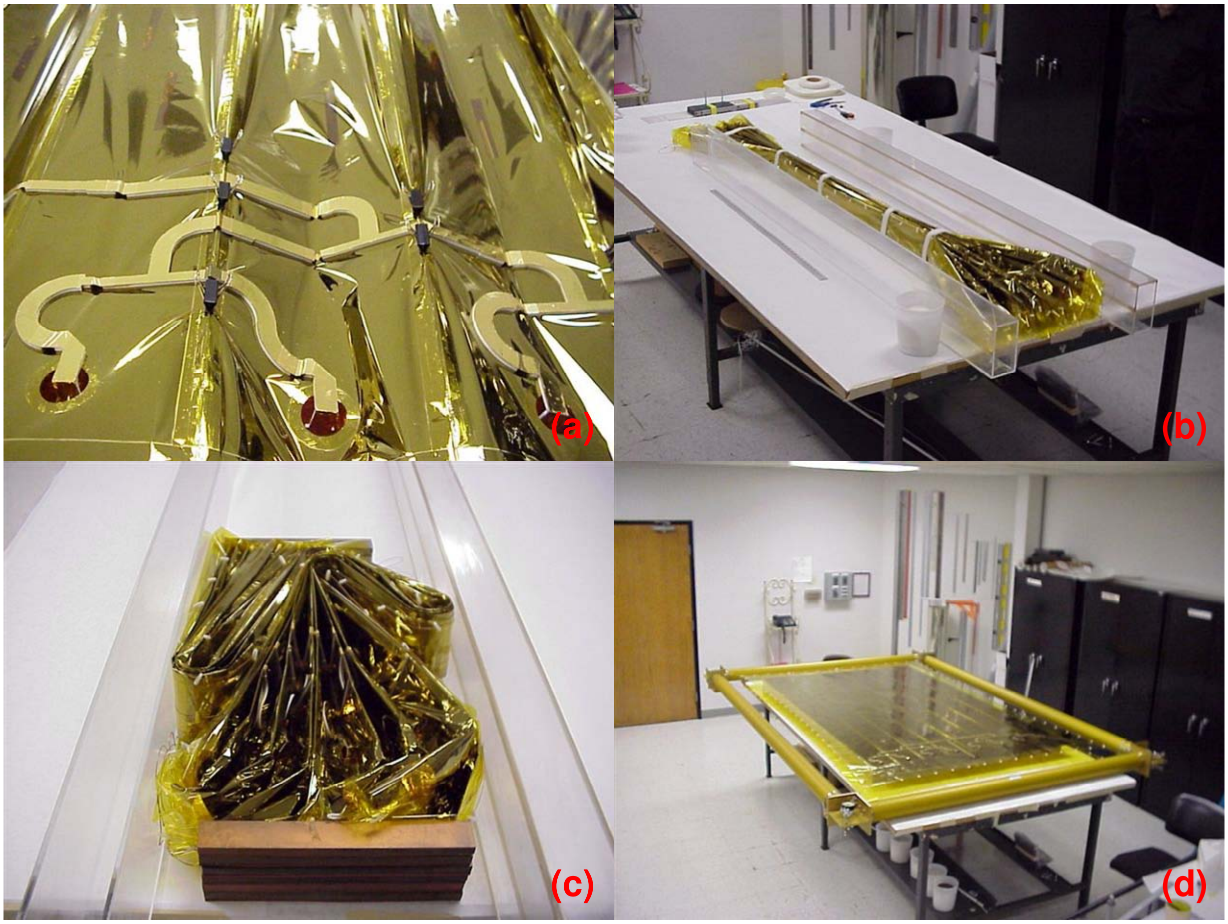

Figure 6. The Waveguide Packaging Scheme is the Reverse of the Deployment Method.

The fully stowed Waveguide Array with packaged integrated feed network is shown in Fig. 6(c). In the foreground are the packaged feeds and network. On either side are transparent plastic walls to simulate the stowage canister volume. Note that the packaged array corners are located near the corresponding corners of the canister. This array stowage arrangement will be required to locate the array corners near support structure attachment points. The prototype array stowed into a volume 0.4 m wide by 0.7 m long and 0.15 m deep. Much of this volume was required by the feed network and feeds which remain inside of the cells. Future packaging methods may include a refinement of this technique to leave the feed paddles oriented parallel to the cell walls after stowage; this will considerably reduce the volume required by the stowed array. After packaging, the array was deployed and reattached to the support structure; see Fig. 6(d).

IV. Testing Results

A. Ambient Deployment

The IPSS system was successfully deployed at ambient conditions as shown in Fig. 7 and the waveguide performed as expected. The feed showed no sign of damage and the system came to near full tension after deployment. Deployment was controlled manually and could be sequenced for an automated system when necessary.

B. Photogrammetry

Measurements were made using photogrammetry to determine the surface flatness of the waveguide. Additionally, for the IPSS measurements the corners of the structure were measured and the flatness was determined. To determine a baseline, photogrammetry was done on the waveguide while it was on the rigid structure. Matlab® was used to determine the best fit plane through points. From this it can be shown that the points are highly planar. Photogrammetry was included along the catenary (Fig. 8) but was not included in the

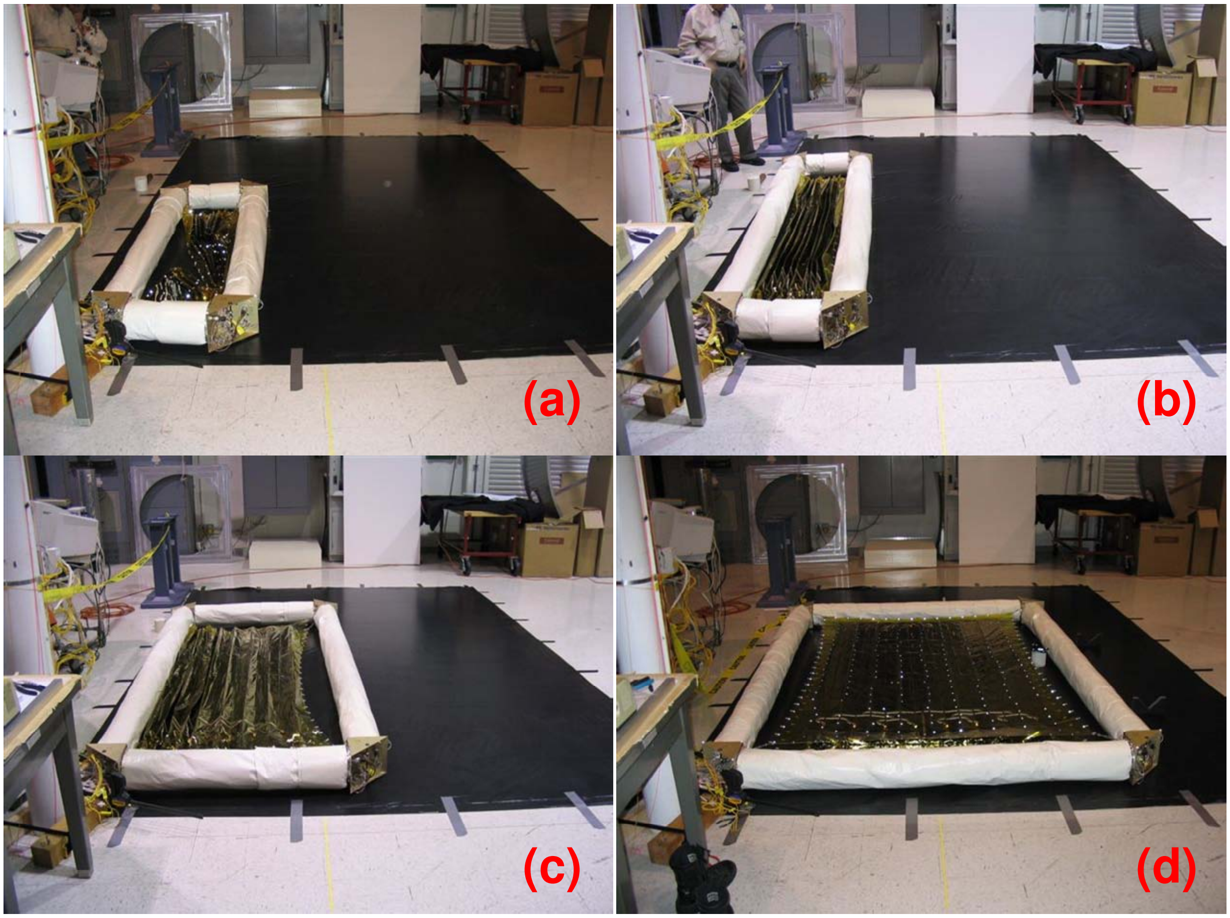

Figure 7. Ambient Deployment (a) start of longitudinal phase; (b) completion of longitudinal phase; (c) start of lateral phase; (d) completion of lateral phase.

surface accuracy calculations since they are not part of the sensing portion. Additionally the corners of the IPSS were measured and calculated in the same manner as the waveguide active area. A summary of the Root Mean Squared surface error is included in Table . From this data it is obvious how gravity severely distorts the surface accuracy by an order of magnitude from vertical to horizontal.

C. Cold Strut Deployment

A test of one strut was conducted at thermal conditions to test the uniformity of the heater design and the deployment at thermal conditions. The tube selected was the same length and cross-section as the long struts on the IPSS. The test was conducted at L'Garde in a thermal chamber designed for tube deployments and measurements. The basic test setup includes a thermal insulating box and a liquid nitrogen (LN2) distribution system.

The test article was instrumented with 16 thermocouples including 15 along the length of the strut evenly spaced along the length at 5 locations each 120 degrees apart and 1 control thermocouple at the innermost fold of the material to prevent an over temperature condition. This provided uniformity measurements around the packaged strut. The strut was also instrumented with a pressure transducer to indicate

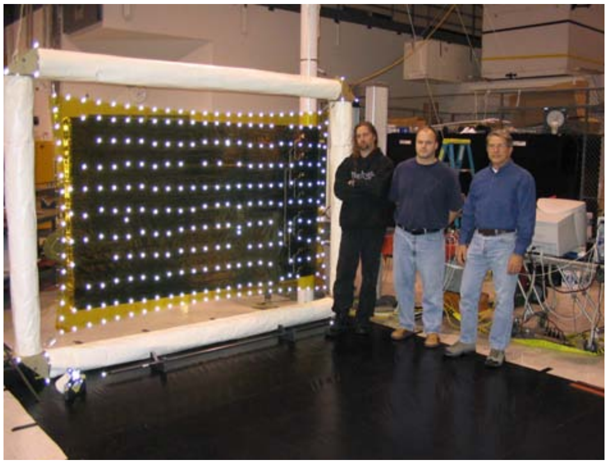

Figure 8. IPSS Inflated/Post Deployment.

Table 1. Photogrammetry Results.

	Tension (lbf)	Orientation	Area Measured	RMS Surface Error (mm)
Waveguide on Rigid Frame	12.5	Horizontal	Sensing Area	6.6090
		Vertical		0.6847
Waveguide on Assembly Jig		Horizontal		5.5346
Waveguide on IPSS low tension (post deployment)	8.9			9.8273
			Frame	1.3767
Waveguide on IPSS (post deployment)	12.5		Sensing Area	6.8377
			Frame	1.3564
		Vertical	Sensing Area	0.8382
			Frame	1.4961

the deployment pressure profile.

The strut was cooled to -40 C for the start of the test. Once at cold temperature the heater was energized and warm-up began. The strut exhibits a thermal gradient across the packaged thickness that must be thermally soaked to allow deployment. For a flight article one must instrument the inner material for over-temperature protection and the outer material folds for deployment readiness indication. Results of the test showed a normal deployment without difficulties.

V. System Study Results

A. Design Optimization

Fig. 9 summarizes the mass performance of the IPSS design. The 9 m by 9 m design is completely scalable in both stiffness, loading, and array size and can adapt to a variety of mission requirements. The performance of the struts was based on thin walled cylinder buckling theory[2] and classical Euler buckling theory.[7] Stowage of the design is currently array limited. The stowed volume for the 9 m by 9 m design is estimated as 1.09 m x 1.09 m x

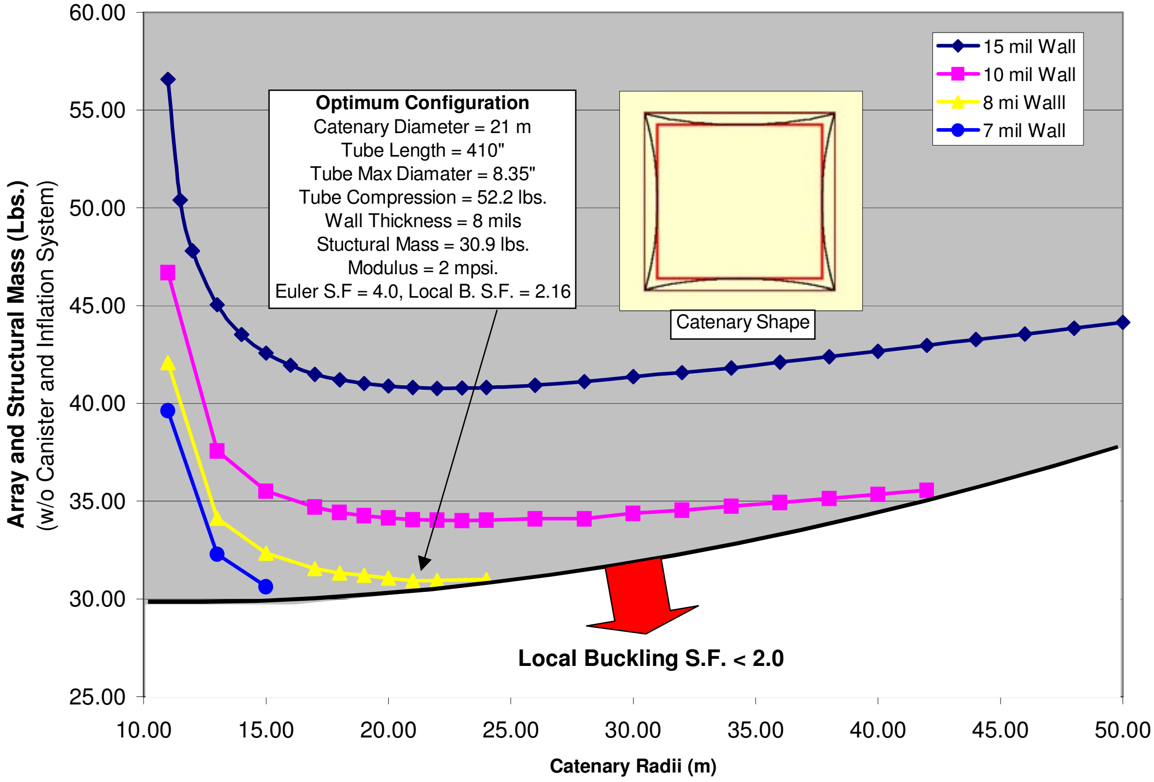

Figure 9. Design Optimization

0.20 m and deploys to a full structural size of 10.37 m x 10.37 m x 0.20 m. As a result of the design study we recognized that the stowed volume increases very slowly for increased aperture sizes. This is due to the efficient packaging method of the conical strut adding little volume when the aperture increases. The package size is driven by the stowage method of the waveguide array.

B. Modal Analyses

The natural frequency of the 9 m square system was calculated by two methods; spreadsheet and finite element analysis (FEA). Good correlation exists between the analytical spreadsheet and the FEA model. Pictures of three prominent modes are included in Figure 10 and exist between 0.63 and 0.74 Hz.

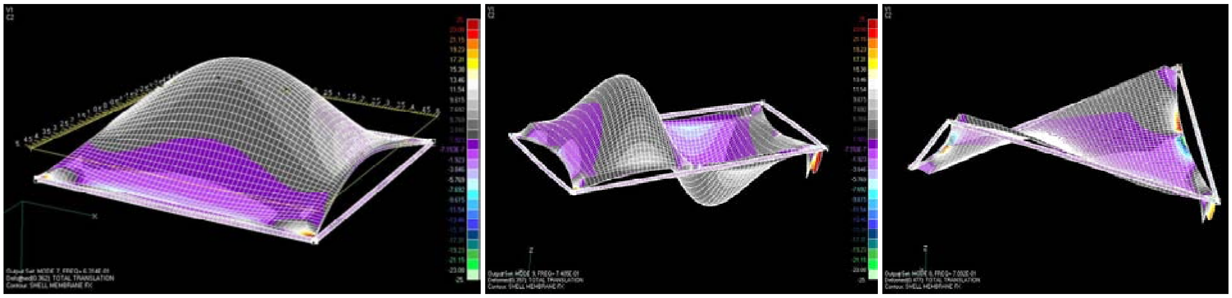

Figure 10. Modal Analyses Results.

VI. Conclusion

Inflation-deployed rigidizable structures offer the advantages of ultra-low mass and stowed volume, high reliability, and low cost space structures that will significantly enhance America’s space competitiveness. L’Garde’s IPSS has demonstrated these advantages through fabrication and testing of an advanced prototype system. The ability to lower the weight and volume of a space structure will be very attractive to satellite manufacturers, since this translates into lower launch costs. This is important to programs that utilize micro satellites where the budget is ever dwindling. However, we expect no commercial sales until the system has been demonstrated in orbit. Recently we secured a program that utilizes much of the technology developed here that is scheduled to fly in 2006. Currently, L’Garde is marketing this technology for several structural applications that the work done on this program has either pioneered or advanced including solar sails, nested antenna, solar array structures, and many more. If these products become successful, we anticipate a modest growth over the years as we compete against other manufacturers and technologies.

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