Deployment and Structural Support of Space Membrane Optics System Using Rigidizable Conical Booms

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Abstract

The use of telescopic rigidizable inflatably-deployed booms for the space deployment and support of membrane optics for space shows great promise because of their light weight and small packaged volume. The telescopic boom deployment mechanism is extremely simple with almost zero parasitic mass for deployment control. We have shown on a subscale level that they possess excellent deployment reliability, package in a minimum launch volume, and cost approximately an order of magnitude less than equivalent mechanical deployable structures. The two major issues in the use of telescopically-deployed membrane optics systems are (a) rigidization scheme and (b) deployment control. The rigidization method chosen is the *Sub-Tg*: in the *Sub-Tg* method, rigidization is achieved by letting the *Sub-Tg* resin impregnated boom passively cool below the resin glass-transition temperature (*Tg*). The *Tg* is tailorable and the choice depends on the mission thermal environment. The controlled deployment is achieved by using a unique concentric packaging arrangement about the boom axis, similar to that of a telescoping tube. Controlled deployment of subscale rigidizable telescopic conical booms has been demonstrated in the laboratory for booms up to 7m long. In the present paper, we present the use of the telescopic conical boom concept with the *Sub-Tg* method of rigidization as applied to a membrane optics system with an optical error-correction system.

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1.0 Introduction

The use of rigidizable, inflatably deployed booms for the space deployment and support of membrane optics for space shows great promise because of their light weight and small packaged volume. In this paper we present the use of telescopically-deployed rigidizable conical booms for structural support of a large membrane optics system. The concept had been demonstrated in the laboratory to have a very high degree of deployment control that results from a unique packaging concept for the conical boom. Consequently, the weight is minimized requiring essentially zero parasitic mass. We have shown on a subscale level that they possess excellent deployment reliability, package in a minimum launch volume, and cost approximately an order of magnitude less than equivalent mechanical deployable structures.

The two major issues in the use of telescopically-deployed membrane optics systems are (a) rigidization scheme and (b) deployment control. The controlled deployment of subscale rigidizable conical booms has been demonstrated during the first and second phase SBIR programs sponsored by AFRL. In the present paper, we present the use of the *Sub-Tg* method of rigidization with structural Kevlar fabric. Whereas the *Sub-Tg* Kevlar boom fabricated during the Phase II study is only 2.75m long, it was designed so that its cross-section and taper is identical to support struts used in a membrane optics system design conceived during the course of the Phase II study. Hence, the deployment characteristics and packaging profile are all traceable to a full-scale membrane optics system. A subscale Sub-Tg rigidizable Kevlar conical boom in the process of deployment is shown in Fig. 1. The first frame shows the stowed footprint, which is about 16 cm high and 16.5 cm diameter.

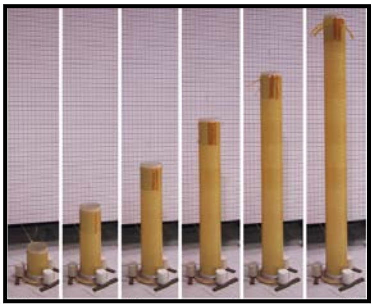

Fig. 1. Deployment of a conical boom. Base diameter: 0.165 m, tip diameter: 0.152 m; boom length: 2.74 m, boom wall thickness: 0.2032 mm.

Figure 2 shows a membrane optics system concept[3]. It consists of a primary and secondary mirror supported by struts and a torus, with the corrective optics located at the spacecraft end. The booms and torus can be made of Sub-Tg rigidizable material. The sunshield necessary for thermal control is not shown.

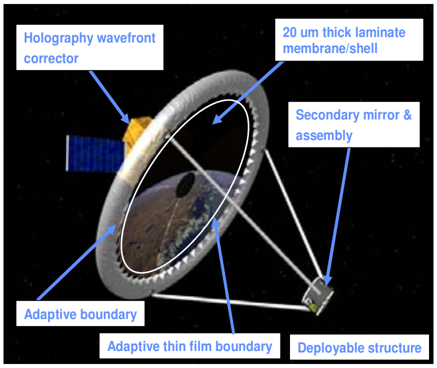

Fig. 2. A membrane optics system. The booms can be made of Sug-Tg rigidizable, conically deployed. The torus supporting the membrane optics can likewise be made of Sub-Tg rigidizable material.

2.0 Sub-Tg Method of Rigidization

At the heart of the composite is L'Garde's *sub-*T_g or cold rigidization matrix. The matrix is a thermoplastic elastomer tailored to be space hazard resistant and become rigid below a designed temperature. Though called cold rigidizables they don't necessarily require cold temperatures. Current matrix T_g's include +50C, +20C, 0C, and –20C to meet the peak temperature requirements that would be seen on a variety of missions. The material is completely passive and in general requires only moderate heating to soften for deployment if the spacecraft environment is below the composite Tg. This is a low power option to thermosetting plastics. Ideally, an elastomer is selected with a glass transition temperature below the equilibrium temperature of the boom when deployed. After deployment, outside the spacecraft's thermal environment, the boom cools passively and becomes rigid.

In a space application, prior and during deployment, the (MLI-covered) rigidizable boom is kept above its Tg and hence flexible. Once deployed by inflation it is allowed to (passively) cool down to its operating temperature which is

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[3] Courtesy of AFRL.

well below its Tg. 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 temperature-time history of such an orbiting boom is shown in Fig. 3. The thermal loadings were obtained from TRASYS [1] and the temperatures were calculated using SINDA.[2]

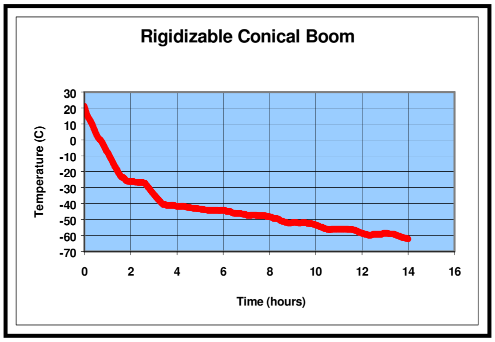


Fig. 3. Temperature-time history of orbiting MLI-covered Sub-Tg boom. (1000 km orbit)

The glass-transition temperature is tailorable and the choice depends on the mission thermal environment. Preliminary measurements show that moduli on the order of 28 to 83 GPa are obtainable, depending on the Sub-Tg resin and structural fabric/weave design chosen. These measured values agree with our predictions using micromechanics theory. Commonly used structural fabrics are graphite, Kevlar, PBO, and glass. A boom with this stiffness such as that shown in Fig. 1, is shown to have the necessary stiffness to support a 10m diameter membrane optics system.

3.0 The Conical Boom

Conical deployment offers excellent deployment predictability and support. The conical boom concept of L'Garde's (patent pending) has been designed, fabricated, and tested in the laboratory environment. Subsequent improvements to the boom deployment were achieved by the design of a nodding reduction mandrel for added stability if necessary. The conical boom is considered by L'Garde as state of the art technology. A graphical representation of the deployment is shown in Fig. 4.

Material choices for this boom design vary but its usual construction is of a Kevlar® fabric impregnated with L'Garde's proprietary sub-T_g matrix. Kevlar is used in the composite to achieve the fabric flesibility required to deploy. To confirm the performance predictions of the laminate, laboratory tests were conducted on a suitable structural composite. The predicted value of 27.3 GPa for Young's modulus compares quite well to the value of 28.2 GPa achieved during laboratory testing before deployment, and the value of 27.0 GPa achieved after stowage and deployment. This allows the same article to be tested for flight for a ground-based qualification program. The *sub-T_g* conical boom has 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 boom design are not tightly constrained and can be tailored to fit a wide variety of missions.

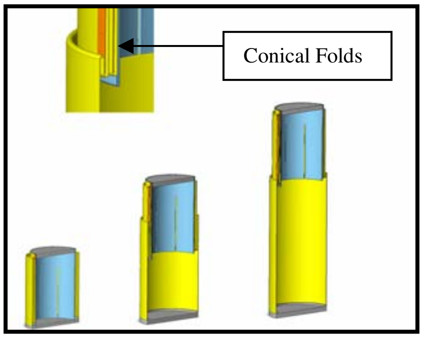


Fig. 4. Boom Deployment Concept.

Using a unique concentric packaging arrangement about the boom axis the concept provides a high degree of deployment control. In this method, a tapered tube is packaged in a manner similar to a telescoping tube. L'Garde conceived this method for applications requiring highly controlled booms and is an offshoot from our decoy work in the 1970'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. In the stowed configuration, the boom is nested along its axis with alternating concentric folds. To deploy the conical boom, inflation gas is introduced at the base. Pressure is exerted against the walls of the tube, the tip, and base endcaps. The inflation pressure squeezes the walls against the outer folds and also unfolds and deploys the outermost folds.

The first step of the deployment sequence is to energize a heater to allow the boom material to become pliable. This is required if the spacecraft thermal environment is colder than the T_g of the boom composite. During deployment, the boom is always enclosed in multi-layered insulation (MLI) to reduce the heat needed to make the boom pliable and minimize thermal gradients on orbit during operation. The outer layer of MLI is coated to have optical properties that allow the temperature of the boom to fall below the T_g of the matrix.

During deployment and until the boom is rigidized, the boom remains inflated (pressure-stabilized) and can carry load both in its partially and fully deployed state. Finally, once the boom is fully extended the heater is de-energized. The inflation gas remains while the boom passively cools below its T_g to rigidize. Once rigidized, the inflation gas is no longer required for support and is non-propulsively vented.

The folding parameters are governed by the length, diameter, and thickness of the boom. The packaging factor, a parameter determined by the type of material, is used to properly size the boom and subsequently provide a taper ratio output. This method is a L'Garde technique developed specifically for conical booms.

Deployment tests have been conducted in the laboratory environment. The overall length of the test sample shown in Fig.5 was 2.74 m with a base diameter of 0.165 m. Complete deployment occurs in ~2 minutes.

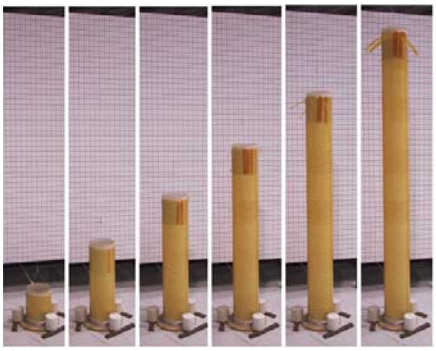


Fig. 5. Deployment of Conical Boom.

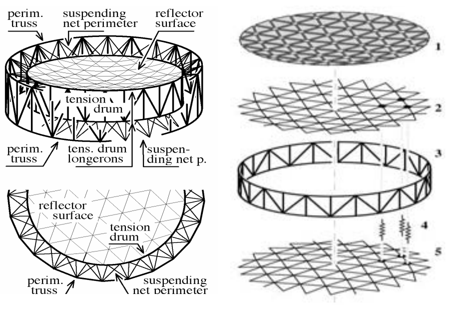
Conically stowed booms are quite robust when it comes to deployment. When properly designed they require minimal control during inflation to reach their final configuration and remain in a confined envelope during deployment. Mission and spacecraft constraints become the driving requirement for additional control of the inflation and deployment. Improvements to the deployment of the conical tube have been ongoing. In some system configurations it may be required to constrain the base and the tip coaxial during deployment. This would come naturally in most system designs where a rigid structure is deployed away from the spacecraft by three or more booms. To accomplish this task when only one or two booms are used without increasing the package volume requires the use of a coaxial stabilization mandrel. The concept is based on providing axial stiffness during the transition period from a fold finishing deployment to the next fold starting deployment. A simple fix would be to extend the mandrel or decrease the fold length. This however would not allow for packaging of the mandrel to the original length. The resulting configuration extends and locks in the extended position in a passive manner. Midpoint stabilizers are used to provide additional support. The concept would be made of lightweight composite material for flight hardware and should result in an additional mass of 0.2 kg for a 0.165 m diameter boom. The mandrel design allows for a passive deployment and full extension locking that occurs when the first fold is half deployed. The nylon bumpers provide support during the transition that occurs at the end of a fold. Deployment occurs with the deployment of the first fold and uses the deploying force of the end cap to extend it. Once in the fully deployed position it locks by using shaft spring locks.

4.0 Net-Membrane Reflector

A lightweight membrane optics system such as that shown in Fig. 2 is compatible with the conical boom deployment. The (membrane) primary mirror of such an optical system that can potentially have the required optical accuracy is the *nanolaminate*.[3] Nanolaminate work is ongoing at the Lawrence Livermore National Laboratory and shows great promise in achieving an optical quality surface. Typical thicknesses are in the range of a few tens of microns. Issues however remain including packaging and deployment. Unless the mirror is broken down into independently supported segments, it is not clear that a monolithic (10 m diameter) nanolaminate primary mirror can tolerate folds and cross folds that result in permanent creases. Rolling is a possible solution but it may not have the required stowed volume for launch. It is hard to assess its packaging and stowage capability without its material properties. It may not be until 5 to 10 years from now before we see an operational nanolaminate-based membrane optics system.

In this paper, we are proposing the use of the more near-term *net-membrane* as the primary mirror - Fig. 6 which, coupled with holographic correction [4] offers diffraction-limited performance albeit over a narrow bandwidth centered at the wavelength of the laser light used in the construction of the hologram. Such a (narrow bandwidth) optical system offers diffraction-limited resolution for surveillance from space.

The reflector surface is formed by a net-membrane structure. The net forms a geodesic surface over which the metallized reflector membrane is stretched. Another net-structure, but without the membrane, is located at the "bottom" and is a mirror image of the top net. The bottom net is used as anchor points for tension ties between it and the top net-membrane. These ties provide tension in the membrane keeping it taut and wrinkle free. The net material is an accurately built low CTE, high stiffness composite network and provides the accuracy and added thermal stability. The struts, which in both cases (inflated or non-inflated configuration) will be a conical boom, are not shown for the non-inflated net-membrane configuration. The perimeter truss support structure can be made of the same Sub-Tg material as the struts (conical booms). This configuration is very similar to the dual tension dome AstroMesh RF reflector [5]



(A) (B)

Fig. 6. Net-membrane reflector. (1 – membrane mirror segments, 2-primary tendon dome, 3- truss ring, 4- soft tensioning[CF springs] chord members, 5-invert dome).

The great success of the dual tension dome architecture for RF applications is largely due to the use of a wire mesh for the reflecting surface. The mesh is compliant and, along with the net domes and the links between, can be stowed with no critical attention paid to folding patterns and deployment mechanisms. The tendons, chords, and mesh can be simply "let crumple" into a loose bundle conveniently confined within the shroud of the stowed truss ring – yet it deploys robustly and with precision.[6] Several such structures have been launched and deployed on orbit. While a version of the above design concept (Fig. 6) has been highly successful for RF applications [5], its application to optical reflectors has not been considered before. It must be noted here that by itself, the net-membrane reflector configuration does not have the accuracy and precision of an optical mirror. Although the precision and accuracy of rigidizable materials have improved over the years – Table 1, the membrane mirror itself is not an optically precise surface, in fact very far from it. A corrective optics system is necessary. This is the subject of the next section.

The membrane optics system will have a positioning error correction system to take out the static positioning errors and the dynamic error components that arise for example during a slew maneuver. The magnitudes of the dimensional errors shown in Table 1.0 are within that which can easily be compensated for on-orbit.

	Systematic		
	Longitudinal	Twist	Bending
Manufacturing	~+25 µm/m	|6E-4| $\text{rad}^{\dagger}$/m	~42 µm/m
Deployment / Packaging	~+100 µm/m		
Environmental	$\alpha_T L\Delta T$, $\alpha_H L\Delta H^{\S}$		

	Random		
	Longitudinal	Twist	Bending
Manufacturing	~+2.54 µm/m	±|3E-4| $\text{rad}^{\dagger}$/m	±20 µm/m
Deployment / Packaging		±|3E-4| $\text{rad}^{\dagger}$/m	±20 µm/m
Environmental			

Table 1.0 Sources of rigidizable boom dimensional errors.

5.0 Holographic Correction [4]

The basic operation of a holographically corrected reflecting telescope is shown in Fig. 7A. It has been shown that poor mirrors can be corrected to the diffraction limit using this technique. There are limitations however. These are (1) a collimated beam is used as reference, implying that there already exists a source of (laser) monochromatic light at some distance away to create the reference beam. Such a scheme would involve deploying the laser as an isolated device, or as an instrument fixed to the International Space Station (ISS). (2) Because the hologram is made at a specific laser frequency, the correction is maximized only at that frequency.

A hologram is a record of the distortions of the primary at any given time, and can correct for these distortions, as long as no changes occur to the mirror between recording and replay. In a space environment, thermal and gravitational gradients will produce minute changes in the shape of the membrane mirror, which means that a single static hologram cannot permanently correct for an aberrated primary. There are several solutions to this problem, including real-time holographic media such as *optically-addressed spatial light modulators* (OASLM) or *photopolymer* materials, or incorporating an inexpensive adaptive optics system in conjunction with a high resolution static holographic medium (Fig. 7B).

The 1m parabolic membrane mirror shown in Fig. 8a was built at L'Garde, Inc. with an F/D of 2.43. It consists of a VDA 0.3 mil kapton with tension ties bonded on the back and pulled to shape. Its surface accuracy was measured to be 0.367 mm rms. The before and after images of a USAF Resolution Chart is shown in Figs. 8b and 8c. Note the diffraction-limited performance.

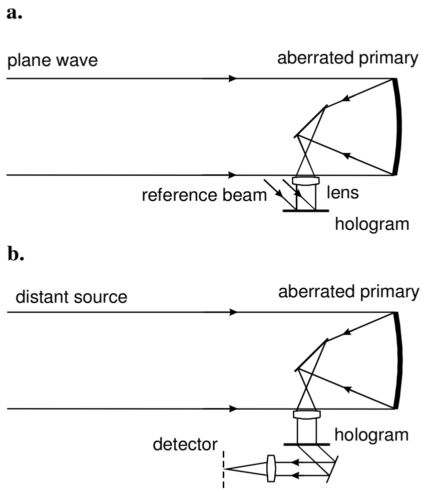


Fig.7A. A schematic of holographically corrected telescope. (a) recording. A distant laser source illuminates the aberrated primary to form the object beam. The hologram is written with a collimated beam incident at an angle. (b) Reconstruction. Light from a distant object (starlight) reconstructs an unaberrated image which is then focused to produce a perfect image of the distant object.

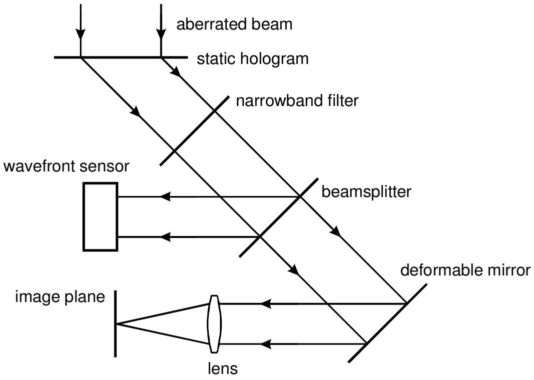


Fig. 7B. Hybrid holographic correction. The large scale aberrations are removed by a static hologram, while minor temporal changes in the mirror are corrected by the small-stroke deformable mirror.

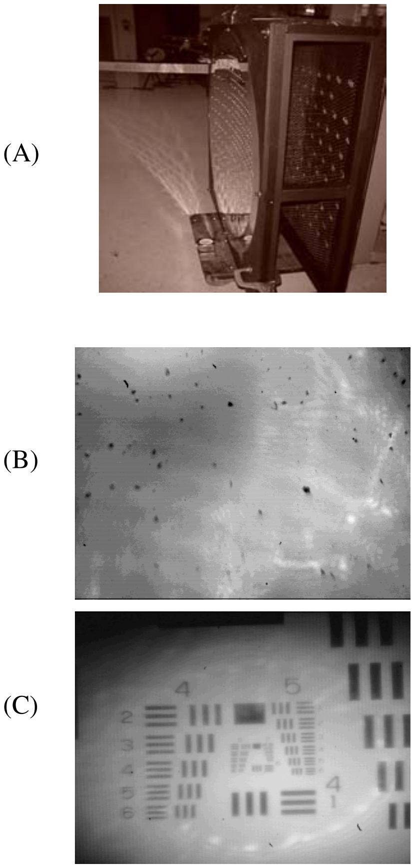


Fig. 8. (A) Net-less membrane telescope. (B) USAFA resolution chart imaged before holographic correction, (C) The same chart imaged after correction: diffraction-limited performance was obtained.

6.0 Summary

We have shown that the rigidizable telescopically-deployed conical boom can be used as support struts of a large diameter (10m) membrane optics system. Its use shows great promise because of its extremely low weight and small packaging volume. The telescopic boom deployment mechanism is extremely simple with almost zero parasitic mass. They possess excellent deployment reliability, package in a minimum launch volume, and cost approximately an order of magnitude less than equivalent mechanical deployable structures. After deployment, positioning errors are present with both systematic and random components. However, their magnitudes are within that which is correctable with a positioning error correction system. It has also been shown that the more near-term *net-membrane* mirror can be used as the primary mirror of the membrane optics system. Although by itself, the net-membrane does not have the required optical accuracy, it is correctable to the diffraction limit, albeit over a very narrow bandwidth, using a holographic correction technique. The technique has already been demonstrated on a similar 1m diameter, aberrated membrane mirror.

7.0 References

[1] TRASYS, Thermal Radiation Analysis System, COSMIC, University of Georgia, Athens, Georgia.

[2] SINDA, Systems Improved Numerical Differencing Thermal Analyzer, COSMIC, University of Georgia, Athens, Georgia.

[3] Drs. Brett deBlonk (AFRL) and Lawrence Robertson (AFRL) , private communication, ~May 2003.

[4] Andersen, G., Knize, R.,Palisoc, A., and Cassapakis, C., Large-aperture holographically corrected membrane telescope, In Opt. Eng., 41(7), pp. 1603-1607, July 2002.

[5] M. W. Thomson. The AstroMesh deployable reflector. In *Proceedings of the 5th International Mobile Satellite Conference (IMSC '97)*, pp. 393-398, Pasadena, CA, June 16-18 1997. NASA Jet Propulsion Laboratory. JPL Publication 97-11.

[6] G. Greschik, Stowage and Deployment Options for a Segmented Optical Dual Tension Dome Reflector, In L'Garde Technical Report, LTR-02-AP-014, p. 2, August 13, 2002.