Inflatable truss support structures for future large space telescopes

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Abstract

This paper proposes the use of precision inflatable truss structures to support future large space optical systems. Truss structures are a new geometric form for space inflatable structures and appear to be well suited to providing dimensionally–stable high–stiffness support while requiring minimal mass and stowed volume. Based on a preliminary assessment of launch vehicle performance and mirror mass and size parameters, a straw man concept for a 400–m^2 primary mirror system is described. The concept utilizes "poker–chip" stacking of hexagonal mirror segments, an inflatable truss structure, and robotic assembly. Issues and required technology development areas associated with precision inflatable structures are described.

Keywords: space telescopes, inflatable structures, ultra lightweight optics, space robotics

1 Introduction

The Next Generation Space Telescope (NGST) is currently scheduled for launch in 2008 and future large space telescopes will likely follow within five to ten years. These may be either large single–aperture telescopes such as a Next–NGST (N–NGST), or elements of an interferometer follow–on to Terrestrial Planet Finder (TPF) with sufficient aperture to allow spectroscopic study of planets orbiting other stars. Assuming a nominal 2015 launch date, the technologies supporting these missions will need to be proven by 2010 to support a decision to authorize mission implementation. One approach to defining technology development needs for these missions is to first estimate the desired performance goals and the available resources. Then based on these inputs, system concepts are developed and evaluated to characterize the performance improvements required of the technologies supporting these missions. New technologies can also be factored in to these concepts to evaluate their potential payoff.

Along these thoughts, this paper looks at the structure technology and mechanical packaging issues for a straw man concept of future large space telescope. We find that inflatable truss structures offer the strong potential of providing a key building block for future large space telescopes. This building block is a very high specific stiffness (ratio of stiffness to mass) telescope support structure that requires minimal stowed volume.

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2 Requirements & resources assumptions

To develop a system concept for evaluating structural/mechanical subsystem performance requirements, we begin by making assumptions on the basic requirements and resources impacting the structural/mechanical subsystem

2.1 Required aperture size

We assume that an N–NGST will be required to have an aperture area in the 400–m^2 range, or about a factor of ten larger than the NGST (a factor of three in aperture diameter). This is the same increase in mirror size over NGST as NGST is over the Hubble Space Telescope. Increasing mirror area by one order of magnitude per generation appears to strike a reasonable balance between not pushing technology advancement hard enough to receive an adequate return on R&D investment, and pushing so hard that the risk of failure becomes excessively high. In addition to being applicable to an N–NGST, a 400–m^2 aperture area is also in the same class as that currently envisioned for a TPF follow–on spectroscopic interferometer mission.

2.2 Funding availability

It seems reasonable and prudent to assume that future large space telescope missions will be as funding limited as they are now. That means we won't have the money we would like for developing the observatory, or for buying a heavy–class launch vehicle. Instead, we have to seek out new approaches, or "enabling technologies," to reduce telescope cost. We also have to develop a telescope that is compatible with the more affordable medium–class launch vehicles such as the EELV Medium–Plus or Ariane 5. This is the same class of launch vehicle for which the NGST is being designed.

2.3 Launch vehicle performance assumptions

The history of launch vehicle performance is one of ever increasing payload mass and volume capability. So, the question arises as to what payload mass and volume performance should be assumed for the year 2015 time frame. Historically, payload–mass–to–orbit performance has been characterized by numerous small increases occurring relatively frequently as various launch vehicle components are upgraded through a continuous improvement process. Competition in the launch vehicle business should help to maintain this trend. Plans have already been approved to increase the performance of the Ariane 5 by 20%, even though that vehicle is just now entering commercial service. Assuming that this trend continues, then for a 2015 launch the future large space telescope designer can likely count on at least an additional 10 to 20 percent improvement in mass performance over near–term capabilities. For 1 AU solar orbits such as a L2 halo orbit or drift–away orbit, the current Ariane 5 performance is 4,200 kg. A 20% increase will boost this to 5,000 kg. Performance estimates for the Delta IV, Boeing's EELV Medium–Plus launch vehicle[‡], currently range from about 3,000 to 5,000 kg, depending upon the number of strap–on solid rocket motors (SSRMs) used. Based on these figures, it seems safe to design to a payload launch mass of 5,000 kg for a 2015 launch, with a good possibility for growth beyond this as launch vehicles are upgraded.

Also important to the designer of future large space telescopes is the available payload fairing volume. The Ariane 5 and both the Boeing and Lockheed Martin EELV Medium–Plus launch vehicles offer "5–meter" diameter fairings, which provide an actual 4.57–meter diameter useable volume to the payload, the

[‡] Published performance data on the Lockheed Martin EELV is currently not available, but indications are that it is similar to the Boeing Delta IV.

same as the Space Shuttle payload bay. Can we expect larger fairings by the year 2015 time frame? Historically, increases in payload volume have come in larger, but less frequent, steps. This is due to the relatively large overall cost impact of increasing payload–fairing size, particularly diameter. Launch vehicle performance currently is and will likely continue to be driven by commercial communication spacecraft needs. Communication spacecraft capability can be expected to continue to increase, thus increasing mass and volume requirements. However, it appears possible that the stowed volume requirements for ever increasing capability communication satellites may grow at a slower rate with respect to spacecraft mass than previously. This is due to the increased use of high packing volume efficiency antennas and deployable thermal radiator panels with pumped fluid loop thermal control. Therefore, increases in required payload volume may be sufficiently small that they can be accommodated by just stretching the payload fairing length rather than developing larger diameter payload fairings. Stretching payload fairing length can be a much lower cost endeavor compared to increasing diameter as new production fixtures are not necessarily required and the impact on other launch vehicle systems is less. Therefore, it seems prudent for now to design to a 4.57–meter diameter stowed volume.

The other dimension with respect to payload fairing volume is height. The Ariane 5 has two payload fairings with heights of 5 and 10 meters, as measured from the payload interface plane to the top of the cylindrical section of the fairing. The Delta IV Medium–Plus fairing has a height of 7.246 m. As will be discussed in Section 3.1, a height of 7.246 m could be quite limiting. It seems reasonable that a taller fairing can be assumed for two reasons. First, the Delta IV Heavy launch vehicle is available with two taller 5–meter fairings, the shorter of which is 12.192 m high. These fairings consist of the 7.246–m Medium-Plus fairing with spacer segments added to increase height. Therefore, the Delta IV Medium-Plus fairing is already designed to incorporate add–in segments to increase height. Furthermore, the core vehicle design is the same, or nearly so, between the Medium–Plus and Heavy versions, so that the core vehicle can withstand the additional structural loads generated by the taller fairings. Although issues of guidance control authority may still need to be addressed, it appears that the fairing height of the Delta IV Medium–Plus can be increased without incurring unacceptably high additional costs. The second reason why an assumption of a taller fairing seems reasonable is that of competition. It will only be a matter of time before commercial communication satellites grow to the point where the additional height offered by the Ariane 5 10–m fairing becomes a competitive advantage. The Delta IV Medium-Plus payload fairing will have to grow to stay competitive.

2.4 Observatory configuration

A primary mirror alone does not comprise a space observatory, and so we must identify what other elements must be accommodated in the launch vehicle's mass and volume capabilities. We assume an observatory configuration similar to that of the NGST. A spacecraft module will be required to provide command and control, communications, attitude control, station keeping, and electrical power. Some form of an instrument module will be required to house either imaging and/or spectroscopic instruments in the case of a single telescope, or beam control and relay optics in the case of an interferometer. Infrared wavelength coverage is almost a certainty, and this requires cooling the telescope and instrument module to cryogenic temperatures. As with the NGST, passive radiative cooling is the only practical method to cool such a large system. Passive radiative cooling requires both a sunshield capable of providing a high degree of thermal isolation from the incident solar thermal flux, and a configuration where the warm spacecraft module is isolated from the cold telescope and instruments. As a result of these assumptions, the deployed configuration of the observatory is as illustrated in Figure 1.

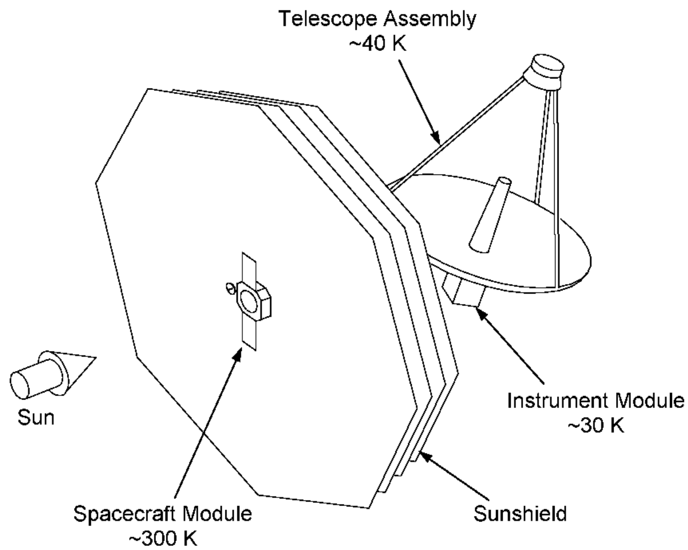


Figure 1

The assumed observatory configuration for an N–NGST consists of telescope plus a spacecraft module with a large sunshield and an instrument module.

3 The structural/mechanical subsystem challenge: providing high specific stiffness and high packing volume efficiency

Given our adoption of a factor of ten increase in aperture area over NGST while employing the same medium–weigh class launch vehicle, the future large space telescope design is going to be very strongly influenced by limitations on both payload launch mass and launch volume. The commonly used metric for describing mirror systems is areal density. For a given mirror system mass, which is a fraction of the total launch mass, the areal density provides a quick means to determine the mirror area. However, areal density alone is not the determining factor in assessing mission feasibility. Packing volume efficiency and specific stiffness are also important considerations. We show this in the following development of a 400–m^2 straw man concept for an N–NGST.

3.1 Assessing stowed volume constraints

Unless the technology is developed that allows a mirror to be folded or rolled up like a soft contact lens, the primary mirror will have to be segmented for stowage during launch. Numerous approaches to segmenting and stowing primary mirrors have been developed. No approach changes the volume of the primary mirror for stowage—instead, the mirror's geometry is changed to better fit the dimensions of the launch vehicle. One of the most efficient approaches in terms of mirror area per unit stowed volume is to divide the mirror into hexagonal segments and then stack the hexagonal segments on top of each other like a stack of poker chips. Figure 2 illustrates a stowed observatory configuration utilizing a vertical stack–up of spacecraft/sunshield module, instrument module, stacked mirror segments, and secondary mirror assembly. All elements except the secondary mirror assembly stow within the cylindrical portion of the payload volume. Overall, this stowed configuration uses payload volume efficiently and provides good structural launch load paths from the perimeter of the mirror segments down through the outer shells of the instrument and spacecraft modules to the launch vehicle interface.

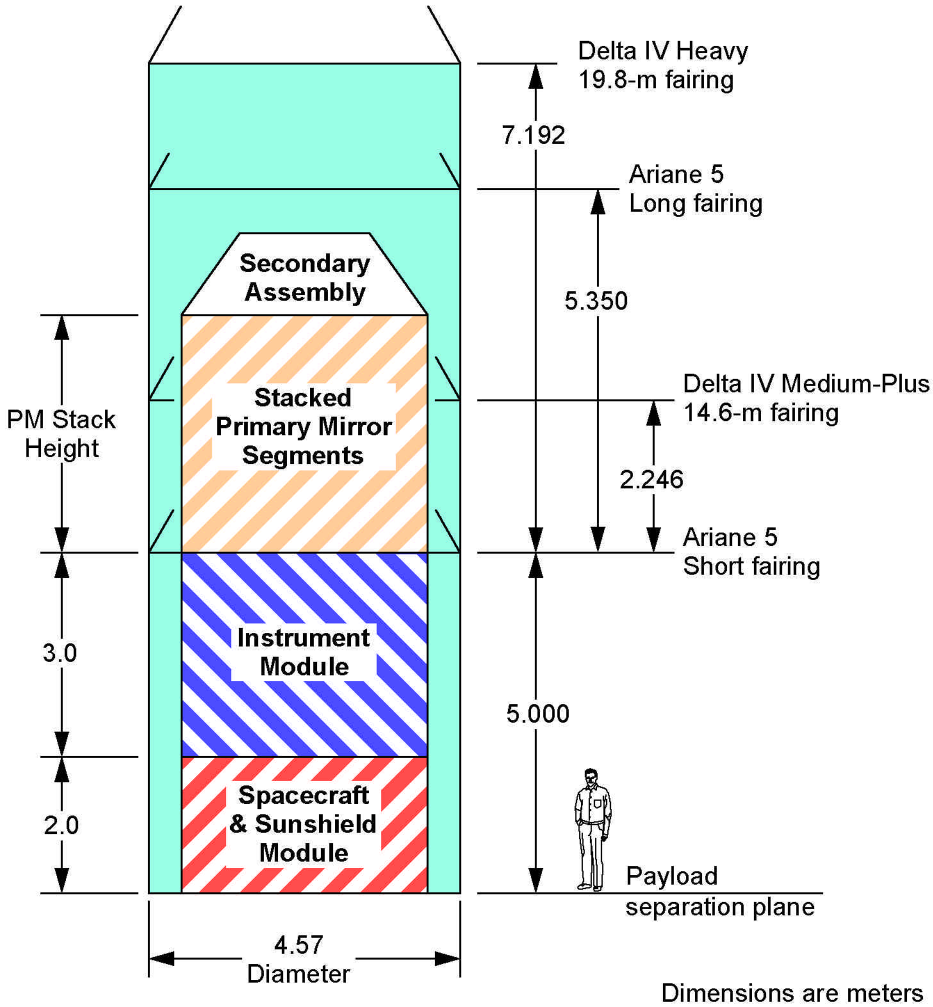


Figure 2

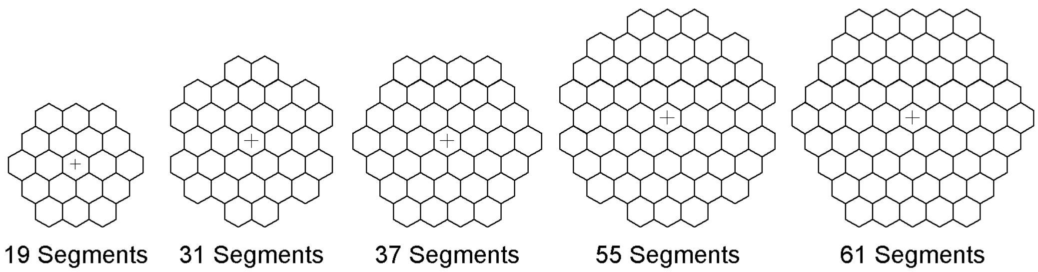
Illustration showing primary mirror stack height available in payload fairing

A total stack height of 5.0 m for the spacecraft/sunshield and instrument modules is estimated based on current NGST concepts. The 2.0–m height for the spacecraft/sunshield module will be driven by the configuration and deployment approach used for the sunshield. The 3.0–m height allocated to the instrument module should be adequate for accommodating instruments and their thermal radiators, but is probably not sufficient to house the telescope's tertiary mirror. It is assumed that the tertiary can be deployed in order to minimize stowed volume. The stowed height remaining for the primary mirror segment stack depends upon the payload fairing used. The height required depends upon the number of segments and the thickness of each segment plus the spacing between segments.

Figure 3 shows several possible tiling arrangements using hexagonal segments. The total mirror area shown for each assumes a segment circumscribed diameter of 4.2 m. This leaves a minimum radial clearance of 185 mm between the corners of the hexagonal segments and the outer edge of the allowable payload volume for such possible items as launch supports, mirror mounts, contamination shield, or additional acoustic insulation on the fairing. At best, the hexagonal segment size could possibly be pushed to about 4.4 m to provide an additional 10% aperture area, but this reduces radial clearance to 85 mm. The

37–segment configuration is the configuration with the minimum number of segments that provides the required 400 m^2 aperture area (see Section 2.1)

Configurations with additional segments can provide the required area by reducing their diameter, but the additional number of segments requires additional stowed stack height. This is shown in Figure 4. This plot also highlights the problem with the Delta IV 7.246–m high payload fairing. If our assumption that a height of 5 m is required for the spacecraft/sunshield and instrument modules is correct, then packing 37 segments into the remaining 2.246 m height requires that the thickness of each segment plus the clearance to the next segment be only 6 cm. With a 50–m radius of curvature, the sagitta of a 4.2–m diameter segment is 4.4 cm. Also, adjustable kinematic mirror mounts need to be packaged within the 6–cm thickness. This appears to be most difficult and may restrict the range of viable mirror technologies. Use of the Ariane 5’s 10.35–m high fairing allows the segment thickness plus clearance dimension to increase to 14 cm. Allowing a couple of centimeters for rattle room between segments, each mirror segment needs to be no more than 12 cm thick, a much more reasonable dimension. It is for this reason and those expressed in Section 2.3 that it is assumed that a 10.35–m high fairing will be available by 2015, allowing a stowed mirror stack height of up to 5.35 m.



Number of hex segments	19	31	37	55	61
Total area (m^2)*	218	355	424	630	699
Circumscribed circle diameter (m)*	18.3	23.4	25.5	30.3	32.8
Fill factor	0.827	0.827	0.827	0.875	0.827

* For segment diameter of 4.200 m

Figure 3

Hexagonal mirror segment tiling configurations.

In actuality, whether the fairing height is 7 m or 10 m has little bearing on the main thrust of this paper. The key point here is that packing a 400–m^2 aperture space telescope into a medium–weight class launch vehicle is very demanding. The allowable mirror segment thickness is minimal and there is essentially no volume remaining to stow any additional support structure.

This assessment of payload volume assumes that no additional upper stage must also be accommodated within the payload fairing. This is an acceptable assumption for 1 AU missions such as Earth–drift–away trajectories or L2–halo orbits. However, missions significantly beyond 1 AU that may be desired to reduce zodiacal background light will likely require an additional upper stage. This stage is typically located in the payload fairing and subtracts from the volume available for the payload, thus worsening an already difficult packing problem.

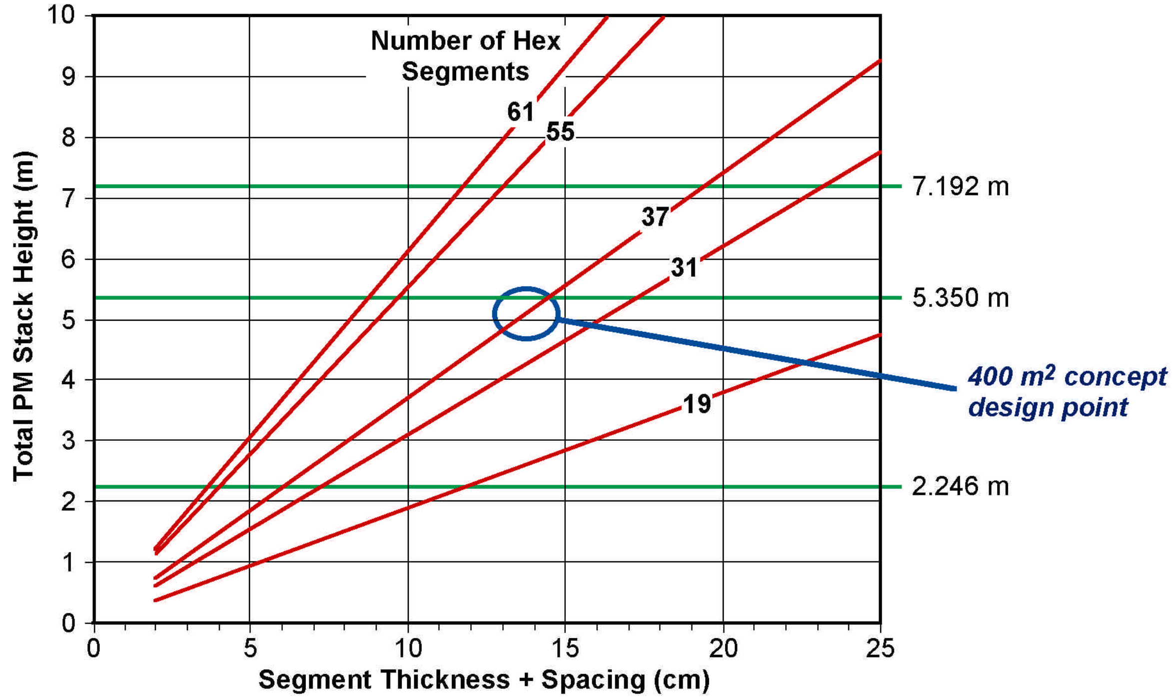


Figure 4

Relationship between total mirror area, number of mirror segments comprising complete mirror, mirror segment thickness, and total stowed mirror stack height.

3.2 Assessing areal density requirements

Figure 5 illustrates the relationship between required primary mirror system areal density, total aperture area, and total observatory launch mass. A 1–AU mission is assumed. For an allowable total launch mass of 5,000 kg (see Section 2.3) and a 400–m^2 aperture area, the allowable mass for the primary mirror system is about 2,400 kg, which corresponds to an areal density of 6.0 kg/m^2. Included in this mass are all of the elements that comprise a mirror system—the mirror optical elements, figure control actuators, kinematic mounts and position actuators, supporting structure, launch restraints, and the deployment system for the mirror segments. The question is, what fraction of the 6.0 kg/m^2 will be required for the other elements that comprise a mirror system?

Inherent in Figure 5 are estimates on the mass of the spacecraft/sunshield module, instrument module, secondary mirror assembly, and a 20% mass reserve. For the 5,000–kg/400–m^2 straw man design point, Table 1 provides the estimated top–level mass breakdown for these items. These estimates are based on current NGST estimates allocations for mass reduction as a result of technology advancements or configuration changes listed in Table 1.

3.3 Providing adequate structural stiffness

Since the telescope is generally not accelerating (inertially stable) when observing, one might think that structural stiffness should not be an issue. The telescope merely must be brought to rest (or to some extremely small angular velocity) pointing in the desired direction. At that point no further control inputs are required and all vibrations will eventually dampen out to acceptably small amplitudes. However, inherent in any control system is noise. Noise in a pointing control system results in essentially continuous actuator input disturbances being applied to the telescope. Also, slews and actuation of instrument mechanisms will generate transient disturbances that must dampen out in a reasonable period of time. Otherwise, the increased sensitivity of larger telescopes will be partially offset by the time lost while waiting for vibrations to dampen out to acceptable levels.

The lower the frequency, the worse the effect of disturbances. Consider a simple single degree–of–freedom system. If we reduce the stiffness of this system by a factor of four, then the initial displacement amplitude due to a given disturbance is a factor of four higher. A factor of four reduction in stiffness causes a factor of two reduction in natural frequency. With half the frequency, twice the time is required for damping to produce a given amount of decay in the amplitude of the disturbance. Thus, reducing the natural frequency by a factor of two results in a factor of eight increase in the time required for the effects of a given disturbance input to decay to a given level. A stiffness figure of merit can be defined with respect to natural frequency as:

$$\text{Stiffness figure of merit} = (\text{natural frequency})^3$$

with higher being better. Therefore, if we allow natural frequency to drop, we potentially pay a steep price to correct by other means.

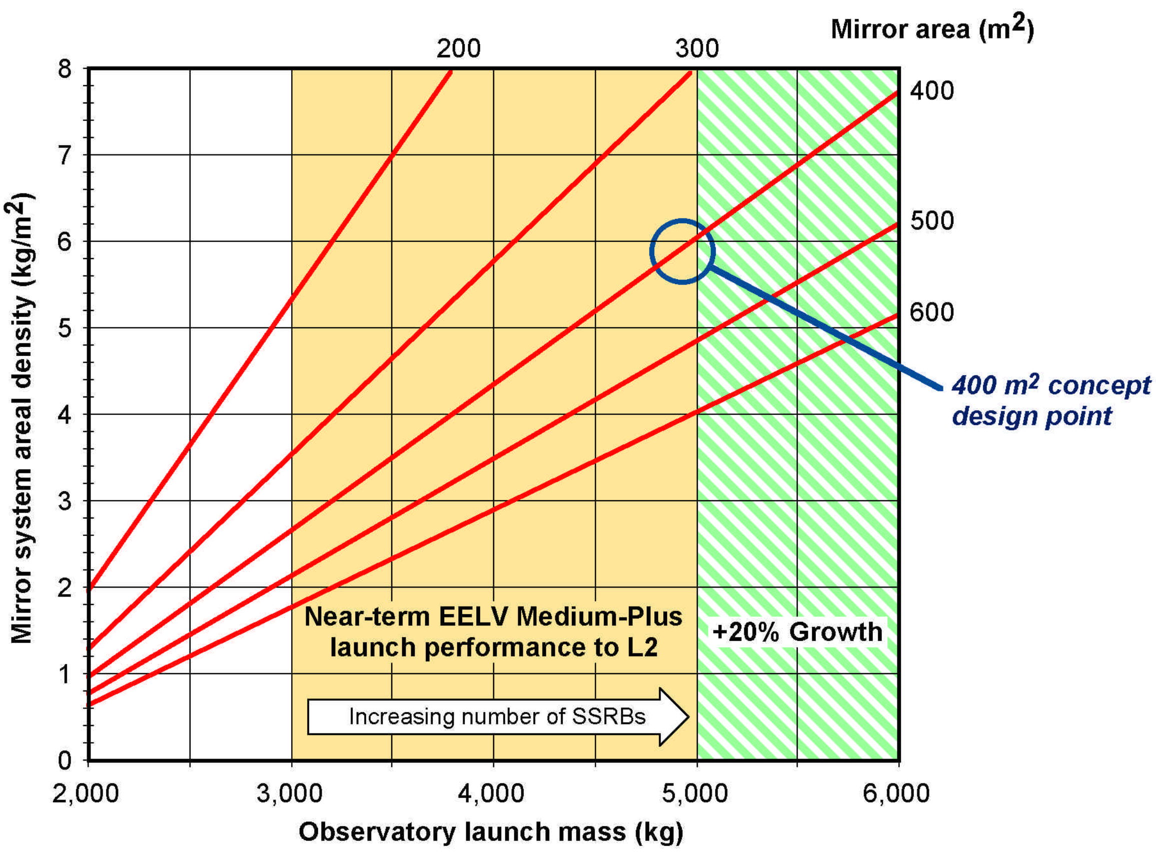


Figure 5

Required primary mirror system areal density as a function total observatory launch mass and mirror aperture area. Primary mirror system consists of optical elements, any figure control actuators, kinematic mounts and position actuators, supporting structure, and deployment system.

Table 1

Top–level mass estimate for a 5,000 kg space telescope with a 400 m^2 aperture area

20% Reserve	1,000 kg
Primary mirror system	2,420
Spacecraft module	510
Propellant	110
Sunshield	180
Instrument module	400
Secondary mirror assembly & miscellaneous	380
Total payload mass	5,000 kg

Above mass estimates are based on current NGST estimates with the following assumptions:

Component	Change from NGST
Spacecraft module	
All electronics, RF components, attitude control sensors, electrical power subsystem components	25% mass reduction by year 2010 due to general advancement of technology
Harness	50% mass reduction through greater use of fiber optics and increased integration of components into fewer boxes
Propulsion system	No change – assumes improved flight dynamics and solar torque management allows larger observatory with no increase in propellant.
Mechanical/structural subsystem	25% reduction due to reduced size of spacecraft module and improved materials.
Thermal control subsystem	30% reduction due to improved materials, more robust electronics, and reduced–size spacecraft module
Sunshield	80% reduction in areal density through use of fewer, more widely–spaced, thinner film layers, and spin–deployment approach or equivalent low–mass deployment approach.
Instrument module	20% mass reduction due to improved materials and fabrication processes

One problem we may face with a primary mirror assembled from ultra–low areal density mirror segments is that the mirror stiffness will be so low that vibration of the mirror adversely impacts image quality. Vibration effects are typically limited to line–of–sight jitter in most telescope systems. Use of a fast steering mirror can control line–of–sight jitter as long as a sufficiently bright guide can be found in the field of view, and as long as the mirrors move as essentially rigid bodies. In a segmented primary mirror, segments can move independent of each other causing the image to break up. A fast steering mirror is of no help in this case. What is required is a deformable mirror located at an image of the primary mirror. However, use of a deformable mirror is limited by both the bandwidth achievable in measuring wavefront errors in fields of view without bright objects, and by the maximum mirror vibration amplitude that can be corrected. Another approach available to cope with a lack of structural stiffness is the use of a dedicated "optical truss" and high bandwidth mirror position actuators. The downside of this approach is its additional cost, complexity, heat dissipation, and failure modes. Since it is always best to build upon a good foundation, the best approach is to provide adequate structural stiffness to begin with if that stiffness can be provided within allowable mass, volume, and cost constraints.

As mirror areal density and segment thickness requirements are reduced, the bending stiffness of mirror segments generally decreases. When we form a deployed primary mirror by latching individual mirror segments together, the effective bending stiffness is further reduced because of the load concentration at the attachment points and the flexibility of the latching mechanisms. Because some minimum level of structural rigidity is required to prevent vibration amplitudes from being excessive, the availability of a support structure to stiffen an array of thin low areal density mirror segments is highly desirable, and perhaps required. If such a structure can be made sufficiently stiff, then there will not be a need to latch mirror segments together. This reduces the structural stiffness requirements and simplifies the design for the mirror segments. However, the mass and stowed volume of this support structure subtracts from that available for the remainder of the mirror system, so the supporting structure must provided the required stiffness with an areal density and stowed volume that are only small fractions of those allocated to the entire mirror system.

What is required is a support structure with high specific bending stiffness and low areal density. High specific bending stiffness can be provided by exploiting geometry—bending stiffness is generally proportional to the square of the thickness of a (hollow) structure. Therefore, we can provide the required bending stiffness by making the structure sufficiently thick. To keep areal density low, a truss structure can be utilized. The use of a truss structure to support an array of hexagonal mirror segments is an ideal approach for the following reasons.

- Mirror segments require three–point kinematic mounts and the nodes of a truss structure provide natural hard points to which mirror mounts can be attached. A truss configuration comprised of front and back layers formed from equilateral triangles provides hard points in the correct location for supporting either hexagonal or triangular mirror segments. Figure 6 illustrates the tetrahedral truss geometry and Figure 7 shows how mirror segments are supported from this truss.
- A tetrahedral truss structure is kinematically determinant, so that the geometry of the truss depends only upon the length of the struts. Therefore, the designers to need concentrate only on providing the correct strut length to begin with so that the deployed truss is the proper shape, and providing a sufficiently low thermal expansion coefficient so that the truss remains stable in the presence of temperature variations.

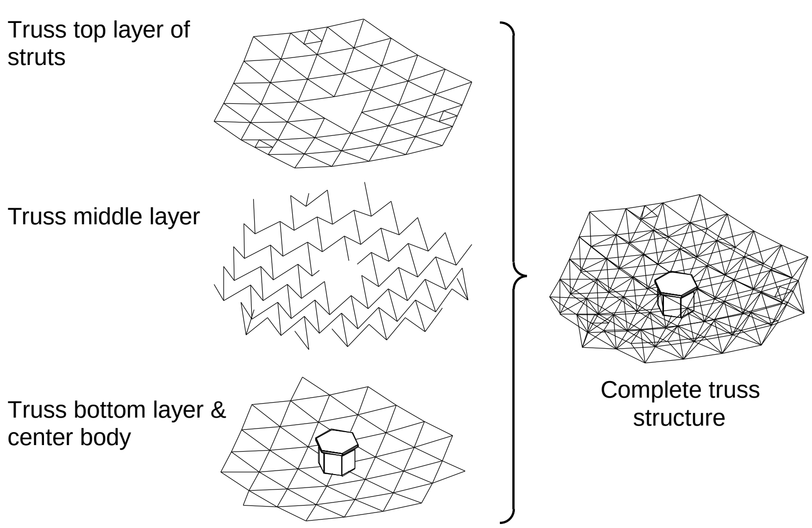


Figure 6

Illustration of tetrahedral truss geometry showing how front and back layers are composed of equilateral triangles

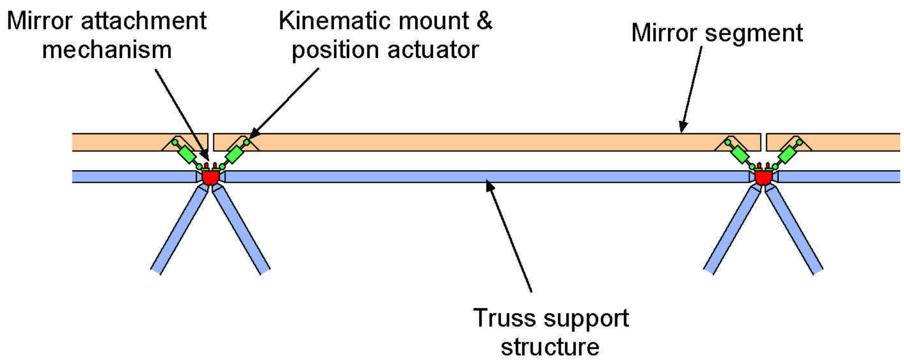


Figure 7

Mirror segments mount to truss nodes through kinematic mounts that incorporate position–control actuators for rigid–body control of mirror segment alignment

- The openness of a truss structure produces less self–shadowing of the structure, which reduces the variation in thermal environment between the front and back layers of the structure. This, combined with the relatively large thickness of truss structures, results in reduced sensitivity to changes in the thermal environment.
- The stiffness of a given truss is solely a function of the cross–sectional area and material modulus of the struts that comprise the truss. This affords the designer additional freedom in selecting strut diameter, wall thickness, and material ply lay–up.

In conclusion, incorporation of a truss support structure into the primary mirror system appears very desirable to provide adequate stiffness. The question is, how do you stow a large truss structure using a minimum of volume and then how do you deploy it?

4 Inflatable truss structures—ideal for providing high specific stiffness with minimal stowed volume

One solution to stowing a large truss structure in a small volume and then deploying it is to use what is called "precision space inflatable structures" technology. The descriptor "precision" is used to indicate that these structures are highly engineered to accurately provide the desired dimensional and structural characteristics once inflated and rigidized. Precision inflatables are a step above spheres and simple habitat structures that once defined the typical space inflatable. Inflatable structures are manufactured from fibers such as carbon, glass, and Kevlar® with the appropriate matrix material and film over–wrapping to yield flexible composite materials. These are essentially softgoods or "flexible composites" and can be flattened, rolled, or folded to stow into very small volumes in a conformal nature. Because they are flexible, the problem of providing launch restraints and surviving launch loads is greatly simplified. For an analogy, consider packing a suitcase for a cross–country trip. Which is easier to pack, clothes or thin glassware?

Once in space, the structure is deployed using an inflation gas. After inflation, the structure is rigidized so that it can function properly without internal pressurization and the inflation gas is vented in a manner to control reaction forces and contamination. Section 7 discusses the various methods available to control deployment, rigidize, and to control venting.

Table 2 summarizes the reasons why inflatable truss structures appear to be well suited to supporting large optical systems in space. Three reasons stand out in comparison to conventional structures that use mechanical revolute or slider joints to stow and deploy.

- The approach of launching soft and then rigidizing once in the vacuum and zero gravity of space decouples the problem of surviving handling and launch loads from the problem of providing a large, high–specific–stiffness structure. Once in space, high strength is not required, only high stiffness. The designer can employ small wall thicknesses and high slenderness ratios as necessary to produce a structure with high specific stiffness and low areal density once deployed in space, but not have to contend with designing these same gossamer structures to survive launch. In essence, inflatable structures change their shape and stiffness to match the requirements of two distinct phases of operation: the launch phase, which requires small volume and high load capacity in a high–g environment; and operation in space, which requires large volume and high stiffness in a low–g environment.

- Stowed volume requirements for inflatable structures are greatly reduced from those for conventional structures. Furthermore, stowage can be of a conformal nature to a large extent; that is, volume can be utilized as it exists with truss stowage requirements having little impact on the shape and size requirements of other systems.

- A deployed inflatable structure is a single monolithic item—there are no mechanical joints as there are required to stow conventional structures. No mechanical joints means no mechanism non–linearities, no issues of mechanism failure on deployment, no issues of mechanism latch–up, no issues of material property mismatch between mechanisms and struts, and no issue of mechanism thermal expansion effects.

5 Concept for a large space telescope utilizing an inflatable truss structure

Figure 8 illustrates how a future large space telescope employing an inflatable truss structure can be stowed to achieve very high packing efficiency. The truss structure is simply folded against the outside of the instrument module. Typically, this should require only two folds in each strut. The radial width required for stowing the inflatable truss is driven by the dimensions of the nodes for the top truss layer which incorporate mirror attachment mechanisms and are estimated to be about 15–20 cm in width. Some minor bracketry is likely required to support the mirror attachment nodes during launch. Launch restraints may be as simple as a set of restraining straps wrapped around stowed package. The deployment approach presented below utilizes a robotic remote manipulator system (RMS) to deploy the mirror segments (see Section 7). As shown in Figure 6, the RMS stows outside the stowed truss.

Figure 9 illustrates the truss structure deployment and mirror assembly sequence. (Note that any structure and/or mechanisms that may be required to support the stowed primary mirror stack during launch are not shown.) In step one, the RMS is swung up out of the way of the stowed truss structure. The two long arms of the RMS are then extended to their full length in step two. This arm extension can be implemented using either mechanical or inflatable means. In step three, the truss launch restraints are released and the truss is inflated. The inflation process occurs slowly, requiring on the order of an hour, and is monitored using the RMS head cameras. The availability of cameras for observing the inflation process provides the option of using ground-based human operators to oversee or control the inflation process.

A good question at this point is how is deployment controlled so that the truss does not become twisted or entangled in itself? This is a valid question and one which requires further study and test to provide a definitive answer. However, there are several reasons to believe that proper deployment control can be provided. First, there are no loose ends to become entangled. To some extent, the truss structure can be thought of as a very low–density open cell sponge that is simply squeezed together for storage and then allowed to expand for deployment. Second, there are several deployment control techniques available. One can control where and at what rate inflation gas is introduced into the truss. For example, the perimeter struts can be inflated first so that they pull out the interior struts. The rate at which the inflation gas passes through nodes from one strut to the next can be controlled through the use of constriction orifices internally located in the nodes. Deployment constraints such as Velcro® patches and break cords can be used to manage the shape during deployment, essentially reducing the number of free degrees of freedom. Finally, analytical techniques for predicting deployment are under development. Since a truss structure consists only of beam elements with a couple of folds each, truss structures may be more amenable to deployment analysis than large membrane structures with their large number of folds and double folds.

Table 2

Summary of reasons why inflatable truss structures are well suited for supporting large space telescopes

Requirement	Inflatable truss structure property
Very high packing volume efficiency	• Stowed as softgoods in minimal volume • Conformal stowage possible • No kinematic mechanical constraints to restrict or complicate stowing
Withstand launch environment	• Launched while soft – provides excellent launch load capability
Large high stiffness structure once deployed	• Rigidized only in zero–g so that load capability requirements are small (i.e., high strength is not required), allowing very thin walls and high slenderness ratio struts • Struts are primarily subjected to axially loading only which allows optimizing fiber selection and ply lay–up to be optimized for high stiffness and low coefficient of thermal expansion • Tetrahedral truss structure provides highly efficient overall configuration that is kinematically determinant • Strut cross–section properties can be varied based on strut location to optimize stiffness of truss structure
Provide array of hard points for hexagonal mirror segment attachment	• Tetrahedral truss configuration provides triangular array of hard points compatible with hexagonal or triangular mirror segments • Other hard point arrangements are possible by skewing truss geometry.
Provide dimensional stability after deployment	• Struts can be made from carbon fibers to provide low coefficient of thermal expansion tailored to operating temperature range • No mechanical joints other than mirror segment attachment points • Open truss structures minimizes variation in exposure to thermal environment, which in combination with relatively large truss thickness reduces thermal distortion sensitivity to variations in thermal environment. • Tetrahedral truss structures are mechanically determinant. The deployed truss geometry depends upon the length of the individual struts, which can be measured and adjusted during the fabrication process.
Low cost	• CAD/CAM design and manufacturing lowers cost • No mechanisms other than for mirror attachment • Simple inflation system for deployment
Robust deployment	• Simple inflation system – no mechanisms

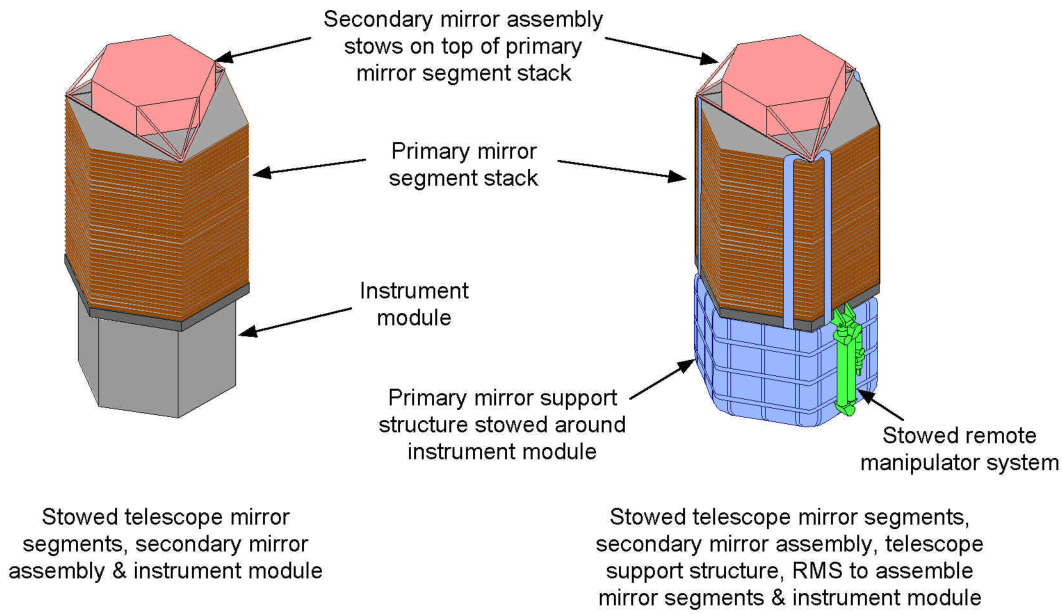


Figure 8

Illustration of an inflatable truss structure simply stowing around outside of instrument module

Once the primary mirror truss structure is deployed, and perhaps rigidized, the secondary mirror support structure is deployed (step four in Figure 9). As a means of deployment control and an example of other functions an RMS can provide, the RMS is shown positioning the secondary mirror assembly close to its final location. Because of the relatively high stiffness provided by the primary mirror support truss, the secondary mirror support structure can attach to the perimeter of the primary mirror support truss. This configuration locates the secondary assembly support structure outside of the return beam from the primary mirror and results in reduce light blockage. To minimize the sunshield size required to shadow the telescope, either a tripod or hexapod structure should be used. A hexapod structure (illustrated in Figure 9) offers far greater stiffness for a given structural mass, but causes more diffraction.

Step five shows the telescope structure fully deployed. At this point the structure is rigidized (see Section 7) and the inflation gas vented in a controlled manner. After deployment and rigidization of the structure is complete, the RMS can, if necessary, survey the truss structure by imaging node locations to determine the as–deployed geometry of both the truss and the extendable RMS arms. Mirror segments are then installed using the RMS as shown in steps six through eight. (See Section 8 for additional discussion on RMS actions and control.) Each mirror segment is installed using the following top–level sequence.

(1) RMS grapples mirror segment

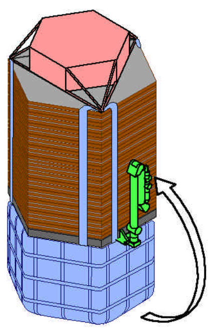
(2) Mirror segment released from stack

(3) RMS flips mirror segment over 180° to position mirror–surface up

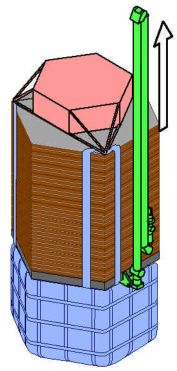
(4) RMS positions mirror segment within capture range of the node attachment mechanisms

(5) Attachment mechanisms actuated to attach mirror segment to support truss

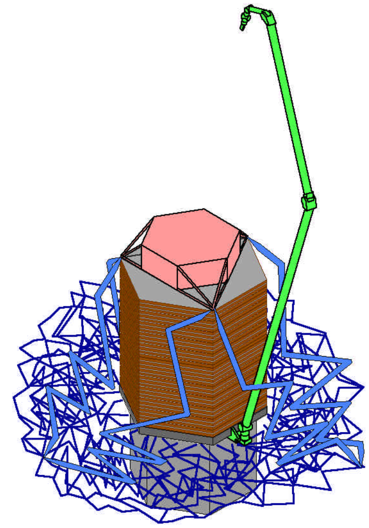
(6) RMS releases mirror segment



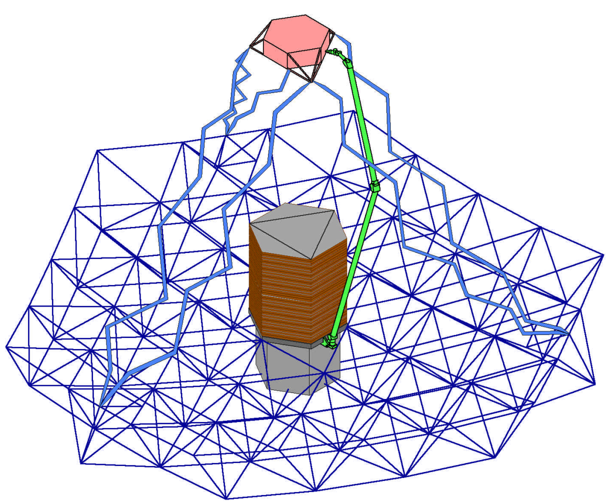
(1) Swing up RMS from stowed position



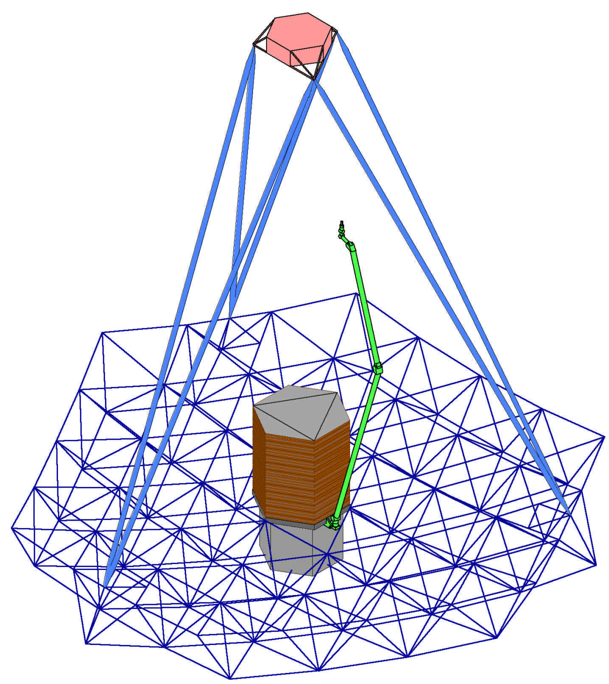
(2) Extend two main RMS arms to full length



(3) With RMS observing, release & inflate truss



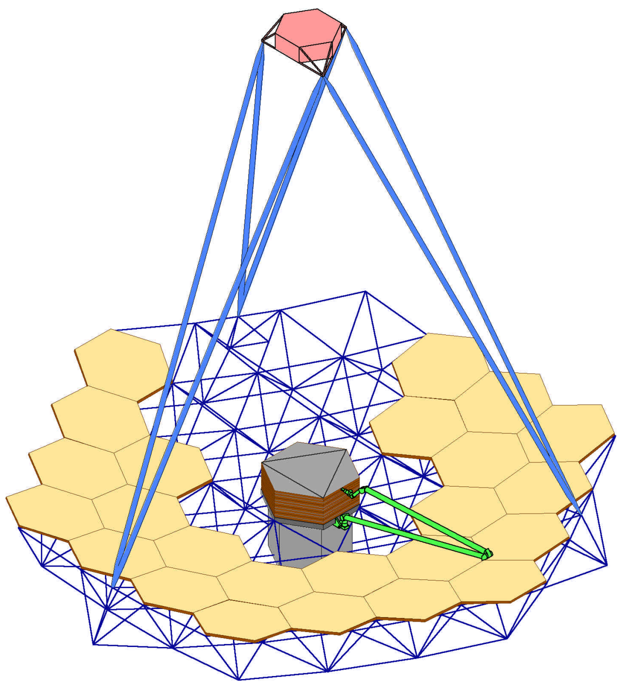
(4) Using RMS to stabilize secondary mirror, inflate secondary assembly support truss



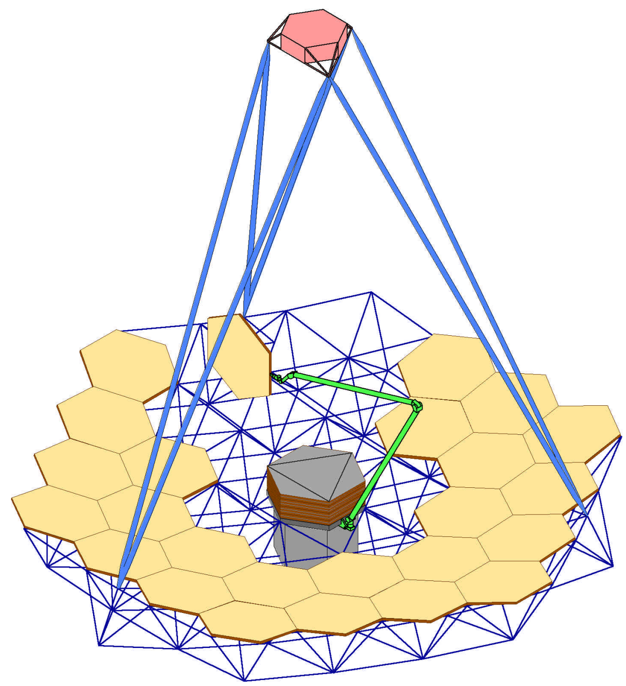
(5) Rigidize structure & survey node locations to update geometry data base

Figure 9

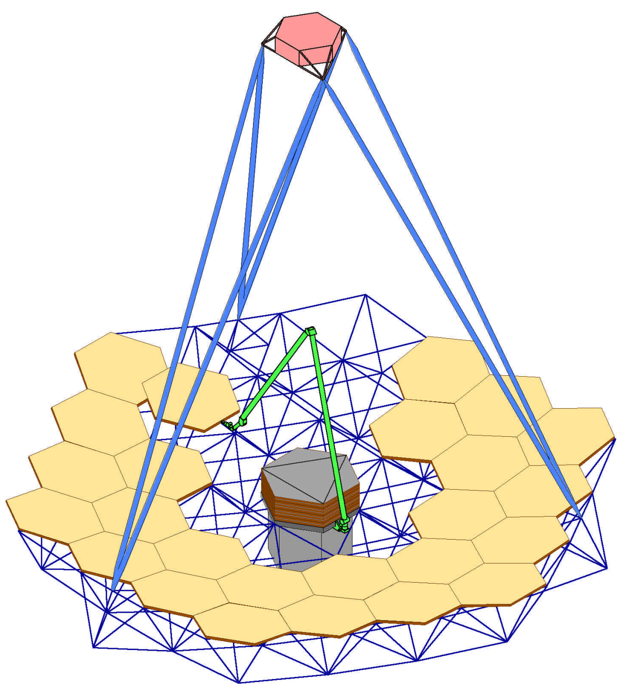
Deployment and assembly sequence of a large space telescope utilizing an inflatable truss support structure



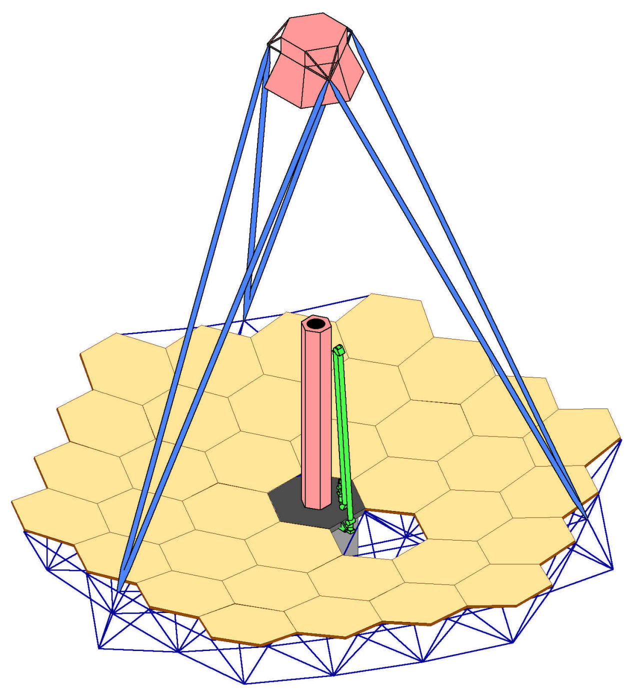
(6) Grapple mirror segment with RMS & release from stack



(7) Flip mirror segment over to position mirror side up



(8) Place mirror segment within capture range of attachment mechanisms



(9) Deploy baffles, position RMS out of light path, & begin optical alignment

Figure 9, continued

Deployment and assembly sequence of a large space telescope utilizing an inflatable truss support structure

Note that the mirror segments are stowed mirror–surface down to reduce contamination deposition. Once installation of the primary mirror segments is complete, the primary and secondary straylight baffles are deployed and the RMS is stowed in a position where it does not block the light path. Telescope deployment and assembly is complete at this point and subsequent sunshield deployment and optical alignment activities can be performed.

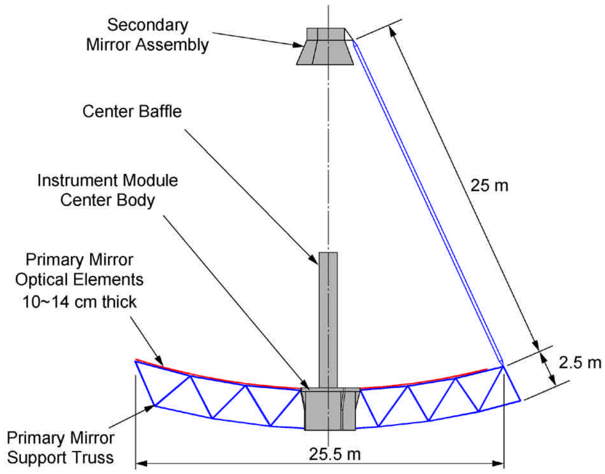
In the illustrated concept, in addition to the center mirror segment which is blocked by the secondary mirror, one additional primary mirror segment location is left unfilled. This is the result of the assumed simple RMS mounting position. With additional complexity, one can reposition the base of the RMS after it grapples the last mirror segment to allow completely filling the primary mirror if the <3% loss in collecting area due to the missing segment is unacceptable.

6 Characteristics of a straw man 400 m^2 telescope concept

A straw man concept for a large space telescope utilizing an inflatable truss support structure was developed and analyzed in order to quantify its physical characteristics. Based on the mirror packing assessments made in Section 3 and the concept described in Section 5, the primary mirror is segmented into thirty–seven 4.2–m diameter hexagons. Thirty-five of the thirty-seven possible hexagon locations are populated with mirror segments. The circumscribed diameter of the primary mirror is 25.5 m and the aperture area provided by thirty-five segments is 401 m^2. A depth of 2.5 m was selected for the primary mirror truss support structure yielding a diameter–to–depth ratio of 10. For an f/1 primary mirror, the struts supporting the secondary mirror are approximately 25 m in length, which is shorter than the struts for the Inflatable Antenna Experiment (IAE) that was deployed in space in the summer of 1996. Figure 10 shows a cross section through the telescope and provides a summary of the calculated structural characteristics. Note the 2,500 N buckling strength of the struts—the truss structure may be gossamer like, but it is not delicate.

To provide a common point for comparison, the primary mirror truss structure is sized to provide a mirror minimum natural frequency comparable to that of the current NASA “yardstick” concept for the NGST. With a material axial–direction modulus of 6.9E10 Pa (10E6 psi), which is achievable with today’s technology, a minimum natural frequency of 5.6 Hz is obtained. By the year 2010 time frame, a modulus of 1.4E11 Pa (20E6 psi) is thought to be achievable, which increases the minimum natural frequency to 7.9 Hz. These results are for a common strut cross section used for all struts. Higher frequencies are achievable by optimizing strut wall thickness and/or diameter according to strut location—increasing the cross–sectional area of struts located near the center of the mirror and decreasing the cross–sectional area of struts near the perimeter.

What is the mass penalty associated with providing this stiffness? We begin with the mass allocation from Table 1 of 2,420 kg for the primary mirror system. Table 3 provides an estimated mass breakdown of all of the components included in the primary mirror system. After accounting for the mass of the support structure, latching mechanisms and associated harnessing, launch restraints for the truss structure and primary mirror segments, inflation system, and remote manipulator system, a mass of 1,843 kg (76%) remains for the mirror segments (optical elements plus position and figure control actuators). The required mirror segment areal density is 4.6 kg/m^2, which is believed to be within the range achievable with NGST mirror technology if developed to its limits. The truss support structure accounts for 14% of the total mass of the primary mirror system, for an areal density of 0.84 kg/m^2. This areal density can be further reduced if a lower stiffness support structure is acceptable.



Primary mirror system truss structure characteristics

Number of struts:	321
Typical strut length:	3.6 m (11.8 ft)
Total length of struts:	1,155 m (3,790 ft)
Strut diameter:	60 mm (2.36 in)
Strut wall thickness:	0.5 mm (0.020 in)
Total volume of strut material:	0.11 m^3 (3.9 ft^3)
Strut buckling load:	2,500 N (550 lbf)
(Pinned-pinned Euler buckling assuming straight struts)	
Minimum natural frequency:	5.6 Hz for E = 6.9E10 Pa (10E6 psi)
	7.9 Hz for E = 1.4E11 Pa (20E6 psi)

Figure 10

Structural characteristics of a 400–m^2 straw man concept for a future large space telescope

Table 3

Estimated mass breakdown for primary mirror system

Component	Mass (kg)	Fraction of total
Primary mirror launch restraints	120	5%
Remote manipulator system	120	5%
Joint drives & end–effector mechanisms	29	
Structure	46	
Harness	7	
Base structure & launch locks	20	
Arm extension deployment mechanisms	10	
Control electronics	8	
Truss structural support system	337	14%
Truss struts – structural	199	
Truss struts – non structural (harness, insulation, vapor barriers)	46	
Truss nodes	13	
Mirror segment attachment mechanisms	29	
Truss launch restraints	20	
Inflation system	30	
Primary mirror segments (4.6 kg/m^2)	1,843	76%
Total – Primary mirror system (6.0 kg/m^2)	2,420	100%

7 Precision inflatable structures: Assessing the current state of the art and the technology development required to produce large inflatable truss structures

7.1 Inflatable structure materials and rigidization

ILC Dover has developed proprietary methods for rigidizing structures in orbit (in situ). These technologies enable a structure to be fabricated from a composite structural laminate, densely packaged into a small volume for launch, deployed via inflation on–orbit, and finally rigidized or cured in situ. After rigidization, inflation pressure is no longer requiring to maintain shape or provide support. This technology can be employed to fabricate many shapes such as tubes, toroids, dish structures, etc., that can be used in the design and manufacture of numerous types of structures. In situ rigidized components can be deployed in various orbits and are designed to remain operational for typical satellite lifetimes of seven to 15 years without concern of damage from meteoroid and man-made debris impacts, radiation exposure, atomic oxygen exposure, or other environmental concerns.

Rigidization is achieved through a number of methods including:

- Thermal Heating
- Passive Cooling
- UV Exposure
- Inflation Gas Reaction
- Thin Wall Aluminum
- Foam Inflation

Many of these technologies have been investigated sporadically since the 1960's but are now yielding reliable structural elements through the use of advanced materials and revolutionary design practices.

<u>Thermal Heating</u>: Rigidization occurs by heating a composite system which is composed of a thermoset matrix resin and a fiber reinforcement such as graphite. The resin hardens after being heated to a specified temperature and maintains its shape and structural properties after venting of the inflation gas. The properties of the composite material are consistent with those of the composite materials typically used in spacecraft design. This system can be designed to cure from energy derived from the spacecraft, or utilizing the sun's solar energy, or a combination of both. An example of a typical composite laminate cross–section can be seen in Figure 11.

<u>Passive Cooling</u>: In this case, the packed structure is warmed to a temperature where it is soft, then inflated and deployed. Over time the structure releases its thermal energy to the environment and becomes rigid. These laminates are also comprised of composite materials that exhibit properties similar to the thermally heated composite laminates.

<u>UV Exposure</u>: This approach works similar to a thermal cured system, except that the resin system is hardened by exposure with UV light. Use of this approach requires the use of an UV resistant reinforcement that does not block the UV light from penetrating the entire laminate. Fiberglass is an inexpensive option that transmits and diffuses the UV light very well. Some mass penalty results with this approach, but a low cost, simple solution is realized.

<u>Inflation Gas Reaction</u>: This method utilizes the reactants contained in the inflation gas used to pressurize the system. The inner wall of the laminate is permeable and allows migration of the reactants and thus rigidization occurs.

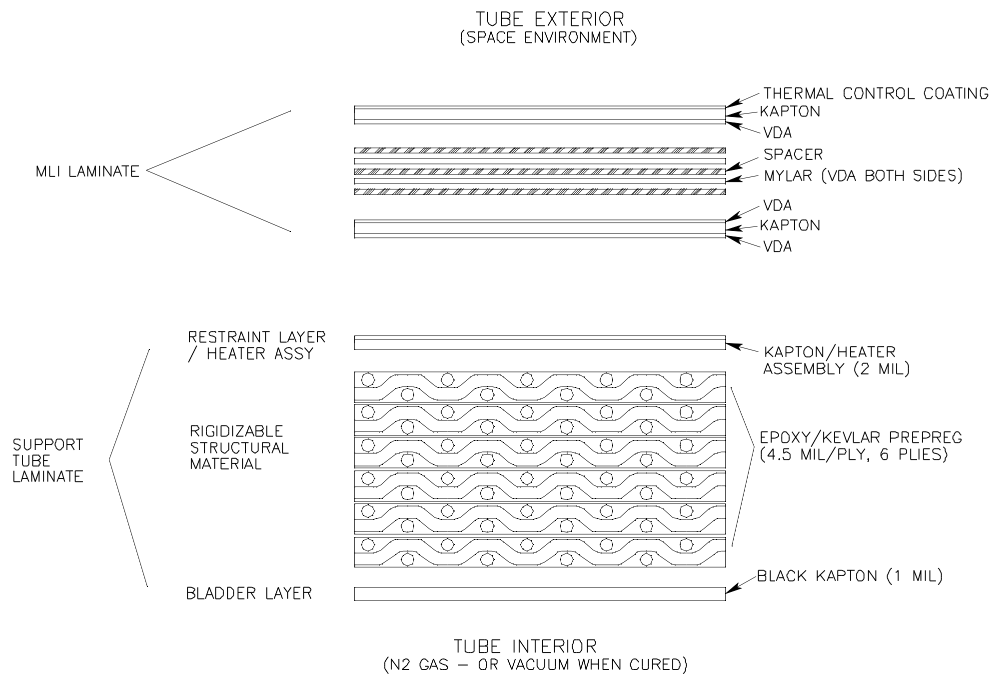


Figure 11

Typical composite laminate cross–section

Thin Wall Aluminum: In this method of rigidization, a laminate is manufactured with a layer of ductile aluminum at its center. Kapton film is positioned on both sides of the aluminum. To rigidize the cross-section, the tube is inflated and the aluminum is slightly yielded to eliminate the wrinkles in the laminate. An example of a typical aluminum laminate cross–section can be seen in Figure 12.

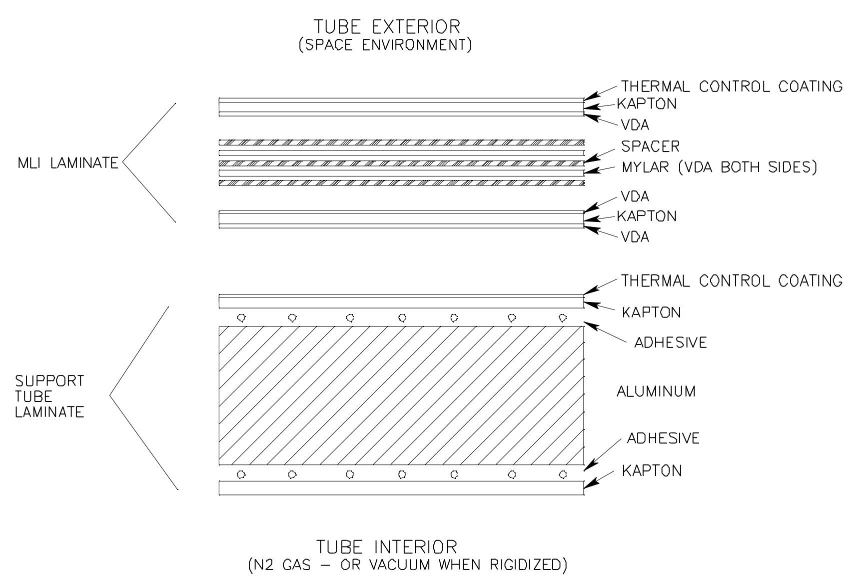


Figure 12

Typical aluminum laminate cross–section

Foam Inflation: In this approach, an inflatable tube is deployed with an inner feed tube. Liquid chemicals are then pumped through the feed tube and out discharge ports to fill the inflatable beam. The chemical reaction in the liquid foam reactants then expands and fills the tube, yielding a rigid element.

For an N–NGST, a good baseline point design is the use of an inflation gas reaction to rigidize the support structure. While this rigidization method is too immature to be considered for use today, it could very well be state of the art in time for an N–NGST. The use of this system eliminates the need for an active curing system such as heating, and further simplifies the inflatable structure system. Contraves of Switzerland baselined this system for an inflatable antenna structure in the 1980s but was unable to optimize the design. More recent testing has answered some of these questions and shows promise for this rigidization method.

7.2 Inflation systems

Inflation gas sources for space inflatables have included compressed gas, gas generators, and sublimation of powders and liquids into gasses. Each of these methods has advantages and disadvantages depending on the application.

Gas generators: Gas generators are lightweight systems, but generally produce gas at rates that are higher than desired for controlled deployment of gossamer–like inflatable space structures. Gas generators are also incapable of providing make-up gas if the structure is expected to maintain pressure for a significant amount of time.

Sublimation: Sublimation of materials to create inflation gas has been used in inflatable structures such as the ECHO 30–m diameter balloons created by NASA Langley Research Center in the 1960s. This technique for inflation is only viable for large volume structures where very low inflation pressures are required to generate the required skin stress. Because of the uncontrolled nature of the deployment event and the mass–competitive nature of compressed–gas inflation systems, this method of inflation would probably not be considered practical today .

Compressed gas: Compressed gas systems have become very low in mass and highly reliable in recent years making them the most practical option for inflating most space structures. Most compressed gas systems consist of a filament wound or titanium gas cylinder, regulator, valving, and a control system. These systems will control the gas flow rate precisely to achieve the desired rate of deployment. It should be noted that the relatively small parasitic mass of the inflation system becomes relatively insignificant when considering very large structures.

After a structure has been rigidized, the inflation gas is vented in a controlled manner. To prevent the escaping gas from imparting inertial forces on the spacecraft, the gas is vented in a non-propulsive manner via expulsion through a "T" fitting. The vent direction is selected to minimize contamination of sensitive surfaces. Filters can be added to the vent line to further reduce the potential for particulate contamination.

7.3 Deployment control

ILC has developed a number of techniques to ensure the controlled deployment of inflatable structures. Their purpose is to:

(1) keep the deploying structure within a known envelope, avoiding defined exclusion zones;

(2) improve reliability of structure deployment by avoiding entanglement with itself or nearby components, and;

(3) minimize impulse to the spacecraft structure from which deployment occurs.

Columnation Devices: Columnation devices (Figure 13) provide a method of axially extending an inflated beam in a straight telescopic motion with some degree of beam stiffness during the deployment. The inflatable tube is axially collapsed on a short mandrel in its packed state. The top of the mandrel has a tube engaging feature (typically a deformable component that expands against the inside of the tube) that applies some resistance to axial motion of the tube. Inflation gas is introduced through the mandrel into the forward end of the tube. As axial load builds in the inflatable, it overcomes the frictional resistance and advances the

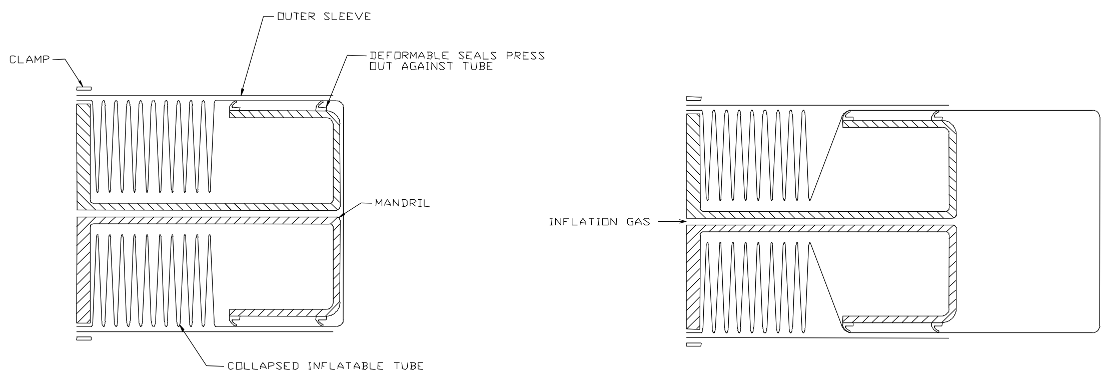


Figure 13

Columnation device

tube. This method places the tube wall in tension during deployment, allowing it to behave as an inflated beam and provide structural stiffness. Several variations of this device, including collapsible mandrels that allow the packed beam to fit into very small volumes, have been developed and tested with good results. Use of a mandrel columnation device is applicable to the extension of the RMS arms.

Roll–up Devices: Inflatable tubes can be rolled up and flattened such that their deployment is controlled by the way in which they are unrolled and inflated. There are two basic approaches, roll–up and reverse roll–up. In the roll–up approach, the tube is rolled up starting at the end farthest from the base (attachment to the structure). Inflation gas is introduced in the tube at the base to force the tube to unroll. Embedded mechanisms (springs, Velcro, etc.) cause the tube to unroll in a prescribed plane, and also provide resistance to unrolling so that some beam stiffness is achieved during deployment. In the reverse roll–up approach, the rolled–up tube is held on a spindle and the free end of the tube extends outward through a set of guides as the tube is unrolled. This approach is simple, reliable, compact, and a benign packing procedure for rigidizable laminates. Its primary disadvantage is that interface with membranes, tubes, or other attachments can be complicated by the unrolling motion (as opposed to a straight telescoping action, where translation is the only motion to consider for such interfaces).

Internal Compartmentalization: Inflatable structures can be fabricated with internal bulkheads or partitions such that there are isolated pneumatic compartments that inflate and pressurize sequentially, as illustrated in Figure 14. The inflation sequence can be through the compartments themselves, or can be via an external manifold. Inflation through the structure requires that the dividing membranes have burst patches or relief valves that open at a prescribed pressure. This enables one section to inflate and assume structural stiffness before the next section begins inflation. Burst patches allow each compartment to equalize at the same

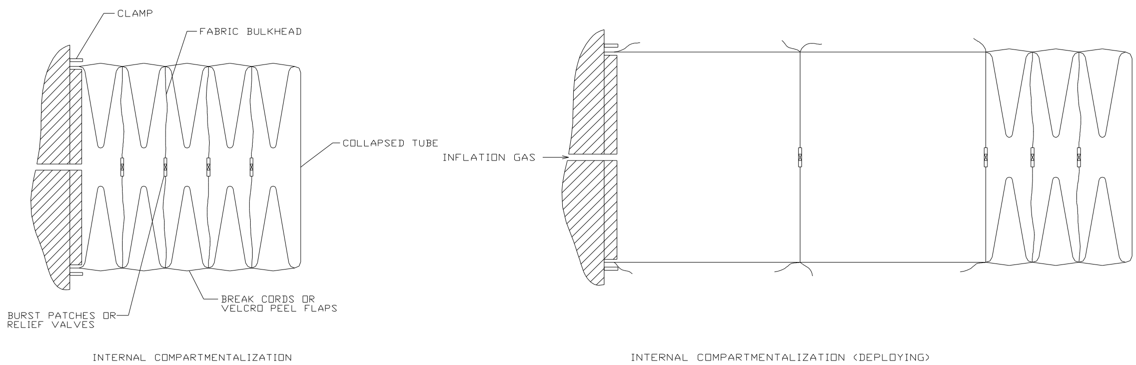


Figure 14

Internal compartmentalization

pressure when inflation is complete; relief valves result in consecutively lower pressures in each adjacent compartment.

Break Cords/Peel Flaps: Uninflated material, as well as single–wall membranes that are supported by inflated structures, can be controlled during deployment through the use of mechanical softgoods mechanisms such as Velcro peel flaps, adhesive peel flaps, and break cords. These devices are used to hold the loose material in a defined position and envelope, and release it in a controlled way when an opening force overcomes them. The opening force can be the load of a deploying inflatable, or other externally applied force. The material is folded in a specified manner, and the folds are secured with Velcro or adhesive flaps, or with cords that are sized to fail at a prescribed load. When the opening force is applied, rather than all of the material being released in an uncontrolled way, it is sequentially dispensed in increments such that the amount of untensioned material at one time is very limited. These devices can also be used for the initial release of the entire packed inflatable from its stowage container or cover.

Becket Loops: Becket loops, also known as daisy chains, are a reliable method of releasing a softgoods assembly from a soft package. The Becket loops secure flaps of the cover to each other, holding the assembly underneath. Immediately before deployment, a mechanical or pyrotechnic device releases the last loop of the daisy chain. Once this loop is released, it sequentially lets all the other loops go, propagating outward from the release point.

The inflation and deployment control system for the N-NGST would most likely utilize a single inflation source with a combination of deployment methods. Because the truss structure has no beginning or end, the use of a roll–up or columnating devices is prevented. Going back to the sponge paradigm, the structure can be folded upon itself and then utilizing a combination of internal pressure compartments with Becket loops or break cords, the structure would slowly unfold itself in stages until becoming fully deployed.

7.4 Fabrication of precision deployable structures

Fabrication techniques have been matured over 50 years which account for material irregularities and allow for precise construction of system geometries. For most applications, all joints today are manufactured with inflatables without utilizing any mechanical systems or nodes. However, for the N–NGST, the node design should be studied with respect to achieving the desired strut length accuracy, overall mass and cost, and the ability to optimize individual strut cross–section properties and replace damaged struts. Traditionally, inflatable structures are simpler and more reliable than mechanical systems. Inflatable systems are inherently less expensive than mechanical designs because they eliminate numerous precision machined components.

8 Remote Manipulator System (RMS) for self–assembly

The telescope concept presented in Section 5 obtains very high packing efficiencies by separating the mirror segments from their support structure so that each may be stowed in the most compact manner. This requires that the mirror segments be assembled to the truss once in orbit. (Membrane mirrors, if and when they are developed, might stow with an inflatable support structure and not require in–orbit assembly.) This can be accomplished either using mechanisms incorporated into each of the mirror segments, or with a single robotic system like the RMS approach presented in Figure 9.

One method for using mechanisms incorporated into each of the mirror segments is the TRW HARD (High Accuracy Reflector Deployment) approach. In the HARD approach, each mirror is connected in series to its adjacent mirror by a rotation–translation mechanism between each pair of segments. The mirrors are deployed sequentially and latch mechanisms structurally couple all mirror segments together. For a low number of mirror segments, the HARD approach is a lower mass and less complex approach than using a RMS. As the number of mirror segments increases, a point is reached where the additional complexity of a RMS is offset by the mass savings of a single RMS compared to a rotation–translation mechanism for each mirror segment.

The use of a RMS for self assembly is not a new major technology development effort. The RMS hardware consists of a 6 or 7–degree–of–freedom kinematic chain (the arm), interface and control electronics, and launch restraint and initial deployment mechanisms. This hardware is functionally very similar to that used on the Shuttle RMS, in the nuclear industry, and on many industrial robots. Unlike the Shuttle RMS that is designed to manipulate 15,000 kg objects, an RMS suitable for assembling the mirror segments is smaller and much lower in mass and stiffness as mirror segment mass is well under 100 kg.

The task of attaching the mirror segments to the truss consists almost completely of predefined simple moves and operations that can be pre–programmed like the typical industrial robot. This design is considerably simpler than the robotic systems that were extensively studied and partially developed for the Spacecraft Servicing System (SSS) and Flight Telerobotic Servicer (FTS) in the 1980's and early 1990's. The workspace geometry is known ahead of time and all mechanical interfaces can be optimized for robotic assembly. Only a single fixed end effector is required, eliminating the need for an end–effector change out mechanism. Mirror attachment mechanisms can incorporate guides to assist assembly alignment and can utilize a "soft–capture–and–latch" assembly approach to reduce the movement accuracy required for assembly operations to the 5–10 mm range. In the "soft–capture–and–latch" assembly approach, as the two halves of the assembly mechanism (one half on the truss and one half on the mirror segment mount) are brought together, they are first captured together in a manner that provides constraint in translation but not rotation. This allows each of the three attachment points for a mirror segment to be mated one at a time. After all three attachment points are captured, then the three attachment mechanisms are actuated and latched to fully rigidize the interface. Several varieties of soft–capture–and–latch mechanisms were developed under the SSS and FTS programs.

The RMS can operate either under full ground control, semi–autonomous control, or full autonomous control. Each mirror segment requires essentially the same governing logic and sequence of steps for assembly. Under semi–autonomous control, the RMS carries out most of its actions under pre–programmed self control. The RMS controller monitors all joint rotation angles to determine the location of the arm, plus other data such as motor current levels and end effector force levels, and can stop its own actions should any parameters exceed pre–set limits. A human operator monitors the operation of the RMS and can also halt motion at any time. In addition to joint angle and other operational data, the operator has slow–scan video from stereo head cameras. As the end effector approaches the end of a move, it stops short of its final end point, by 30 cm for example, and awaits human operator authorization to proceed. This allows the human operator to verify that the desired position is correct, that the next operation is correct, and to intervene if necessary. The RMS then approaches the final position and, if desired, stops again a few centimeters short. Once again, human operator authorization is required to proceed. Similarly, all operations such as grasping, actuating, and releasing require human operator authorization prior to being performed.

The 12–second round–trip communication time delay between Earth and L2 is adequate for semi-autonomous or full ground control. Given the 100–day travel time to L2, time is a fairly abundant resource and all motions can be performed very slowly, allowing a low RMS control bandwidth.

If desired, a second independent system can be provided for monitoring operation of the RMS. The deployed secondary assembly provides a good vantage point for mounting a pair of CCD cameras to track LEDs located on the joints of the RMS. This system can track RMS motions and halt operation should RMS geometry fall outside of allowable limits.

In addition to assembling the primary mirror, the RMS can perform other functions such as assisting in the deployment of the secondary mirror, visual inspection of other deployment activities, and mirror cleaning. With the proper mechanical design, the RMS could even become the structural link between the cold telescope/instrument module assembly and the warm sunshield/spacecraft module assembly. The articulation capability of the RMS could be used to control the relative geometry between the center of mass and the center of pressure for the observatory and/or the tilt of the sunshield with respect to the sun for solar torque control.

9 Other uses for inflatable truss structures

The geometry described above for supporting large segmented mirrors is that of a circular semi–planar truss. Circular or rectangular planar trusses can also be used to support large solar arrays or phased–array antennas. Truss *beams* are another useful geometric form and can replace simple beams in applications where high bending stiffness and low mass per unit length is required. Truss beams can either be straight, curved, or made into a circle to form a torus. Truss beams offer the following advantages over simple beams.

- The ability to decouple the overall beam dimensions from the strut cross–section dimensions provides additional design flexibility.
- Truss beams have higher local buckling strength.
- Unlike simple beams with a circular cross section, truss beams can be designed to have high stiffness in a preferential plane.
- Truss beams require less inflation gas than simple beams of a comparable stiffness by virtue of their reduced volume.
- Truss beams require less power to heat for rigidization by virtue of their reduced surface area.

Because of these advantages, truss beams will likely find applications in very large structures where use of large diameter simple beams will be too heavy. By incorporating flexible circuits and/or flexible fluid lines, inflatable truss structures can provide the core framework for a wide range of future space systems.

10 Conclusions

We have shown that inflatable truss structures have the strong potential of being a key element of future large space telescopes. This conclusion is reached following the logic flow and assumptions outlined in Figure 15. Of particular value is the capability of inflatable truss structures to provide high specific stiffness in a monolithic structure free of mechanical joints while requiring minimal packing volume.

The deployment approach described in this paper continues a trend of increasing deployment sophistication. In the Hubble Space Telescope (HST), the only deployments are the high–gain antennas and solar arrays. The optical system and baffles are both fixed. NGST will use a deployable segmented primary mirror where the primary mirror segments and their support structure are rigid elements that deploy using simple pivot mechanisms. Additionally, a deployable secondary mirror and a lightweight deployable sunshield that stows with high packing efficiency are incorporated. In the concept described here for an N–NGST, the primary mirror segments and their support structure are separated for stowage to allow maximum packing volume efficiency for each. Through the use of an inflatable truss structure, both very high packing efficiency and high specific stiffness is achieved. Once in orbit, the mirror segments are assembled to the truss structure using robotics in the form of a relatively simple remote manipulator system. Each of the evolutionary steps from HST to NGST to N–NGST provides a factor of ten increase in aperture area within the same 5–m class diameter payload volume. Perhaps one day, inflatable truss structures combined with membrane mirrors will provide another factor of ten increase for an N^3GST.

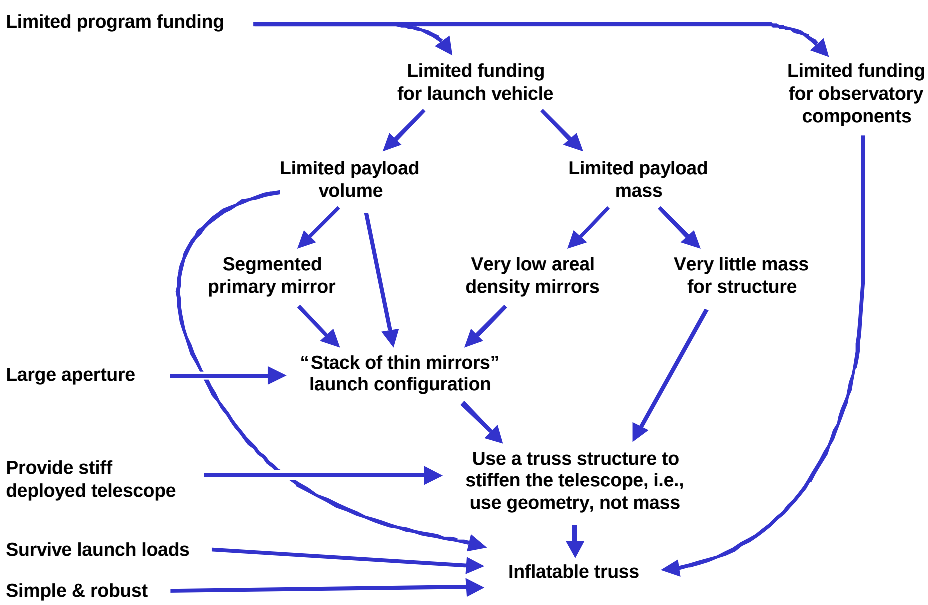


Figure 15

Logic flow leading to the conclusion that inflatable truss structures have the potential of being a key element of future large space telescopes