PRECISION-DEPLOYABLE, STABLE, OPTICAL BENCHES FOR COST-EFFECTIVE SPACE TELESCOPES

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Introduction and Summary

To explore the universe at the arcsecond resolution of Chandra, while increasing collecting area by at least an order of magnitude and maintaining affordability, we will need to make creative use of existing and new technology. Precision-deployable, stable, optical benches that fit inside smaller, lower-cost launch vehicles are a prime example of a technology well within current reach that will yield breakthrough benefits for future astrophysics missions. Deployable optical benches for astrophysical applications have a reputation for complexity; however, we are offering an approach, based on techniques used in space for decades, that reduces overall mission cost.

Currently, deployable structures are implemented on JAXA's Astro-H and NASA's NuStar high-energy astrophysics missions. We believe it is now time to evolve these structures into precision, stable optical benches that are stiff, lightweight, and suitable for space telescopes with focal lengths of 20 meters or more. Such optical benches are required for advanced observatory class missions and can be scaled to Explorer and medium-class missions.

To this end, we have formed a partnership between Space Structures Laboratory (SSL) at the California Institute of Technology, Northrop Grumman Aerospace Systems (NGAS), and Northrop Grumman Astro Aerospace (Astro). Combining the expertise and tools from academia and industry is the most effective approach to take this concept to Technology Readiness Level (TRL) 6. We plan to perform small sub-scale demonstrations, functional tests, and analytical modeling in the academic environment. Using results from SSL, larger prototypes will be developed at facilities at NGAS in Redondo Beach and Carpinteria, CA.

About our Collaboration

From pioneering High Energy Astrophysics Observatories (HEAO) through launch of the Compton Gamma-ray Observatory and the Chandra X-ray observatory, NGAS has over 40 years of experience in designing, building, and operating high-energy astrophysics missions for NASA.

Since 1958, Astro Aerospace, a wholly owned subsidiary of NGAS, has been a pioneer in creating technologies and a major provider of reliable, space-deployable structures. Astro has a 100 percent on-orbit deployment success record on hundreds of flight units; its deployables play a key role in upcoming NASA missions such as the James Webb Space Telescope (JWST).

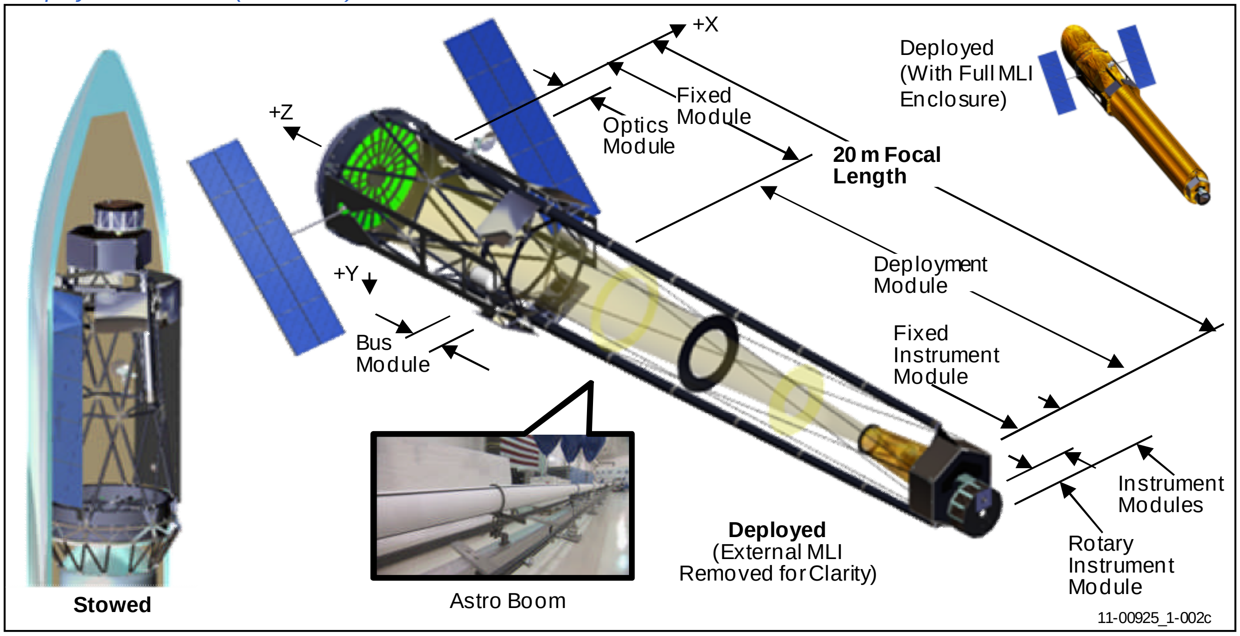
In 2007, Dr. Sergio Pellegrino of the California Institute of Technology established the Space Structures Laboratory (SSL). Dr Sergio Pellegrino has over 25 years of research experience in lightweight deployable structures. He was the founder in 1990 and then director until 2007 of the Deployable Structures Laboratory at the University of Cambridge (www.pellegrino.caltech.edu). Dr. Pellegrino will be personally involved in the SSL activities described below.

Deployable Optical Bench Architecture

NGAS has developed a deployable optical bench (DOB) architecture based on a Tensegrity perimeter truss. Tensegrity structures base their integrity on a balance between tension and compression members and have been established in architecture for decades. Tensegrity structures are attractive for space missions since they achieve very high stiffness at very low masses. The compression members (shown during a deployment test in Figure 1) in our DOB concept (Figure 2) are two segmented Astro Booms, which are compressed in their deployed configuration by six tension lines. During deployment, the booms move without tension line pre-load, and only once they are fully deployed and latched are the tension lines engaged. Six precision stepper motor driven linear actuators are used to preload the tension lines, stiffen the structure, and accurately position the focal point. The perimeter truss effectively accommodates large diameter X-ray mirror assemblies and features a large, unobstructed volume along the central axis, removing all scattering elements from the path of the X-ray photons. This approach was initially conceived for the International X-ray Observatory (IXO) [1, 2], but applies to missions with focal lengths from 7 to over 40 meters.

Figure 1. Telescopic Tube Mast. *Extremely light with compact packaging, the Astro Telescopic Boom provides high performance and flexibility over a wide range of lengths and stiffnesses. In addition, the design incorporates a staged deployment feature and retractability for ground testing and specialized on-orbit applications. Flight-qualified hardware of 100-ft length has been produce, demonstrating high stiffness and strength capability in a low-weight package.*

Figure 2. Conceptual Observatory Design. *The deployable optical bench was initially conceived for the International X-ray Observatory with a focal length of 20 meters. Two Astro Booms, preloaded after deployment by six tension lines, are the key elements of this lightweight structure. Once deployed and preloaded, the structure is highly stable and stiff and forms a large, unobstructed volume along the central axis. This perimeter truss effectively accommodates large diameter X-ray optics, while removing all scattering elements from the path of the X-ray photons. The structure will be completely enclosed in a deployable MLI tent (see insert).*



A key goal of our design was to not impose additional pointing limitations on the observatory other than those required by the X-ray optics. Hence, the optical bench must maintain tight structural tolerances over a wide range of sun-orientations. To this end, our lightweight structure is built from near-zero coefficient of thermal expansion (CTE) material and is completely enclosed in multilayer insulation (MLI). By combining near-zero CTE construction with the benign thermal environment inside the MLI tent, we were able to dramatically expand the field of regard of the mission.

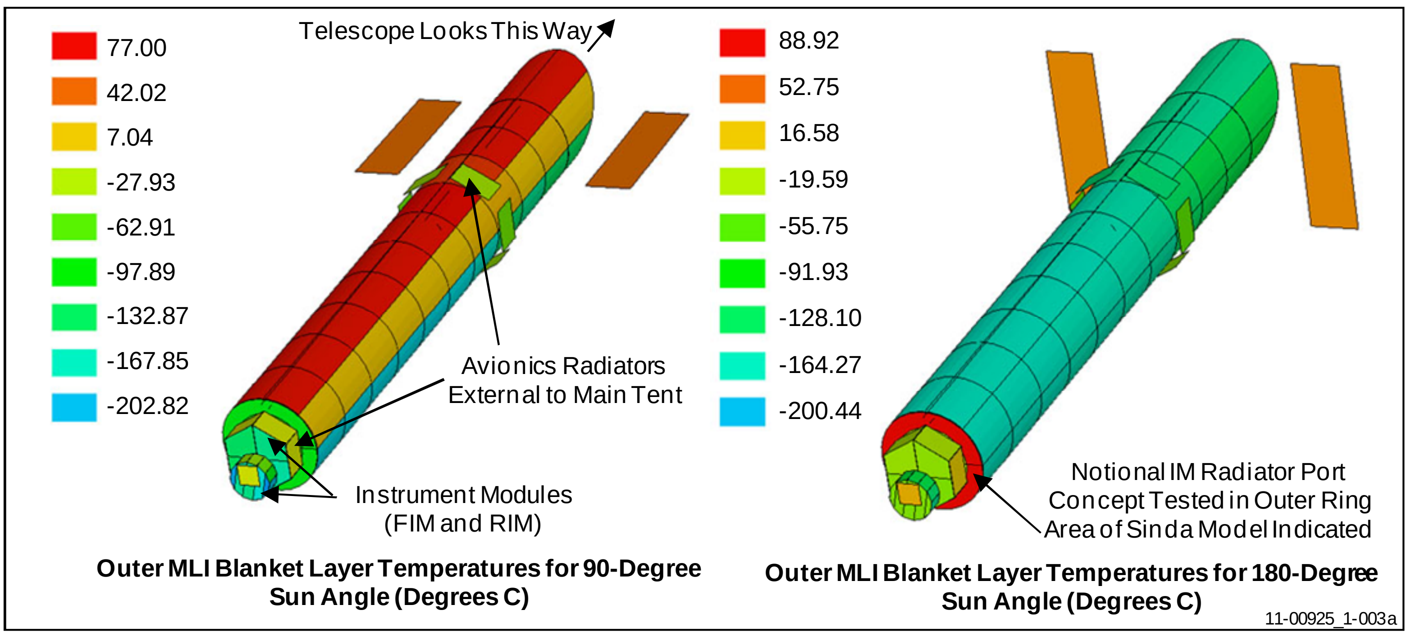
Analysis Demonstrates Viability of Architecture

When we began this work in 2008 [3,4,5], it was clear that we had to first characterize the thermal environment of the structure in order to predict the deformation of the optical bench as the observatory swings between the extremes of possible Sun-orientations. We performed this analysis to determine whether the structure could maintain the alignment tolerances between the X-ray optics on one end and the instrument package on the other. We briefly review the results of this analysis below.

Figure 3 shows the external MLI temperatures for two extreme incident sun-angles. In the 90-degree case, solar radiation is normal to the telescope bore sight. In the 180-degree case, the telescope points directly away from the Sun.

We used a simplified thermal model to develop an efficient MLI tent design to reduce the temperature variations of the Tensegrity structure by more than an order of magnitude below the external MLI temperature variations with Sun-angle. Inside the tent, the primary heat source is the X-ray mirror assembly, which is maintained at 20^{o}C. The only thermal view that the internal optical bench has is of the inner MLI tent layer and the mirror assembly. All avionics supporting spacecraft and instrument functions are kept external to the main MLI tent to minimize any temperature fluctuations that these might cause. Figure 4 shows the resulting temperatures in our baseline thermal design along the inner

Figure 3. External MLI Temperatures. *Our thermal model predicts a wide range of temperatures along the outside layer of the MLI tent as the observatory reorients between two extreme Sun orientations. In the 90-degree case, solar radiation is normal to the bore sight of the observatory (left). In the 180-degree case, the observatory points directly away from the Sun, and the only hot surface is the small, fully enclosed area of the instrument end (right). We note that our model shows that even in full Sun, the ambient temperature cryo-radiator can dissipate the required thermal power.*



MLI layer and the two optical bench booms. While the boom temperature varies slowly from the instrument cluster to the X-ray optics over about 20°C, the temperature at a given position along the observatory axis never changes more than 8°C between the two extreme Sun-angles.

We finally used the temperatures predicted by our 3-dimensional thermal model as inputs to a finite element model (FEM). As the observatory swings from one extreme Sun-orientation to the other, we expect the structure to change dimensions due to the changing temperatures. Table 1 shows the resulting structural distortion margins from our finite element model for four different thermal designs. We used a requirement of 1.6 mm lateral and 0.3 mm axial as the maximum thermally induced structural deformation. Our baseline thermal design meets these requirements even after considering large modeling uncertainty factors by at least a factor of 10 in the lateral and close to a factor of 4 in axial deformations. This thermal distortion analysis showed that, through well-established thermal management and near zero CTE structural construction techniques, the focal point position can be maintained as required to meet IXO stability requirements. This stability was shown without requiring active thermal or actuator control of any kind of the optical bench (although these active control concepts offer order of magnitude tighter stability should the need arise). Therefore, we decided to focus on the most challenging aspect of the optical bench design, the Tensegrity structure, as the first component for further development.

Figure 4. Internal Boom Temperatures. *The temperatures inside the MLI tent are dominated by thermal emission of the X-ray mirror assembly, actively maintained at 20°C (on right). While the inner layer of the MLI (dashed lines) shows slow variation from the cooler instrument side (left) to the warm mirror assembly (right), and large temperature changes from one extreme Sun orientation to the other, the thermally isolated booms (solid lines), vary only slowly along the length of the observatory. Most importantly, each section of the booms varies by less than 8 degrees as the observatory swings between the two extreme Sun-orientations.*

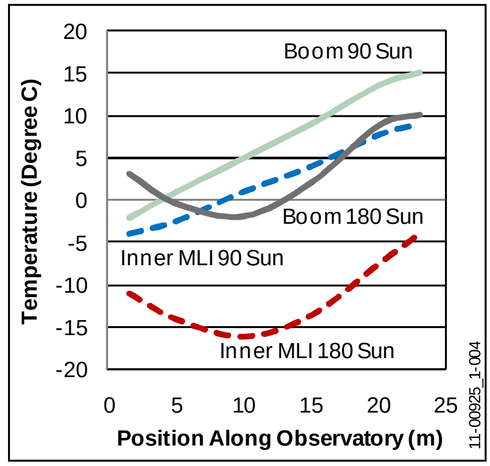


Table 1. Thermal Distortion. *The near zero CTE design, assuming the predicted temperature variations from our thermal model, meets the thermal distortions requirements with large margins even after taking into consideration large modeling uncertainty factors.*

IXO Thermal Distortion Summary	Thermal Distortion Margin After 90-Degree Observatory Pointing Change		
Thermal Design	X@3σ	Y@3σ	Z@3σ
Silver Teflon Outer Layer – Passive 90 – Passive 180	435%	396%	34%
Silver Teflon Outer Layer – Passive 90 – Active 180	1,212%	1,045%	372%
SI/Kapton/VDA Outer Layer – Without Port Radiator	189%	154%	-34%
SI/Kapton/VDA Outer Layer – With Port Radiator	1,212%	1,045%	372%
Distortion Delta Requirement [m]	1.60E-03	1.60E-03	3.00E-04

2-meter Class Engineering Model

In 2009, we constructed a 2-meter class, low fidelity engineering model (Figure 5) to demonstrate the deployment concept and to become familiar with the structural properties. The model was approximately at 1/10th of the scale of IXO. For cost and schedule reasons, the model was developed from aluminum, steel, and brass components and used commercial brush direct current (DC) gear motors to drive deployment and preload the truss. We also developed a FEM to predict the modes of the 1/10-scale model. While no test instrumentation was installed to record modes, observed modes were qualitatively in line with predictions. This model would also be suitable to demonstrate pathfinder models of other subsystems such as the deployable MLI enclosure and a deployable harness (see Table 2 for more details).

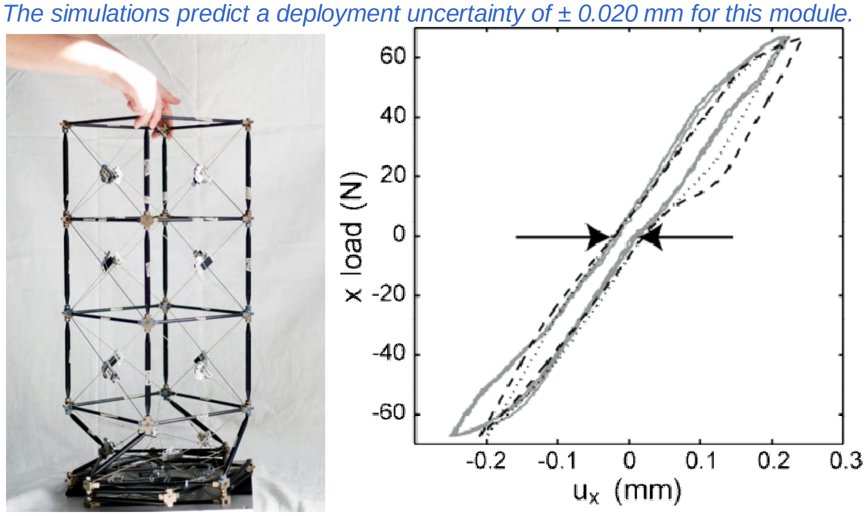
Comparison to Other Approaches

A recent study completed at SSL has investigated the deployment accuracy and repeatability of the 10.15 m long ATK Adam mast that forms part of the deployable bench for the NuSTAR X-ray observatory. The study has shown that uncertainty in the deployed shape of this modular structure can be linked to the stochastic behavior of the latches contained in each module. Numerical simulations that combine standard finite-element models representing the overall structural behavior with an experimentally-determined database of latch responses and joint friction properties were demonstrated on a two-bay module of the Adam mast (see Figure 6) and were also able to predict accurately a deployed shape accuracy on the order of ± 0.5 mm for the flight structure. An additional ± 1.5 mm would result from thermal distortion.

Figure 5. 2-meter Class Engineering Model. *In 2009, we built a proof-of-concept model of the DOB structure. While this model was not instrumented, observed modes were qualitatively in line with predictions.*

We will build on the experience with this analysis and apply this modeling approach to the development of the next generation of precision deployable structures. Since our DOB architecture is tunable, we predict that the deployment of the focal point can be controlled two orders of magnitude more tightly than the modeled Adam mast. In our architecture and for a 20-meter focal length, this accuracy, 4 μm lateral and 1 μm axial, would be available over an adjustment range of more than 10 mm (see below for details). In addition, fully enclosing the structural elements in MLI largely isolates the structural elements from thermal changes and enables a wide range of Sun-orientations without exceeding allowable structural deformations. The smooth tubular telescoping booms even act as a deployment guide for the MLI tent.

Figure 6. Behavior of Adam Mast. *Six-bay model of Adam mast partially folded and hysteresis of two-bay module subject to horizontal shear. The solid lines were measured experimentally; the dotted and broken lines were obtained from finite element simulations that incorporated stochastic behavior of the latching elements. The simulations predict a deployment uncertainty of ± 0.020 mm for this module.*



Technology Roadmap

Over the last three years, we have brought together subject matter experts throughout our collaboration to map out a technology maturation path for the DOB architecture. Table 2 shows in details the progress and future steps required to bring the entire system of the DOB to TRL 6. Our roadmap identifies a two-step process of a 2-meter class, lower fidelity model (1/10th of the IXO scale) followed by a 7-meter class high-fidelity prototype. The 7-meter class was chosen since it is close to full-scale for an Explorer type mission and can still be reasonably handled within existing facilities.

Table 2. Technology Roadmap. *TRL 3 is reached via analysis and laboratory experiments with a lower fidelity, 2-meter class) model. TRL 5 and 6 are reached via a 7-meter class, high-fidelity prototype. Bold items are completed.*

TRL Definition and Hardware Description	Deployable Optical Bench Observatory Assembly - Key Component TRL Exit Criteria		
	DOB Structure	**Deployable MLI Enclosure**	**Deployable Harness**
TRL 3: Analytical and experimental critical function and/or characteristic proof-of concept **Hardware:** Analytical studies to set the context and 1/10th scale (2-meter class) mechanical model to physically validate that the analytical predictions are correct.	• **Observatory system level models: solid model, thermal model, FEM, dynamic/ACS model** • **Preliminary mechanical system analysis showing positive margins against requirements** • **1/10th scale proof of concept model: stowed to deployed configuration transition and Tensegrity truss stiffening**	• **Observatory system level models: solid model, thermal model and stray light model** • **Preliminary thermal analysis showing positive margins against requirements, checking FMA gradients and truss temperature stability** • Preliminary stray light analysis showing positive margin against noise background requirement • Minimize complexity of internal stray light baffle and optimize performance of inner MLI layer • 1/10th scale MLI tent & stray light baffle; deploy with 1/10th scale deployable optical bench • Deploy several times to demonstrate integrity of design; visual Inspection only	• Observatory system level electrical block diagram indicating EE architecture and deployable harness requirements • Preliminary EDI assessment of deployable harness capabilities including wire count and shielding • 1/10th scale proof of concept and deploy using 1/10th scale deployable optical bench • Deploy with 1/10th Scale model to demonstrate Integrity of Design, visual inspection only
TRL 5: Component and/or breadboard validation in relevant environment **Hardware:** 7-meter class medium fidelity system brass board is built and operated to demonstrate overall performance in a simulated operational environment with realistic support elements that demonstrates overall performance in critical areas. Performance predictions are made for subsequent development phases.	• Develop high percentage graphite forward and aft truss prototypes • Deployment booms (subset of flight Astro boom assemblies, STEM driven) • Tensegrity truss lines and tensioning system using graphite tension link material and DC brush gear motors • NEA release/HiShear retraction system • Develop secondary equipment modules using aluminum honeycomb panels and aluminum truss and mass simulators • Generate scaled requirements • Visual demonstration of functional deployment, stowed/deployed modal tap, deployment repeatability, sine burst vibe, amplified ambient thermal distortion, focal point adjustment/control, mass properties tracking • Correlate test data to scaled, prototype FEM, verifying positive test margins • Applied scaling to full scale FEM correlation	• Deployable MLI tent prototype with graphite tubing frame and tension linkage, graphite face sheet/aluminum honeycomb end panels and 12-layer MLI blanket complete with "weathered" MLI • Develop internal stray light baffle • Generate requirements for MLI tent • Deploy several times using overhead crane to demonstrate integrity, followed with stowed vibe test, visual demonstration of proper deployment and MLI coatings for scuffs, tears; measure emittance and solar absorptance, transmittance, and deployment drag • Correlate test data to scaled FEM, showing positive test margins • Applied scaling to full-scale FEM correlation as required • Adjust full-scale thermal model as required, showing positive thermal margins • Adjust full-scale stray light model as required, showing positive stray light margins • Applied scaling to full-scale deployment predictions	• Deployable harness to be Installed in Astro Boom Assemblies • Generate requirements for deployable harness • Deployment, followed with stowed vibe test, demonstration of harness deployment, visual inspection for harness scuffs • Deployment followed with stowed vibe test, visual demonstration of harness deployment, visual inspection for harness scuffs, measure resistance change, check for grounding shorts and measure deployment drag • Verify positive electrical resistance change margin and that no shorts or detrimental scuffs detected • Applied scaling to full scale deployment predictions
TRL 6: System model or prototype demonstration in an operational environment **Hardware:** 7-meter class prototype that adequately addresses all critical scaling issues is built and operated in a relevant environment to demonstrate operations under critical environment conditions	• Enhance prototype graphite deployable optical bench assembly, adding graphite rotary instrument module structure including launch locks, rotary position actuator, deployable MLI tent, fixed MLI and harness • Deploy several times to demonstrate integrity of combined assembly, followed with stowed vibe test, visual demonstration deployment, visual inspection of MLI coatings for scuffs and tears. Measure emittance and solar absorptance, transmittance and MLI tent deployment drag • Measure fixed instrument module deployment repeatability • Rotary instrument module release and repeatability precision testing • Thermal vacuum testing for observatory temperature control over 135 degree Sun angle range • Thermal vacuum environment for advanced thermal distortion testing • Add stray light vane mockups at aperture entrance and stray light baffle for ambient stray light testing • Correlate test data to scaled, prototype FEM, verifying positive test margins • Applied scaling to full-scale FEM correlation as required • Adjust full-scale thermal model as required • Adjust full-scale thermal model as required, showing positive thermal margins • Adjust full-scale stray light model as required, showing positive stray light margins • Applied scaling to full-scale deployment predictions		

Table 3. DOB Performance and Requirements. *Full-scale (20 m) Predicted Performance Traced to IXO Mission Requirements and Scaled Test Requirements for 7-Meter Prototype*

Requirement	IXO Baseline Design (1)	IXO NGAS Design Requirements	Full-Scale Predicted Performance – NGAS	Scaled Requirement for 7-meter Class Test Article	Scaling Method
T1: Focal Point Deployment and Control					
Deployment force margins	See Note 2	>100% static force margin at any point, starting from v = 0			Will comply with NASA-STD-5017
Lateral deployment accuracy (Assumed calibration feedback)	See Note 2	0.60 mm (4)	4 *um*	0.60 mm (4)	Linear actuator error based * (R/F)
Axial deployment accuracy (Assumed Calibration Feedback)	See Note 2	0.112 mm (4)	1 *um*	0.112 mm (4)	Linear-actuator-based
Adjustment range (lateral)	5 mm (3)	5 mm (3)	>10 mm	1.875 mm	Pointing-based lateral delta = angular strain * F
Adjustment range (axial)	5 mm (3)	5 mm (3)	>10 mm	1.875 mm	Linear distortion strain * F
Adjustment resolution (lateral) (4)	0.60 mm (4)	0.60 mm (4)	4 *um*	0.60 mm (4)	Linear actuator error based*(R/F)
Adjustment resolution (axial) (4)	0.112 mm (4)	0.112 mm (4)	1 *um*	0.112 mm (4)	Linear actuator based
T2: Characterization of Deployed Dynamics					
Jitter	**200 mas (3σ) over 200 milliseconds**				**Angle-based – nonscalable**
Tension line and Astro boom modes	N/A	Higher than fundamental optical bench modes			Basic requirement – nonscalable
First optical bench torsion mode (deployed)	1 Hz (unconstrained)	4 Hz (unconstrained) (5)	5 Hz (unconstrained)	7 Hz (UC) Hz (fixed base)	Assumes cantilever beam scaling combined with nonscalable effects
First optical bench bending mode (deployed)	1.6 Hz (unconstrained)	5 Hz (unconstrained) (5)	6 Hz (unconstrained)	10.4 Hz (UC) 4 Hz (fixed base)	
T3: Long-Term Stabililty					
Optical bench temperature delta requirement	10°C (6)	10°C (6)	10°C (6)	10°C (6)	Nonscalable
Long-term slow changing lateral stability (2 weeks)	1.6 mm (3σ)	1.6 mm (3σ)	0.14 mm (3σ)	0.60 mm (3σ)	Pointing-based lateral delta = angular strain * F
Long-term slow changing axial (focus) stability (2 weeks)	0.3 mm (3σ)	0.3 mm (3σ)	0.06 mm (3σ)	0.112 mm (3σ)	Linear distortion strain * F
T4: Stowed Load Verification					
Stowed lateral mode (at separation plane)	8 Hz	8 Hz (fixed base)	8.2 Hz (fixed base)	16 Hz (fixed base)	Assumes cantilever beam scaling combined with nonscalable effects
Stowed loads	Case 1 – 2 G lateral with 3 G axial Case 2 – 1 G lateral with 5 G axial		TBD following CLA	2.5 G lateral with 10 G axial	Payload planner's guide assuming Taurus 3210 for 3/8th scale

(1) Documented in GSFC tabletop data except as noted.

(2) IXO Baseline: assumes use of translation for each instrument in Z direction with none required in lateral directions; nulled using off-pointing.

(3) IXO Baseline: offset pointing for focal point instruments and lateral translation stage for the XGS. IXO NGAS: bench makes all adjustments, range, and resolution for all instruments.

(4) No value given in the table top data – assumed 38% of long-term stability budget

(5) Higher (K/m) and (F/m) ratio design inherently more stable

(6) GSFC data taken from tabletop boom data under 0-20 observatory roll attitude swing. NGAS data assume 90° observatory swing. Both assume TUF = 1.4

On each scale we address the same three key subsystems: (1) deployable Tensegrity structure, (2) deployable MLI enclosure, and (3) deployable harness. We have previously completed the items highlighted in green to reach TRL 3 for the Tensegrity structure, the most critical element of the system. We also have made progress on the system level models of the deployable MLI enclosure.

The current TRL 3 assessment for the Tensegrity structure is based on detailed system analysis and building a 2-meter class model at NGAS between 2008 and 2010. During this time, we developed the basic deployment concept, as well as preliminary system-level models and performed preliminary system-level margin analysis. At the time, we used the IXO requirements as a bench mark. This model has been used to demonstrate the basic transition from the stowed to the deployed configuration, including the ability to fully preload the Tensegrity truss, generating deployed modes in the same order of magnitude as deployed FEM predictions. Scaling and cost limitations created numerous differences in the detailed approach of the 2-meter class model and limited comparisons to analytical models, but we accomplished a basic proof of concept.

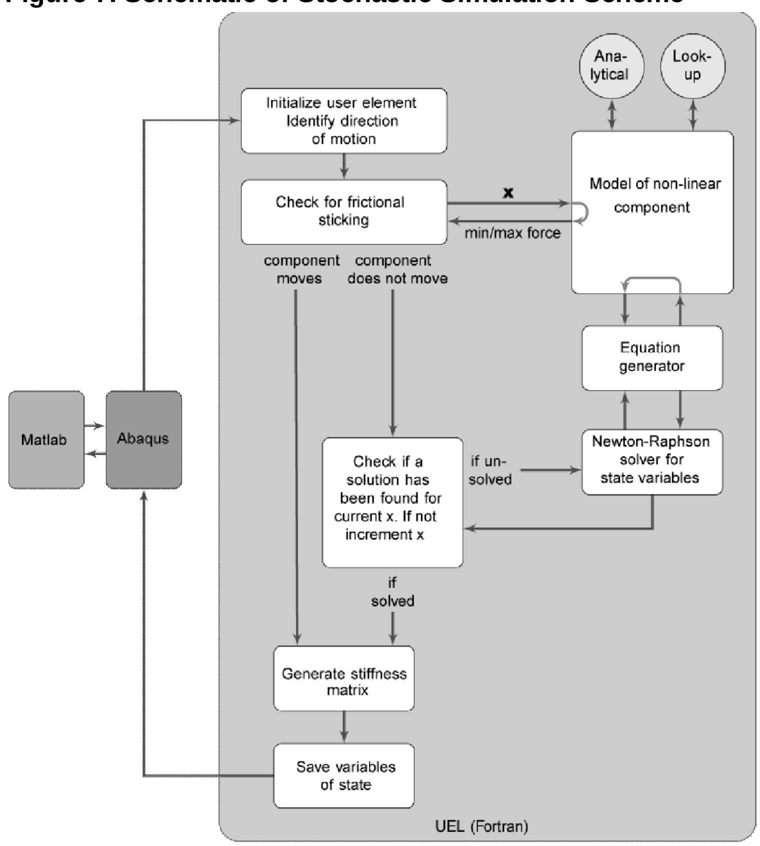
The next step now is to develop the deployable MLI enclosure and the deployable harness at the same scale as the 2-meter class model and to combine them into a subscale system. With these components in hand, we will be ready to move onto to a larger scale, high-fidelity prototype to reach TRL 5 (see Table 2 for details). The components can then be brought together for thermal vacuum testing and detailed modeling to reach TRL 6.

Remaining TRL 3 Level Work

While the Tensegrity structure has reached TRL 3, other components of the system, the deployable MLI tent and the deployable harness have work remaining. Additionally, we plan to further refine our modeling of the Tensegrity structure. The modeling methodology previously established for the Adam mast will be applied to the DOB. The modeling effort will include multiple tests, under a range of thermal conditions, of representative components of the DOB (such as pairs of segments of the Astro telescopic boom) that are expected to show hysteretic behavior. The objective of these tests is to identify each set of components that contributes to stochastic variability in the distribution of deployed shapes, and to quantify the effects of varying the pre-stress levels on the overall accuracy of the structure. The complete model will be validated against the variability measured during deployment tests on an appropriately upgraded 2-meter class model.

Figure 7 shows a schematic representation of the simulation scheme, in which a Matlab interface provides the required inputs to the Abaqus finite element software, which in turn uses a user-defined element that combines analytical models of a frictional component with experimentally obtained look-up tables.

Figure 7. Schematic of Stochastic Simulation Scheme



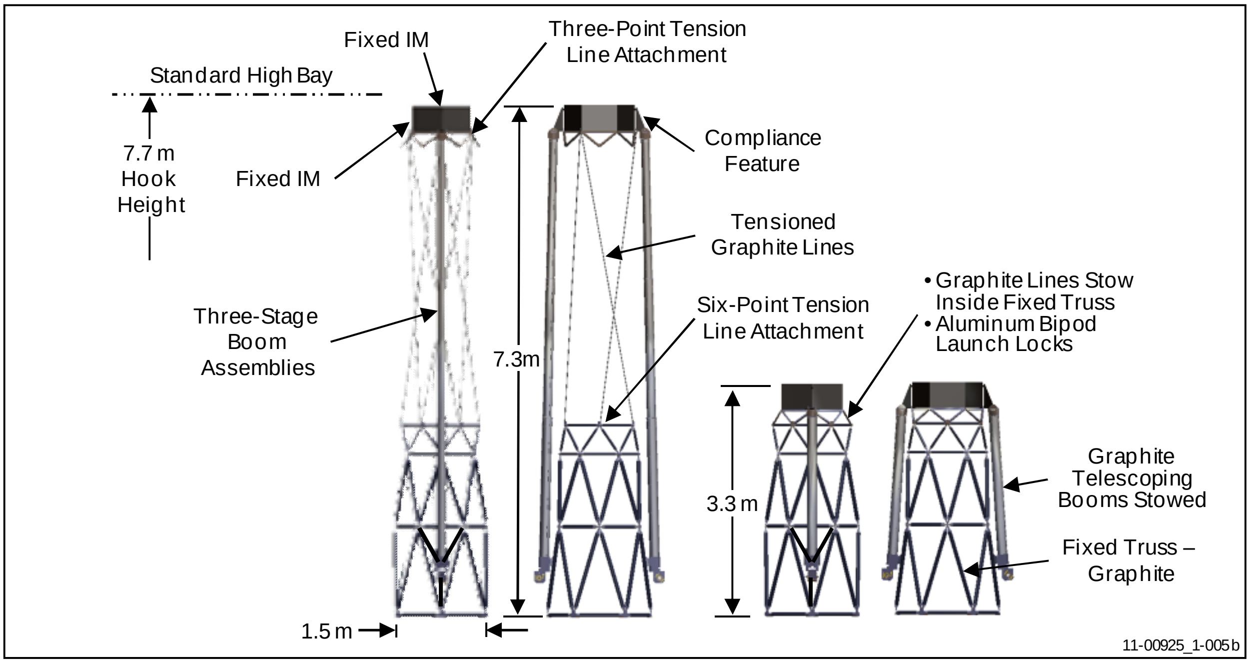
Folding schemes for the MLI covering the DOB will be made, first by means of numerical simulation tools, in order to identify solutions that provide reliable and predictable deployment without the cost and complexity of multi-staged deployment. One or more selected packaging schemes will be implemented on the 2-meter class model and investigated experimentally. The management of the cable harness to the instrument modules will be considered alongside the packaging of the MLI.

We finally will develop the deployable MLI enclosure and the deployable harness at the same scale as the 2-meter class model and combine them into a subscale system. With these components in hand, we are ready to move onto to a larger scale, high-fidelity prototype.

Path to TRL 5 and 6

Our technology roadmap, outlined in Table 2, envisions a 7-meter class, high-fidelity prototype (Figure 8) as the final step on the path to TRL 5 and 6. The scale of the prototype matches Explorer class concepts and is a realistic subscale (about 38%) for observatory class applications. The prototype Tensegrity truss structure will use lower-cost non-flight substitutions (from the baseline full-scale design), providing the most cost-effective solution possible to advance the mid-TRL of the DOB architecture.

Figure 8. Deployable Optical Bench Structure. *A high-fidelity test article of the Tensegrity structure, shown here in deployed (left) and stowed configuration (right) and in two orientations (rotated by 90 degrees), will be built from existing hardware (Astro Booms) combined with non-flight graphite material. This test article will be used to demonstrate that the architecture meets all requirements of the IXO observatory-class mission and has wide applicability to medium and Explorer class missions.*



The key elements of the prototype are the two deployable, tubular Astro Booms. Astro will modify the prototype from the elements of existing flight-like hardware available, shown in Figure 1.

The fixed portion of the optical bench module consists of truss struts manufactured using a very common structural form – graphite tubing in a near-zero CTE layup. A low-cost, non-flight alternative graphite will be substituted in the form of sporting goods grade. Strut end cone fittings will be made from machined aluminum as a substitute to save cost. Truss node connection fittings will also be machined from aluminum. The fixed instrument module (FIM) will be a simplified aluminum box.

Tension lines will be manufactured using graphite telescopic tubing with machined aluminum end fittings, stowed into a mechanism form that will be highly controllable during deployment as well as stowing and can be properly restrained to survive launch loads by using simple mechanical clips, hoops, and brackets (all restraints capable of detailed margin calculations). Mass simulators will be machined steel blocks mechanically attached at the upper hex ring node fittings and machined aluminum plates kinematically attached to the FIM side plates and one location in the off-center center of gravity (CG) location representing the instrument module mass, which will be bolted to the top of the FIM. A base plate will be machined from aluminum for fastening to the high-bay floor.

We have developed a set of technology milestone to demonstrate that the prototype meets requirements. To illustrate the expected performance, we are including here the derived requirements for the IXO. Table 3 lists the initial IXO baseline requirements; a column showing our requirement choices where we found no relevant requirement; and the final, full-scale predicted performance of our architecture. From those, we developed a set of scaled requirements for the 7-meter class prototype that, if demonstrated, would give us confidence that the full scale (20 meter) DOB would meet predictions. The rightmost column in Table 3 shows the method we used for scaling.

Impact of Technology Program

Our proposed technology development enables affordable observatory class high-energy astrophysics missions and is also applicable to medium and Explorer class missions. The Tensegrity deployable bench architecture offers a low total system mass, allowing the use of smaller launch vehicles, while meeting all stability requirements without the need for active thermal or actuator control. Our perimeter truss design effectively accommodates large diameter X-ray mirror assemblies while providing a large, unobstructed central volume, reducing photon scattering. The passive thermal design eliminates the power required for active thermal and structural control. The ability to tune and adjust the structure on orbit removes the need for lateral and axial adjustment mechanisms on the instrument side, greatly simplifying the design of the instrument platform.

Fully enclosing the structural elements inside an MLI tunnel and thermally enclosing the instrument module dramatically increases the allowable sun-angle and thereby the portion of the sky accessible at any given time. This facilitates time-critical follow-up observations. Our straightforward design simplifies the design of the MLI enclosure. The smooth surface of the telescoping booms, free of sharp angles and protruding elements, will act as snag-free guide rails to control the deployment of the MLI tunnel.

Finally, Tensegrity truss structures are not limited to high energy astrophysics. These structures also enable sparse aperture telescopes as well as structurally connected, long-baseline interferometers. All of these systems will benefit from the availability of stable, precision-deployable optical benches.

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Supplemental RFI Information

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RFI Category: Enabling Technology
Brief Description: We map an affordable path to stable, optical benches that are stiff and light-weight for breakthrough high energy astrophysics missions.

Answers to RFI Questions:

- Will you be willing to participate and present your concept at the workshop if invited? **Yes**
- Does your organization have any sensitive or controlled information (e.g., export controlled, proprietary, competition sensitive) that might be useful for this exercise? **Yes**
- If so, are you willing to discuss this information with NASA if proper arrangements can be made to protect the information? **Yes**