

In-Space Modular Assembly: An Approach for Reliable, Affordable, Precision Space Apertures

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In-space assembly will revolutionize the creation, upgrade, and evolution of future space systems. In-space assembly represents an alternative deployment strategy that is not constrained by the requirement of using a single launch vehicle and enables a greater freedom of design for the initial emplacement of assets and their evolution over time. In-space assembly enables assets, such as observatories and science platforms, to become persistent, evolving over time like their terrestrial counterparts. Also, in-space assembly provides a direct path for utilization of in-space manufactured components designed exclusively for the operational environment. To highlight the advantages of an in-space assembly approach, the modular assembly of a 3 m to 4 m precision optical aperture based on thin meniscus technology coupled with structurally efficient TriTruss modules is presented. The 3 m to 4 m aperture stows compactly within two standard ride share slots (0.61 m by 0.71 m by 0.97 m). Placing instruments and the robotic system used for assembly in an adjacent ride share slot enables a capable observatory to be placed into service via modest ride share opportunities. Further, recent hardware assembly tests of similar modules and progress toward hardware tests to validate the overall architecture via diffraction limited testing will be summarized.

I. Acronyms and Nomenclature

a	=	Side length of TriTruss top triangle
EELV	=	Evolved Expendable Launch Vehicle
ESPA	=	EELV Secondary Payload Adapter
g	=	Earth gravity, 9.8 m/sec ²

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H	=	TriTruss height
ISA	=	In-Space Assembled
iSAT	=	in-Space Assembled Telescope
JWST	=	James Webb Space Telescope
LaRC	=	NASA Langley Research Center
SOA	=	State-of-the-Art
UAz	=	the University of Arizona
β	=	Area reduction factor for TriTruss core members compared to face members

II. Introduction

Future space systems will benefit from in-space assembly (ISA) to build the initial asset, followed by subsequent visits to the persistent asset to upgrade and evolve the asset over time. The term evolve is used to acknowledge that the capabilities of a persistent space system, i.e., a persistent asset, can evolve beyond the capabilities initially envisioned, much like terrestrial observatories continue to evolve as research innovates and develops new approaches. ISA increases the design freedom for teams creating space systems enabling them to leverage multiple launches over the course of years, if appropriate.

The assembly of a primary mirror and surrounding light shield or shroud will be presented in this paper, with similar features to the Hubble Space telescope, Fig. 1. It will be shown that an assembled primary mirror can stow compactly and is an order of magnitude less massive than the current state-of-the-art. The assembly of the primary mirror was identified as a tall pole by the in-space assembled telescope (iSAT) study in 2019 [1]. To address this tall pole a modular structural architecture has been developed resulting in the TriTruss modular architecture. An example application of the TriTruss modular architecture to form the telescope backing structure is depicted in Fig. 2. In this architecture all TriTruss modules for a specific implementation are the same. For a doubly curved structure, such as the reflector depicted in Fig. 2, a novel optimization scheme is used to arrange the TriTruss modules which computes the dimensions of small (typically less than 0.1% of the side length of the top triangle of a module) connectors used to join the TriTruss modules together [2]. The mirror module, Fig. 2b and 2c, can be: i) integrated with the TriTruss module, ii) preinstalled onto the TriTruss module, or iii) installed upon the TriTruss module in-situ generally after a portion of the backbone structure has been completed. An important aspect of the TriTruss architecture is that the assembled support structure forms a very efficient structure as depicted in Fig. 3a. The connected modules form a truss isogrid on the top and bottom support structure layers along with lightweight core members resulting in an efficient structural form similar to a honeycomb panel [3]. In Ref. 2, the connectors are called multi-nuts because a bolted interface was used; in this paper a more general term “TriTruss connectors,” as indicated in Fig. 3b, is used because the connectors can be implemented as either a bolted multi-nut interface or a bonded connector interface depending on the precision requirements. Fig. 3b is a close up view of the connection between three modules as indicated by the circle and arrow in Fig. 3a. Similar connectors will be used to affix the shroud as depicted in Fig. 3c and 3d which will be addressed in section IV.

NASA Langley Research Center (LaRC) has extensive experience in ISA with initial efforts considering ways to construct orbiting stations and lunar bases [4, 5, 6, 7] progressing to assembly of telescopes by astronaut [8, 9] and robotic [10, 11, 12] agents. More recently, supported by the NASA Science Technology Mission Directorate (STMD) Game Changing Development (GCD) program, efforts to develop systems for supervised autonomous modular assembly of a telescope primary mirror support structure have been pursued [13, 14]. References 14 and 15 discuss strategies for assembly of TriTruss modules [15]. The contents of this paper will concentrate on the compact packaging and mass savings available by exploiting modular in-space assembly. It will be shown that a 2 m to 3 m precision optical aperture, based on thin meniscus technology, coupled with structurally efficient TriTruss modules may be packaged into two Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter (ESPA) slots. Also, hardware plans to integrate the TriTruss architecture with thin meniscus mirrors, developed at the College of Optical Sciences at the University of Arizona (UAz), culminating in a diffraction limited test of an assembled TriTruss mirror system will be presented.

III. ESPA Sized TriTruss Modules

A TriTruss system designed to be packaged in a standard ESPA slot is depicted in Fig. 4. Notice in the front view, Fig. 4a, that the top equilateral triangle (420 mm side length) is smaller than the bottom equilateral triangle (455 mm side length), illustrating the tapered modules which, when assembled, naturally form a curved support structure for

the reflector. The three equilateral triangular layers; bottom, top and middle are where the name TriTruss originated. The taper angle when viewed from the side is 2.82 degrees as depicted in Fig. 4b. To reduce mass, the cross-sectional area of the face members can be adjusted independently of the core members as will be discussed. In the top view, Fig. 4c, the equilateral shape is clear.

TriTruss modules are assembled from 6 mm composite tubes using an assembly fixture, as shown in Fig. 5a, and weigh 178 g assembled. The assembly fixture employs registration pins through the packaging restraint holes to locate the TriTruss structural nodes. Thus, the TriTruss module is assembled in the stowed configuration depicted in Fig. 5b. Deployment occurs in an inverted configuration by displacing the bottom triangle vertically from the top triangle, Fig. 5c, to a fully extended state, Fig. 5d. Next, the central triangle is translated down to lock the central joints, rigidizing the TriTruss module, Fig. 5e. An isotropic view of the rigidized module is shown in Fig. 5f.

A standard ESPA ring is depicted in Fig. 6a, which is one of several ESPA configurations available [16]. The TriTruss modules for a 3-ring reflector package into approximately one third of the standard ESPA volume of approximately 711 mm by 610 mm by 965 mm (Fig. 6b). An ESPA adapter is used to provide attachment points for the stowed TriTruss modules and launch restraints. An assembly tool is pre-attached to the top of the ESPA package for use by a generic robot during assembly. Use of an assembly tool removes the need for distributed deployment devices throughout the structure. A packaging prototype has been constructed to verify the packing and deployment hardware as shown in Fig. 6c. From the prototype, it was learned that a uniform small clearance (0.05 mm) between the assembly tool and central deployment guide is critical. A similar packaging scheme for TriTruss modules with preattached mirrors is depicted in Fig. 6d. A significant difference is that the deployment guide is packaged attached to the side of the launch lock structure. During assembly, this guide is attached to the assembly tool. The launch lock structure is attached using pretensioned cables to the ESPA adapter to securely contain the TriTruss modules and assembly tool during launch. Cross section views of the packaged modules of Fig. 6b and 6d are depicted in Fig. 7a and 7b, respectively. In Fig. 7b, the mirror, depicted in green, has a thickness of 6 mm; the TriTruss, is depicted in light and dark brown. Pyrotechnic launch locks are identified as well as constant force springs used to restrain the modules until they are acquired for assembly. The assembly tool, depicted in green, used to deploy and manipulate the TriTruss modules is preattached to the top TriTruss module, depicted in blue, and a launch restraint structure secures the package. Comparing Figs. 7a and 7b, the effect on spacing between modules increases to accommodate the preattached mirrors. Several ways to measure the aperture of a segmented mirror are depicted in Fig. 8, and used in Table 1 to describe the predicted aperture for one to six rings of the ESPA hardware of Fig. 7. Note that aperture diameter refers to the diameter of a circle with the same total area as the segmented mirrors. In Table 1, the two entries highlighted in green indicate the limiting case for a single standard ESPA volume, i.e. a 4.207 m equivalent diameter for a five ring structure which reduces to 2.683 m aperture diameter for a three ring structure with preattached mirrors.

Table 1. Aperture information for one to six rings of TriTruss modules. Aperture based on planar area.

Description	Units						
Number of Rings	#	1	2	3	4	5	6
Aperture Diameter(equivalent)	mm	1167	1922	2683	3445	4207	4970
Aperture, flat to flat	mm	1260	2100	2940	3780	4620	5460
Aperture, point to point	mm	1283	2114	2950	3788	4626	5465
Number of Modules	#	7	19	37	61	91	127
Structure Stack Height	mm	192.5	282.5	417.5	597.5	822.5	1093
With Mirror Stack Height	mm	273	501	843	1299	1869	2553

To highlight the efficiency expected from an assembled TriTruss structure, a study of the TriTruss structural mass required for an equivalent aperture of 2.683 m was performed using the method introduced in Ref. 13. The mass of the three-ring supporting truss assembly was calculated and the results are plotted in Fig. 9. Total truss mass versus a nondimensional parameter, H/a , is shown in Fig. 9. The H/a parameter is based on two characteristic dimensions of a TriTruss module, the module height, H , and the side length, a , of the top equilateral triangle, as illustrated to the right of the plots. The supported areal panel density was assumed to be 12 kg/m² based on the thin meniscus technology under development at UAz. Pairs of black and blue traces are show in Fig. 9 for two values of β , where β is the ratio

of the core members cross sectional area to that of the face members. The black traces in Fig. 9 are for a β of 1, indicating the core members have the same cross-sectional area as the members in the top and bottom triangles, while the blue traces correspond to a β of 0.5, i.e., the core members have half the cross-sectional area of the members in the top and bottom triangles. The designs corresponding to β ratio of 0.5 are preferred designs where the core members primarily need to resist core collapse while the face sheets, formed by the top and bottom triangles, carry the predominate bending load. Three pairs of traces are depicted for three different global frequencies of the TriTruss mirror system: 20 Hz, 30 Hz, and 40 Hz. The total truss mass falls rapidly initially with increasing H/a up to an H/a of 1 to 1.5, depending on frequency. The total truss mass then tends to level out for higher ranges of H/a. Note that if H/a continues to increase, the mass begins to increase again as the core member mass dominates the overall structural mass. Excessive increase of H/a is generally not favorable because of the core mass increase, alternatively the size of the top and bottom triangle should be increased to maintain a reasonable H/a. A total truss mass of 0.5 kg is readily achievable resulting in structural areal density of 0.088 kg/m². In a similar analysis, Fig. 10 depicts the results for a mirror system like used on JWST with an areal density of 26.16 kg/m² and a segment size of 1.32 m flat to flat. The support structure for two rings with an equivalent diameter of 6.5 m is expected to have a total mass below 10 kg resulting in an areal density of 0.30 kg/m², well below the state-of-the-art (SOA) of the James Webb Space Telescope (JWST) of 29.2 kg/m² [17, 18]. It is important to note that the JWST system was designed to support mirror segments during launch and operate at cryogenic temperatures. Here, the compact packaging of the modules, coupled with the thin meniscus mirrors greatly reduces the loads that are expected to be encountered at launch. A more detailed launch environment analysis is needed, which was beyond the scope of the current work.

IV. Modular Shroud

A modular shroud concept shows promise as depicted in Fig. 11. Like the TriTruss modules, all shroud modules are the same (Fig. 11a), with unique connectors between the shroud modules and the perimeter TriTruss modules (Fig. 11b). The shroud modules are sized to provide clearance around the supported mirror segment and are designed to be reusable, to allow a segmented mirror to be expanded by adding an additional ring. Then the existing shroud modules can be reused and augmented by a few more shroud modules to encompass the expanded mirror. The individual shroud modules contain panels that telescope to the needed height following assembly as depicted in Fig. 11c. The shroud modules package compactly upon a retractable pin, Fig. 11d detail, enabling a single panel to be acquired using a robotic tool shown in its storage location attached to the package shroud modules in Fig. 11e. Each shroud module includes a closeout strip (detail in Fig. 11d) which overlaps with the module neighbor to cover the slight gap between modules. Preliminary thermal analysis indicates that, if the shroud angle (Fig. 11a), between two connected shrouds, remain sufficiently shallow to prevent multi-bounce reflections, the thermal performance is reasonable. Further thermal analysis is needed to refine the shroud design, including number of thermal layers and the layer spacing.

V. Thin Meniscus Mirrors

In a parallel effort, the UAz and LaRC are developing mirror modules composed of a thin meniscus mirror supported by a TriTruss. In this collaboration, three mirror segments from the second and third ring of a three-ring mirror assembly will be tested as depicted by the yellow segments in Fig. 12a. The dimensions of the mirrors in the UAz collaboration are provided in Fig. 12c. Note that these mirrors have different dimensions than the ESPA sized mirrors depicted in Fig. 4. The UAz collaboration mirrors are larger, representing a more challenging alignment task. The thin meniscus mirrors rely on a series of actuators to carefully control the mirror surface shape. The actuators lie between the mirror actuator support structure and the meniscus mirror as depicted in Fig. 13a. A 7 mm-thick meniscus is planned for testing to assure additional robustness in the first-generation design. It is anticipated that a thinner meniscus can be used in a flight system that would result in an areal density of 12 kg/m². The electronics for the actuator control are arranged in three electronics boxes (Fig. 13b). The wiring harness is expected to be pre-attached to the interior of the top triangle which does not interfere with packaging. Flexures are planned to interface the mirror module to the TriTruss system as depicted in the upper right of Fig. 13b. In a flight system, it may be possible to integrate the top triangle of the TriTruss system into the mirror actuator support raft.

An example of a thin meniscus mirror undergoing polishing at UAz is shown in Fig. 14a, and a thin meniscus mirror with actuator system, similar to that planned, is shown in Fig. 14b. The optics group at UAz has extensive experience and expertise in the measurement and characterization of the polished mirror surface. During polishing, progress is monitored by an optical measurement of the mirror surface resulting enabling a map of the surface topography displayed in plots like that shown in Fig. 14c which are used to guide subsequent polishing.

The culminating test of the collaboration between LaRC and UAz, expected to occur in 2024, will be to test the diffraction limited performance at visible wavelength of a three-module system composed of thin meniscus mirrors supported by an assembly of three TriTruss modules. The mirrors are planned to be installed on the TriTruss modules prior to assembly of the three-module system to mimic the process of an in-space assembled system.

VI. Conclusions and Closing Remarks

In 2024, diffraction limited performance test of three modules composed of a thin meniscus mirror and TriTruss reflector support structure is expected to occur. The test will validate the ability to assemble high-performance optical systems using thin meniscus mirrors and a common structural module based on the TriTruss architecture. The TriTruss architecture packages compactly allowing a 3 m to 4 m aperture to be packaged into two ride share slots, with a total areal density of 12 kg/m². The TriTruss support system for a ride share mirror system is expected to have an areal density of 0.088 kg/m² (which may increase because of global mirror stiffness/frequency requirements). A more detailed launch environment analysis is needed to refine the modular approach presented.

VII. Acknowledgments

The authors wish to thank Mr. Ron Neale and Mr. David Long who developed the visualizations presented.

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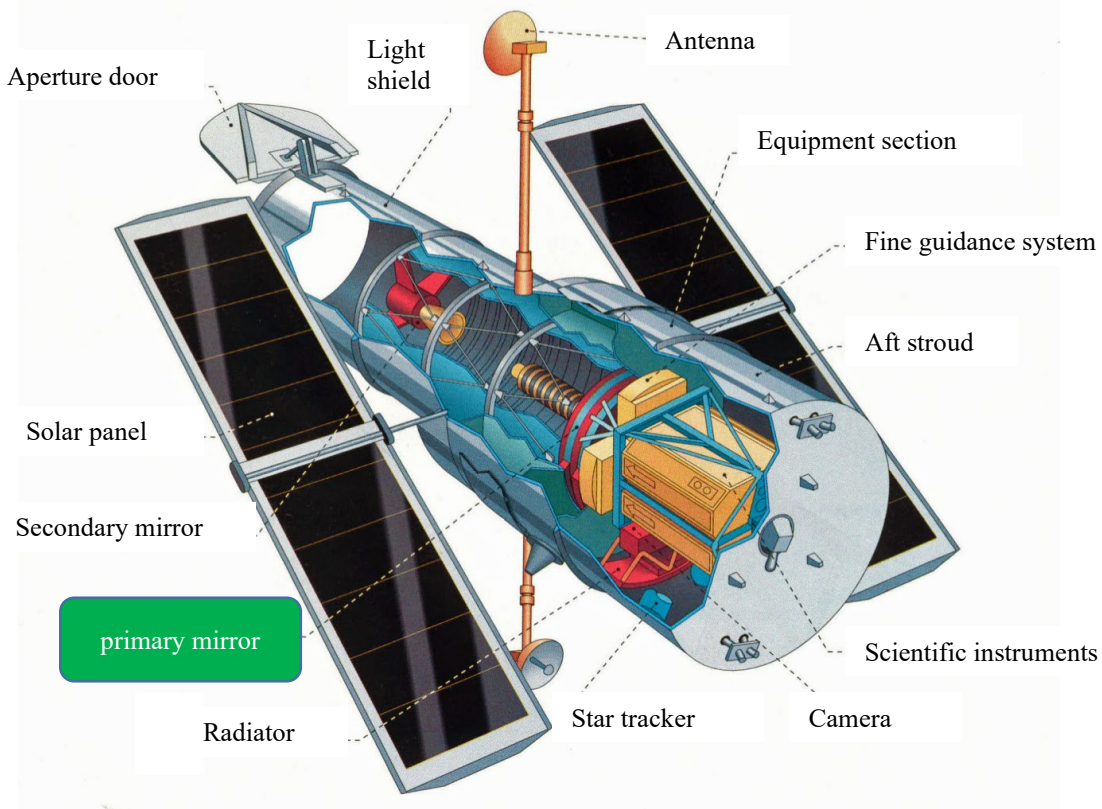


Figure 1. Hubble Space Telescope highlighting the primary mirror.

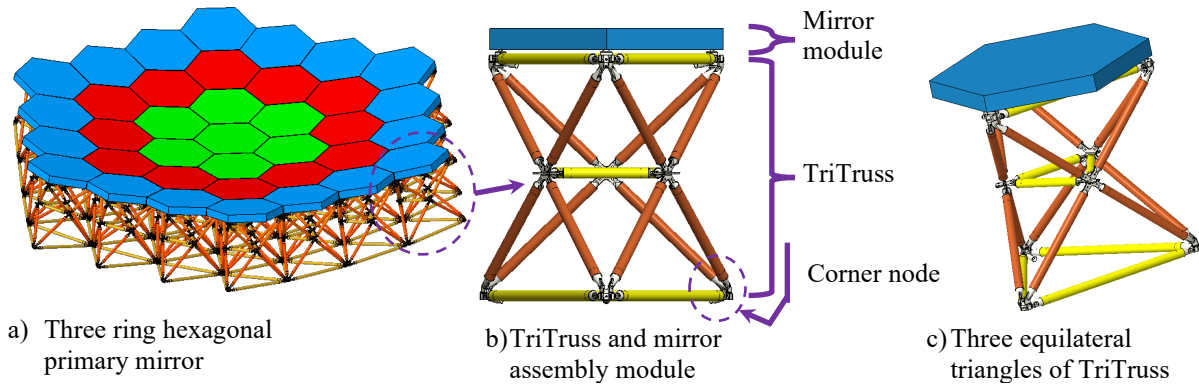


Figure 2. Three-ring primary mirror with TriTruss support structure.

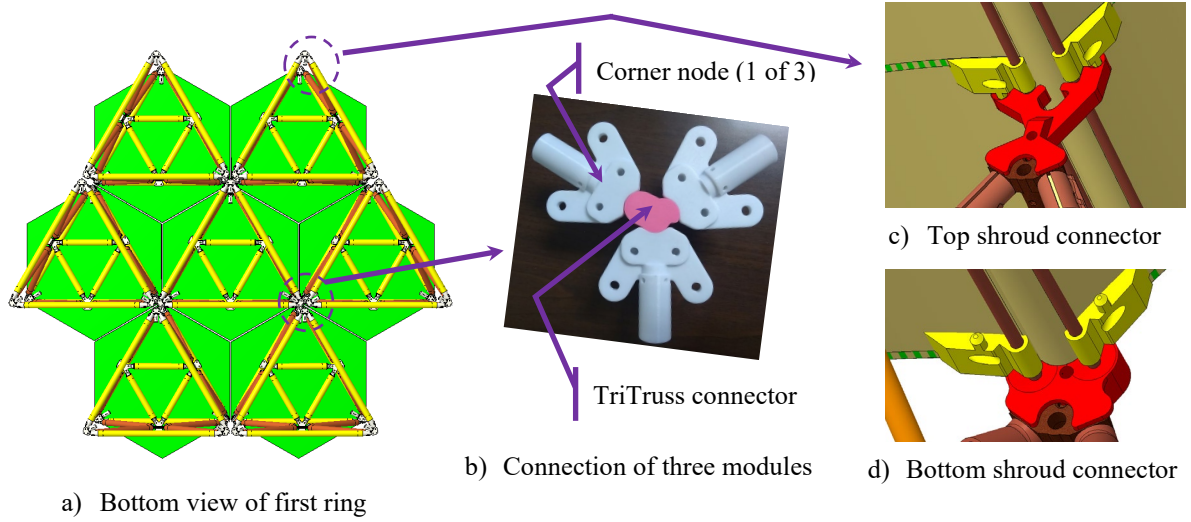


Figure 3. TriTruss architecture where all modules are the same with unique TriTruss connector to support a doubly curved surface and shroud attachment.

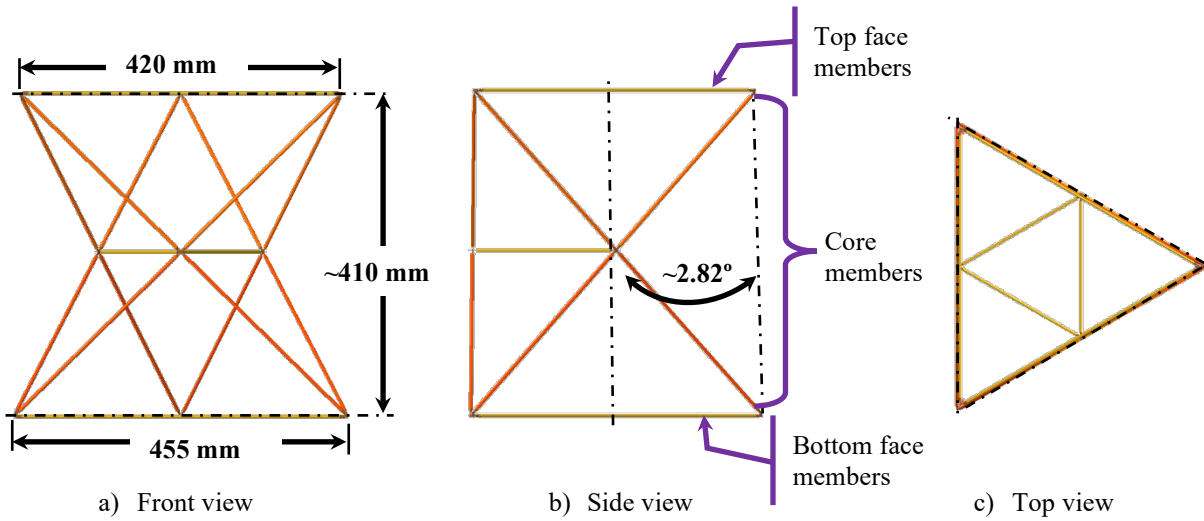


Figure 4. TriTruss designed to package compactly into standard ESPA slot.

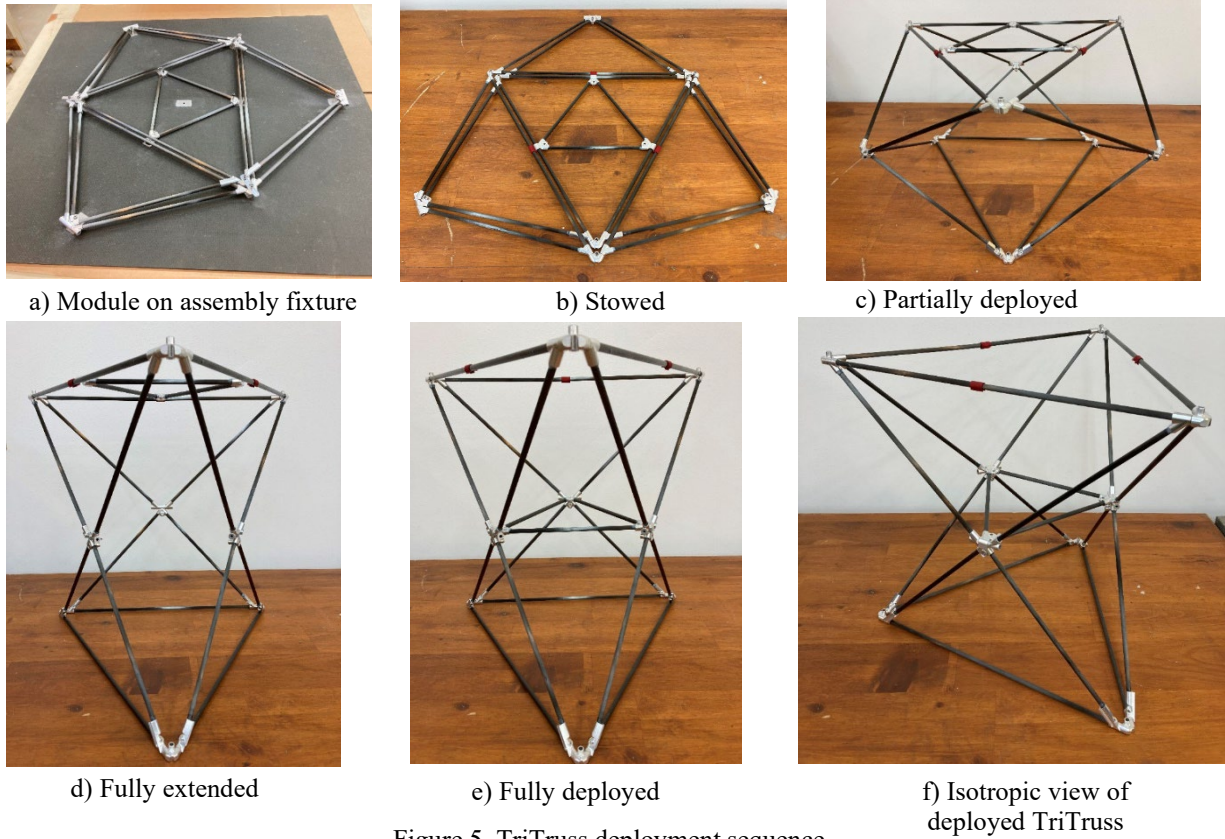


Figure 5. TriTruss deployment sequence.

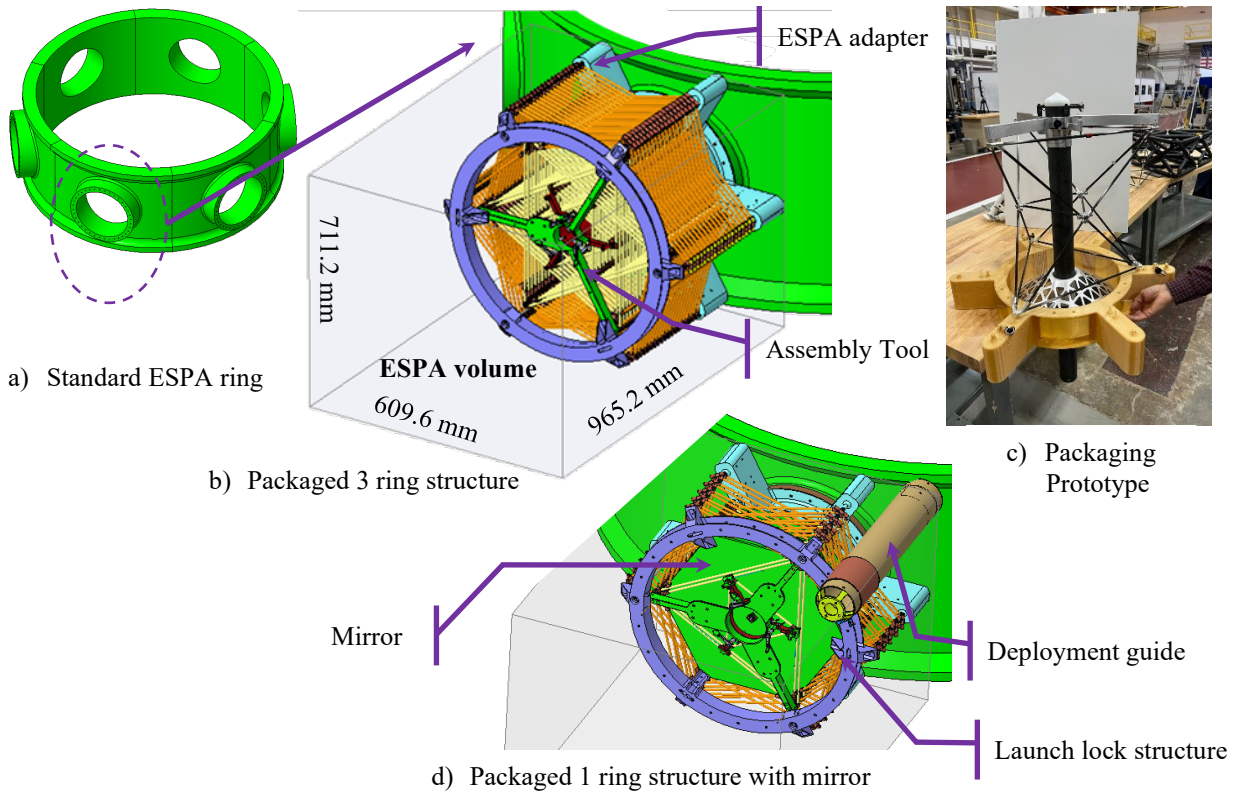


Figure 6. Packaged three-ring TriTruss primary mirror structure (no mirrors).

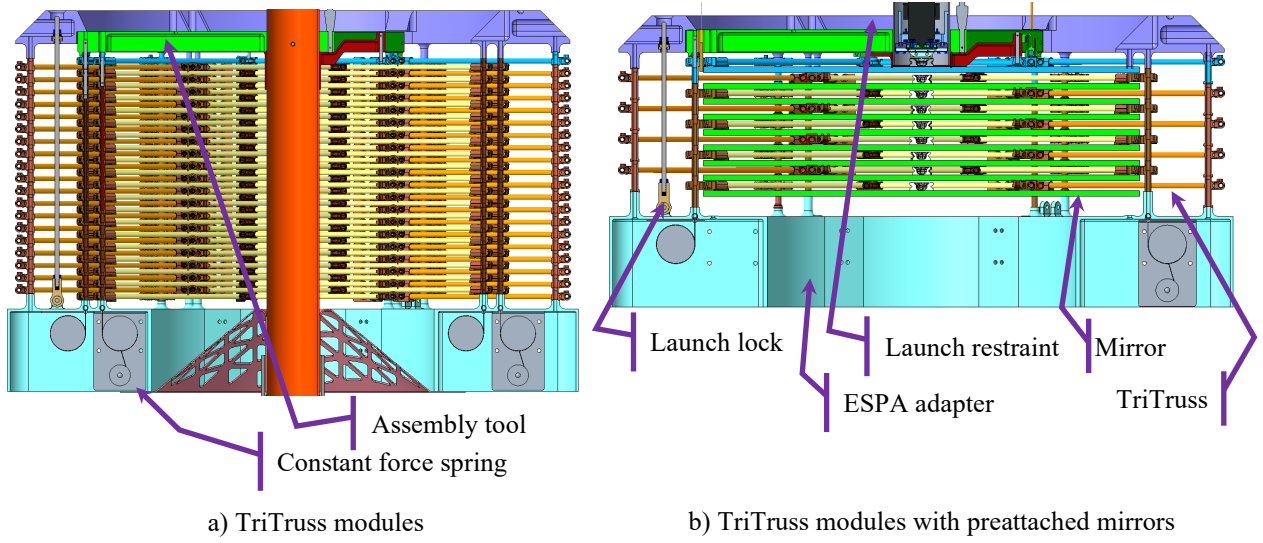


Figure 7. Cross Section of packaged TriTruss module options.

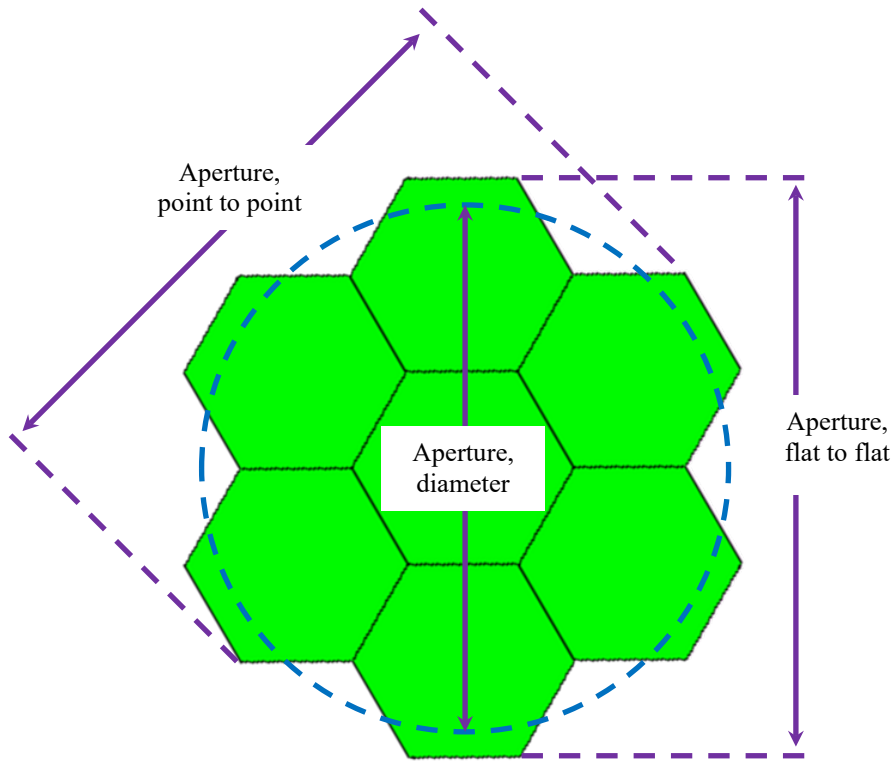


Figure 8. Segmented reflector aperture descriptions used in Table 1.

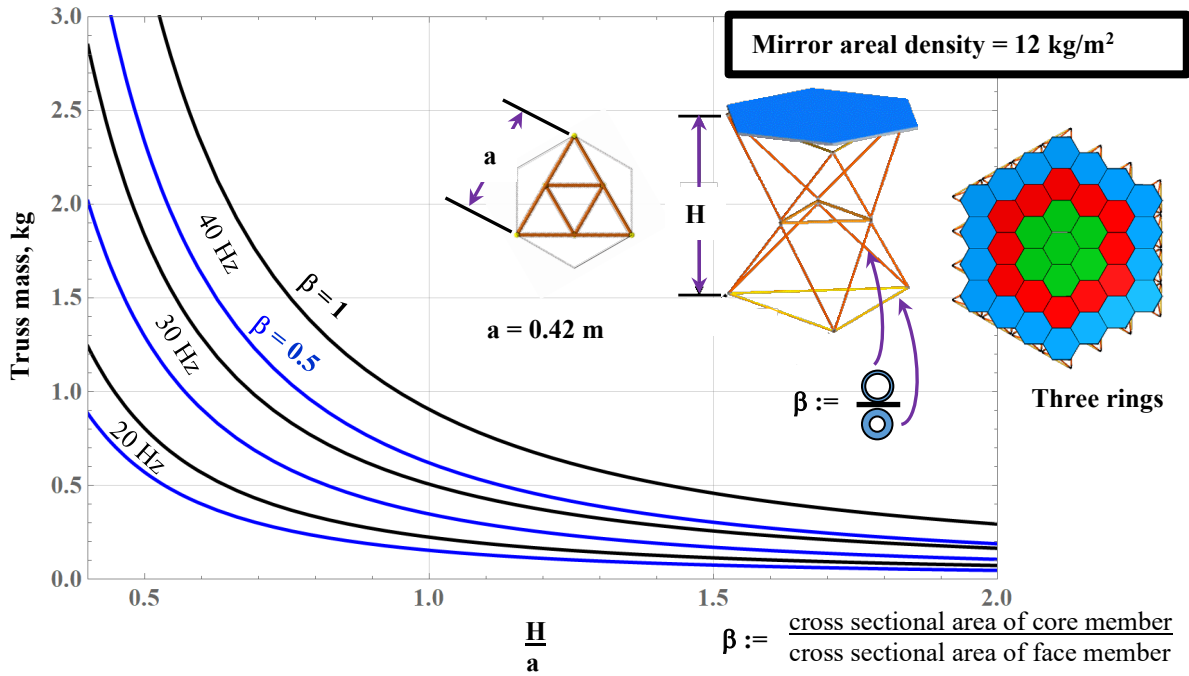


Figure 9. Predicted total mass of 2.683 m three-ring ESPA TriTruss structure supporting thin meniscus mirrors.

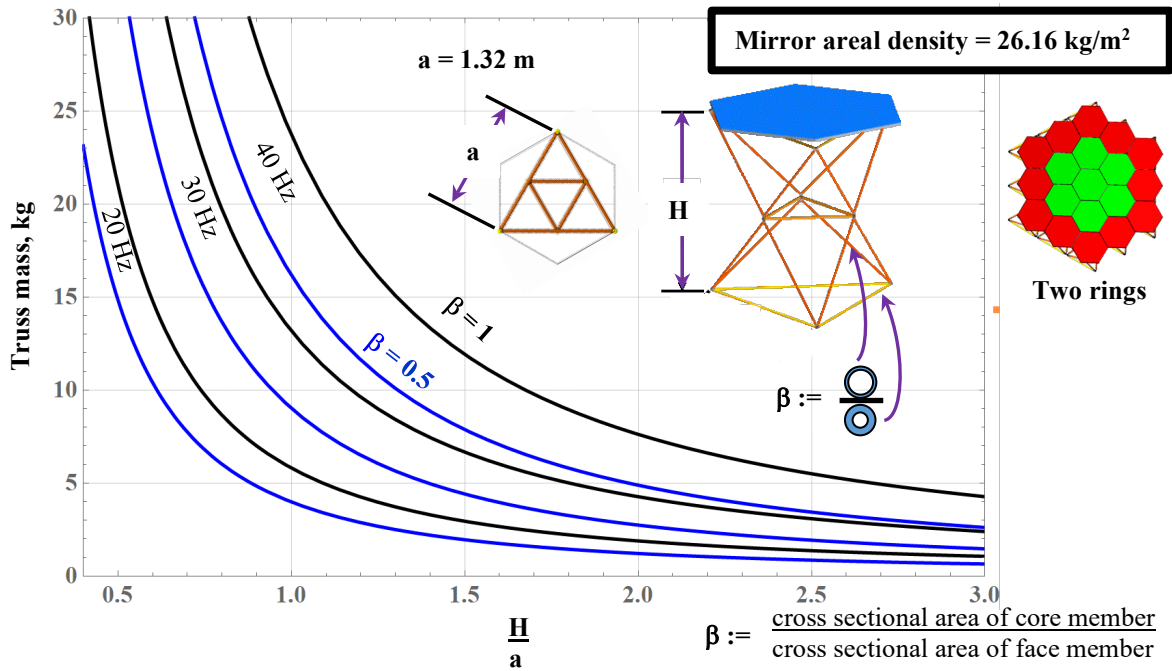


Figure 10. Predicted total mass of 6.5 m two-ring TriTruss structure supporting mirrors with mass similar to JWST mirrors.

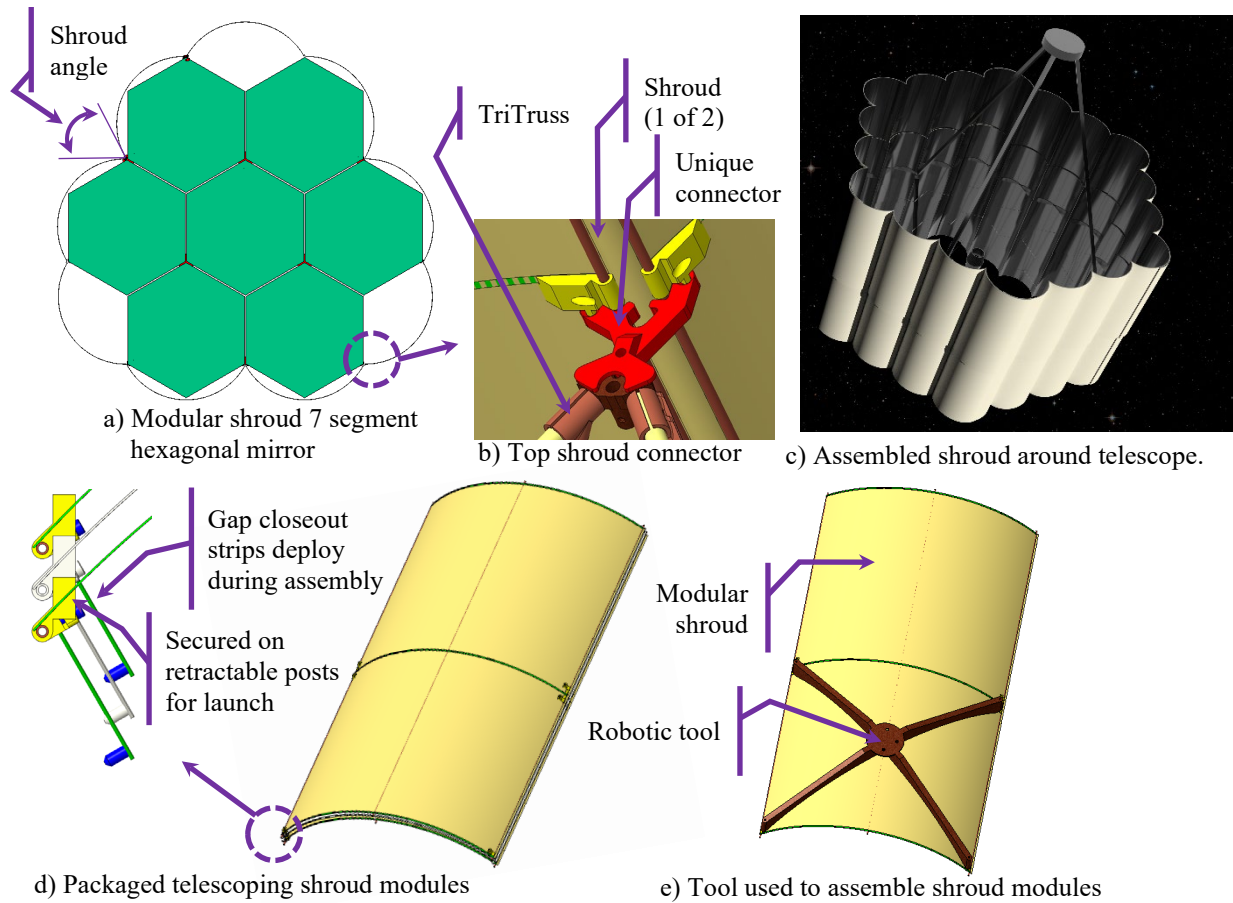


Figure 11. Modular shroud concept.

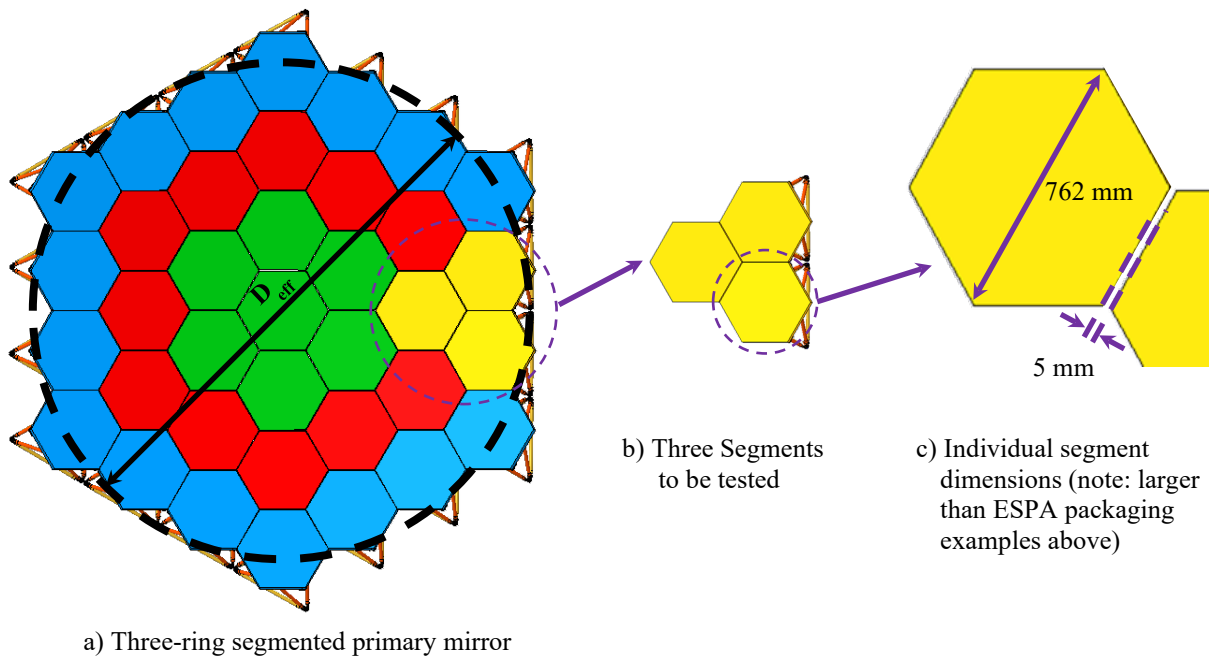


Figure 12. Three segments (yellow) under fabrication of three-ring primary mirror.

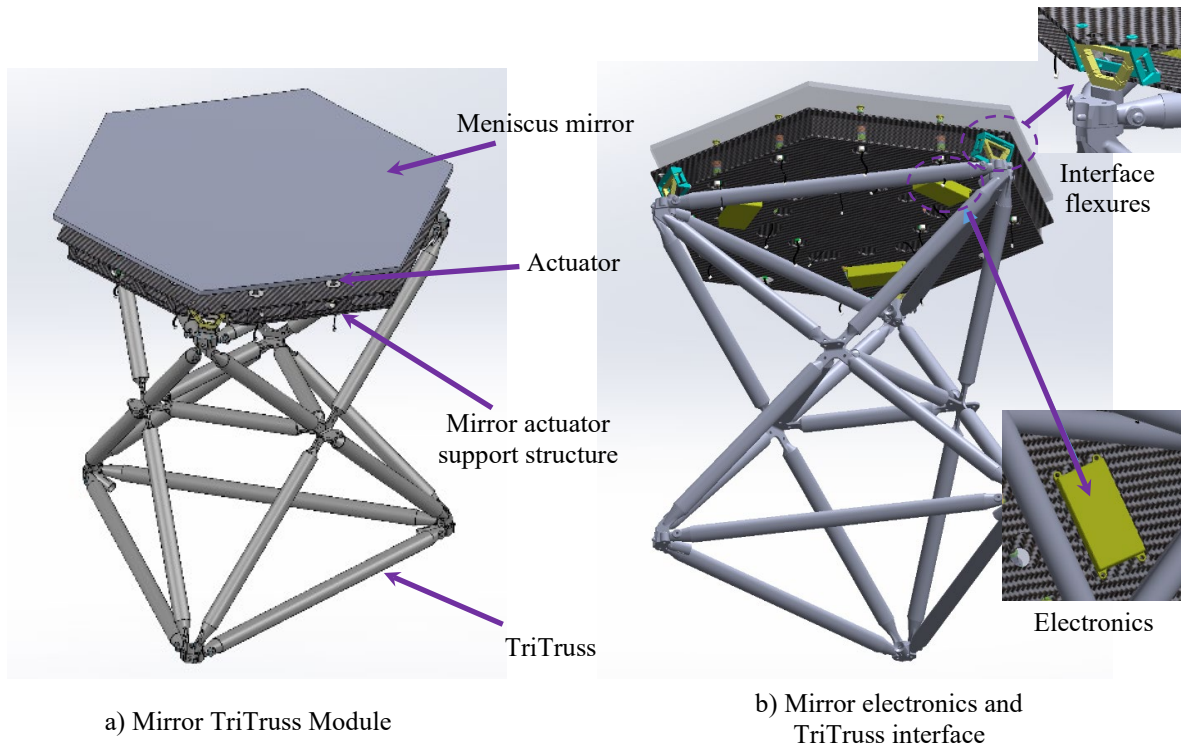
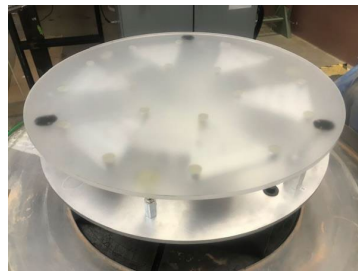


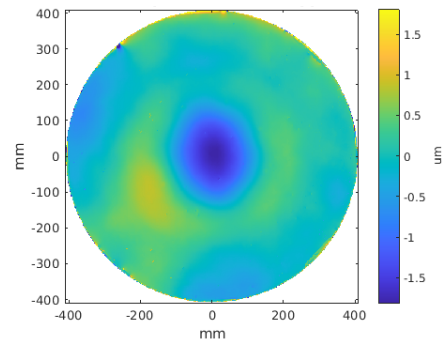
Figure 13. Mirror actuator and electronics arrangement for each hexagonal segment.



a) Mirror blank polishing



b) Prototype mirror



c) Mirror surface topography prior to final polishing

Figure 14. Thin meniscus mirror.