TriTruss Packaging and Deployment Trade Study

Julia E. Cline[1], Lauren Raffanello[2], Kyongchan Song[3], Brace White[4], Gillian McGlothin[5], John T. Dorsey[6] and William R. Doggett[7]

NASA Langley Research Center, Hampton, VA, 23681, USA

Rounak Mukhopadhyay[8], Iok Wong[9]

National Institute of Aerospace, Hampton VA 23666, USA

A trade study was conducted that evaluated viable concepts of operation for the packaging and deployment (P&D) of novel deployable modular truss modules, called TriTruss modules, that can be assembled to form a large aperture In-Space Assembled Telescopes (iSAT). In this first phase of an ongoing more comprehensive trade study, concepts were proposed and then evaluated based on initial metrics representing features of an ideal P&D concept. The ideal TriTruss P&D concept is defined as one that: allows for efficient packaging, has sufficient geometric versatility to be launch vehicle independent, provides a stiff and lightweight structure, has low mechanical complexity, and has component modularity. The P&D concept should allow for prelaunch subsystem or utility integration if required. The concept should be kinematically simple and be robotically deployed using a minimum number of specialized tools. The P&D concepts evaluated are categorized as: core collapse, face collapse, and erectable structures. Sub-scale models were constructed to help understand the kinematics and mechanical complexity required to enable P&D. Based on a weighting scale, the most promising candidate P&D concepts have been selected and will undergo more rigorous structural design, analysis, and testing in the study's next phase. The ultimate goal of the comprehensive trade study will be to recommend a single TriTruss design and associated P&D concept that will be built and evaluated at NASA Langley Research Center's In-Space Assembly Laboratory.

I. Nomenclature

a	=	Length of face triangle strut
H	=	TriTruss module depth
L	=	Length of tape spring member
L_b	=	Length of batten member
L_c	=	Length of central triangle strut
P_{cr}	=	Critical buckling load
d_s	=	Strut diameter

[1] Research Aerospace Engineer, Structural Mechanics and Concepts Branch, Mail Stop 190, member, julia.e.cline@nasa.gov
[2] Research Aerospace Engineer, Structural Mechanics and Concepts Branch, Mail Stop 190, non-member
[3] Research Aerospace Engineer, Structural Mechanics and Concepts Branch, Mail Stop 190, member
[4] Research Aerospace Engineer, Structural Mechanics and Concepts Branch, Mail Stop 190, member
[5] Pathways Intern, Structural Mechanics and Concepts Branch, Mail Stop 190, non-member
[6] Research Aerospace Engineer, Structural Mechanics and Concepts Branch, Mail Stop 190, AIAA Associate Fellow
[7] Research Aerospace Engineer, Structural Mechanics and Concepts Branch, Mail Stop 190, AIAA Associate Fellow
[8] Graduate Research Assistant, member
[9] Research Engineer, non-member

II. Introduction

Space operations are on the cusp of a revolutionary new operational paradigm that leverages modular systems and repeated robotic visits to "Persistent Assets", enabling asset maintenance, repair, and enhancement. A "Persistent Asset" (PA) is defined here as any near zero-gravity (zero-g) or planetary surface system that benefits from multiple visits [1]. These visits can be used for assembly, servicing, repairs, reconfiguration, and upgrades [2-6]. The PA paradigm, introduced, defined and extensively described in Ref [1], includes the following attributes: 1) provides rapid emplacement of capabilities followed by planned upgrades and enhancement, 2) benefits from multiple visits, 3) can be anywhere in space (near zero-g or planetary surface), 4) incorporates modular systems and connectors, 5) enables modules to be integrated and tested before launch, 6) modules can be assembled, serviced, repaired, exchanged, etc., 7) emphasis on robotic (as opposed to crewed) interactions, 8) modular components are launch-vehicle agnostic, 9) space operations make use of a standard toolbox of technologies, capabilities, and infrastructure tools, and 10) modules can be reused for multiple missions. From the preceding attributes, successfully architecting and designing modular systems (such as structures), and their associated modular connectors, is key to realizing the next generation of efficient space systems. Modular structures that can be assembled on-orbit will be the backbone for PAs, including in-space assembled telescopes (iSAT) and testbed platforms for science and communications (Fig. 1).

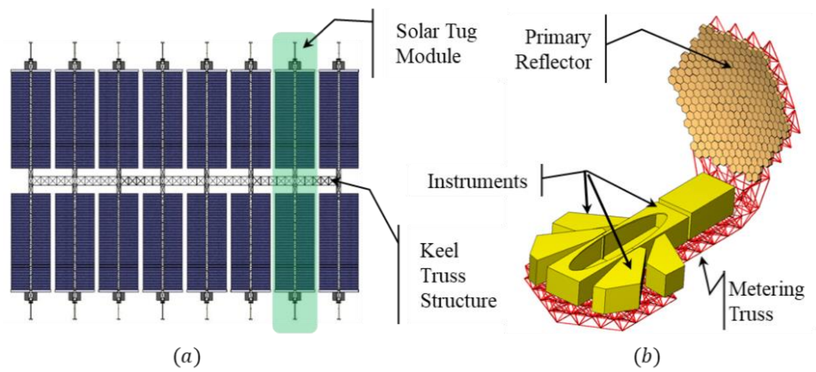
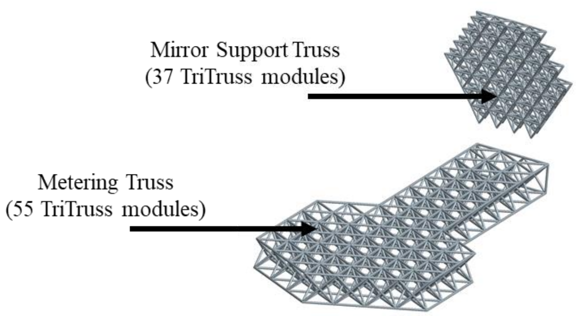


Fig. 1 Target missions for modular assembly include: (a) a generic persistent platform and (b) a large in-space assembled telescope [7].

A 2019 study [8,9] assessing the architecture and feasibility of a next generation large astrophysics observatory, the iSAT, concluded that robotic in-space assembly of modular components is necessary to achieve large apertures (>15-meter diameter primary aperture). The study also concluded that embracing the PA approach would offer cost-saving opportunities for smaller, 5-meter to 15-meter diameter telescope apertures. The final architecture of the 20-meter diameter iSAT is shown in Fig. 1b. During the study, a modularization approach was developed to decompose the telescope into modules (modular truss elements, mirror "rafts", instruments, sunshade modules) that would be assembled in space [8] and support assets (robotics, and spacecraft bus). Modularizing the telescope provides the following advantages: 1) versatility in choosing launch vehicles and/or fairings, 2) efficient packaging in the launch fairing, and 3) ability to use multiple launches. The iSAT study [8,9] recommended that the foundational structure, consisting of the primary mirror support truss and the metering truss (Fig. 2), be assembled from modular truss elements that would be collapsed and packaged for launch, deployed on-orbit and robotically assembled into the final configuration. Although a detailed design was not developed during the iSAT Study, the iSAT structures team baselined the modular TriTruss [8,9] system for the telescope foundational structure.

The TriTruss [7] is a new and innovative structural module that is being developed by researchers at the NASA Langley Research Center (LaRC) for near zero-g platform and telescope applications. The TriTruss is a triangular-shaped, structural concept has been specifically designed to embrace the PA paradigm. Some of the TriTruss innovative features include: very compact packaging for launch, the possibility of staged packaging, simple robotic deployment, ease of embedding payload components, an innovative structural connector that has linear structural performance, ease of module-to-module robotic assembly, design versatility, and ease of customizing its design for specific applications. Reference [7] introduced the TriTruss concept and defined its structural configuration and design parameters (Fig. 3).



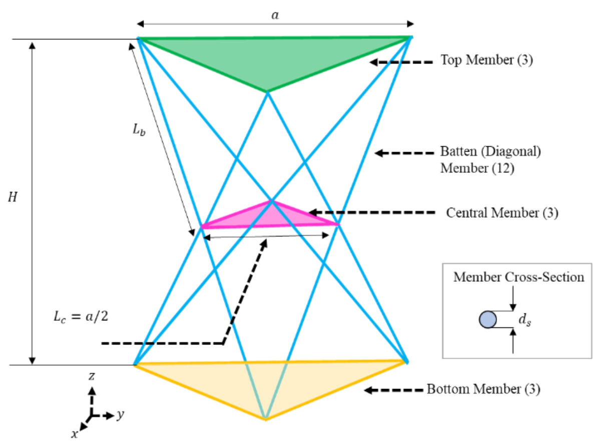
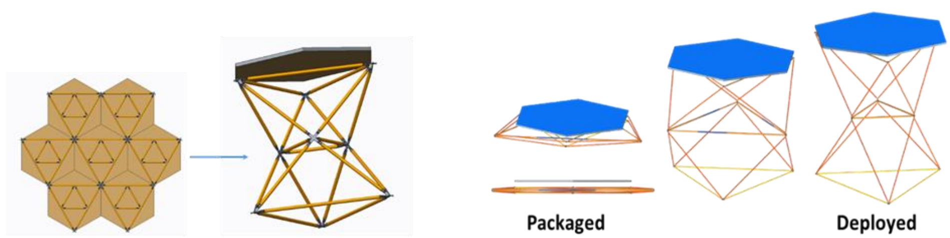


Fig. 2 The foundational truss structure of an iSAT. **Fig. 3 The TriTruss geometry and design parameters.**

Reference [7] also described how the TriTruss can serve as the foundation for many different mission applications, in particular, an even larger 20-meter diameter large space telescope and a beam-type platform that can host a variety of payloads and instruments. The geometry of the TriTruss and the various truss design variables were also described. The TriTruss module geometry consists of top and bottom face equilateral triangles (strut length, *a*) with an equilateral central triangle (strut length, *a/2*) located halfway between the two faces. Core struts (length, L_b, depending on truss depth, *H*) connect the central triangle with the face triangles. The TriTruss lends itself to a large variety of packaging schemes and a notional packaging/deployment architecture was illustrated during initial development (Fig. 4).



(a) (b)

Fig. 4 Notional TriTruss packaging and deployment architecture illustrating (a) the deployed TriTruss with a mirror raft and (b) transitioning from the packaged state to the deployed configuration.

In order to transport the 92 TriTrusses (37 trusses in the mirror support structure and 55 trusses for the metering truss) to the assembly location, the TriTrusses would be launched in the collapsed state, robotically deployed and assembled at the mission site to complete the foundational structure. Developing a specific design for the truss structure, including details on packaging and deployment (P&D), were beyond the scope of the iSAT study. However, the structures team identified "Deployable TriTruss Modules" as one of the top five structures technology and engineering challenges (in particular, efficient packaging, robotic deployment and jigging, and structural stiffness and linearity of the deployed structure) that should be addressed as the next step for increasing the technology readiness level of the assembled truss structure as a key in-space assembly capability. As a result, a team was formed at NASA LaRC to develop a wide range of TriTruss P&D concepts, having different attributes, and perform a trade study to compare and assess the concepts.

This paper will describe and summarize the results of the first phase of an ongoing trade study that investigated viable concept of operations (ConOps) for the P&D of single TriTruss modules [7] that could be used to assemble the large aperture iSAT (Fig. 1b, 2). Desirable features for the TriTruss P&D concept include: 1) efficient packaging with sufficient geometric versatility to be launch vehicle independent, 2) a stiff and lightweight structure with low joint complexity, and component modularity, 3) a kinematically simple deployment concept accomplished robotically using a minimum number of specialized tools, and 4) the ability to integrate subsystems or utilities prior to launch if required. In the trade study summarized in this paper, several concepts were evaluated against the list of desirable features.

This paper discusses the proposed P&D concepts and their general packaging architecture type, which fall into three categories: core collapse, face collapse, and erectable structures. Each concept is described in detail along with the sub-scale models which were constructed to aid in understanding the kinematics and joint complexity required to enable P&D. Based on a weighting scale, the most promising candidate P&D concepts were selected for more rigorous structural design, analysis, and testing which will occur in the next phase of the trade study.

III. Defining the Trade Study

A. Goals, Approach and Assumptions

The goal of the comprehensive TriTruss trade study is to initially develop and evaluate a set of novel TriTruss design concepts with associated P&D methodologies and select a final concept that will be designed, fabricated and tested as part of a forthcoming Precision Assembled Space Structure (PASS) project. PASS will demonstrate the autonomous assembly of a modular three-ring, 20-meter class, doubly curved iSAT mirror backbone structure in an end-to-end ground demonstration.

While developing the TriTruss P&D concepts in the first phase of the trade study, unifying assumptions were made regarding assembly and deployment. First, the assembly would be accomplished robotically, without the need for Extra Vehicular Activity (EVA) or astronaut involvement. The availability of multiple robotic arms and agents was assumed. Second, the packaged TriTruss would only be required to deploy once (i.e. repackaging the structure is not necessary). Finally, all TriTruss modules in the iSAT foundation structure were assumed to have the same geometry: that is, $H/a = 1$ (Fig. 3). The TriTruss modules would be assembled together to form the foundational structure using a customized, pre-attached multi-nut [10] connector. For packaging, a 5-meter-diameter launch vehicle fairing (with a dynamic envelope of 4.6 meters) was chosen to ensure packaged TriTruss modules are launch vehicle agnostic with respect to currently available low-cost options such as a SpaceX Falcon 9, a United Launch Alliance (ULA) Atlas V or a ULA Vulcan. The TriTruss modules are assumed to be deployed either using internal strain energy of the truss members or by robotic manipulation.

B. Trade Study Overview

Phase 1 of the trade study developed and investigated novel concepts considering the basic kinematics of TriTruss packaging using scaled models constructed from low cost materials. Evaluation criteria, based on the set of desired P&D attributes, in combination with a weighting scheme were developed to down-select concepts for further study.

The concepts developed for this study focused on implementing novel packaging methods that leverage past work at LaRC on modular joint and truss designs. Table-top scale models were constructed and proved to be very valuable for demonstrating and understanding the packaging envelope and deployment kinematics for each design. The models were made with items that were easy to procure, such as household items or 3D printed parts. The models allowed the identification of any major issues and indicated areas of improvement that helped drive which concepts would be selected for further analysis. Candidate TriTruss P&D concepts were evaluated against four key metrics of the desired P&D concept: 1) packaging efficiency, 2) versatility, 3) mechanical complexity, and 4) deployment complexity.

The "packaging efficiency" metric considered: the packaged shape, dimensions, and volume; the approximate number of packaged TriTruss modules that can fit within the specified payload fairing dimensions; and the number of launches required to transport all 92 TriTruss modules (that form the iSAT foundational truss structure) to orbit. For this study, the fairing dimensions were based on the Falcon Heavy payload fairing dimensions, i.e a dynamic envelope diameter of 4.6-m and a length of 6.7-m. The thickness of the various TriTruss modules in the packaged configuration were estimated as a multiple of the assumed strut member diameter, d_s. The TriTruss module internal joints will be unique for each design, and the volume they add within the packaged thickness will also be unique to each design. While specific joint design is not part of the initial phase of the trade study, the joint size was estimated based on the tabletop models and included in the estimated size as a multiple of d_s..

The "geometric versatility for subsystem integration" metric considered the TriTruss module as a system and included the capability for integrating subsystem components, such as the mirror rafts, electrical wiring, data systems, propulsion modules, communication instruments, and other equipment. Depending on the subsystem function, pre-integration of space telescope components to a TriTruss module prior to launch and assembly, may be advantageous, especially if installation on-orbit would be challenging using robotics. The ability of a TriTruss P&D concept to only collapse partially for launch provides the ability to integrate subsystems pre-launch. If the face triangles maintain their geometry, then mirror rafts could be pre-integrated.

The "mechanical complexity" metric considered: the joint kinematics, the number of telescoping members required for packaging, and the number of Degrees of Freedom (DOF) required for each design. The DOF counts included rotational DOFs in the single-axis hinges within the joints and translational DOFs for telescoping members. Several concepts employed strain energy members, which can be used as truss members or as replacements for mechanical joints. Generally, each additional DOF allowed the design to package more efficiently but adds complexity and weight to the system. Also, a larger number of DOFs may increase the possibility of jamming during deployment and/or decrease the module stiffness. In some cases, decreases in stiffness may be mitigated by adding mechanisms that lock each DOF once the concept is fully deployed. However, this may require additional mass to be integrated at each DOF.

The TriTrusses will be deployed on-orbit using autonomous robotics. For the "deployment complexity" metric, we desire deployment mechanisms that are not overly complex. Each proposed concept has a unique packaging method and thus, a unique deployment method, which will vary depending on how the packaged module is mounted within the payload fairing. Except for the erectable concepts, the proposed P&D methods package a fully assembled TriTruss module that only requires deployment (no construction) after launch. Concepts were evaluated based on the anticipated robotic assistance required for module deployment. For example, a strain energy deployment concept will require a robot to control the release of energy during deployment. Other module concepts might require the robot to pull at specific locations on the TriTruss while other locations are held stationary to complete deployment. Any additional infrastructure, such as a support jig, to secure a packaged TriTruss during deployment was also assessed as part of deployment complexity. Concepts requiring specialized canisters or mechanisms to hold the packaged shape were considered more complex than those that will remain packaged unassisted. Additionally, those requiring specialized end effectors were considered a more complex deployment concept.

The overall packaging efficiency, geometric versatility, and mechanical and deployment complexity for each concept were assessed using the ranking scale in Table 1 and assigned a numerical value, with higher values representing better performance. Each metric was weighted equally and two to three concepts with the highest total score were selected to move forward into the next phase of the trade study. For packaging efficiency, and geometric versatility, scores indicating better performance were given to concepts having more efficient and versatile P&D methods. For mechanical and deployment complexity, low complexity was desired and receives the higher scores.

Table 1. Metric scoring values to down select TriTruss P&D concepts in phase 1.

Ranking Scale	Packaging Efficiency and Geometric Versatility	Mechanical Complexity and Deployment Complexity
Low	1 point	5 point
Medium	3 point	3 point
High	5 point	1 point

IV. Proposed Packaging and Deployment Concepts

The trade study began with a thorough review of the state-of-the-art in deployable truss concepts. Deployable truss structures have been used in space, mainly as masts, booms or beams, where the total deployed length is much greater than individual truss bays. For example, the Folding Articulated Square Truss Mast (FASTMast) (Fig. 5a and 5b) is used on the International Space Station (ISS) to support the solar arrays [11,12] and the Shuttle Radar Topography Mission (SRTM) used a 60-m long deployed FASTMast to support scientific instruments mapping the Earth's topography [13]. The FASTMast and SRTM both used coilable longeron booms. Continuous and flexible fiberglass or carbon epoxy composite material longerons run the length of the truss, and steel cables and flexible battens were used for truss bracing [14]. As the truss is coiled into its packaged form, the composite longerons elastically bend to retract into the storage canister (Fig. 5c). The strain energy stored during coiling allows the mast/boom to self-deploy, however, a drive mechanism was required to control the truss deployment rate.

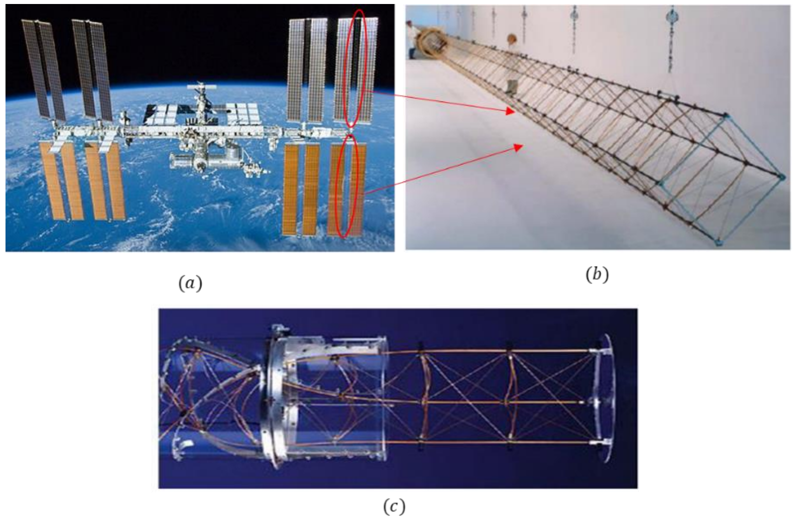


Fig. 5 The (a) trusses supporting the ISS solar arrays are deployable (b) Folding Articulated Square Truss (FAST) Masts using coilable longeron technology. To stow for launch, trusses are coiled into a (c) specially designed canister.

The Assembly Concept for Construction of Erectable Space Structures (ACCESS) project successfully demonstrated erectable assembly in space as performed by astronauts on EVA [15, 16]. Oak Ridge National Laboratory demonstrated telerobotic construction of a similar erectable structure [17] following the ACCESS project. NASA LaRC has decades of experience in researching and developing capabilities that enable robotic assembly of large space structures [18] including: the Tendon Actuated Lightweight In-Space MANipulator [19] (TALISMAN) robotic arm, the Strut Assembly, Manufacturing, Utility and Robotic Aide [20] (SAMURAI), and the NASA Intelligent Jigging and Assembly Robot [20] (NINJAR), all of which aid in assembling large structures in space. LaRC also has extensive experience in developing large space structural concepts, such as the TriTruss module, and various robotic and manual structural joining methods [1-7]. Erectable approaches have been a favored strategy because they provide high packaging density and decreased mechanical complexity when compared to conventional deployable systems [15,16].

The iSAT structure is different from that of a mast or boom, which are deployed sequentially while already being connected to one another. Furthermore, the field of autonomous robots has advanced significantly to the point where in-space assembly of large space structures can be accomplished robotically. Truss modules can be deployed by robotic agents, and no longer require complicated motor-driven deployment mechanisms like used for coilable longeron trusses. The trade study focuses on deployment of single TriTruss modules that can be robotically deployed.

While the geometry of the planar TriTruss module is not overly complex, there are many possible methods to package and deploy the module, depending on the desired features and performance. Several concepts were initially proposed for this study and evaluated based on the criteria detailed in Table 1. The P&D concepts fall into three categories: 1) core collapse, where the diagonal batten members retract and the depth of the TriTruss decreases, 2) face collapse, where the face triangles contract, and the width decreases, or 3) erectable structures, where the TriTruss structure is disassembled into components or sub-components that are assembled robotically on orbit. Subscale models were developed to aid in understanding potential design features since the concepts required varying degrees of joint complexity to enable P&D.

A. Core Collapse Concepts

1. Telescoping Middle Triangle

The telescoping middle triangle TriTruss, shown in deployed (Fig. 6a) and packaged (Fig. 6b) configurations, is a concept designed to maintain high strength and stiffness for the top and bottom planes of the TriTruss, and thus the high stiffness required in the assembled observatory. The telescoping middle truss has fixed-length members in the top and bottom face triangles and batten members. The central triangle is comprised of three telescoping members that deploy outward to collapse the module into its packaged state. Eighteen single axis hinges located at the nodes of the truss allow the batten members to rotate as the central triangle expands and the depth of the TriTruss decreases.

A scale model was constructed from aluminum tubes and 3D printed joints to understand the kinematics of the TriTruss motions. Telescoping pointer sticks were used for the central triangle members.

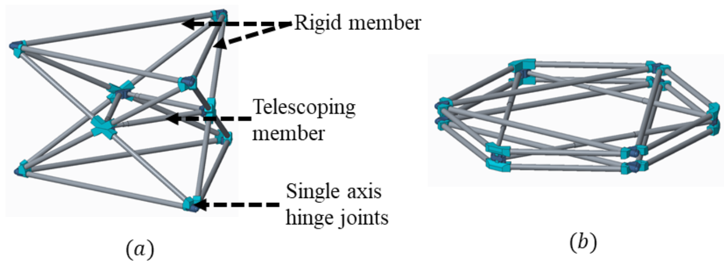


Fig. 6 Telescoping middle TriTruss concept in the (a) deployed and (b) packaged configuration. The TriTruss here has a $H/a = \sqrt{3}/3$.

To deploy the TriTruss, a robotic arm would grapple and pull up on the top triangle members which would retract the telescoping members and increase the depth of the TriTruss. The bottom face triangle would either be fixed to the stowage canister during deployment or the packaged TriTruss would be transported to the assembly area where it would be mounted to a jig for deployment. Alternatively, two robotic arms could each grapple one end of the TriTruss module and pull on the module to deploy it. However, this deployment technique requires coordinating two autonomously operated systems which is likely more technically challenging. Likely, a (launch) storage canister design that can advance the stack of TriTruss modules upward as modules are removed would be necessary to avoid requiring an extremely long-reach robotic arm that could access the bottom of the storage canister. Alternatively, a side opening in the canister might also alleviate the need for a long-reach robotic arm.

The telescoping middle triangle truss collapses into a compact hexagonal shape when viewed from the top. For a TriTruss of $H/a = 1$, the middle plane expands radially past the profile of the top and bottom plane (see Fig. 6) which would be outside of the desired payload fairing dynamic envelope diameter. In order to fit in the fairing, the telescoping middle triangle concept is limited to an $H/a = \sqrt{3}/3$ for the TriTruss. However, limiting the depth of the TriTruss limits the stiffness of the overall modular structure since the stiffness is proportional to the truss depth. Since the method of actuation for this design is expansion of the middle plane, the TriTruss cannot be partially packaged to accommodate internal sub-systems before being launched. The telescoping middle triangle TriTruss requires a mechanical joint system with eighteen hinge joints and three telescoping members. The mechanisms required to package the TriTruss are anticipated to be a complex system and add additional weight to the structure.

2.   Telescoping Diagonals

The deployable telescoping diagonals TriTruss concept is based on the variable geometry concept [21] and shown in the deployed (Fig. 7a), packaged (Fig. 7b) and half-packaged (Fig. 7c) configurations. The fundamental module of a telescoping diagonal TriTruss consists of two equilateral triangles, one each in the top and bottom plane, one equilateral triangle in the middle plane, and six pairs of telescoping diagonal batten members. The batten members are connected to the top, bottom and middle plane members by hinge joints at the nodes. The hinge joints allow the batten members to rotate as all six pairs of telescoping members retract and allow the TriTruss to package vertically. To deploy, the batten members are extended to the deployed position and pins or screws lock the telescoping members into place. Alternatively, a spring could be inserted into the telescoping diagonal struts to provide strain energy for self-deployment. The spring would be compressed in the packaged state, and the strain energy released as the spring expands and extends the telescoping members to the deployed configuration. Fig. 7 shows the subscale model of the of the telescoping diagonal TriTruss concept in packaged and deployed configurations. The model was constructed from 3D printed polylactic acid (PLA) joints, wooden dowel rods, and polyvinyl chloride (PVC) pipe.

A telescoping diagonal TriTruss packages efficiently and is geometrically versatile. When the TriTruss is collapsed, its packaged volume is seven percent of the fully deployed TriTruss volume. This concept can be fully collapsed for packaging (Fig. 7b) or partially collapsed (Fig. 7c) depending on the choice of packaged diagonal lengths in each half bay. This half-collapse configuration allows subsystem components and scientific or other instruments to be integrated with the TriTruss prior to launch. Also, since the assembled equilateral top triangle geometry does not change during P&D, a mirror raft can be installed on a TriTruss prior to launch. The telescoping diagonal TriTruss requires 24 hinge joints, 12 telescoping struts, and 12 springs for the version deployed using strain energy. The mechanisms required to collapse the TriTruss are anticipated to be a complex system and add additional mass to the structure. Using composite joints may reduce some weight. As with the telescoping middle truss, a launch canister designed to advance truss modules to the top of the canister would preclude the need for a long-reach robotic arm.

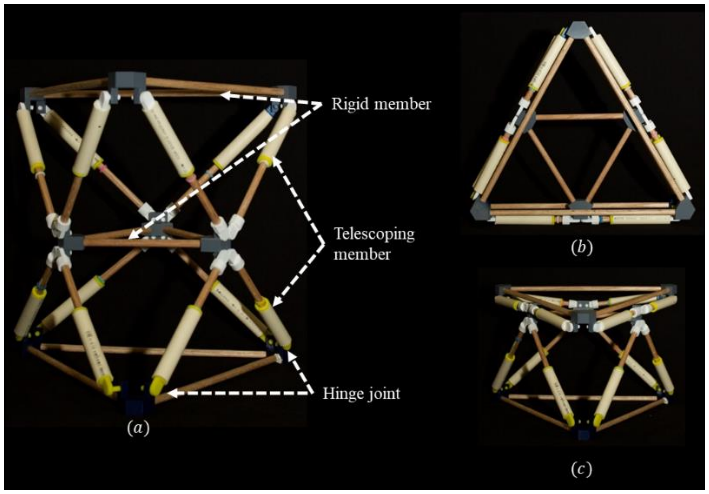


Fig. 7 The telescoping diagonal TriTruss concept in the (a) deployed, (b) packaged, and (c) half-collapsed configurations.

3. Collapsible Cross-section

Deployable Composite Booms (DCB) are thin-walled, lightweight, foldable or rollable composite tubes, that are being developed at NASA LaRC to enable large deployable structures (like solar sails or antennas) on small satellites [22-24]. The booms could also be adapted to serve as TriTruss members. DCBs are composite tape springs that can be inexpensively manufactured, can have several different cross-sections and can be compactly rolled or folded for stowage. Closed cross-section DCBs (Fig. 8) are high stiffness and dimensionally stable booms that can be designed for bi-stability (i.e. stable in packaged form as well as deployed configuration. [25]. Incorporating a DCB as a diagonal TriTruss member provides a novel application of the technology that may enable compact TriTruss packaging for launch and simple, strain-energy guided deployment on-orbit.

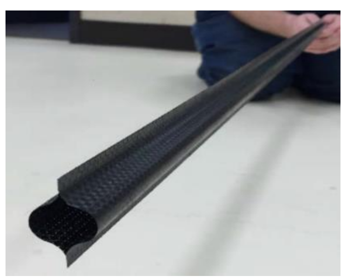


Fig. 8 Example of a mini DCB with a double omega closed cross section that can be used for diagonal truss members in the collapsible configuration TriTruss [22-23].

A collapsible cross-section truss consists of two equilateral triangles for the top and bottom faces and a mid-plane equilateral triangle with rigid members. The diagonal batten members would all be DCBs. Since DCBs can fold anywhere along their length (and in multiple locations if desired), the complexity of the node connectors to attach the diagonal truss members to the face and middle triangles is likely reduced, significantly reducing the structural complexity. To package the truss, the diagonal members fold at multiple points along their length. A simple subscale model, for studying the kinematics of folding the diagonal members into a packaged state, was constructed using milkshake straws to represent DCBs, 3D printed PLA joints, and wooden dowel rods (Fig. 9). Binder clips were used to lock the diagonal members in their folded position. The top, bottom, and middle triangles have fixed-length members, and the diagonal members fold in two places to achieve the packaged configuration.

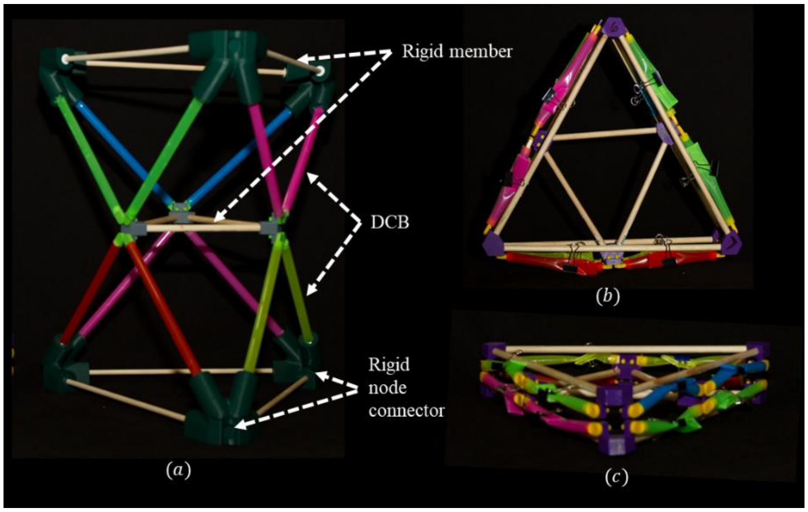


Fig. 9 The collapsible cross-section TriTruss in (a) deployed configuration and packaged configuration from the (b) top view and (c) side view illustrates how the diagonal members fold into a compact triangular shape.

The main advantages of the collapsible cross-section TriTruss are that it makes use of lightweight DCB structural members that allow efficient packaging and deployment using internal strain energy once launch locks are removed. The concept can be launched with the TriTruss in a half-deployed state, allowing for subsystems to be pre-integrated within the module during assembly on the ground prior to launch. Mirror rafts could also be integrated to the top triangle prior to launch since the top triangle is not collapsed for packaging. The joints required for this packaging mechanism are likely not complex since the DOFs required to fold into the packaged state can be accommodated by the DCB, thus reducing truss module weight and complexity.

A collapsible cross-section TriTruss module would require a robotic agent to control deployment. Likely, the TriTruss modules will be mounted in a canister for launch, with launch locks holding the truss in its packaged configuration. The robotic agent would release the launch locks holding the top end of the truss and slowly allow the strain energy members to unfold the truss to the deployed configuration. Once deployed, the robotic agent would release the launch locks holding the bottom of the truss and relocate the truss to its assembly location.

B. Face Collapse Concepts

1. Side Fold

The side fold deployable TriTruss concept is based on the variable geometry concept [21] and is pictured in the deployed (Fig. 10a) and packaged (Fig. 10b) configuration. The fundamental module of a side fold TriTruss consists of two assembled fixed-length faces, three collapsible connecting members, two pairs of telescoping diagonal members in the collapsed cross-section, and a pair of telescoping members in the middle plane. The diagonal members on one side of the TriTruss are replaced with telescoping members that connect to the top, bottom, and central triangle members with hinge joints. Two of the central triangle members that connect to the telescoping member diagonal section are also telescoping members. The central triangle member perpendicular to the telescoping diagonals has a hinge joint in the center of the rigid member that folds inward. The hinge joints at the corners of the top and bottom triangles, perpendicular to the telescoping diagonal section, allow the rigid cross sections to rotate inward. To collapse to a packaged state, the telescoping members contract and the diagonal members rotate to a vertical orientation. The hinge joints close to collapse the face and central triangles. In the deployed configuration, folded connecting members are unfolded, and telescoping members are extended to the deployed position. Pins or screws lock the telescoping diagonal members into place.

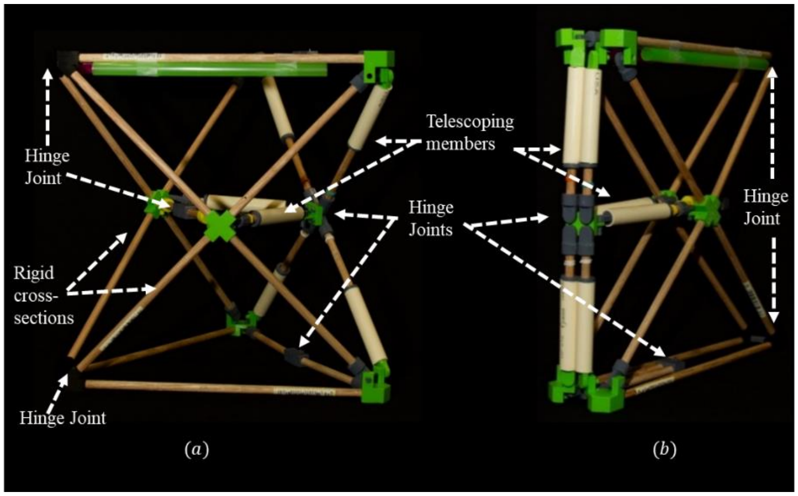


Fig. 10 Side fold TriTruss in (a) deployed configuration and (b) packaged configuration illustrates how the members fold into a flat configuration.

The main advantages of a side fold TriTruss are packaging efficiency and a mechanical joint system that is simpler compared to other deployable TriTruss concepts. Similar to the telescoping diagonal TriTruss, when a side fold TriTruss is collapsed, its packaged volume is seven percent of the fully deployed TriTruss volume. A side fold TriTruss is anticipated to require a complex mechanical joint system having fifteen hinges and six telescoping members to package. Other concepts can be implemented for the folding mechanism instead of mechanical joints and telescoping members. For example, a composite tube joint can be used to fold connecting struts instead of a hinge joint and folding DCB could replace telescoping members.

Another concept for packaging a side fold TriTruss is to utilize the semi erectable approach shown in Fig. 11. Instead of collapsing one side of the TriTruss using telescoping members, the side is removed from the module, assembled from rigid truss members, and packaged as a separate sub-module (Fig. 11a) along with the folded TriTruss (Fig. 11b). To deploy the semi-erectable side fold TriTruss, the folded cross-sections are opened (Fig. 11c), and the detached cross-section is attached at rigid nodes by the robotic agent. The semi erectable approach can reduce the number of mechanical hinge joints and eliminate the need for telescoping members.

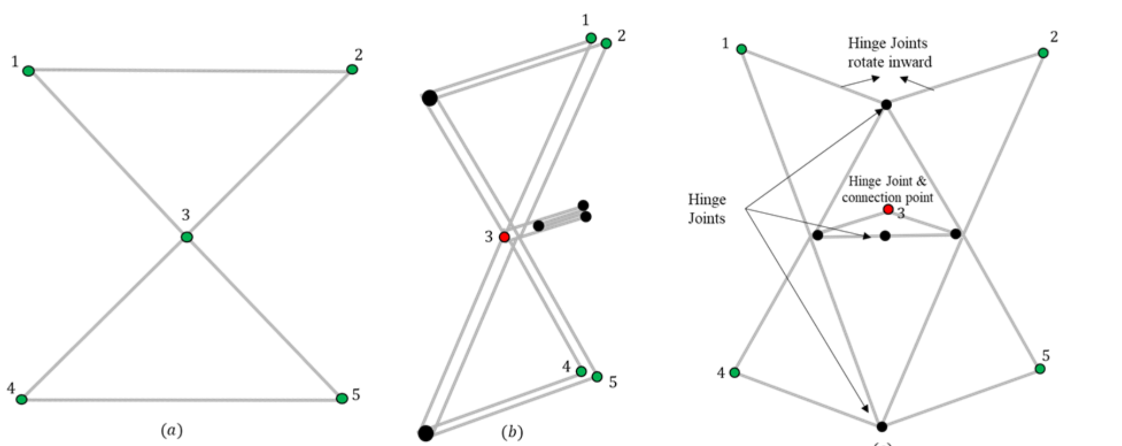


Fig. 11 Semi-erectable side fold TriTruss concept. A (a) semi-erectable sub-module is packaged separate from the (b) folded TriTruss and installed on-orbit. The module is (c) deployed and the sub-module is installed at the labelled connection points to complete the module.

The main disadvantage of a side fold TriTruss is the lack of geometric versatility. The side fold TriTruss does not allow half the depth to remain extended prior to launch which limits subsystem integration options. Also, since the three equilateral triangles at the top, bottom, and middle plane are collapsed when packaged, a mirror raft cannot be installed on the packaged TriTruss before launch.

2. Camping Chair

The camping chair concept packages in both the x- and y-directions (see Fig. 3) like a foldable camping chair [26] (Fig. 12). All surface and central triangle members have hinge joints that allow the members to fold to the packaged configuration (the batten member length, L_b, stays constant, the width, a, contracts). The members are designed to fold inward to the TriTruss mid-plane to make the module as compact as possible. The diagonal members are continuous from the TriTruss top surface to the bottom surface. Each pair of crossing diagonal members rotate about a center pin, forming a scissor joint. Each of the three center pins are also connected to the nodes of the middle triangle. The mid-nodes are free to rotate relative to the diagonal members to keep the middle triangle parallel to the top and bottom triangles.

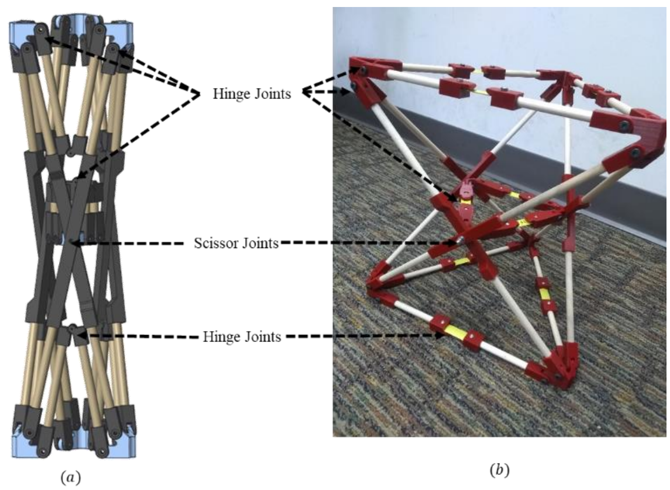


Fig. 12 The camping chair TriTruss concept in the (a) packaged and (b) deployed configuration.

Two iterations of the concept design have been fabricated. The first design used hinge joints where the surface and central triangle members fold in half. The hinge line was offset from the strut axis to allow the end faces of the strut halves to align with each other in the deployed configuration (Fig. 12a). However, a potential problem arises from this hinge location; the triangle side lengths must increase slightly beyond the fixed length of the struts as the hinge nears full deployment. This geometric phenomenon is explained in detail in Reference 27. To deploy the TriTruss autonomously in space, a robot would have to secure one corner of the module and pull one of the other corners outward. Spring-loaded over-center latches would be a viable option to fully deploy the horizontal members and lock them in place.

In the second concept design, the hinge joints in the horizontal members were replaced with tape springs (Fig. 12b). This reduced the number of joints in the model by nine. In the packaged configuration, the tape springs are folded in half, and the TriTruss must be locked in place to prevent it from self-deploying due to the elastic strain energy in the tape springs. To deploy the module in space, a robot would unlock the module and control the self-deployment rate.

The camping chair model offers highly efficient packaging and the option of pre-integrating multiple modules together in the packaged configuration allowing for sequential or synchronous deployment. Preliminary analysis determined the packaged to deployed volume ratio to be approximately 5% for a full-scale model. The camping chair configuration requires a significant number of joints (42), which may reduce the stiffness in the surface members and the assembled telescope foundational structure. In the camping chair concept, a reduction in stiffness is chosen to allow the surface members to fold in half. The packaging concept does not allow half the depth to remain extended prior to launch which limits subsystem integration options and prevents mirror raft integration before launch.

C. Erectable Concepts

As an alternative to deployable concepts, TriTruss modules can be constructed from individual truss members (fully erectable), or a group of pre-connected truss members (semi-erectable). While a fully erectable structure generally has the greatest packaging efficiency and likely simpler nodal connectors than deployable concepts, they require a greater number of assembly steps (for each strut as opposed to each module) and requires additional infrastructure, such as an assembly jig. In comparison, the complexity of assembling a semi-erectable structure, falls somewhere between a fully erectable structure and a deployable one. For the semi-erectable approach, substructures are pre-assembled to reduce the number of steps in the assembly process needed to complete and verify the final structure.

1. Fully-Erectable

The fully erectable approach has the potential to offer maximum packaging efficiency compared to the other proposed concepts, because the entire TriTruss is decomposed into components that can be stowed compactly for launch. Figure 13a shows an assembled TriTruss module with the different member components highlighted. An optimal packing configuration was not developed for this trade study, but it was assumed that three quivers would be used to stow the TriTruss members and nodes. The fully erectable concept does not require additional DOF at any of the joints, which reduces the mechanical complexity. Subsystems cannot be integrated prelaunch, and specialized end-effectors and an assembly jig are required to construct the truss structure.

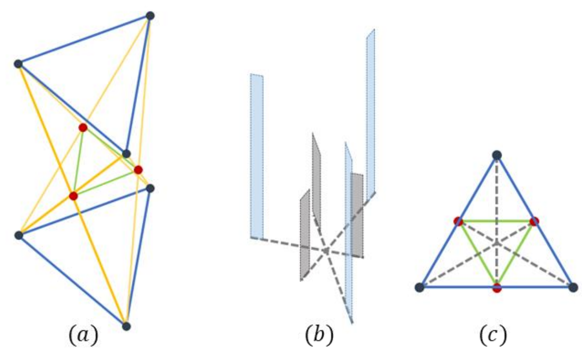


Figure 13. (a) A schematic Tri-Truss illustrating the three different sized truss members in blue, yellow, and green, and two different joints in red and dark grey. (b) A conceptual design of the assembly Tri-Jig for the erectable TriTruss concepts and a (c) top down view of a TriTruss on the Tri-Jig.

Depending on the infrastructure available, there are many options for assembling a TriTruss module using the fully erectable approach. The method described in this paper is based on the following principles: 1) minimize the complexity of required robotic actions; 2) ensure that each step of assembly results in a stable structure; and, 3) use the assembly jig (described below) only when it is absolutely needed to help achieve the previous principles.

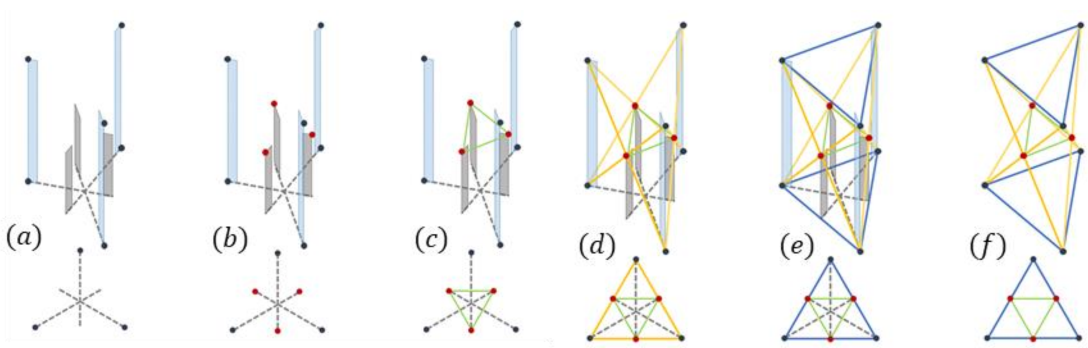


Fig. 14 Step-by-Step assembly of a fully erectable TriTruss using the Tri-Jig. (a) secure all the cross joints to the Tri-Jig, (b) secure all the corner joints to the Tri-Jig, (c) install the central triangle members, (d) install the diagonal members, (e) install the top and bottom triangle member, and, (f) release the joints from the Tri-Jig and remove the assembled TriTruss from the Tri-Jig.

A triangular shaped jig, called a Tri-Jig, that is slightly smaller than the TriTruss, will be needed to keep members stable during assembly (Fig. 13b). A top down view of a TriTruss on the Tri-Jig is shown in Fig. 13c. The steps required to assemble the TriTruss are illustrated in Fig. 14. Two end effectors are needed for the fully erectable assembly method: a joint gripper, and a strut installer. The joint gripper is actuated by a single motor to grapple joints.

The strut installer has grippers that grab the strut member, and drivers that drive a locking mechanism to secure the strut to the joints. Once the TriTruss is complete, the joint gripper can grapple the TriTruss at the cross-joint and remove it from the Tri-Jig. An additional end effector will be needed to assemble the TriTruss modules together. Depending on the requirements, internal components can be mechanically connected or welded with laser or electron beam [28] to the truss module after assembly.

2. Semi-Erectable

TriTruss modules can also be assembled using the semi-erectable approach. In the concept developed for this trade study, the TriTruss will have two types of submodules; a side submodule (three required per TriTruss), and central triangle submodule (one required per TriTruss), as shown in Fig. 15.

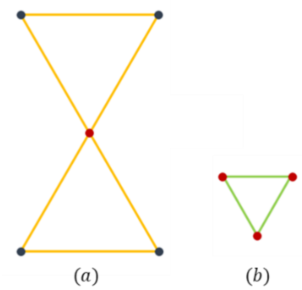


Fig. 15 Components for the semi-erectable TriTruss include three (a) side submodules and, one (b) central triangle submodule.

The semi-erectable concept packages compactly and does not require additional DOFs at any of the joints to enable packaging, which reduces mechanical complexity. Most subsystems cannot be integrated prior to launch and would have to be attached after the module was assembled. Mirror rafts could be attached to the top triangle members pre-launch. Specialized end-effectors and an assembly jig would be required to assemble a semi-erectable TriTruss.

Like the fully erectable approach, there are many ways to decompose the structural module into submodules. The method described in this paper is based on the following principles: 1) each submodule must be self-stable; 2) planar submodules will not be decomposed further unless they are too large for the launch vehicle fairing or more efficient packaging is needed; and, 3) connections needed to assembly the full structure are minimized. A Tri-Jig will be used for assembly, but unlike the fully erectable approach where the Tri-Jig is stationary, the Tri-Jig will also be used to perform the module-to-module assembly. The TriTruss assembly steps are illustrated in Fig. 16.

Using the semi-erectable approach can greatly reduce the steps needed to assemble a TriTruss module compared to the fully erectable approach, while enabling options to achieve greater structural performance that deployable concepts cannot achieve. Semi-erectable assembly concepts are a viable option for constructing large-scale TriTruss based space structures. As with the fully erectable approach, semi-erectable truss components can be mechanically connected or welded using laser, or electron-beam techniques.

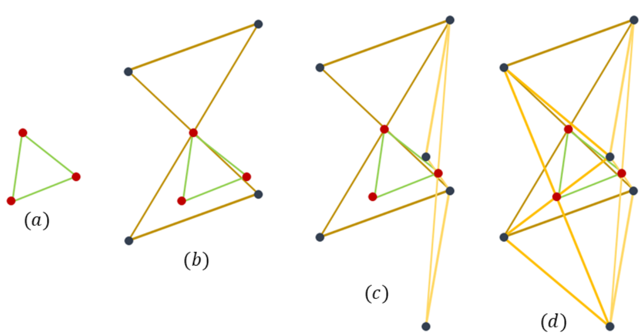


Fig. 16 Step-by-step assembly of a semi-erectable TriTruss. The Tri-Jig is used for assembly but hidden in the images for clarity. Assembly starts with the (a) central triangle submodule, then the first side panel is attached in step (b), the second in step (c) and the last side panel in step (d).

V. Results and Discussion

In this section, the results of the phase 1 down selection process are presented. Each concept is evaluated using the criteria described in Section III. B: 1) packaging efficiency; 2) geometric versatility; 3) joint complexity; and 4) deployment concept complexity.

A. Packaging Efficiency

To evaluate packaging efficiency, the team considered the packaged shape, estimated packaged dimensions and volume, the estimated number of TriTruss modules that would fit inside a Falcon Heavy fairing, and the number of launches required to assemble the foundational truss structure (92 modules for the combined mirror support and metering trusses). The packaged shape, including cross-section dimensions, thickness and volume, of the various concepts was assessed using subscale models. The module volume is calculated based on the packaged planform area and a thickness based on joint and strut estimated dimensions. The calculation does not account for any separation between packaged modules. The number of launches was estimated by assuming fully packaged TriTrusses without any subsystem integration or mirror rafts attached.

The packaged cross-sectional shape and dimensions for each concept are shown in Fig. 17. The telescoping middle triangle TriTruss (Fig. 17a) packages into a hexagonal shape but it is noted that a 1:1 TriTruss with this P&D concept exceeds the fairing diameter. In order to fit within the fairing, the TriTruss H/a must be reduced to $\sqrt{3}/3$ (estimates are included for this truss configuration in Table 2). The telescoping diagonal and collapsible cross-section (Fig. 17b) concepts package into a triangular cross-section with the dimensions determined by the top and bottom triangles. The middle triangle fits inside the top and bottom triangles as shown. The side fold TriTruss (Fig. 17c) folds into a rectangular shape with a triangular cutout. The camping chair (Fig. 17d) compactly folds into a tall rectangular shape with a triangular planform area. The semi-erectable TriTruss (Fig. 17e) is assembled from triangular and cross shaped components that can be stacked on top of each other in the fairing. The fully erectable TriTruss would require three quivers to store the different sized truss members and a storage canister for the joints. For all concepts, there is the potential to package subsystems and other telescope components into the open space between truss modules.

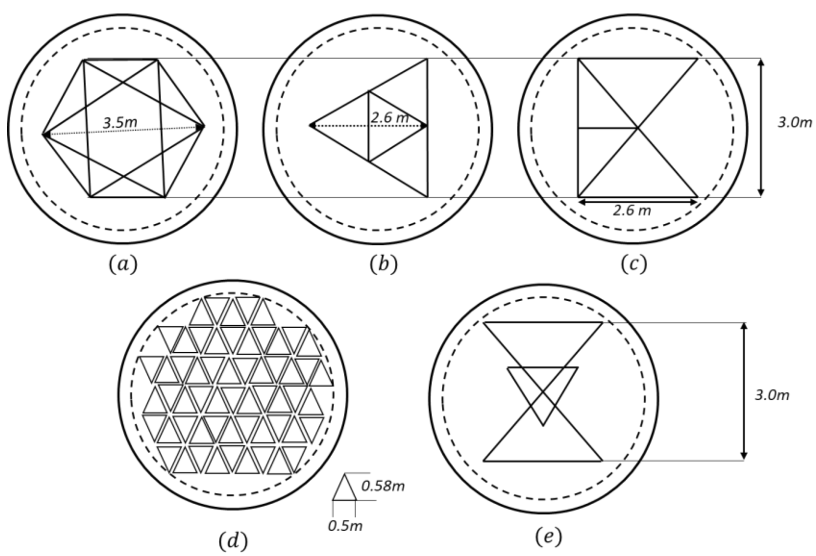


Fig. 17 A top down view of the packaged TriTruss concepts in a 4.6-m dynamic envelope diameter fairing: (a) telescoping middle triangle, (b) telescoping diagonal and collapsible cross-section, (c) side fold, (d) camping chair, and (e) semi-erectable.

Packaging dimensions and volume are estimated based on the TriTruss dimensions (*H = 3 m, a = 3 m*); Fig. 17 provides the planform dimensions of each configuration. The TriTruss packaged thickness is estimated as multiples of the strut diameter with an additional estimate made for joint sizes (Table 2). For the volume calculation, the strut diameter was assumed to be $d_s = 0.054\ m$. Results shown in the table are for a single TriTruss module. The erectable options provide a low packaging volume because struts and joints can be packaged without any open spaces. Of the deployable concepts, the camping chair has the lowest packaged volume. For the concepts that fit into the fairing, the overall packaging efficiency scores given were based on the number of launches that would be required to deliver all the foundational truss modules.

The packaging efficiency of each concept was ranked and is summarized in Table 2: the fully erectable concept has the highest packaging efficiency followed by the camping chair. Those concepts requiring three to four launches for the entire structure are considered to have medium packaging efficiency. The telescoping middle triangle concept is ranked as low in this study due to its limited geometric versatility that prohibits it from fitting in the specified fairing.

The iSAT trade study estimated that a total of twelve launches would be required to launch the entire 20-m diameter observatory, with five launches dedicated to the truss structure. Choosing a compact packaging scheme such as the camping chair or the fully erectable approach would benefit the iSAT architecture by significantly reducing the number of launches required for the foundational structure. However, the packaging of end effectors and specialized tooling required to assemble erectable structures has not been included in the calculations and may reduce packaging efficiency somewhat.

Table 2. Metrics used to estimate the packaging efficiency of P&D concepts.

Metric	Telescoping Middle*	Telescoping Diagonal	Collapsible Cross-section	Side Fold	Camping Chair	Semi Erectable	Fully Erectable
Packaged Module Thickness	$3d_s$	$3d_s$	$3d_s$	$4\ d_s$	$4.22\ m$	$4d_s$	Struts and joints packaged lengthwise into fairing
Module Packaged Volume	1.26 m^3	0.63 m^3	0.63 m^3	1.26 m^3	0.61m^3	0.071m^3	0.015m^3
Number per launch	31	31	31	24	118	31†	686†
Number of Launches to assemble the foundation Structure	3	3	3	4	1	3	1
Overall Packaging Efficiency	Low	Medium	Medium	Medium	High	Medium	High

*Telescoping middle truss is based on an H/a ratio of $\sqrt{3}/3$.
†The values are not calculated from an optimized packaging scheme for the erectable concepts.

B. Geometric Versatility

Table 3 summarizes the subsystem integration metrics evaluated for each P&D concept. Here, subsystem refers to scientific instruments, and electronic systems. The telescoping diagonal and collapsible cross-section concepts are the most versatile, allowing for both full and partial packaging as well as subsystem and mirror raft integration prior to launch. Since each module is fully assembled prior to launch, the functionality of the module can be verified. The telescoping middle P&D concept does not allow for subsystem integration because the middle triangle must expand radially to allow it to fully package. The face-collapse concepts do not allow for partial packaging and subsystem integration because the width of the TriTruss folds inward to package. Additionally, the erectable approaches are not versatile, though the semi-erectable concept would allow truss members to be installed at the base of the mirror rafts prior to launch. The overall versatility rating for subsystem and mirror raft integration is given for each concept based on the five criteria in the table. The concepts with the highest versatility are the telescoping diagonal and collapsible cross-section concepts.

Table 3. Metrics to determine the overall versatility for subsystem and mirror raft integration.

Metric	Telescoping Middle	Telescoping Diagonal	Collapsible Cross-section	Side Fold	Camping Chair	Semi Erectable	Fully Erectable
Partially Package	No	Yes	Yes	No	No	N/A	N/A
Fully Package	Yes	Yes	Yes	Yes	Yes	N/A	N/A
Integration of Mirror Prelaunch	Yes	Yes	Yes	No	No	Yes	No
Integration of Subsystems Prelaunch	No	Yes	Yes	No	No	No	No
Verify Module Prior to Launch	Yes	Yes	Yes	Yes	Yes	No	No
Overall Geometric Versatility	Medium	High	High	Low	Low	Low	Low

C. Mechanical Complexity

To assess mechanical complexity, the number and type of; joints, telescoping members, and strain energy members required for each concept to package were evaluated, resulting in the summary data and complexity ratings given in Table 4. The telescoping middle truss has dowel pin hinges at the middle triangle plane and hinge joints where each diagonal member meets a face or middle triangle and there are 3 telescoping members within the middle triangle. Telescoping members are also used in the telescoping diagonal truss and the side fold truss. In the telescoping diagonal truss, telescoping members are required for all the diagonals along with hinge joints where the diagonals connect to the face triangles. Internal springs could be included with the telescoping members to enable strain energy deployment instead of using a robot to pull the TriTruss into its deployed configuration. The side fold concept has additional joints in one member of each of the face triangles that allow it to fold. The camping chair has the greatest number of joints since each face triangle member has a joint allowing it to fold and hinge joints are located at each location where members intersect. Scissor joints on the diagonal members allow the cross section to fold. The fully erectable, and semi-erectable concepts do not require any hinges at the joints where struts are connected. The strain-energy DCB diagonal members of the collapsible cross-section TriTruss do not require complex joints to package since the DCBs bend and fold by collapsing the cross section.

The telescoping diagonal concept is considered to have high mechanical complexity due to the number of joints and the types of members required to achieve packaging and deployment. The erectable and collapsible cross-section concepts require few or no mechanical joints or telescoping members and are thus judged to be less complex. The camping chair requires many joints to package compactly but the joints themselves are kinematically simple.

Table 4. Metrics to determine the mechanical complexity of TriTruss P&D concepts.

Metric	Telescoping Middle	Telescoping Diagonal	Collapsible Cross-section	Side Fold	Camping Chair	Semi Erectable	Fully Erectable
Type of joints required	Hinges at the middle triangle	Hinges where diagonals meet face triangles	Connecting joints only; fixed	Hinges on the folding side and face triangles	Hinges in every member of face triangles, scissor joints on diagonal; hinges at each joint	Connecting joints only; fixed	Connecting joints only; fixed
DOF: rotational	18	24	0	11	42	0	0
DOF: translational	3	12	0	6	0	0	0
Telescoping Members Required	Yes, middle triangle	Yes, diagonal members	No	Yes, diagonal members and middle triangle	No	No	No
Number of Telescoping Members	3	12	0	6	0	0	0
Strain Energy Members Required	No	Optional; springs in diagonals	Diagonal members	Optional; springs in diagonals	Optional; tape spring hinges	No	No
Number of Strain Energy Members	0	12	12	4	42	0	0
Overall Mechanical Complexity	Medium	High	Low	Medium	Medium	Low	Low

D. Deployment Concept Complexity

Each concept was evaluated for deployment operations complexity considering the evaluation metrics and the results are summarized in Table 5. Each concept is assumed to require the assistance of robotic agents to deploy from its packaged state and will be packaged in a launch canister. The launch canister is assumed to have either a drive mechanism that advances each TriTruss to the top of the canister, such that the robotic arm would not be required to reach deep into the canister, or the canister has a hatch in the side allowing extraction in that direction. In the case of the telescoping middle, telescoping diagonal, side fold, and camping chair concepts, the packaged TriTruss would remain attached to the canister launch locks on the bottom side while the top is grappled and robotically manipulated into its deployed configuration. Alternatively, the packaged TriTruss could be released entirely from the launch canister and transported to the assembly area where one end would be mounted to a jig for deployment. A robotic agent could apply a force to the free end of the TriTruss and pull it into its deployed configuration, or multiple robotic agents could be used to hold and deploy a TriTruss. Once deployed, the robotic agent would lock hinge joints and telescoping members in place, before transporting the truss module to the iSAT assembly site.

Strain energy member concepts will require the robotic agent to control the deployment rate to avoid rapid energy release. The telescoping diagonal spring-variant and collapsible cross-section members would be released from their launch locks on one truss face and remain attached to the launch canister on the other face. The robot would grapple the TriTruss, apply a force to balance the release of strain energy, and slowly allow the TriTruss to deploy. Once deployed the TriTruss would be transported to the assembly area.

Table 5. Metrics to determine TriTruss P&D concept deployment complexity.

Metric	Telescoping Middle	Telescoping Diagonal	Collapsible Cross-section	Side Fold	Camping Chair	Semi Erectable	Fully Erectable
Robotic Assistance Required	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Canister Design	Locking mechanism to hold trusses	Locking mechanism to hold trusses	Locking mechanism to hold trusses	Locking mechanism to hold trusses	Locking mechanism to hold trusses	Organized storage of components	Organized storage of components
Fabrication Jig Required	No	No	No	No	No	Yes	Yes
Deployment Strategy	Robotic arm pulls truss to deployed configuration and locks members into position	Robotic arm pulls truss to deployed configuration and locks members into position	Robotic arm controls deployment	Robotic arm pulls truss to deployed configuration and locks members into position	Robotic arm pulls truss to deployed configuration, locks joints into position	Full robotic assembly	Full robotic assembly
Overall Deployment Complexity	Low	Low	Low	Low	Low	High	High

Erectable approaches require specialized end-effectors to complete module construction from individual struts (with pre-integrated erectable joints). The erectable concepts also require robotic assistance to acquire, hold and operate end-effectors to assemble other components to the truss module. A canister will be required to keep the struts organized and restrained for launch and ordered for assembly. Overall deployment and construction are considered the most complex for the erectable concepts. The erectable concepts are also considered to have high deployment complexity due to the number of steps required to assemble a truss module, the canister design, and the end-effectors and jigging required to construct the trusses on-orbit.

The telescoping middle, telescoping diagonal, side fold and camping chair concepts require the robot to grapple the TriTruss and apply a force to deploy the module. Once deployed, the robotic agent will need to lock or secure the joints and telescoping members in place. For the collapsible cross-section, a robotic agent is needed to control deployment of the strain energy members. The robotic operations required for each of these concepts is considered to be minimal compared to the erectable concepts and are ranked as low deployment complexity.

E. Phase 1 Down Select

The evaluation criteria were used to select the subset of TriTruss P&D concepts that will be carried forward into the study's next phase, where designs will be refined and developed in more detail. After reviewing the summary of the overall performance in each metric category (see Table 6) and assigning the weighting criteria (see Table 1), the collapsible cross-section TriTruss received the highest ranking. Late in the phase 1 study, it was determined that the telescoping diagonal and collapsible cross-section TriTruss P&D concepts were similar enough (just having different concepts for the diagonal members) that the two concepts could be combined for the phase 2. Currently, the preference is to pursue the collapsible cross-section concept due to the potential for extremely light weight truss members, but subject to more detailed structural analysis to determine if the DCB can provide adequate structural stiffness. Options for using the DCB include using a solid cross section member with DCB or composite cross-section joints spliced along the length where folding needs to occur. Once deployed, strengthening sleeves could be bonded to the joint to increase stiffness.

The camping chair scores highest of the face collapse concepts and has the highest packaging efficiency of all deployable concepts considered. However, the concept employs 42 rotational DOF to achieve its efficient packaging and the truss member stiffness will need to be evaluated to ensure adequate structural performance in the deployed state. DCB or composite joints could possibly be used in place of mechanical joints which might reduce the structural mass. If analysis and testing indicate that the stiffness of the structure is insufficient, sleeves could be incorporated to slide over the composite joint and can be bonded in place to stiffen the joint.

Table 6. Overall ranking and scoring of P&D concepts.

Metric	Telescoping Middle	Telescoping Diagonal	Collapsible Cross-section	Side Fold	Camping Chair	Semi Erectable	Fully Erectable
Overall Packaging Efficiency	Low	Medium	Medium	Medium	High	Medium	High
Overall Versatility	Medium	High	High	Low	Low	Low	Low
Overall Mechanical Complexity	Medium	High	Low	Medium	Medium	Low	Low
Overall Deployment Complexity	Low	Low	Low	Low	Low	High	High
Score	12	14	18	12	14	10	12

The side fold concept employs eleven rotational DOF and six translational DOF to package, which is the lowest number for the concepts that use mechanical joints and telescoping members. The design allows for most of the members to be continuous while only one portion of the truss module requires telescoping members. The concept packages efficiently and could be designed to use composite joints or DCB members in place of mechanical joints and telescoping members. The side that folds can also be designed to be semi-erectable which would significantly reduce the number of hinge joints required and eliminate telescoping members from the design. Neither the camping chair nor the side fold TriTruss concepts allow subsystems or mirror rafts to be pre-integrated. However, these two designs can be a viable option for sections of the iSAT that are purely structural and do not require subsystems integration prior to launch.

The trade study team has chosen the collapsible cross-section, the camping chair and the side fold TriTruss concepts for further study and development because they use straightforward deployment operations that are executed by robotic agents. The collapsible cross-section and camping chair TriTruss concepts score highly based on the weighting scale. The side-fold TriTruss is chosen because the concept allows for most of the truss members to remain continuous, which is likely beneficial from a stiffness standpoint. The selected concepts make use of novel technologies (DCB) and have the potential to use composite joints and members in place of mechanical systems to enable packaging. Deployment can be accomplished by a robotic arm that either pulls on the top (collapsible cross-section) or the side (side fold and camping chair) of the TriTruss module. For a semi-erectable side fold concept, deployment becomes more complex with the added step of installing the TriTruss side panel.

Concepts not selected for further consideration in the next study phase still have attributes that make them viable P&D concepts for other applications not considered here. For example, the telescoping middle concept was eliminated from our study because the geometric versatility is limited due to expansion of the middle plane. For a larger fairing diameter or a reduced H/a TriTruss, this concept would be applicable. The erectable concepts are attractive options from a packaging efficiency and mechanical complexity standpoint but are removed from our study due to the more complex assembly requirements and low versatility for subsystem integration. Erectable approaches have very high packaging and structural efficiency and jigging/assembly robots (including NINJAR and SAMURAI) [20] have demonstrated efficient in-space assembly truss construction.

VI. Conclusions and Future Work

In phase 1 of the TriTruss trade study presented here, seven P&D concepts were developed and evaluated based on a set of criteria for desired attributes for assembling an iSAT foundational truss structure in space. An ideal TriTruss P&D concept has the following features: 1) allows for efficient packaging while also being geometrically versatile and launch vehicle agnostic; 2) be stiff, lightweight, and have component modularity with low joint complexity; 3) be kinematically simple such that deployment could be accomplished robotically while minimizing the number of required specialized tools; and, 4) allow for subsystems or utility integration prior to launch, if necessary. The P&D

concepts selected in this trade study will be both novel and innovative in nature and allow for efficient assembly of a 20-meter diameter iSAT.

This study developed the evaluation criteria and ranked proposed P&D concepts based on packaging efficiency, versatility, mechanical complexity, and deployment concept complexity, with the study focusing on packaging and deployment kinematics. In order to compare P&D concepts, the study assumes: a constant geometry TriTruss; the availability of multiple robotic agents to aid in deploying and assembling TriTruss modules; and, that a TriTruss is not required to repackage after deployment on-orbit. For the purposes of sizing, the packaged TriTruss modules are required to fit inside a fairing with a dynamic envelope of 4.6 meters. Deployment is assumed to occur using either internal strain energy in the truss members or robotic assistance for a controlled deployment. Concepts are evaluated as an entire system, including the packaged TriTruss, subsystems, electrical wiring harnesses, data connections and mirror rafts. Subscale models were constructed for each concept to aid in understanding the packaging kinematics and associated mechanisms.

The proposed P&D concepts fall into three categories. Core collapse concepts, where the diagonal members retract and the height of the TriTruss decreases, included the telescoping diagonal, telescoping middle, and collapsible cross-section TriTruss concepts. Face collapse, where the face triangles contract, and the width decreases included the side fold and camping chair TriTruss concepts. The study also considered fully and semi-erectable structures, where the TriTruss structure is packaged as individual components or sub-components, respectively, that are assembled robotically on orbit.

At the conclusion of this trade study three P&D concepts were selected for further refinement and evaluation: 1) collapsible cross-section, 2) side fold and 3) camping chair. The trade study team concluded that the selected concepts best satisfied the evaluation criteria established at the beginning of the study and represent novel concepts which should be further studied. The collapsible cross-section scored highest in the weighting criteria and most closely represents an ideal P&D concept. As justified previously, the collapsible cross-section and telescoping diagonal concepts were combined into one concept focused on collapsing diagonal members. The camping chair also scores highly of all the concepts based on high packaging efficiency. The side fold TriTruss is also chosen for further study because the TriTruss folds compactly into a rectangular shape and can be designed to use mechanical or composite joints, or, alternatively, it could be implemented as a semi-erectable option. The team opted to not pursue further study of erectable structures for this application because the deployment complexity is considered high compared to deployable concepts. The ideal P&D definition highlighted the need for a kinematically simple deployment concept and minimal requirement for extra tooling for assembly. The telescoping middle TriTruss was eliminated from this study because of the packaged shape and limited geometry.

The selected concepts will be further designed and analyzed to develop scale TriTruss models that can be tested in the laboratory and used to assemble a mirror support truss as part of the PASS project.

Acknowledgments

The authors would like to acknowledge those who have assisted us during the trade study: Mr. Juan Fernandez (NASA LaRC) for helpful discussions about the collapsible cross-section concept and supplying DCB for scale models; Mr. Garry Qualls and Mr. Lawrence Taylor of the NASA LaRC Makerspace for their help and assistance with 3D printing joints and connectors for the scale models; and, summer interns Mr. Ryan Ernandis and Mr. Hermann Kaptui Sipowa for their work on TriTruss P&D preliminary designs.

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