# REALIZING LARGE STRUCTURES IN SPACE

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**Introduction**

Since the dawn of space access in 1957 the size of spacecraft payloads and solar arrays has steadily grown. Yet the demand for larger apertures and higher power on spacecraft continues to outpace availability. In many cases, the larger the antenna or telescope, the more effective the mission data return. Exoplanet discovery is no exception. Larger optical apertures and bigger starshade occulters are needed to both reach a larger number of stars for greater Earth-like exoplanet discovery opportunities as well as to access a broad range of the electromagnetic spectrum for exoplanet spectral characterization. Future antenna and radar missions also require larger apertures to provide more communication spot beams to ground soldiers, to generate higher resolution radar imaging for Earth science, or to keep up with the higher data throughput demands of modern hand-held technology. Common radio frequency antennas will range in size from 4 meters to 22 meters diameter, and the largest space telescope aperture currently in development is 6.5 meters. But size is not all that matters.

Dimensional precision and stability are also important. Both optical and radio signal quality is directly related to the precision of the surface from which the signal is emanating. In addition, the larger the structure, the more difficult it is achieve a given figure precision. Radio frequency missions operate on long wavelengths so precision requirements are not as stringent as optical missions, but signal gain scales inversely with the square of wavelength so radio antennas require larger apertures than optical. Furthermore, once unfolded in space these structures face extreme temperature swings that can cause large static and dynamic dimensional changes. Spacecraft in a geosynchronous orbit will endure daily temperature swings from -200°C to +200°C over a typical 15 year lifetime. Materials must exhibit a low coefficient of thermal expansion. Assembly interfaces are extensively tested to control thermal expansion characteristics.

Figure 1 illustrates the indirect relationship between aperture size and dimensional precision. As this ratio grows, payload cost escalates. Some of the highest performing space structures to date are represented on this chart, yet they are restricted to relatively low diameter-to-precision ratios when compared to future needs in the tens to hundreds of meters.

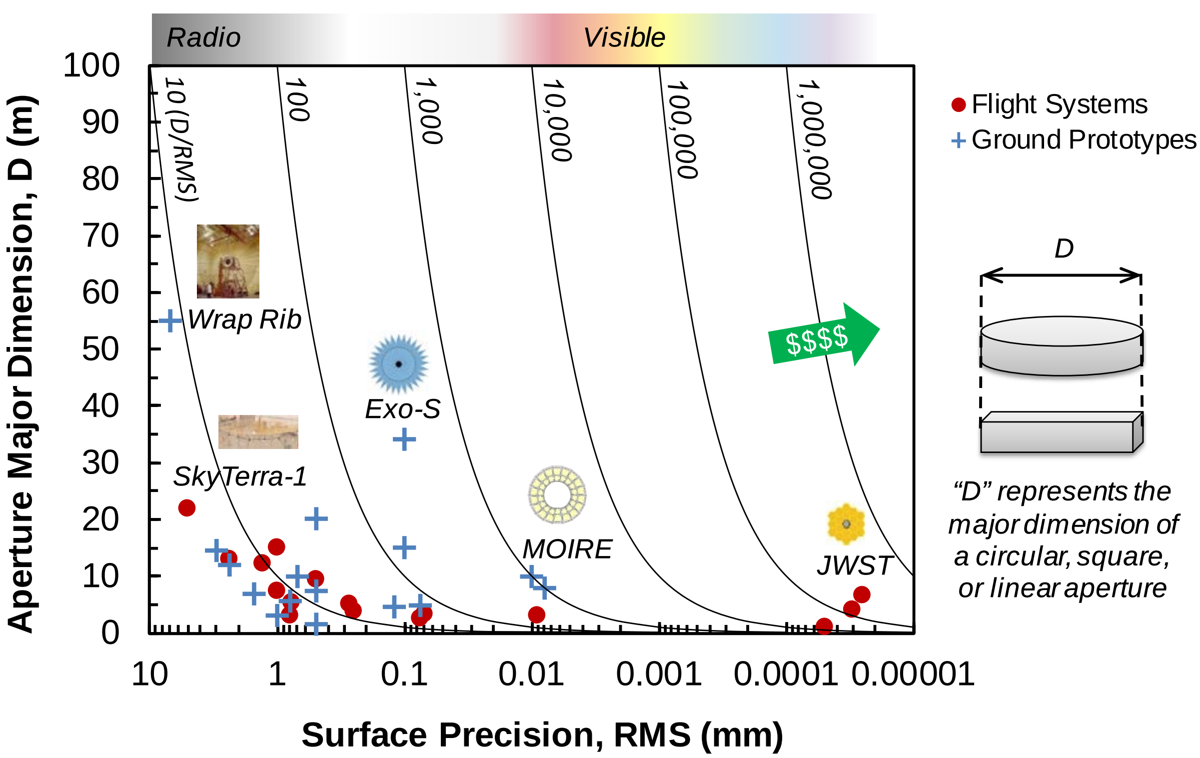


*Figure 1. Size and surface figure precision are indirectly related in space structures design.*

Aside from dimensional precision challenges, large space structures also face severe packaging requirements and a violent launch environment. Once designed, built, and stowed in a 5 meter launch vehicle fairing, these payloads endure 10 to 70 g's accelerations during the 10 minute trip to low Earth orbit, reaching the velocity of 7 km/s. Then once on-orbit, the structure must unfold precisely and reliably. As an example, an exoplanet starshade must unfurl from 5 meters to 34 meters, into a shape that is within a 0.1 mm precision, approximately the width of a human hair. Figure 2 and Table 1 show the relative scale of the largest launch vehicles, the typical large structures that must stow within them, and the respective packaging ratios of those structures.

*Table 1. Packaged size of typical precision space apertures and booms.*

| **State of Practice** (rank order of structural performance) | **Deployed Size** | **Stowed Size** | **Packaging Ratio** |
|---|---|---|---|
| *JWST Primary* | 6.5 m | 4.0 m | 1.6:1 |
| *Exo-S Starshade* | 34 m | 5.0 m | 9:1 |
| *SkyTerra-1 Mesh Reflector* | 22 m | 2.4 m | 9:1 |
| *NG Telescopic Tube* | 33 m | 2.4 m | 14:1 |
| *ATK Graphite Coilable Boom* | 40 m | 0.4 m | 100:1 |
| *Graphite Slit-Tube STEM* | 17 m | 0.3 m | 57:1 |

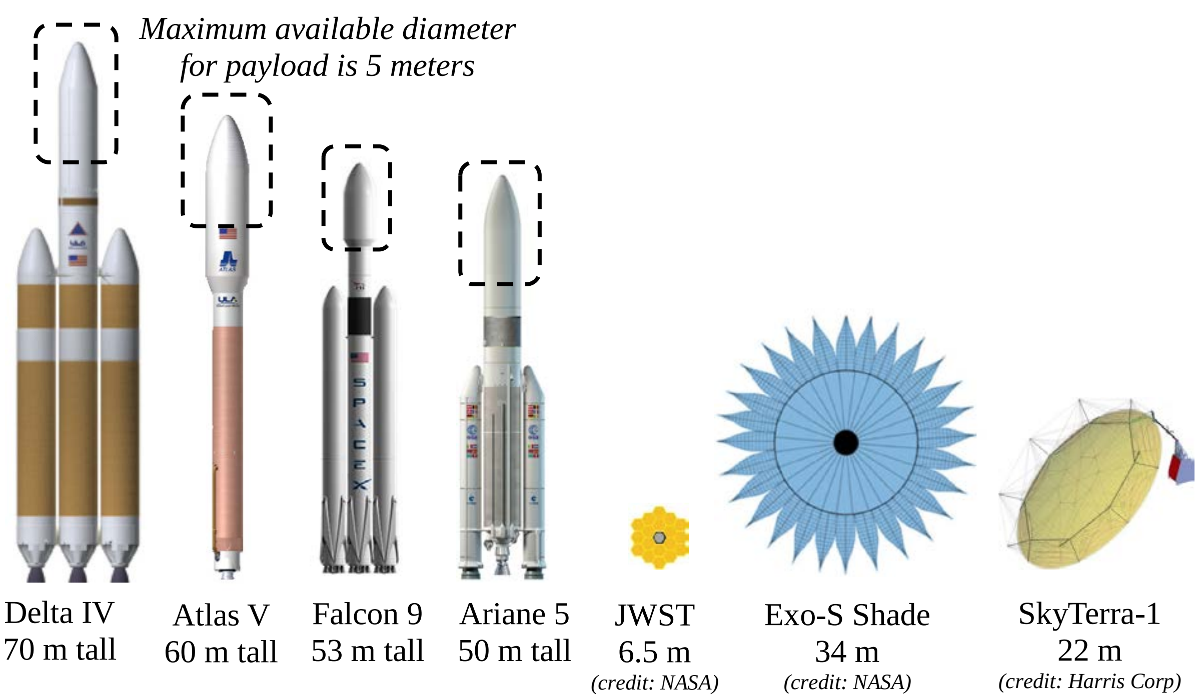

*Figure 2. Scale of the largest launch vehicles relative to representative large space apertures.*

The heritage approach for realizing large antennas, telescopes, and radar apertures has generally been to fold a deep truss structure then self-deploy using multiple pin-clevis joints, motors, torsion springs, and dampers. This approach has led to incremental improvements in size, weight, and power over the last 50 years, but these heritage mechanisms and structural support approaches are reaching size and mass limits. Adding more hinges to package larger payloads into these limited launch volumes is causing reliability concerns and cost escalation.

## Emerging Approaches

Structural designers have begun to move beyond these heritage approaches. Two techniques have emerged as showing high payoff potential: 1) tension-aligned precision apertures and 2) foldable high strain composite structures. Actually these methods have been used successfully for decades, but in very limited form due to the absence of high strength carbon fiber composites and robust analytical tools. In fact, two of the most efficient packaging space structures to date are high strain composite based: the Continuous Longeron Mast of the 1960's and the Wrap-Rib reflector of the 1970's. However, it was not until recently when the testing and analysis tools started coming online and the use of high strength carbon fibers in aircraft became prevalent did feasible new space architectures begin to surface. For example: in 2007 the Innovative Space Based Radar (Lane, 2011) truss was ground tested, in 2010 the Flexible Unfurlable Refurlable Lightweight solar sail (Banik, 2010) was ground tested, in 2013 the Membrane Optical Imager for Real-Time Exploitation (Domber, 2014) telescope brass-board was ground tested. And most recently, the Roll-Out Solar Array (Spence, 2015) was manifested for a space flight experiment to the International Space Station in 2016. Other concepts currently under development by government and industry all share high strain composite features and/or tension as the means of structural stability: a low-cost Multi-Arm Radial Composite radio-frequency reflector (Footdale, 2016), a stray-light baffle (Jeon, 2016), a starshade occulter as shown in Figure 3 (NASA, 2015), an Extremely High Expansion Deployable Structure (Warren, 2007), the Triangular Rollable and Collapsible mast (Banik, 2010) and a tensioned planar membrane antenna (Warren, 2015).

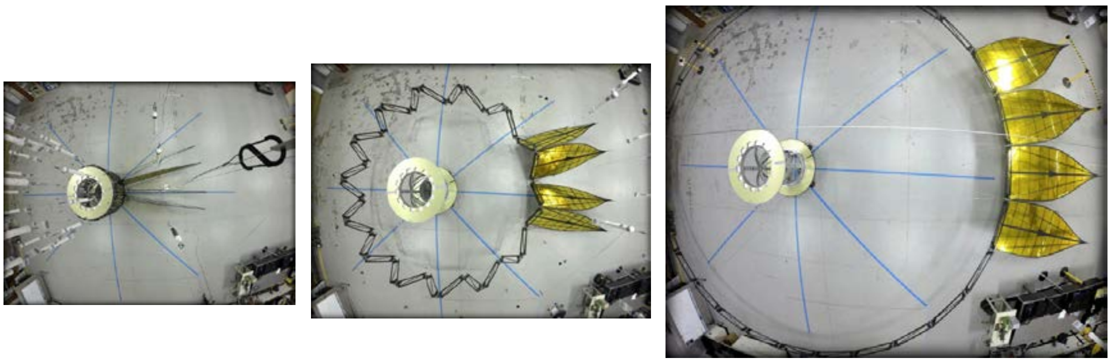

*Figure 3. Ground deployment of a starshade demonstration model. credit: JPL*

High strain composites are defined as thin carbon and glass fiber polymer matrix laminate materials used to construct shell structures that undergo large elastic deformations during folding then release stored strain energy to enforce deployment. Architectures constructed from these materials have 7x greater deployment force, 20x greater dimensional stability, and 4x higher stiffness when compared to traditional metallic flexure mechanisms (Welsh, 2007; Murphey, 2013; Murphey, 2015). Moreover, when compared to traditional pin-clevis-type hinges, the payoff is reduced mechanism part count and more robust deployments that are less susceptibility to binding. These hinges have greater lateral and torsion compliance during the transition from folded to deployed, a critical transition when binding is at a high risk such as when asymmetric solar heating and subsequent expansion induces side loads on hinges. High strain composite hinges can operate through this state yet reach a repeatable, dimensionally stable locked-out condition due to the near-zero coefficient of thermal expansion of carbon fibers. When combined with the kinematic determinacy of a tensioned aperture, together these technologies are cracking open the door to a new era of space structures where 100-meter apertures, 500-meter booms, and Megawatt-class solar arrays are all plausible.

**Long Term Possibilities**

Despite the current potential of tension supported payloads and high strain composites, even these will eventually reach limitations in size scaling, mass efficiency, and dimensional stability. Pushing beyond these limits will be necessary to meet the long-term needs of civil and military space. As the promise of robotic assembly and in-space additive manufacturing technologies are beginning to emerge, the best tack is not yet clear. Therefore as we reach toward these exciting new technologies we must keep one hand firmly gripped to the unique realities of spaceflight.

Few industries are more risk-averse. NASA and DoD program managers regularly spend millions (sometimes billions) of dollars on a single spacecraft to assure themselves of mission success. For example, the price tag on the 6.5 meter James Webb Space Telescope has reportedly reached $8.7B over a 16 year program duration from inception to launch (Leone, 2011). If we continue in this current paradigm, a 20 meter space telescope will be in development for 87 years (Arenberg, 2014). It is a spiraling effort. As more money is spent, additional testing and analysis is required to ensure a higher certainty of spacecraft success. Schedules are then drawn out, requiring even more money to be spent. Spaceflight is a one-shot business. Hundreds of critical systems must work together flawlessly the first time or else the mission is lost. Deployable structures are notoriously known as one of the highest sources of failure. This reality has driven mission managers to spend great effort testing in space simulation chambers. But even then the effects of gravity and the lack of a true combined environment always raise questions of the validity of these tests despite decades of heritage.

Of course, these challenges should not deter us from pursuing these innovations. Rather this should motivate us to continue evaluating new architectures against *all* measures of success, not just structural performance, but also cost factors, for example: ease of ground testing and validation, simplicity of analysis methods, and a low quantity of mechanical interfaces and unique parts. Each of these key cost factors are difficult to quantify in the early conceptual design phase. Nevertheless quantifiable cost metrics are needed more than ever. Until those are ready, we are left with structural performance metrics to provide rational comparison of competing structural architectures. A common list is provided in Table 2. Notice the telescope mission cost metric from Stahl and Arenberg.

*Table 2. Common metrics for evaluation of large space structures performance.*

| Metric | Description | Equation |
|---|---|---|
| *Packaging Ratio* | deployed length / stowed length | $\frac{L_d}{L_s}$ |
| *Linear Packaging Density* | deployed size / stowed volume | $\frac{D}{V}$ |
| *Areal Packaging Density* | deployed area / stowed volume | $\frac{A}{V}$ |
| *Beam Performance Index (Murphey, 2006)* | Strength moment, bending stiffness, linear mass density | $\mu = \frac{\left(M^2 EI\right)^{1/5}}{w}$ |
| *Solar Array Scaling Index (Banik, 2015)* | acceleration load, frequency, boom quantity, length, area, blanket areal mass density, total mass | $\kappa = (af)^{0.216}\, n^{0.231} L_{pb}\, A^{0.755}\, \frac{\gamma_b^{\,0.176}}{m}$ |
| *Aperture Mass Efficiency* | major dimension / mass | $\frac{D}{m}$ |
| *Aperture Precision Efficiency* | major dimensions / RMS figure precision | $\frac{D}{RMS}$ |
| *Dimensional Stability* | coefficient of thermal expansion | $\alpha$ |
| *Telescope Mission Cost (Arenberg, 2014)* | diameter, wavelength, temperature of operation | $MC = \frac{C\, D^{1.7} \lambda^{-0.3} T^{-0.25}}{0.11 + 0.09 ln\left(D\right)}$ |

*(Stahl, 2012)*

## Conclusions

The challenges we face in realizing large space structures are great, but if successful the opportunities enjoyed will be well worth the journey. No doubt, one of the most exciting is discovery of Earth-like planets that could have or perhaps still do contain life.

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