Realizing Large Structures in Space

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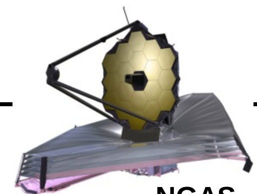
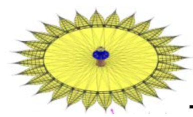
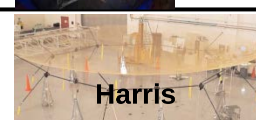
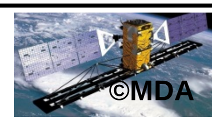
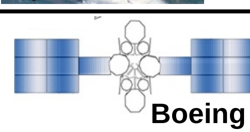
Integrity ★ Service ★ Excellence

[Credit: http://news.discovery.com/space/toyota-tundra-to-tow-shuttle-endeavour-121013.htm]

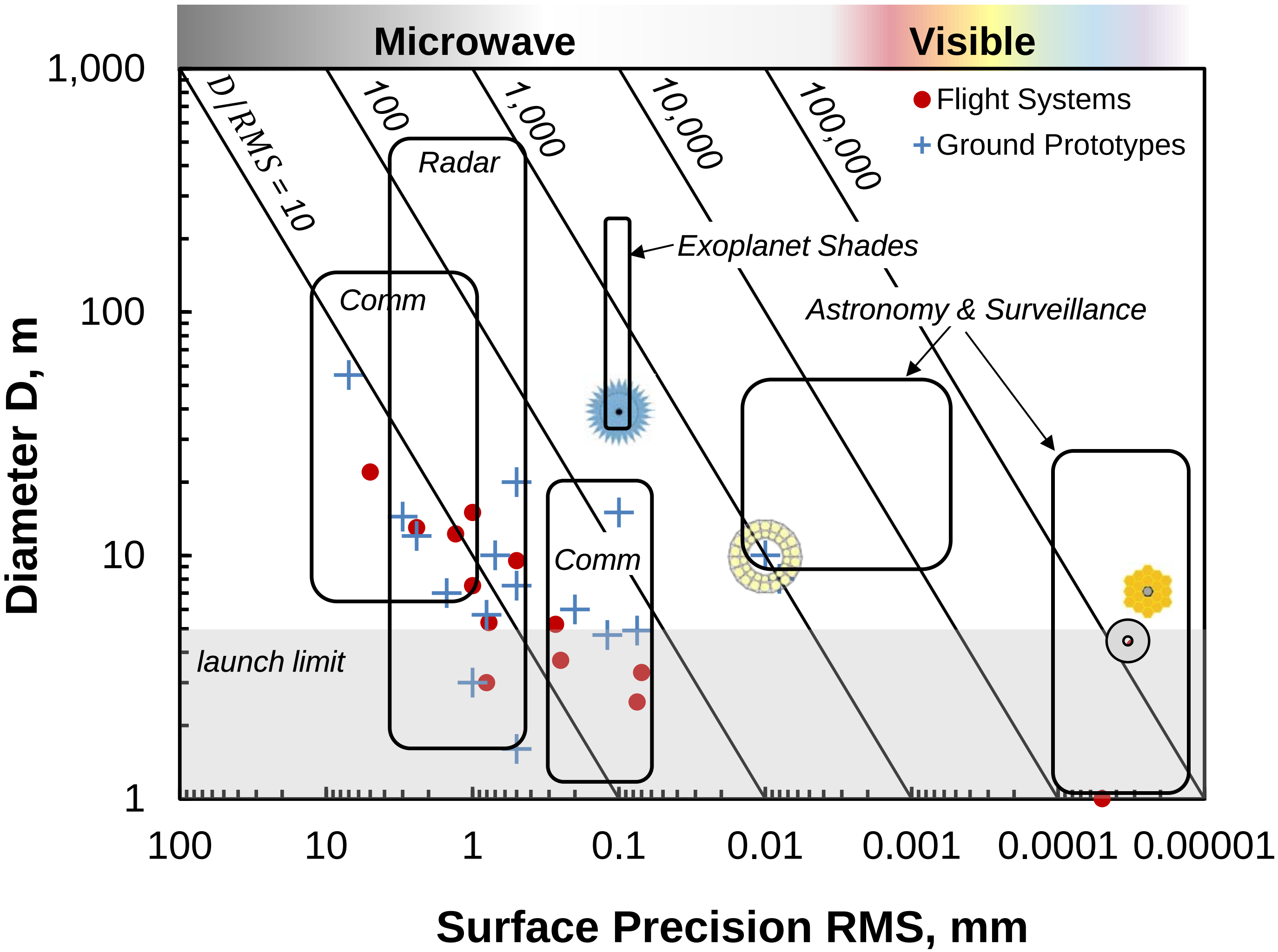
Why Large Structures In Space?

To Manipulate the Electromagnetic Spectrum

	Largest Available Today			Future Size	Benefits of Going Bigger
Telescopes	JWST primary	6.5 m		3x	***Better Resolution***
Sun Shields	JWST sun shield	22 m		n/a	***Cooler Optics***
Star Shades	Exo-S Starshade	34 m		10x	***Directly Image More Planets***
Solar Sails	Sunjammer	20 m		50x	***Higher Propulsion Thrust***
Antennas	SkyTerra-1 reflector	22 m		9x	***Smaller Ground Antennas***
Radar	RadarSat-II	15 m		30x	***Track more Objects***
Photovoltaic Arrays	Rigid panel array	47 m^2		30x	***Higher Power***

Precision is Challenging

Surface Figure Errors Scale with Aperture Size



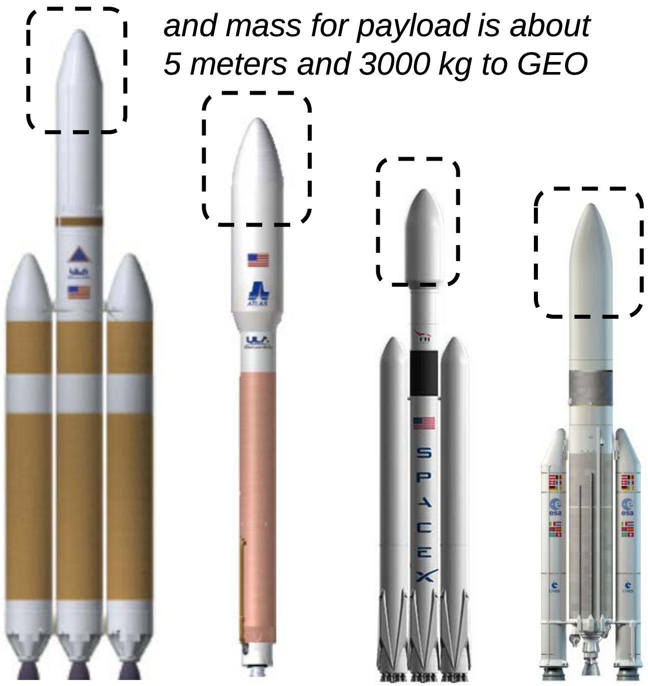
Getting to Orbit is Challenging

Rockets are Volume and Mass Limited

Launch is violent!

- **~50x Earth's gravitational accelerations (50 g's)**
- **0 to 7 km/s in 10 minutes**

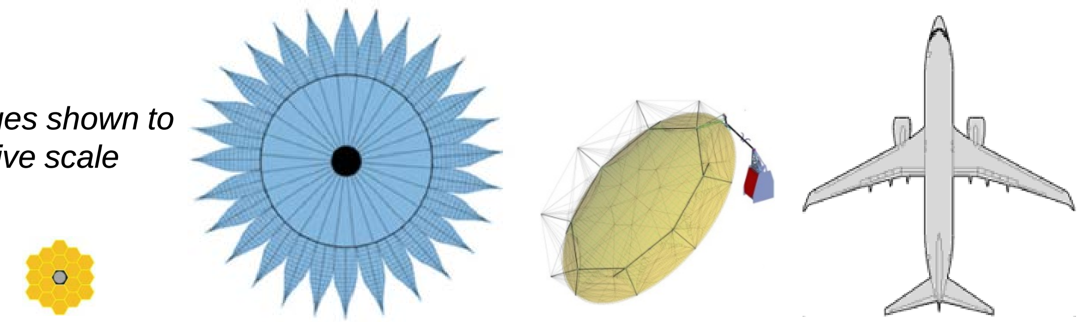
Maximum available diameter and mass for payload is about 5 meters and 3000 kg to GEO



Delta IV 70 m tall | Atlas V 60 m tall | Falcon 9 53 m tall | Ariane 5 50 m tall

State of Practice (rank order for 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 STEM	17 m	0.3 m	57:1

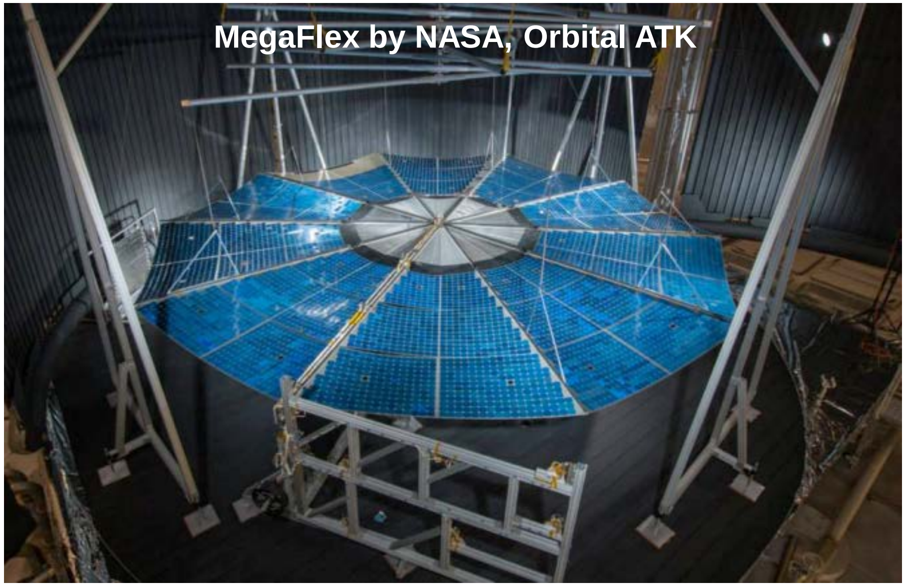
Images shown to relative scale



JWST 6.5 m | Exo-S Shade 34 m | SkyTerra-1 22 m | Boeing 737-400 33 m x 29 m

Deployment Reliability and Affordability are Challenging

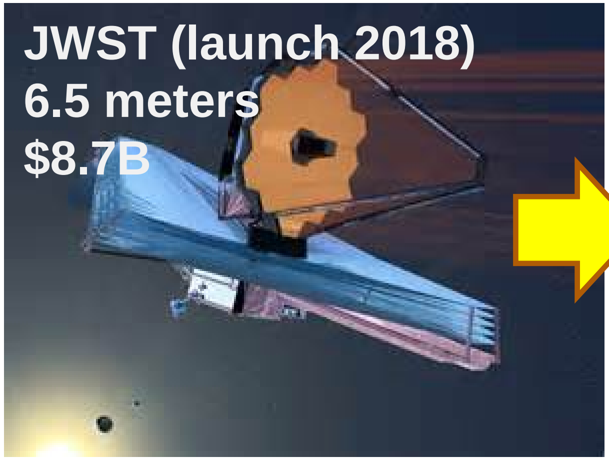
Space flight programs have one chance at success, ideal to test as you would fly—*$billions are on the line*

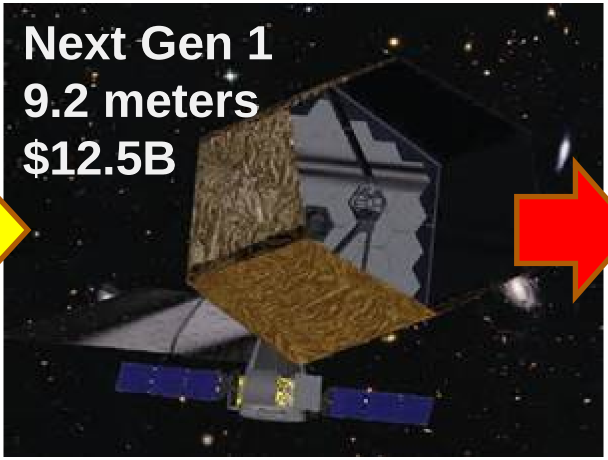


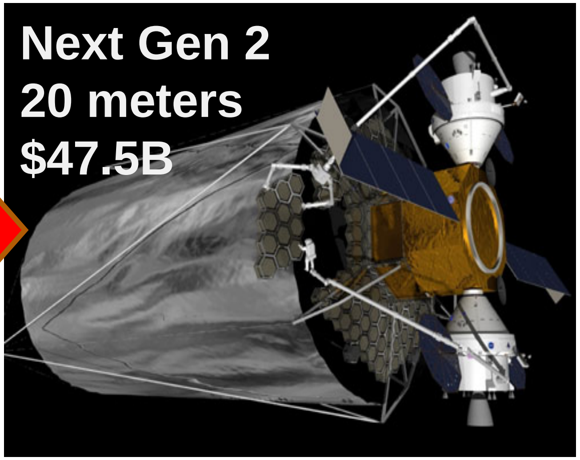
Zero-gravity deployments are approximated with elaborate suspension cable systems.

In-space thermal-vacuum environment is simulated by large chambers.

Current Technologies are Leading Us to "Astronomical" Costs







	JWST	Next Gen 1	Next Gen 2
Diameter, D (meters)	6.5	9.2	20
Development Cost*	**$8.7B**	**$12.5B**	**$47.5B**
Development Time	**16 yrs**	**23 yrs**	**87 yrs**

*Mission cost parameter [Credit: Jon Arenberg, NGS[23]]

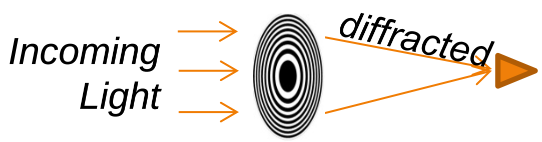
Emerging Approaches:

1) High Strain Composite Mechanisms

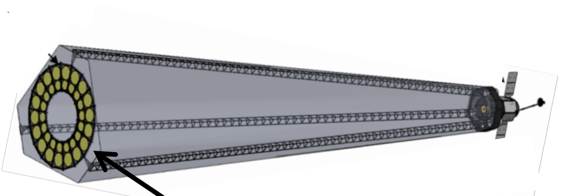
2) Tension-Aligned Apertures

Alternative to Reflective Optics: Tension-Aligned Transmissive Optics

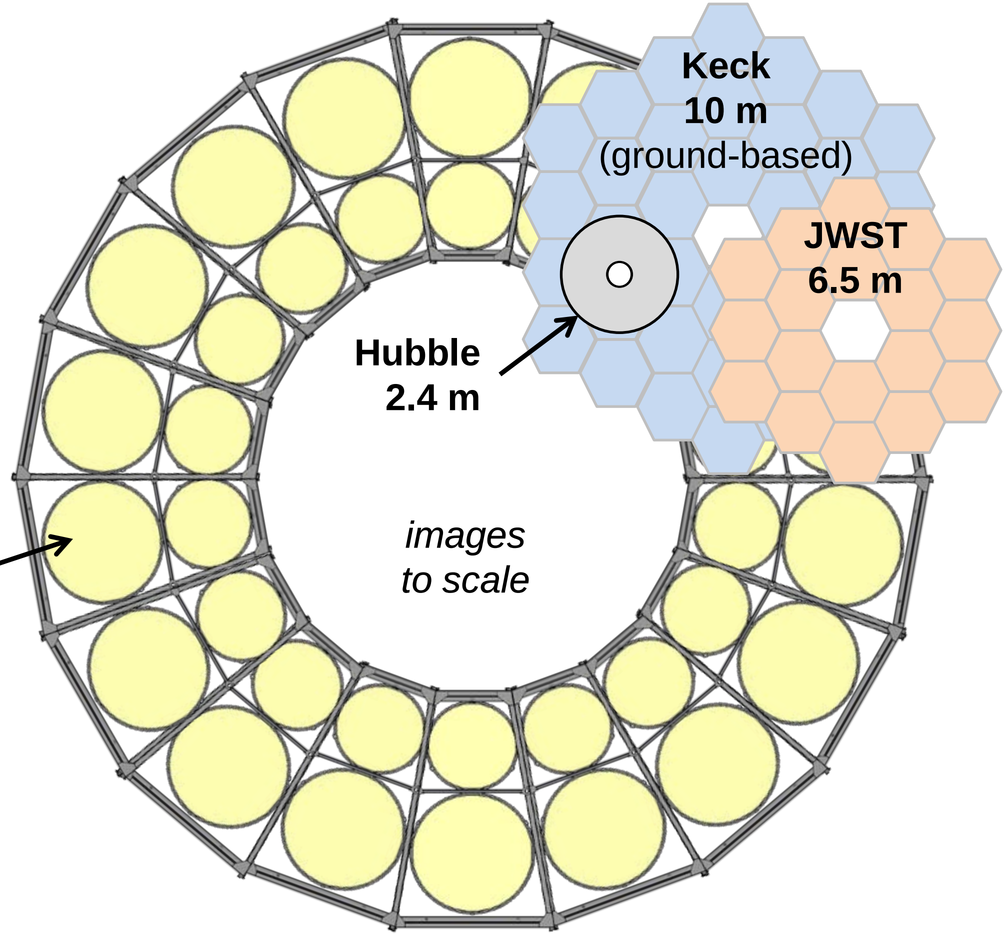
How it Works



Fresnel Zone Plate



MOIRE 20 meter diffractive optic



6 segments of a 5 meter diffractive optical aperture ground demo

[Credit: Ball Aerospace and DARPA MOIRE]

Half-Scale Deployment Test-bed

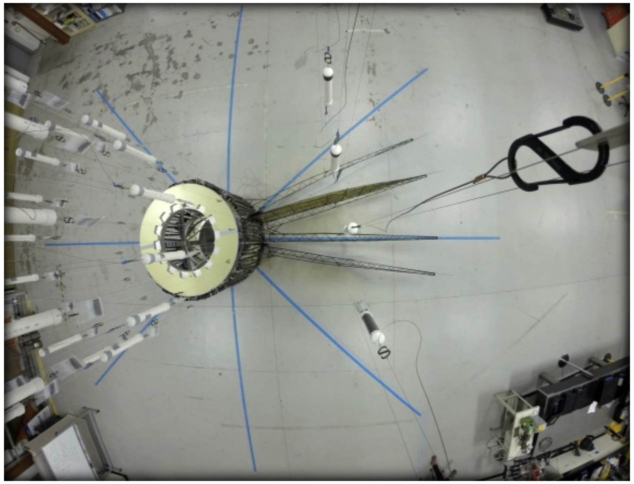
[Credit: JPL]

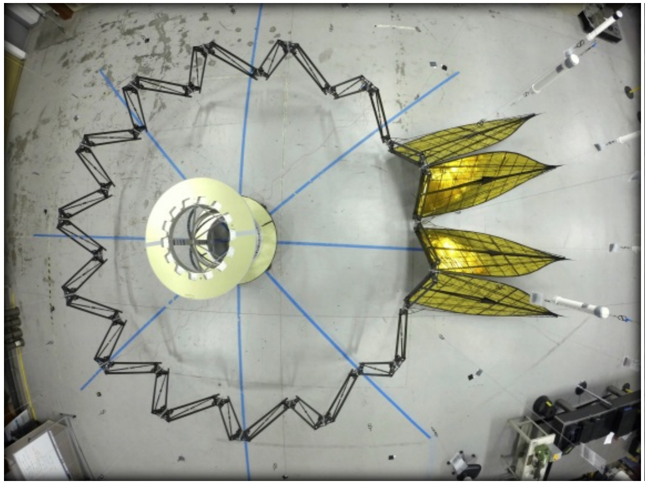
JPL Ground Demo Starshade

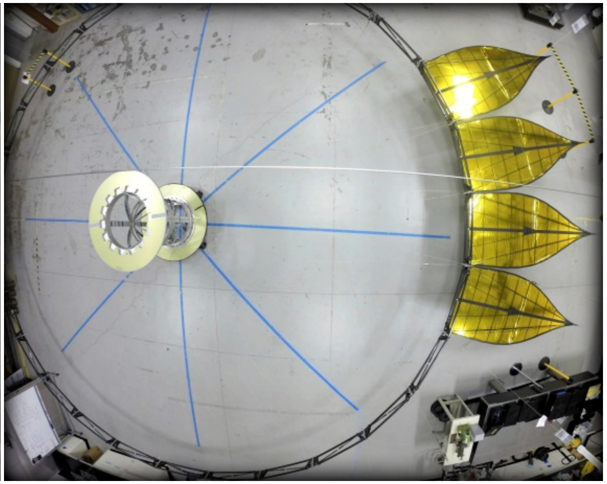
Also Tension-Aligned

Error Source	Required Tolerance
Petal Segment Shape (Random)	±68 µm
Petal Segment Position (Random)	± 45 µm
Radial Petal Position (Bias)	± 150 µm

Petals need sub-millimeter accuracy across 34 meters

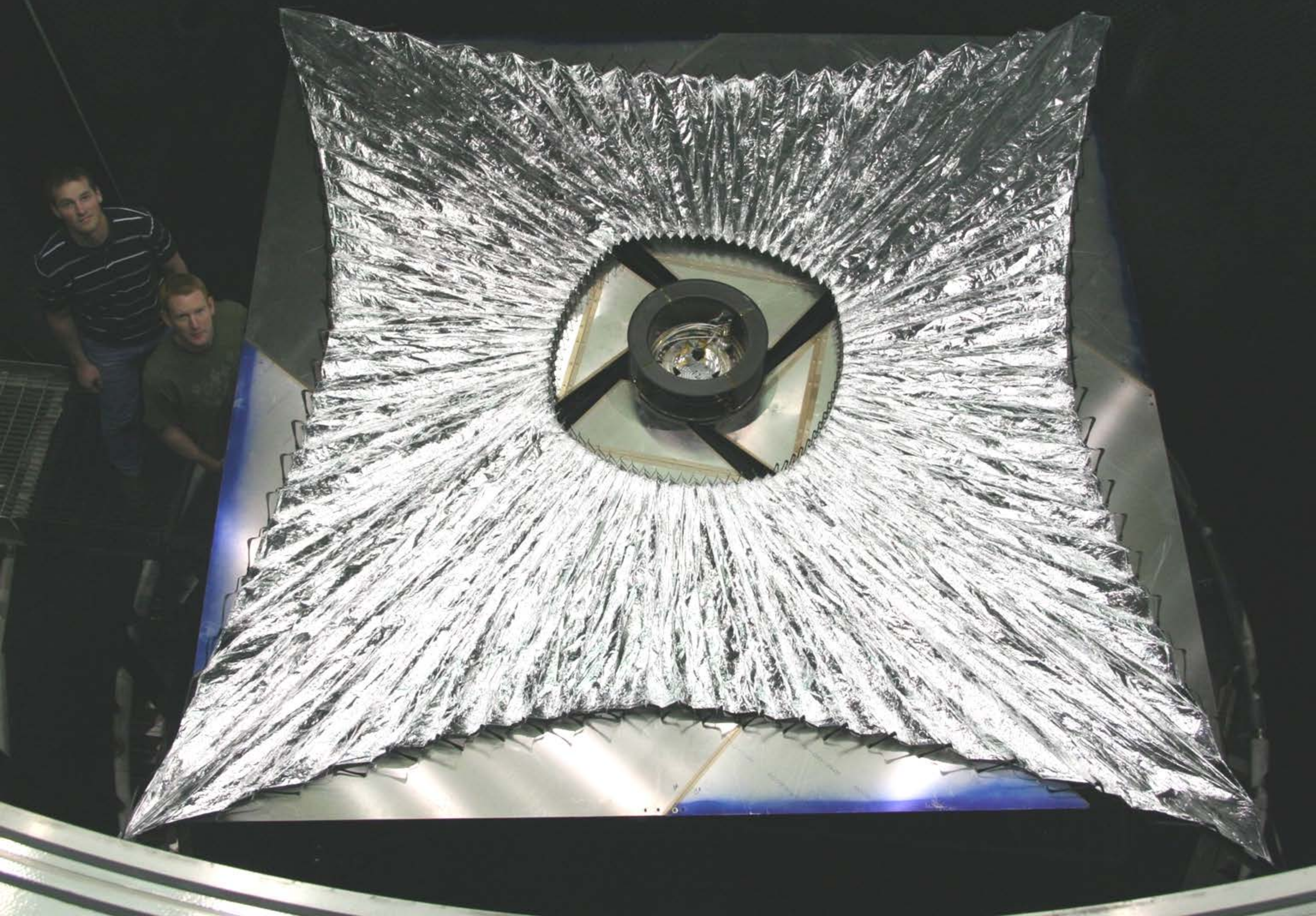






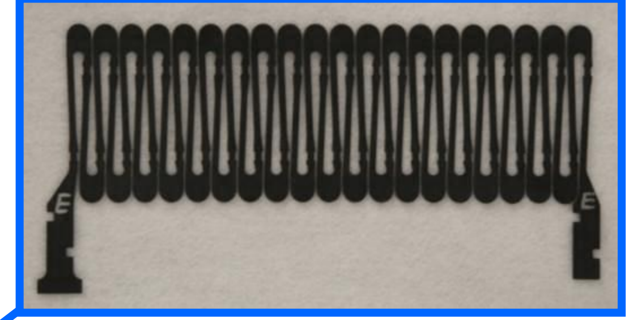
Credit: JPL

AFRL FURL DEPLOYMENT VIDEO

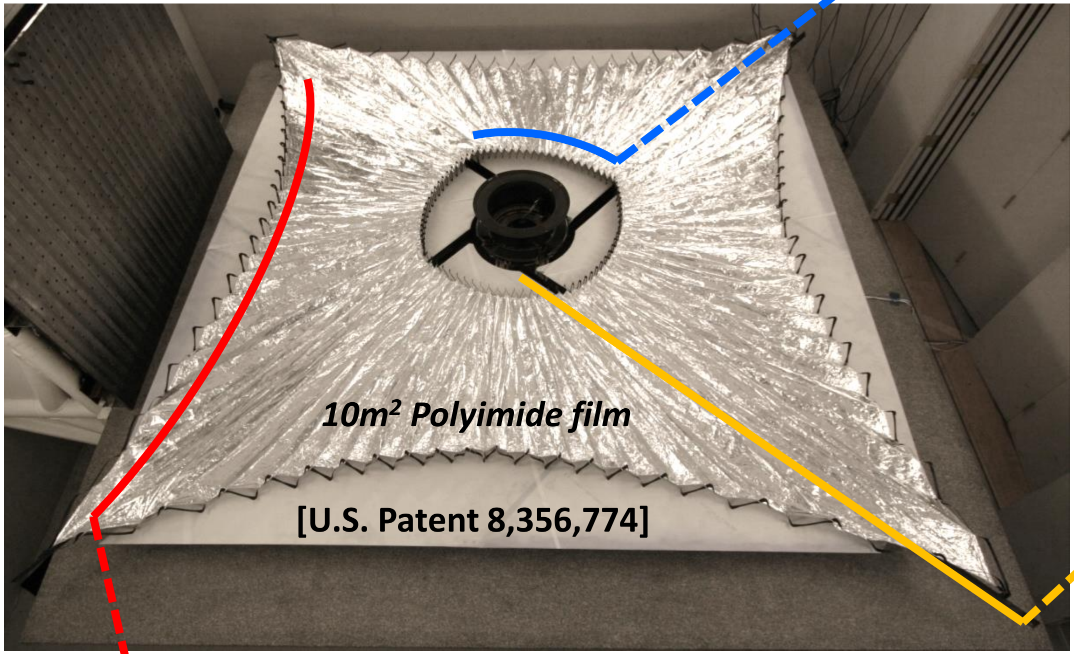


Flexible Unfurlable Refurlable Lightweight Solar Sail
Tension-Aligned, High Strain Composite Deployment

Stowed FURL

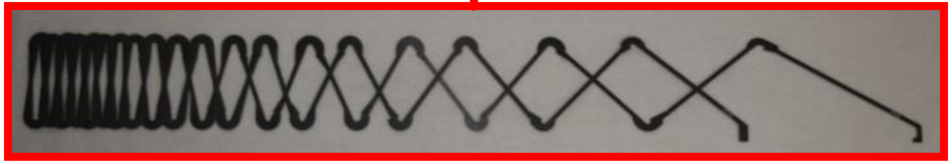


Composite Inner Spar



TRAC Mast

Outer Spar



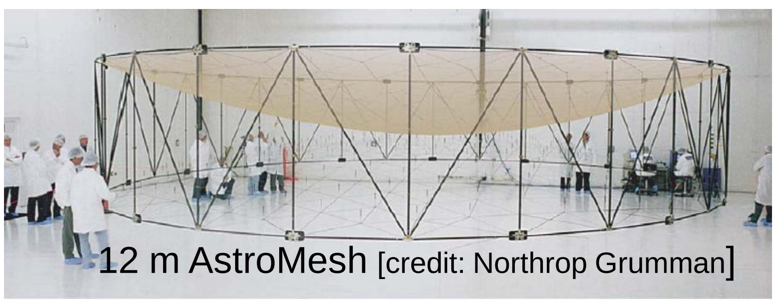
High Strain Composites

An Alternative to Traditional Pin-Clevis Mechanisms

*__Definition__: Thin traditional laminates constructed from high strength carbon unidirectional and biased weave reinforced resins. Ultimate strains are **2-3x** higher than metals. The resin systems are typical aerospace grade.*

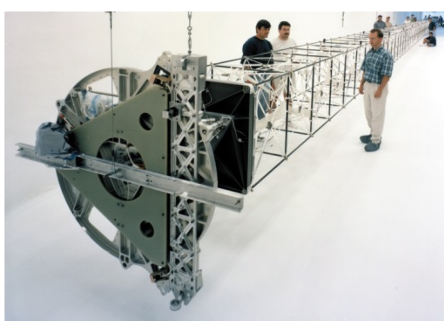
Heritage Mechanisms

Typical friction-sensitive pin-clevis hinge.
[Credit: AFRL Powersail]

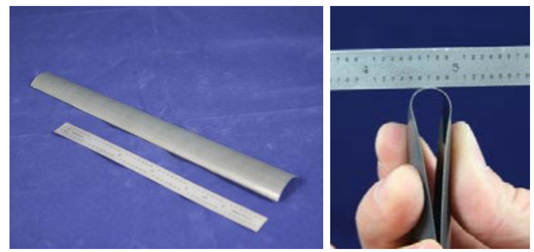


12 m AstroMesh [credit: Northrop Grumman]

Articulated SRTM mast, 60 meters.
[credit: Orbital ATK]



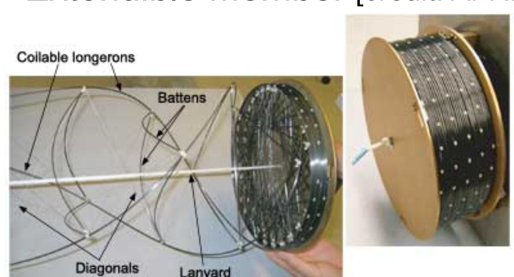
High Strain Composite Mechanisms



High strain hinge [45 PW, 0, 45 PW] folded to 2% strain

Foldable reflector shell
[credit: AFRL]

Carbon Storable Tubular Extendible Member [credit: AFRL]



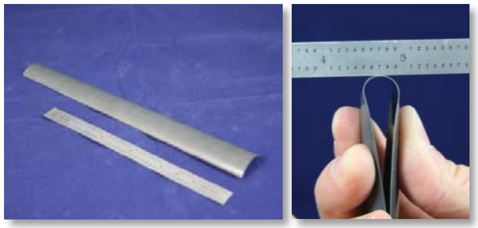
ST8 mast achieved 100:1 packaging [credit: NASA, Orbital ATK]

ISAT truss achieved 110:1 packaging [credit: AFRL, DARPA]

Sparse Aperture Telescopes

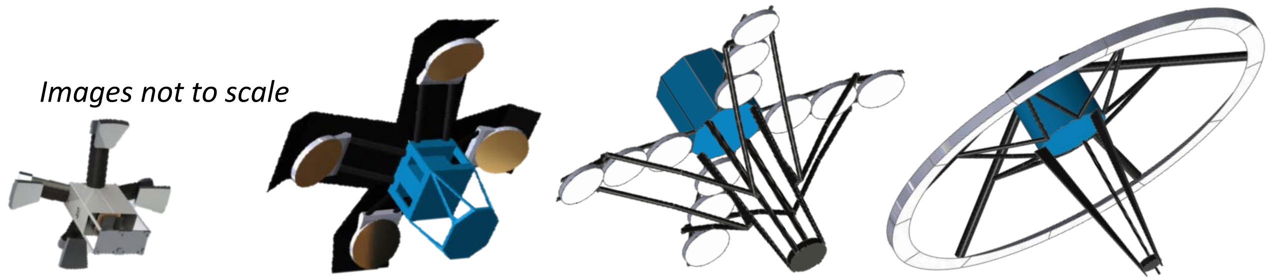
Another example of high strain composites

Deployable In Space Coherent Imaging Telescope by MIT Lincoln Labs



Foldable support struts are dimensionally stable, repeatable in deployment, and fold to high strains

Images not to scale



Application	Earth Surveillance	Earth/Space Surveillance, Earth science	Earth/Space Surveillance, Astronomy	Earth/Space Surveillance, Astronomy
Launcher	6U Cubesat	ESPA	Minotaur-C	Falcon Heavy
Mass (kg)	10	150	< 1,500	< 10,000
Aperture OD (m)	0.7	2.5	7.5	20
Aperture Segment	4 @ 10 x 20 cm	4 @ 50 cm	16 @ 100 cm	12 @ 100 x 10 cm

An Ongoing Debate

and a method to evaluate the merits

Does it make sense to embrace in-space construction techniques (now)?

Self Deployment?

Robotic Assembly?

Additive Manufacturing?

"Using the automated orbital assembly of a small number of self-deployable subsystems would be a prudent approach of a large sized operational system"
– Bob Freeland, Richard Helms, Martin Mikulas (2006)

"Additive manufactured space structures can be much lighter because they don't need to endure launch loads and ground testing."

What about the COST and COMPLEXITY of robotics?

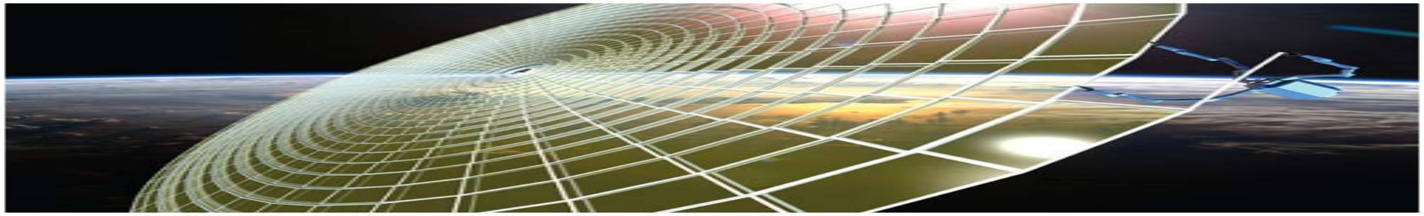
"First we must fully exploit the performance potential of self deployable structures and high strain composites."

How precise are the payload-structure ITERFACES?

How will we VALIDATE in a relevant environment on the ground?

"Just build bigger rockets."

"Forget large structures, use formation flying of sparse apertures instead."



SpiderFab proposes to combine additive manufacturing with robotic assembly to construct structures in space. [Credit: Tethers Unlimited and NASA]

Evaluate with Metrics

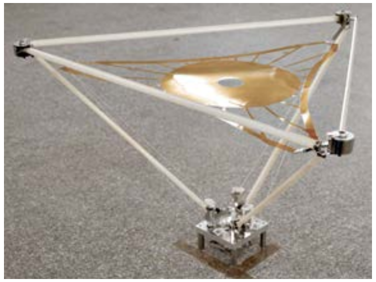
How does the new approach compare to heritage?

Metric	Description	Equation	Units (SI)
Packaging Efficiency	deployed length / stowed length	$\frac{L_d}{L_s}$	m/m
Linear Packaging Density	deployed size / stowed volume	$\frac{D}{V}$	m/m^3
Areal Packaging Density	deployed area / stowed volume	$\frac{A}{V}$	m^2/m^3
Beam Performance Index[17]	Strength moment, bending stiffness, linear mass density	$\mu = \frac{(M^2 EI)^{1/5}}{w}$	$N^{3/5}\ m^{9/5}\ /\ kg$
Solar Array Scaling Index[18]	acceleration load, frequency, boom quantity, length, area, blanket areal mass density, total mass	$\kappa = (af)^{0.216}\, n^{0.231} L_{pb}\, A^{0.755} \frac{\gamma_b^{0.176}}{m}$	$m^{2.374}/(kg^{0.824}\ s^{0.648})$
Aperture Mass Efficiency	diameter / mass	$\frac{D}{m}$	m/kg
Aperture Surface Precision	diameter / RMS figure error	$\frac{D}{RMS}$	m/m
Dimensional Stability	coefficient of thermal expansion	α	$1/°C$
Telescope Mission Cost Parameter[22,23]	diameter, wavelength, temperature of operation	$MC = \frac{C\, D^{1.7} \lambda^{-0.3} T^{-0.25}}{0.11 + 0.09 \ln(D)}$	--

Large Structures in Space are Challenging!
Where Do We Go From Here?

Lean into these new approaches:

1) Tension-aligned apertures and compression support structures
2) High strain composite mechanisms
3) Evaluate in-space manufacturing with metrics



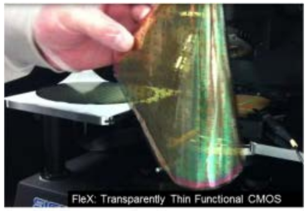
AFRL compact telescope

Pursue answers to these questions:

1) What is mechanical complexity and how do we measure it (early)?
2) What causes unreliable deployments in strain-energy structures?
3) How might we qualify a strain-energy structure by analysis?

Invent and develop new technologies:

1) Thin materials that are dimensionally stable, tough, and flexible
2) Flexible electronics that are radiation tolerant
3) Analysis and test tools to characterize high strain composite materials



[credit: American Semi]

> "It seems that perfection is attained not when there is nothing more to add, but when there is nothing more to remove."
> *--Antoine de Saint Exupéry, 1939* [26]

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