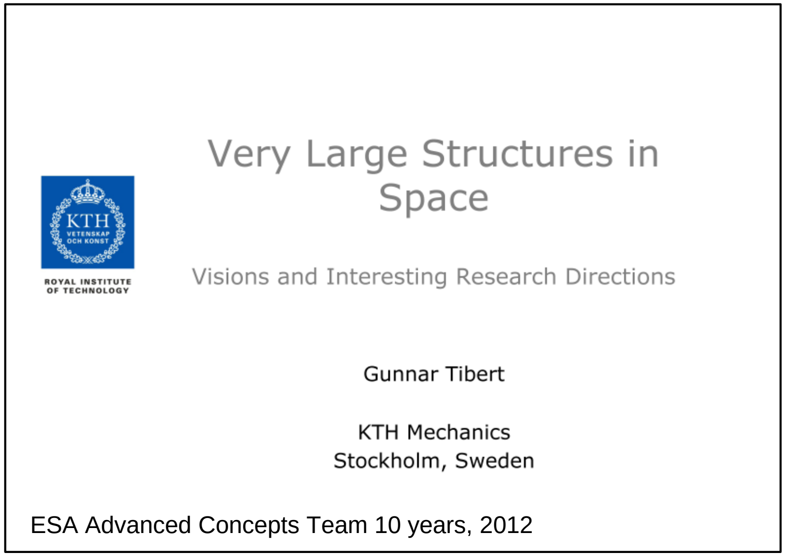
Challenges in Realizing Large Structures in Space

Gunnar Tibert

KTH Space Center ”Space Rendezvous”, 13 Oct 2016

Large Structures in Space



Very Large Structures in Space

Visions and Interesting Research Directions

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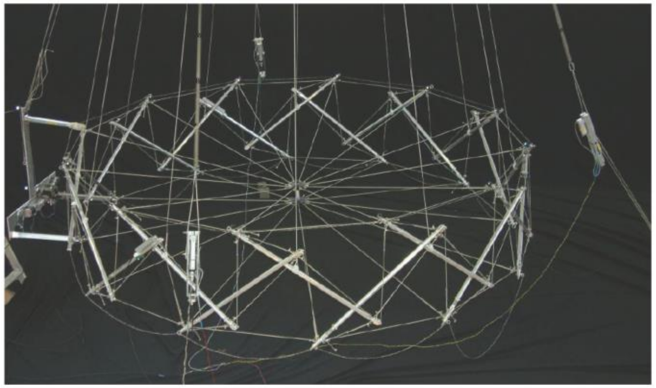
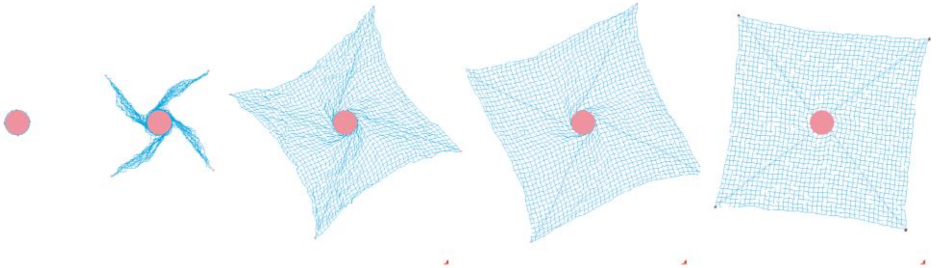
ESA Advanced Concepts Team 10 years, 2012



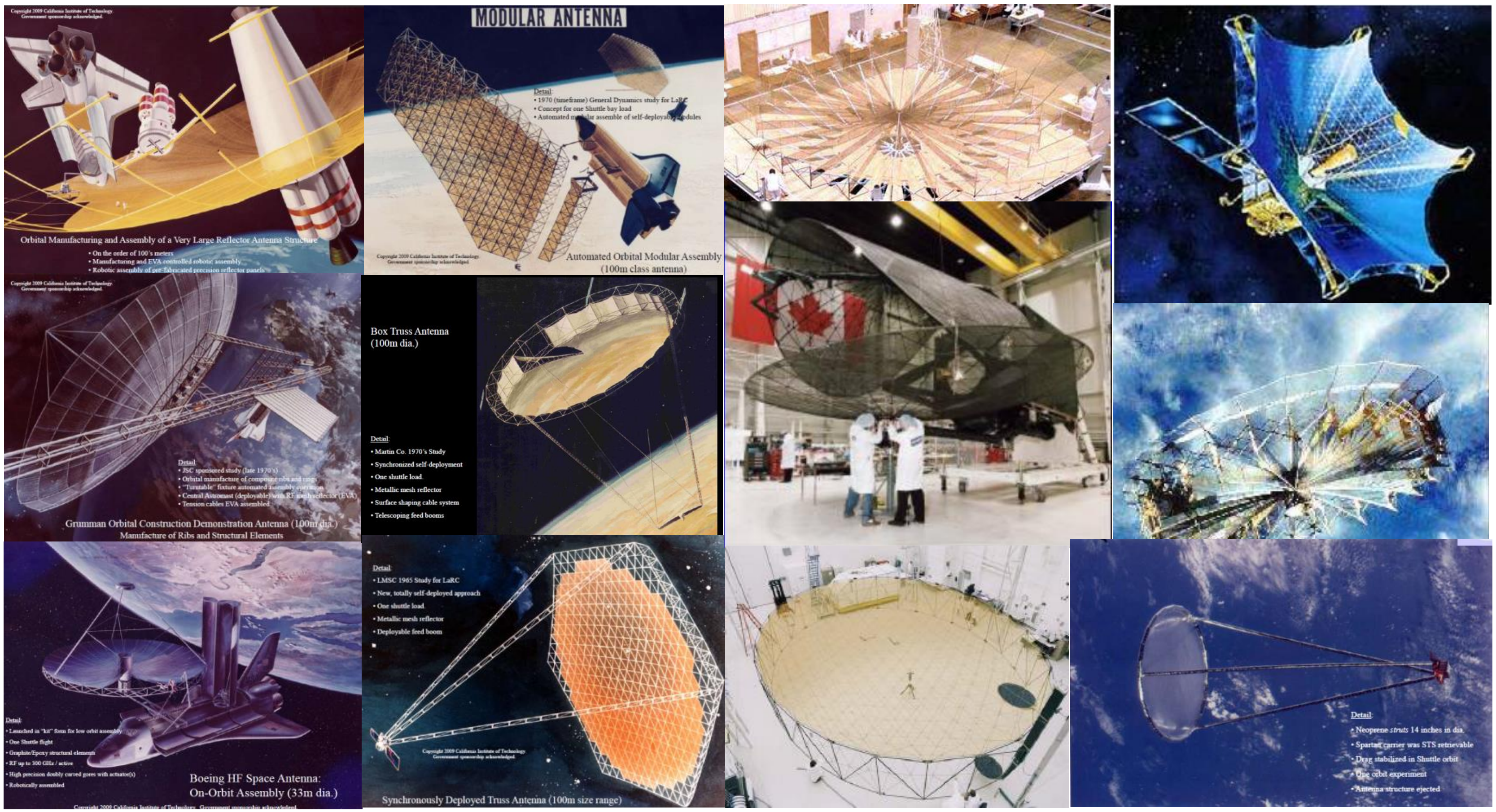
My experience on large space structures:

- Centrifugally deployed **Space Webs** for robotic assembly of solar space power satellites! Simulations and *Suaineadh REXUS* experiment (2×2 m^2).
- **Deployable ring structure** based on the tensegrity concept for large reflector antennas (breadboard model $D = 3$ m).



Large Structures in Space

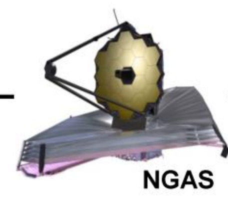
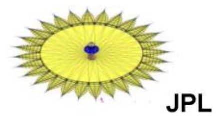
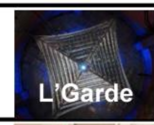
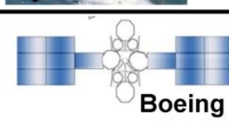
No shortage of ideas and flight-proven large space structures based on traditional technology but there is a need for larger structures



Credit: *CalTech- KISS Large Space Apertures Workshop, 10–11 November 2008.*

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***

Credit: *Banik, J., Realizing Large Structures in Space, National Academy of Engineering 2015 US Frontiers of Engineering, 9-11 September 2015.*

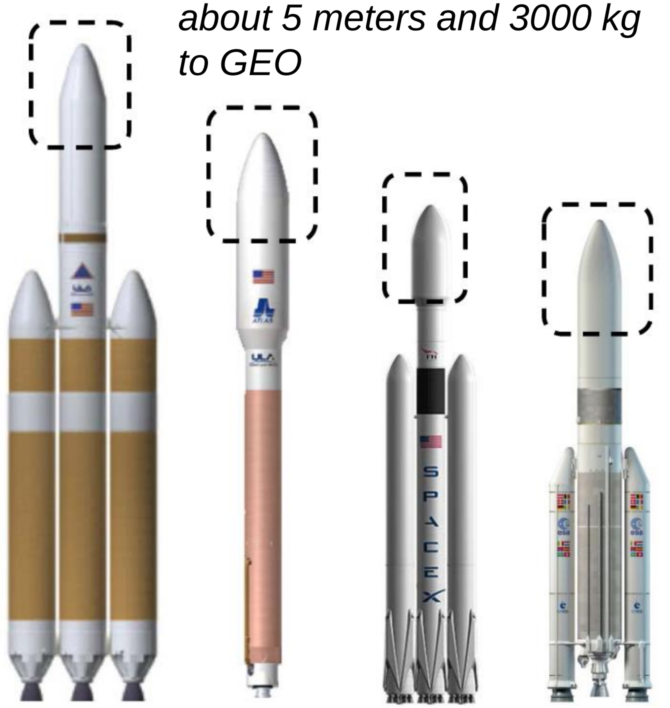
Getting to Orbit is Challenging

Rockets are volume and mass limited

Launch is violent! 50g acceleration levels

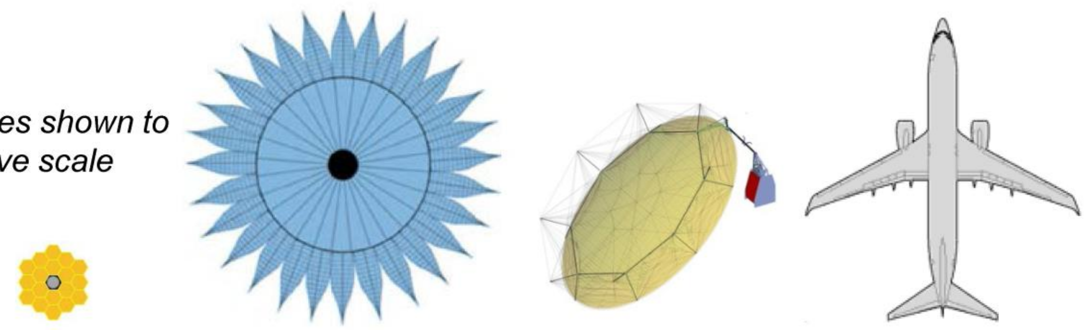
Maximum available diameter and mass for payload is about 5 meters and 3000 kg to GEO

Structure	Deployed size (m)	Stowed size (m)	Packaging ratio
JWST primary	6.5	4	1.6
Exo-S starshade	34	5	6.8
SkyTerra-1 mesh reflector	22	2.4	9.2
IKAROS solar sail	20	1.6	12.5



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

Images shown to relative scale

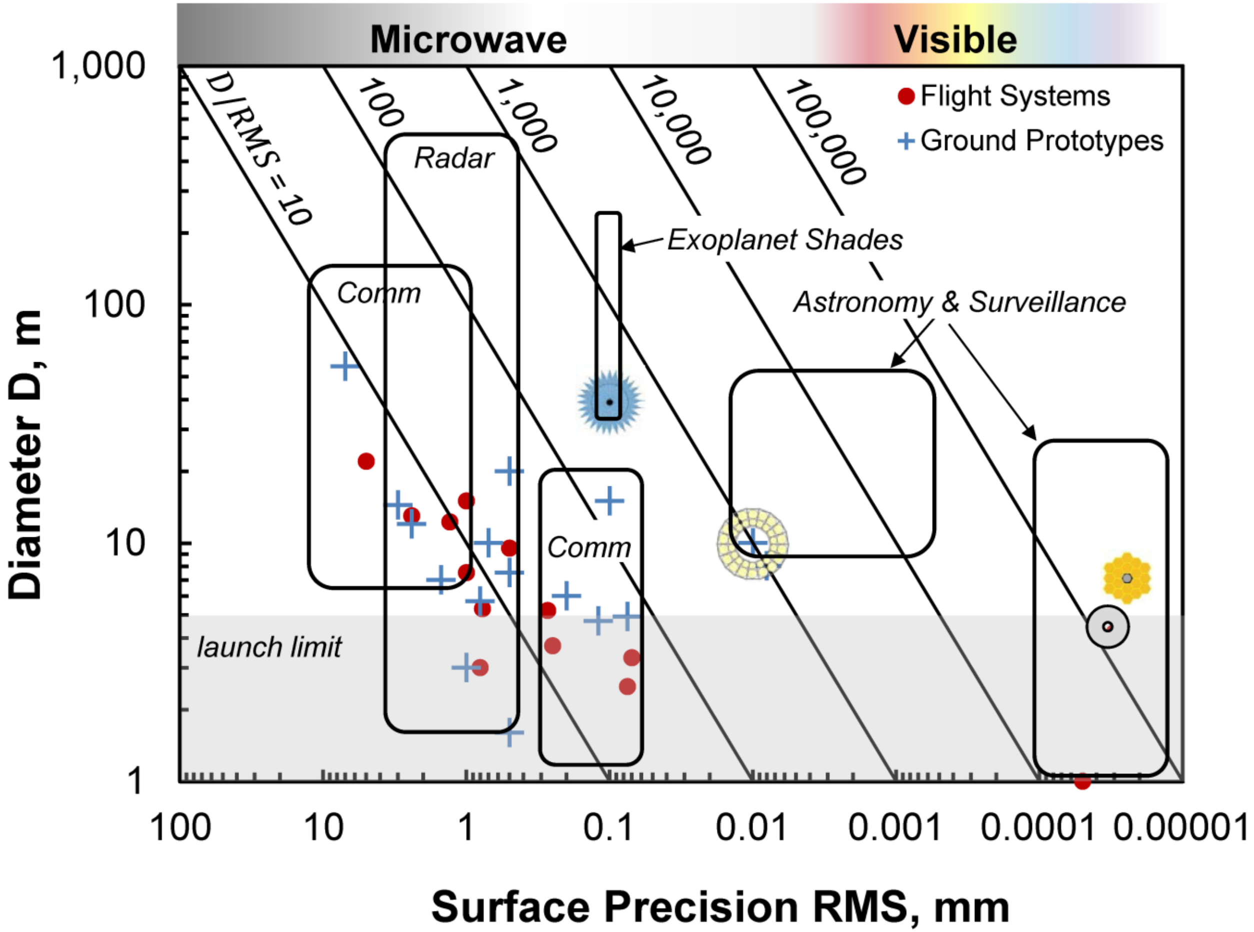


JWST 6.5 m
Exo-S Shade 34 m
SkyTerra-1 22 m
Boeing 737-400 33 m x 29 m

Credit: *Banik, J., Realizing Large Structures in Space, National Academy of Engineering 2015 US Frontiers of Engineering, 9-11 September 2015.*

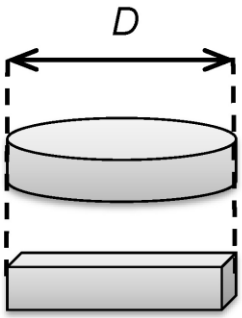
Precision is Challenging

Surface errors scale with aperture size!



Ruze's equation :

$$\text{Gain} \propto \left(\frac{D}{\lambda}\right)^2 \exp\left[-\left(\frac{x_{rms}}{\lambda}\right)^2\right]$$



"D" represents the major dimension of a circular, square, or linear aperture

Credit: *Banik, J., Realizing Large Structures in Space, National Academy of Engineering 2015 US Frontiers of Engineering, 9-11 September 2015.*

Structural Requirements for Large Space Telescopes

rms surface error (wave-front control requirement)

rms magnitude of inertial acceleration vector

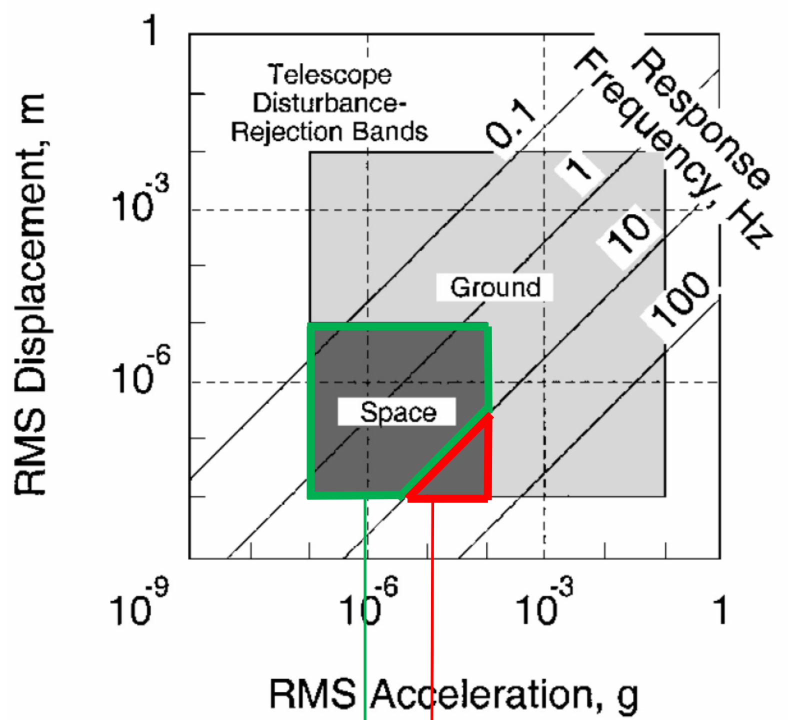
Acceleration loads:
- Gravity gradient
- Slewing
- Solar pressure

$$x_{rms} \propto \frac{a_{rms}}{\zeta f_0^2} \propto \frac{a_{rms}}{\zeta}\left[\frac{D^4}{\eta h^2 (E/\rho)}\right]$$

Modal damping ratio (≈ 1%)

Lowest natural frequency

Passive response of structure
D = diameter
η = structural mass fraction
h = structural depth
E/ρ = material specific stiffness



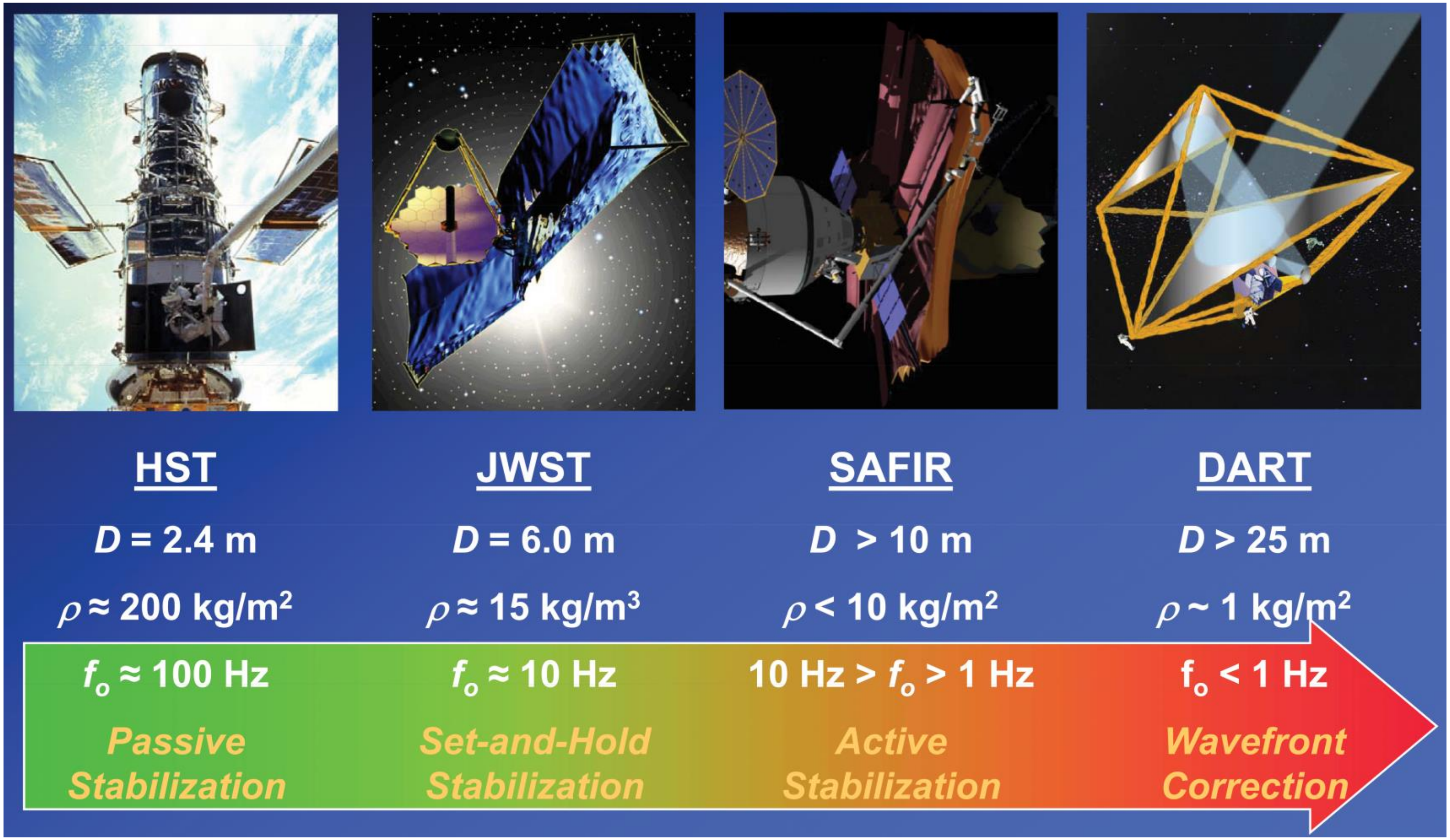
Example:
f_0 = 10 Hz
Passive control by structure
Active control requirement

Note! *Assuming thermally stable materials,* CTE = 0.

Credits: Lake, M.S., Peterson, L. D., and Levine, M. D., "A Rationale for Defining Structural Requirements for Large Space Telescopes," Journal of Spacecraft and Rockets, Vol. 39, No. 5, Sept-Oct., 2002.

Lake, M. S., Peterson, L. D., Mikulas, M. M., Space Structures on the Back of an Envelope: John Hedgepeth's Design Approach to Design, Journal of Spacecraft and Rockets, Vol. 43, No. 6, 2006.

Structural Requirements for Large Space Telescopes

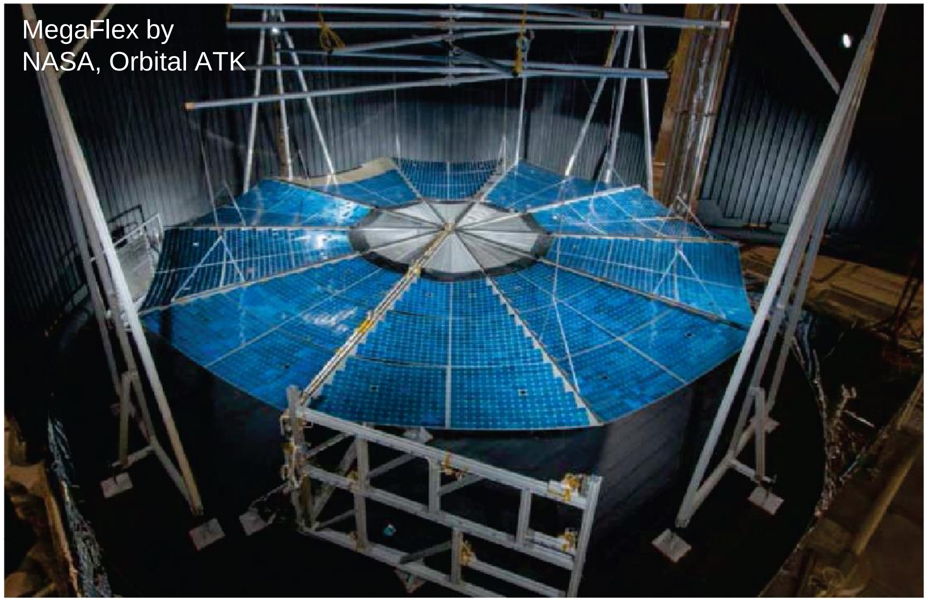


Credit: *Lake, M. S., A Vision for Reflector Technologies, CalTech- KISS Large Space Apertures Workshop, 10–11 November 2008.*

Deployment Reliability and Affordability

Space flight programs have one chance at success!

Validation through simulations only not possible!

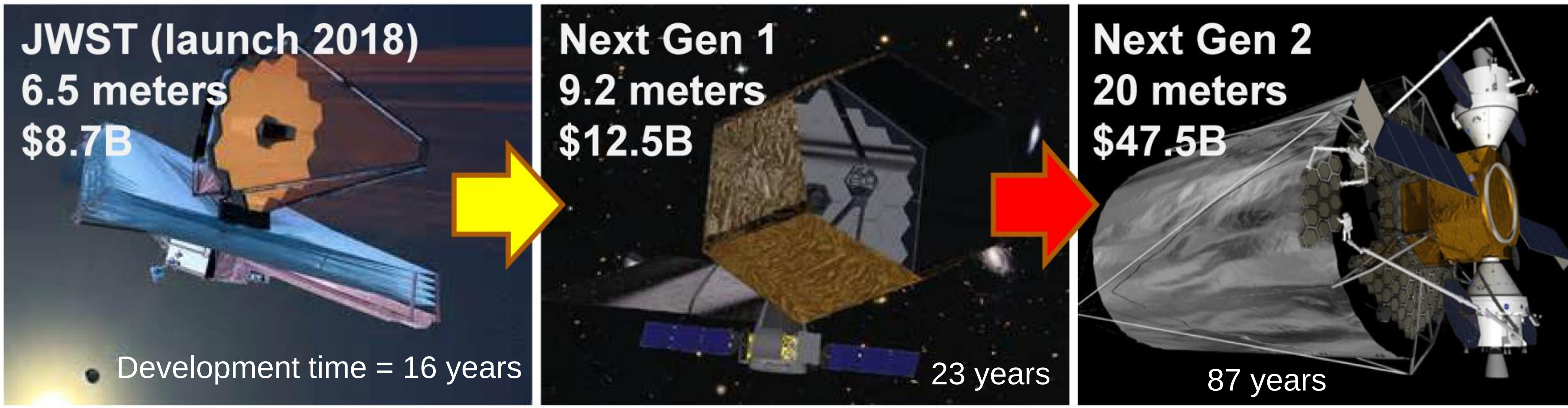


Zero-gravity deployments are approximated with elaborate suspension cable systems.

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

Credit: *J. Banik, Realizing Large Structures in Space, National Academy of Engineering 2015 US Frontiers of Engineering, 9-11 September 2015.*

Current Technologies Leading to “Astronomical” Costs for New Telescopes



$$MC = C\,\frac{D^{1.7}\lambda^{-0.3}T^{-0.25}}{0.11 + 0.09\ln D}$$

MC = mission cost
C = currency constant
D = aperture diameter

λ = wavelength
T = operating temperature

Credits: *Banik, J., Realizing Large Structures in Space, National Academy of Engineering 2015 US Frontiers of Engineering, 9-11 September 2015.*

Arenberg, J., Atkinson, C., Breckinridge, J., Conti, A., Feinberg, L., Lillie, C., MacEwen, H., Polidan, R., Postman, M., Matthews, G., Smith, E., “A New Paradigm for Space Astrophysics Mission Design,” SPIE Astronomical Telescopes and Instrumentation, Montréal, Quebec, Canada. Paper 9143-36. 22-27, June 2014.

Metrics to Compare Technologies

Simple performance metrics are critical to a thoughtful cost–benefit analysis of competing technologies

Metric	Description	Equation
Packaging efficiency	deployed length/stowed length	L_d / L_s
Linear packaging density	deployed size/stowed volume	D / V_s
Areal packaging density	deployed area/stowed volume	A / V_s
Aperture mass efficiency	diameter/mass	D / m
Aperture surface precision	diameter/rms surface error	D / x_{rms}
Dimensional stability	coefficient of thermal expansion	α
Beam performance index	strength moment, bending stiffness, linear mass density	$(M^2 EI)^{1/5} / w$
Solar array scaling index	acceleration load, frequency, boom quantity, area, blanket areal mass density, total mass	$(af)^{0.216} n^{0.231} L_{pb} A^{0.755} \gamma_b^{0.176} / m$
Telescope mission cost	diameter, wavelength, temperature of operation	$C \dfrac{D^{1.7} \lambda^{-0.3} T^{-0.25}}{0.11 + 0.09 \ln D}$

Credits: *Banik, J., Realizing Large Structures in Space, National Academy of Engineering 2015 US Frontiers of Engineering, 9-11 September 2015.*

The Ongoing Debate

“*Using the automated orbital assembly of a small number of self-deployable subsystems would be a prudent approach of a large sized operational system*”

Self deployment?

Robotic assembly?

Additive manufacturing?

Formation flying?

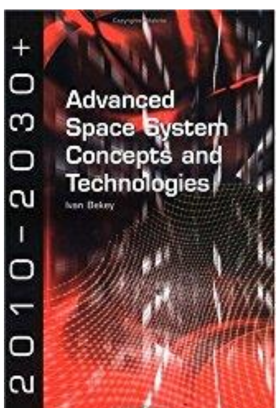
“*Additive manufactured space structures can be much lighter because they don’t need to endure launch loads and ground testing.*”

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

“*Just build bigger rockets.*”

“*Forget large structures, use formation flying of sparse apertures instead.*”

What about the COST and COMPLEXITY of robotics?



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

How precise are the payload-structure INTERFACES?

Credit: *J. Banik, Realizing Large Structures in Space, National Academy of Engineering 2015 US Frontiers of Engineering, 9-11 September 2015.*