Deployable and Inflatable Structures: New Frontiers for Space Exploration, Astronomical Observation, and the Development of Advanced Technologies

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HUMANS IN SPACE

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Scuola Politecnica e delle Scienze di Base – P.le Tecchio

What Do We Mean by “Deployable”?

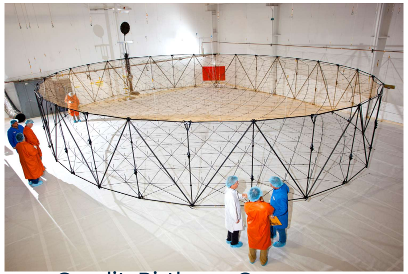
Deployables: structures that can be packaged and then extended or opened once they reach their designed in-orbit dimensions.

SOLAR ARRAY

International Space Station Solar Arrays - rigid panel segments.

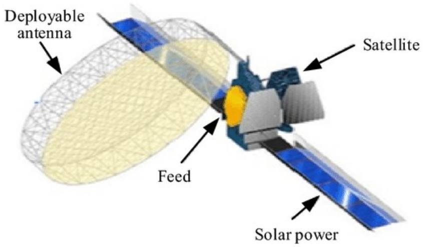
Roll-Out Solar Arrays (ROSA) – flexible panels

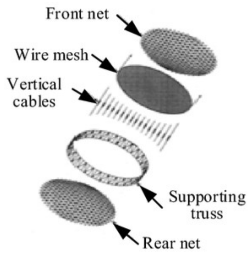
MESH REFLECTOR



Credit: Birthrop Grunman

AstroMesh Reflectors by Northrop Grumman





SEGMENTED MIRRORS

James Webb Space Telescope

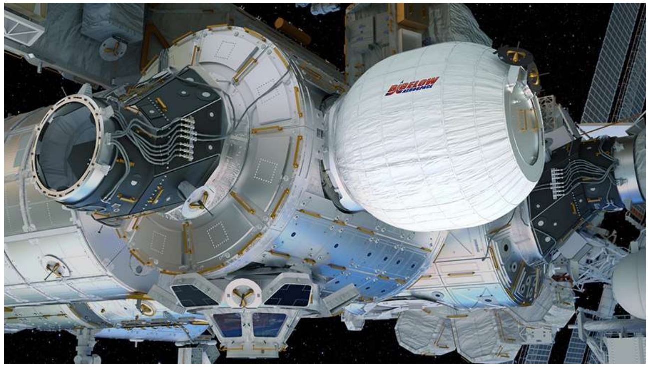
Credit: NASA

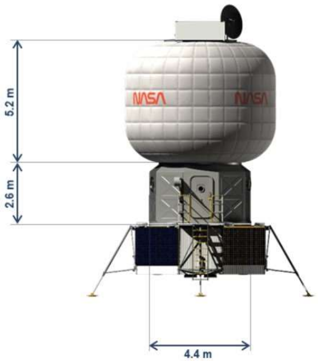
What Do We Mean by “Inflatable”?

Inflatable: Structures that require inflation with a fluid (usually a gas) to achieve their final shape. Typically made from high-strength polymer materials, with thermal and debris protection layers.

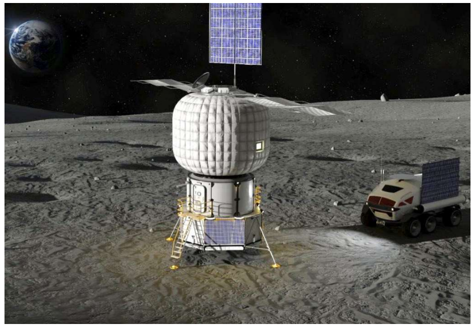
HABITAT MODULES

Bigelow Expandable Activity Module (BEAM)



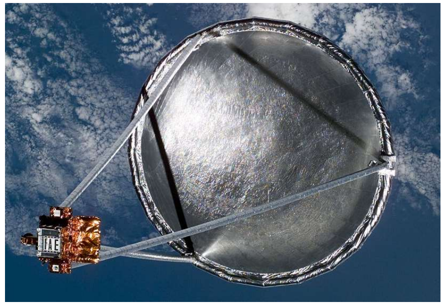


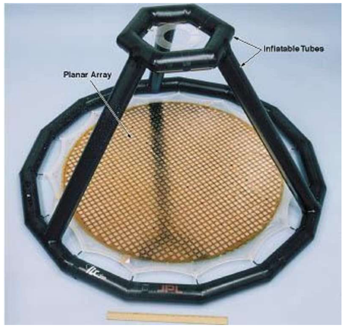
Lunar Surface Habitat (proposal)



INFLATABLE ANTENNAS

Inflatable Antenna Experiment (IAE)

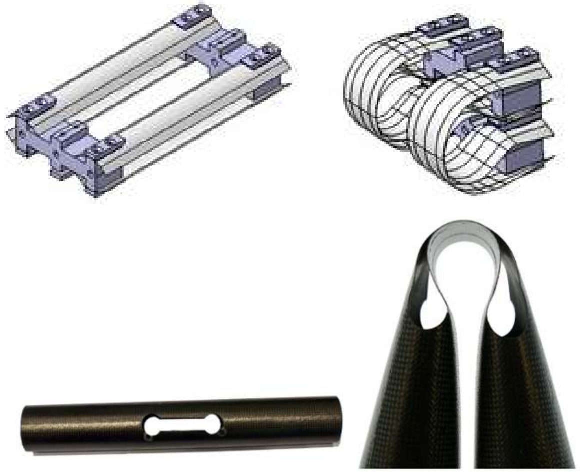




Inflatable Circular Toroidal Tubes

Common features and key differences

- Both aim to **dramatically reduce launch mass and volume**
- They change configuration after launch: <u>from compact to extended</u> (deployable) <u>or inflated</u> (inflatable).
- Both require <u>rigorous testing</u> for resilience and reliability in the extreme space environment.



<u>Differences</u>

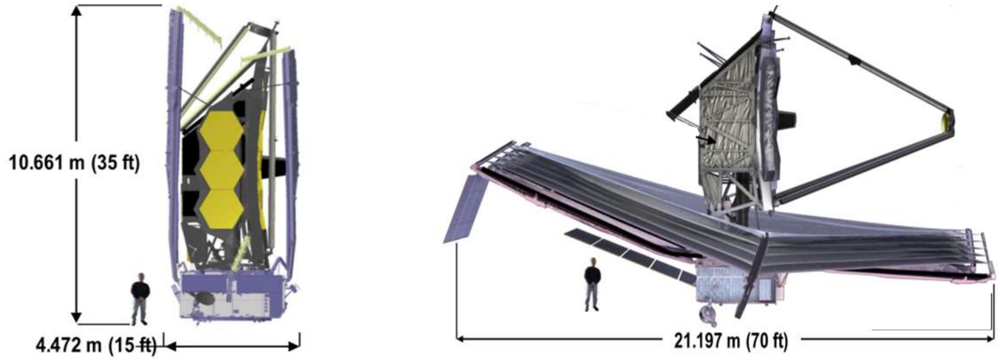
- **Activation mechanism:**
  - Deployable: mechanical mechanisms.
  - Inflatable: inflation with gas and pressure containment systems.

- **Final structure:**
  - Deployable: generally, stiffer once extended.
  - Inflatable: usually more “flexible” (though hybrids with rigid reinforcements exist), often pressurized.

- **Associated Risks:**
  - Deployable: mechanical parts can jam or fail to deploy.
  - Inflatable: potential gas leaks, micro-tears, managing internal pressure.

Why Inflatable and Deployable Structures?

Reduced Launch Volume:
- Inflatable and foldable components can be "packed" into a much smaller volume compared to fully rigid structures.

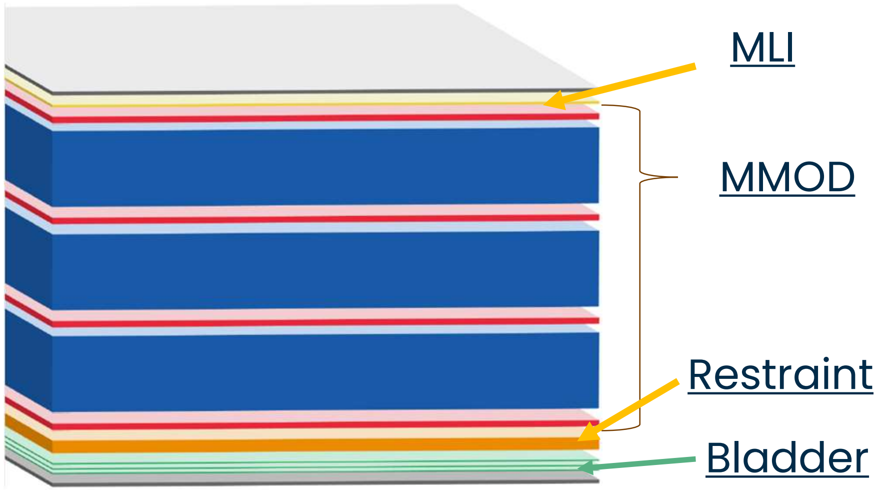


Lower Overall Mass
- Flexible materials often weigh less than metal equivalents.
- Mechano-deployable systems can eliminate heavy support structures.
- Every kilogram saved reduces launch costs significantly (some agencies quote $10,000–$20,000 per kg to LEO, depending on the launcher).

Ease and Speed of Deployment
- Once in orbit, a mechanism to inflate or unfold can quickly bring the structure to full operational form.
- Reduced complexity for ground crews or astronauts.

Enabling More Ambitious Missions

Key Materials and Their Importance

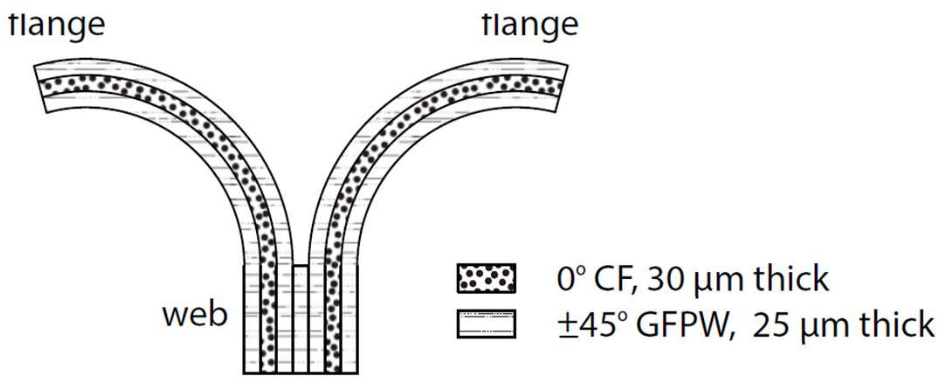


High-Strength Fabrics (e.g., Kevlar, Vectran)
- High tensile strength, good puncture resistance, relatively low mass.
- NASA/Bigelow's BEAM module uses Vectran layers as part of its micrometeoroid and orbital debris (MMOD) shield.

Polymer Films (e.g., Mylar, Kapton)
- Lightweight, can handle extreme temperature variations, often used as reflective or insulating surfaces.
- Lining or layering for inflatable antennas, sunshields, thermal control surfaces (e.g., James Webb's sunshield uses Kapton).

Composites (Carbon Fiber, Glass Fiber)
- Very high stiffness-to-weight ratio, can be molded into complex shapes.

Metal Alloys and Articulated Joints
- Aluminum or titanium alloys for hinges, brackets, or structural interfaces.

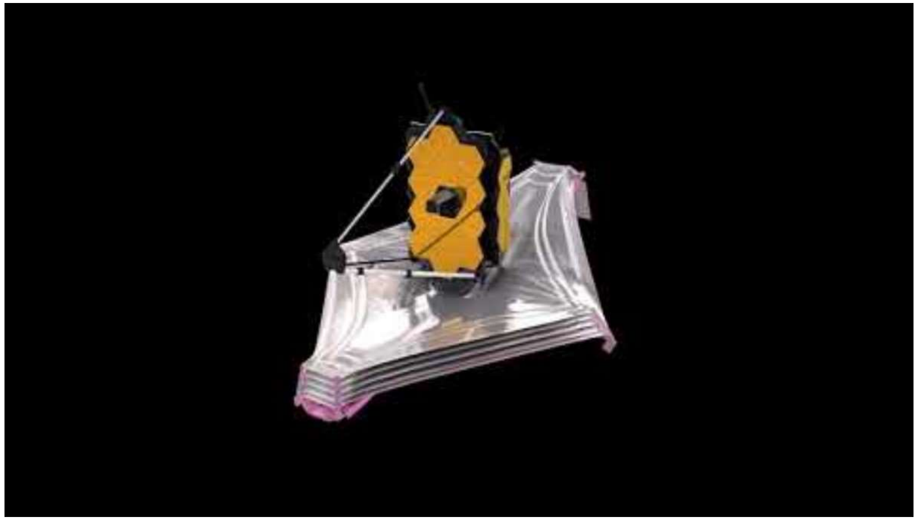


Mechanisms of Deployment: From Stowed to Operational

Mechanical Deployment Methods
- Hinges, springs, motorized arms, telescoping booms.
- Energy stored in tapes or rods that "unfurl" in microgravity.

Inflation Processes
- Gas canisters, pumps, or in-situ resource usage.
- Importance of controlled pressurization to avoid rapid expansion or structural damage.

Self-Deployment
- Systems that naturally open when released from constraints (e.g., coiled booms that uncoil once a latch is removed).

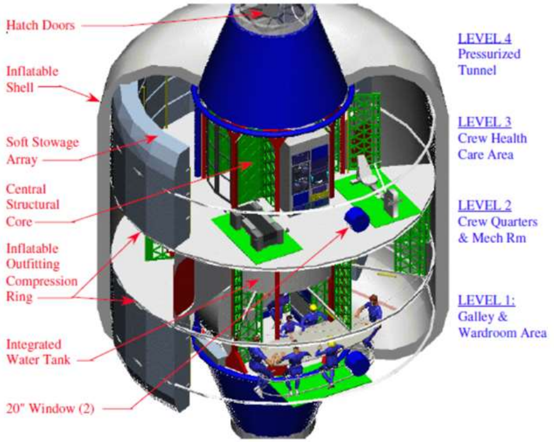


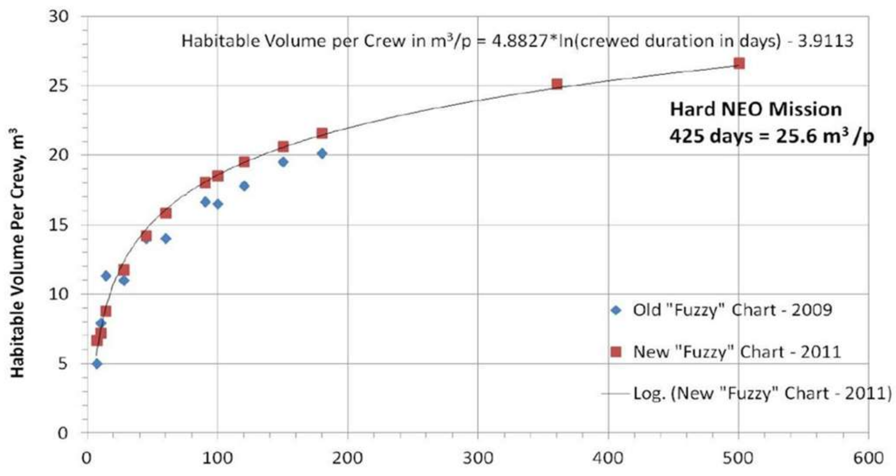
See attached File "Video HUMANS IN SPACE - Augello 08_04_25" Slide n. 2

Locking / Latching Mechanisms
- Once deployed, mechanical "locks" or tension cables hold the structure rigidly.

Risks and Failures
- Potential for jammed hinges or stuck segments.Incorrect inflation pressure leading to material stress or leaks.

Inflatable Habitats for Orbital and Planetary Missions





Credit: NASA-STD-3001

Why are they needed?

- To maximize usable volume while minimizing launch mass and stowed volume.
- To lower transportation costs and expand potential crew or cargo capacity.

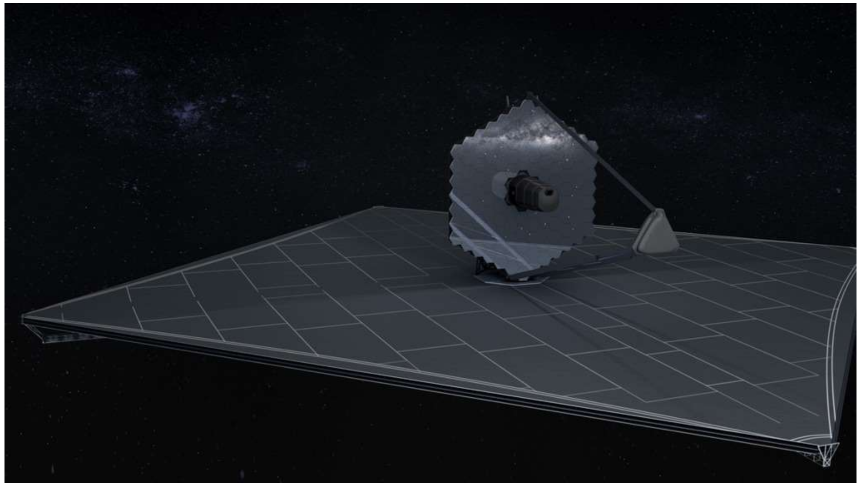
What is an inflatable habitat?

- A pressurizable volume that starts off in a compact shape and inflates to provide living or working space for astronauts.
- Utilizes advanced fabrics, multi-layer insulation (MLI), and structural restraints to create a safe internal environment.

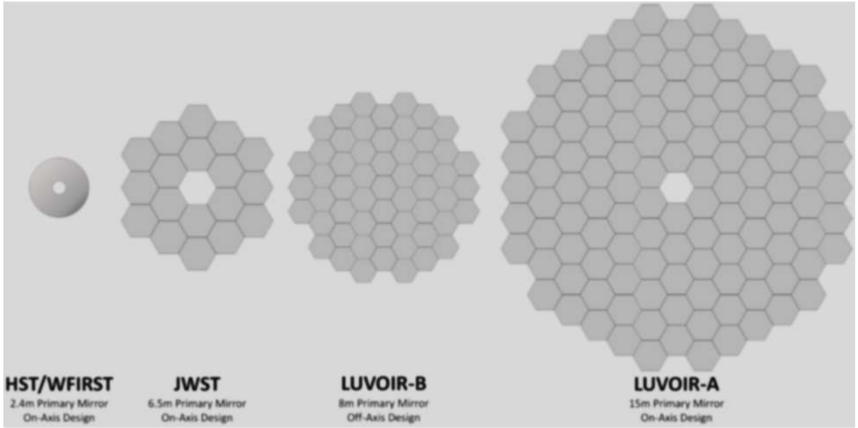
Challenges

- Atmospheric leakage, micro-meteoroid punctures, ensuring safe pressure containment.
- Internal environment control (air quality, temperature).
- Systems must quickly identify and patch leaks if the module is punctured.

Deployable Structures for Telescopes and Antennas



Credit: NASA



Importance of Large Aperture
- Bigger collecting area for light or radio waves = more sensitive observations.
- Launch vehicle constraints make large deployable designs essential.

Foldable Mirrors
- JWST as a prime example of segmented mirror deployment.
- Ongoing/next-gen concepts (e.g., LUVOIR, Origins Space Telescope).

Mesh Antennas
- Used in high-frequency communication or radio astronomy satellites.
- Deployed from a stowed “drum” or canister.

Precision and Alignment
- The necessity of extremely tight tolerances for optical surfaces.
- Active control systems (actuators) to fine-tune alignment post-deployment.

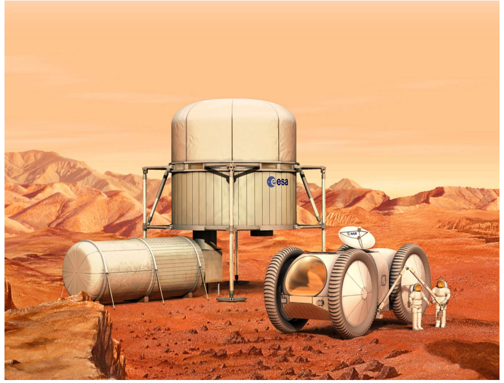
Deployable and Inflatable Concepts for Lunar and Martian Missions

Planetary Rovers with Deployable Components
- Inflatable Wheels or suspensions for rough terrain (NASA or ESA concept studies).
- Fold-out Solar Panels or communication antennas to minimize stowed volume during transit.

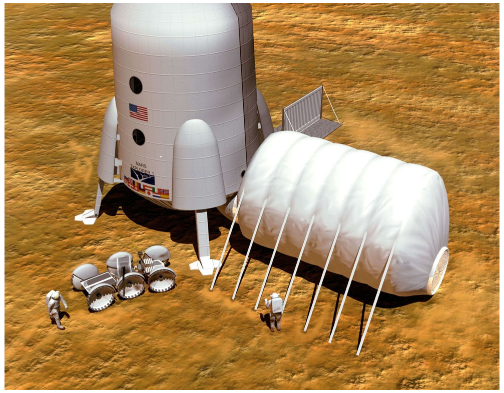
Surface Habitats
- Inflatable Lunar or Martian Modules:
  - Could be lightweight and compact during transit.
  - Then inflated on the surface, possibly covered with regolith for extra radiation shielding

Advantages in Low Gravity
- Eases deployment and reduces stress on inflated walls or mechanical joints.
- Materials still must handle wide temperature extremes (lunar day/night cycles or Martian seasons).

Challenges
- Dust Abrasion, Thermal Extremes, Atmospheric Pressure, Radiation.

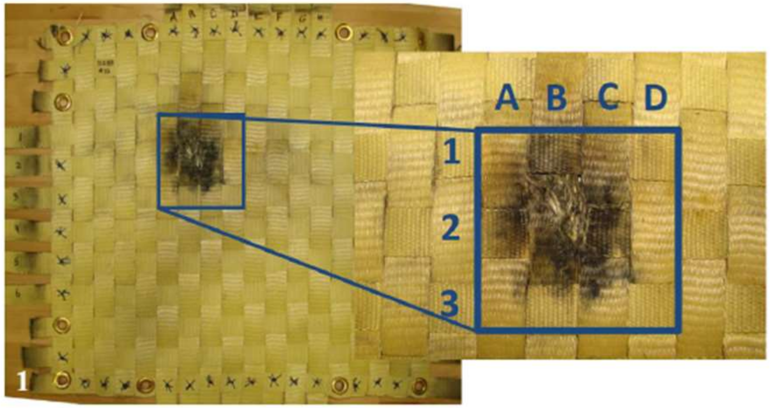


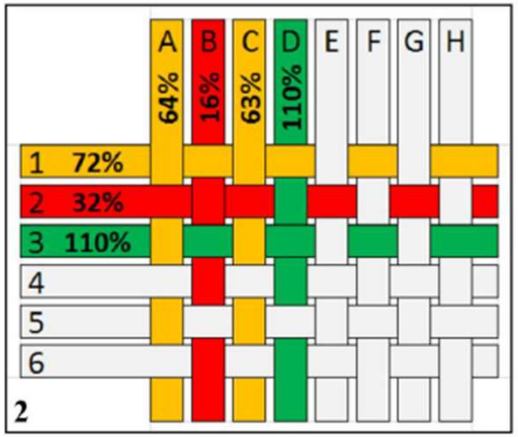
Credit: ESA



Credit: NASA

Challenge #1: Structural Integrity & Impact Resistance





Environmental Hazards in Space
- Micro-meteoroids, debris traveling at high velocities.
- Erosion effects from atomic oxygen in LEO.

Material Layers
- Multiple layers of fabric (Kevlar/Vectran) and advanced composites to absorb impacts.
- Concept of “whipple shields.”

Testing for Impact
- Hypervelocity impact tests to simulate collisions with small debris.
- How test results drive thickness or multi-layer designs.

Reliability and Redundancy
- If an outer layer is punctured, inner layers remain intact.
- Leak detection and repair strategies.

Inflatable vs. Deployable
- Inflatable: risk of depressurization if punctured.
- Deployable: rigid or semi-rigid once deployed, but still susceptible to structural damage.

Challenge #2: Extreme Temperatures & Radiation

Temperature Extremes
- In direct sunlight vs. in shadow
- Mars or lunar surface environment is also extreme

Thermal Insulation Strategies
- Multi-Layer Insulation (MLI) blankets.
- Reflective coatings (Kapton, Mylar).
- Active thermal control (heaters, radiators).

Radiation Hazards
- Cosmic rays, solar particle events.
- Need for thick or specialized materials to shield inhabitants (particularly for crewed missions).

Inflatable Module Solutions
- Some setups incorporate hydrogen-rich materials (e.g., polyethylene) in walls to reduce radiation.
- Potential layering with water or regolith in planetary habitats.

Monitoring and Redundancy
- Sensor arrays to continuously check internal temperature and radiation levels.
- Contingency measures for solar flares (storm shelters).

Challenge #3: Achieving Stability and Rigidity

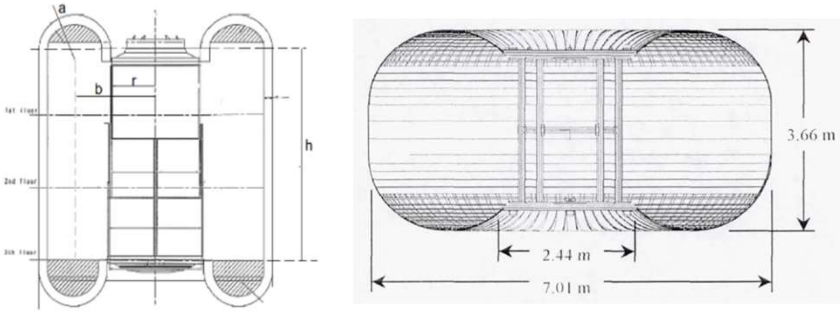
Vibrations and Oscillations
- Launch vibrations or micro-vibrations during operation (e.g., from attitude control thrusters).

Methods to Increase Rigidity
- Rigidizing materials (composites that harden after deployment).
- Tension cables or internal pressurized ribs.
- Hybrid designs (inflatable + support trusses).

Structural Analysis
- Finite Element Modeling (FEM) used to predict stress/strain.
- Testing in microgravity simulations or parabolic flights.

Real-Time Control
- Active damping systems, sensors that adjust tension or orientation.

Trade-Offs
- More rigidity often means heavier or more complex structures.
- Inflatable solutions must keep pressure stable to maintain shape.



Preliminary sizing


Numerical simulations (FEM)

Validation & Testing: Ensuring Reliability Before Launch

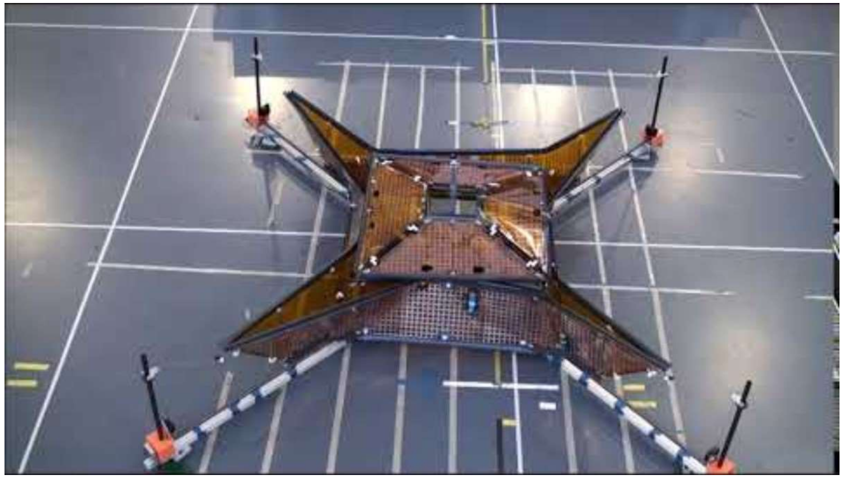
Vacuum Chambers & Thermal-Vac Testing
- Simulating vacuum and temperature extremes.
- Checking for leaks or material failures.

Vibration and Acoustic Tests
- Replicate launch conditions: high acoustic loads, intense vibration.
- Ensure stowed structure survives liftoff.

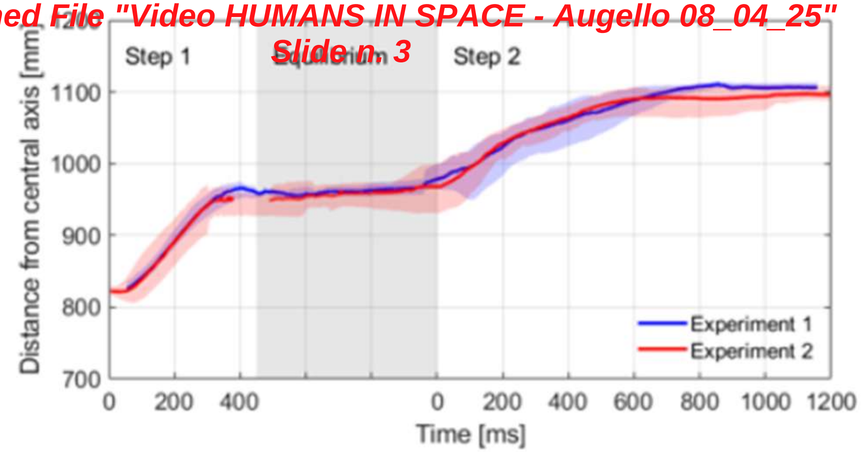
Deployment Testing
- Multiple cycles of folding/unfolding or inflating/deflating.
- Checking mechanical joints, tear points.

Microgravity Simulations
- Parabolic flights or neutral buoyancy facilities for partial testing.
- Some aspects are still “best guess” until real in-orbit demonstration.

Prototyping and Iteration
- Rapid prototyping with updated materials or designs.
- Multiple test campaigns to achieve flight qualification.



See attached File "Video HUMANS IN SPACE - Augello 08_04_25" Slide n. 3



Case Study: Bigelow’s BEAM on the ISS

Overview
- Launched in 2016 to the ISS via SpaceX CRS-8.
- Primary goal: test structural integrity, thermal performance, radiation shielding, and long-term leak rates.

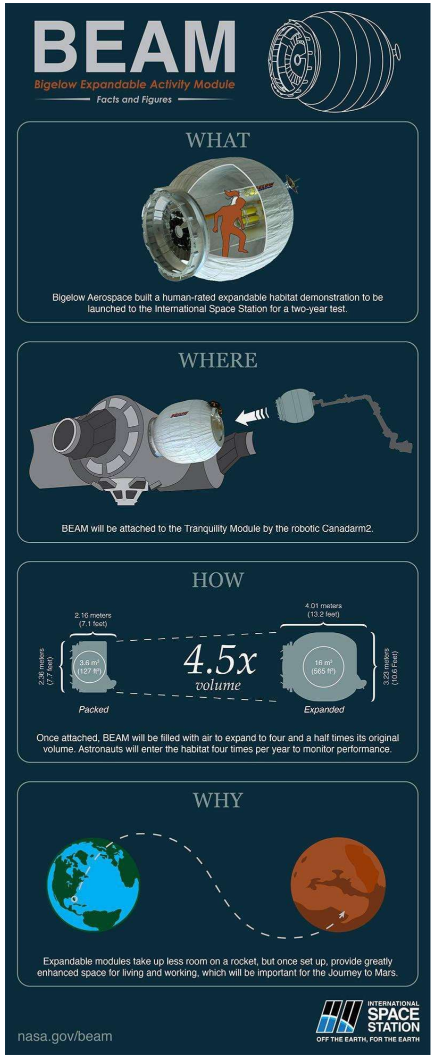
Credit: NASA TV

See attached File "Video HUMANS IN SPACE - Augello 08_04_25" Slide n. 4

Deployment Process
- Slowly inflated while attached to the ISS.
- Astronauts monitored internal pressure

Test Results
- So far, good performance: minimal leaks, stable temperature.
- Data on micrometeoroid impacts: no critical damage reported.

Habitable Volume
- Offers 16 m³ (approx.) of internal volume, used for stowage and occasional crew visits.

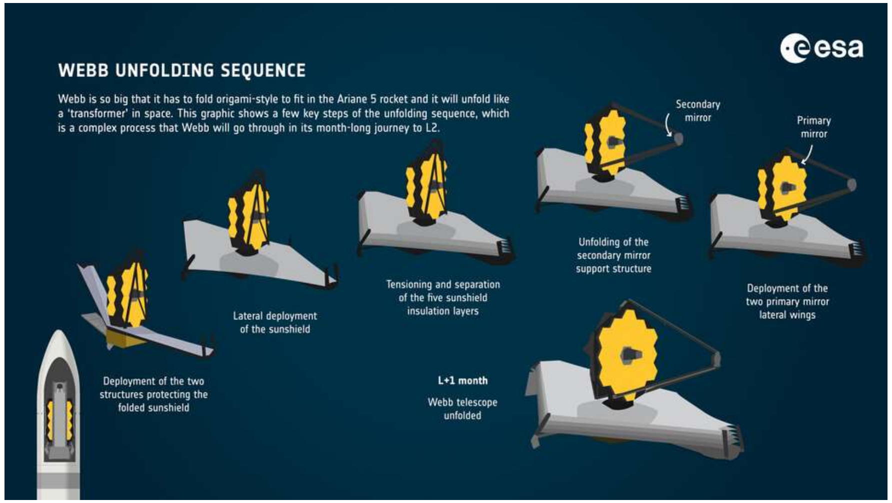


Case Study: JWST's Deployable Mirror and Sunshield

Mission Overview
- Launched December 2021, orbit at L2.
- 6.5-meter segmented mirror + five-layer sunshield.

Mirror Deployment
- 18 hexagonal segments folded inside Ariane 5 fairing.
- Step-by-step unfolding, alignment using actuators.

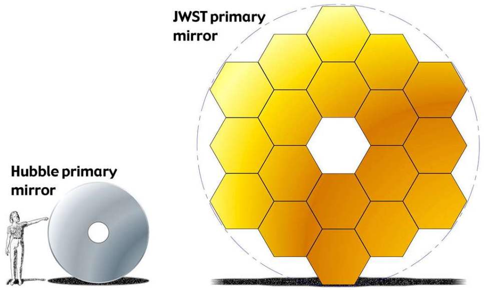
Sunshield
- Large kapton layers folded multiple times.
- Tensioned in orbit to maintain shape and thermal separation.



Credit: ESA

Risk Management
- Over 300 single-point failure items.
- Redundant motors, cables, latches.

Achievements
- Successfully deployed, now delivering groundbreaking infrared images.
- Demonstrates feasibility of extremely large, complex deployable structures.



Credit: NASA

Current R&D and Emerging Projects

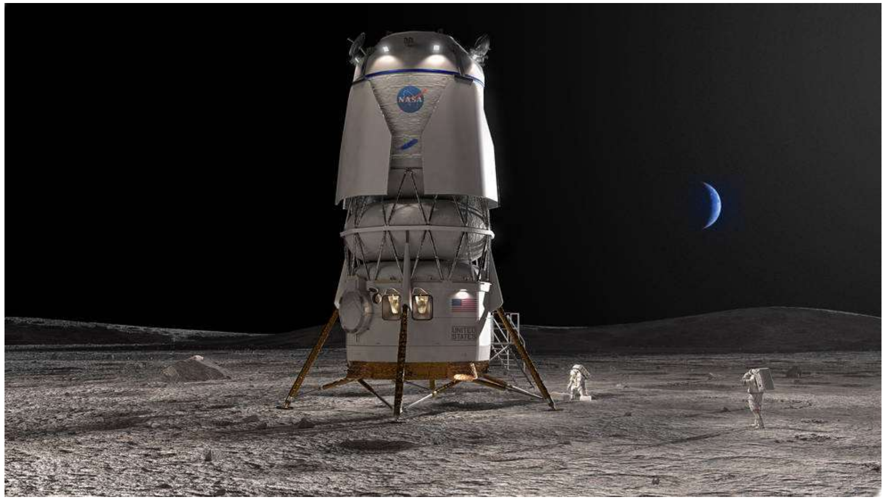
NASA Programs
- NextSTEP habitat prototypes, inflatable airlocks, advanced deployable solar arrays.

ESA Efforts
- Large Deployable Antenna (LDA) initiatives, Moon Village concepts using inflatable modules.

Private Ventures
- Bigelow Aerospace expansions, Sierra Nevada Corporation’s inflatable designs, Nanoracks’ outpost concepts.

International Collaborations
- Joint missions focusing on large radio telescopes or habitats for Gateway, future lunar bases.

Key Technology Gaps
- Materials that self-heal, advanced sensors, robotic assembly in orbit, and more cost-efficient large-scale manufacturing.

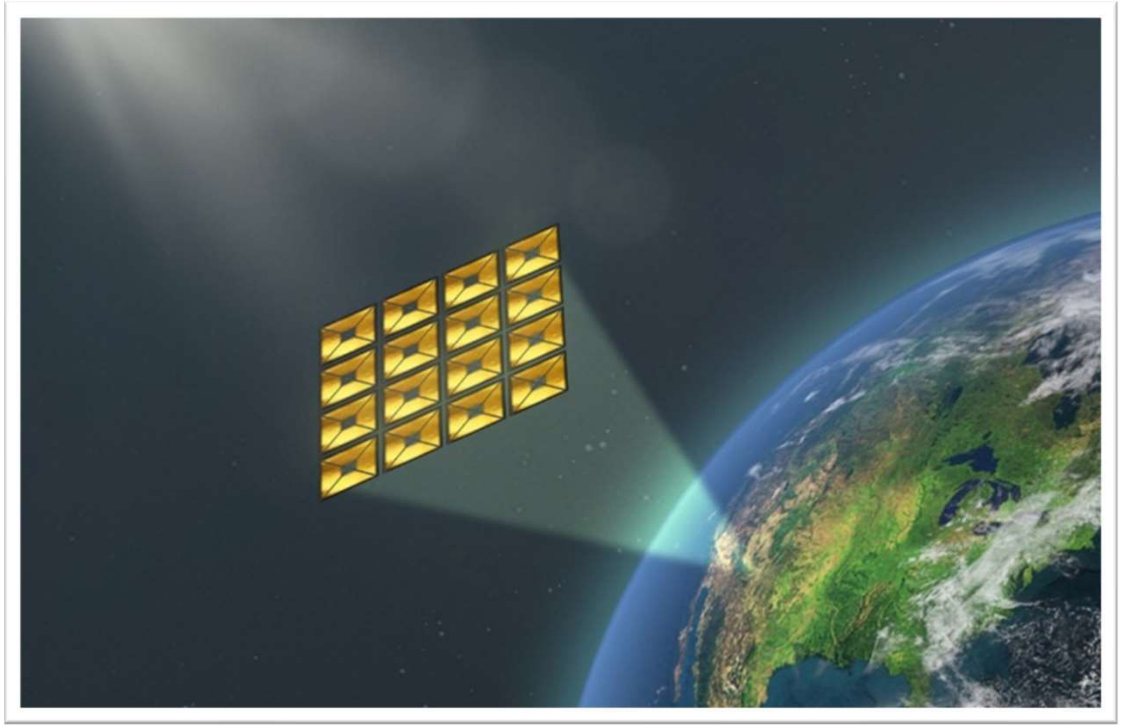


Credit: NASA

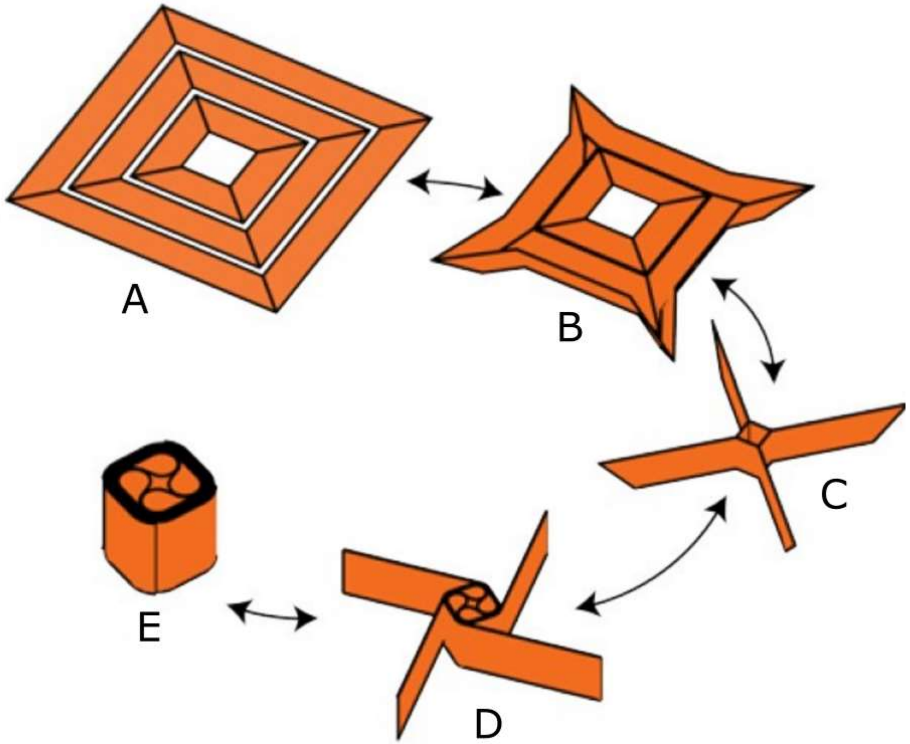
Credit: ESA

Project Background: SSPP Structure

- Solution for harvesting solar energy in space
- Collects sunlight and wirelessly transmits power to Earth



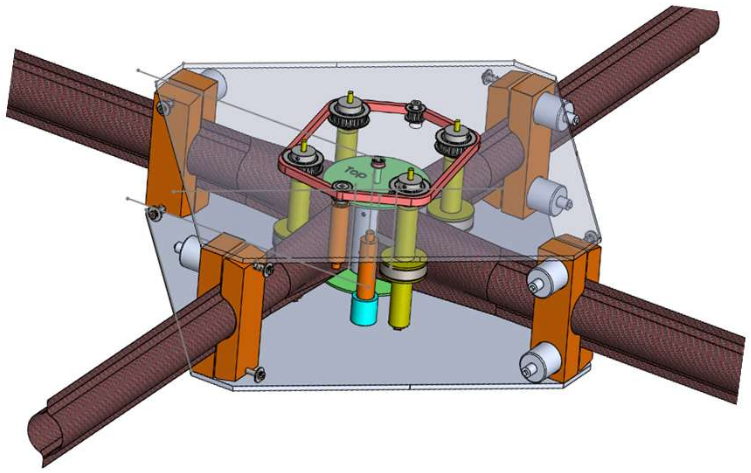
Packaging concept



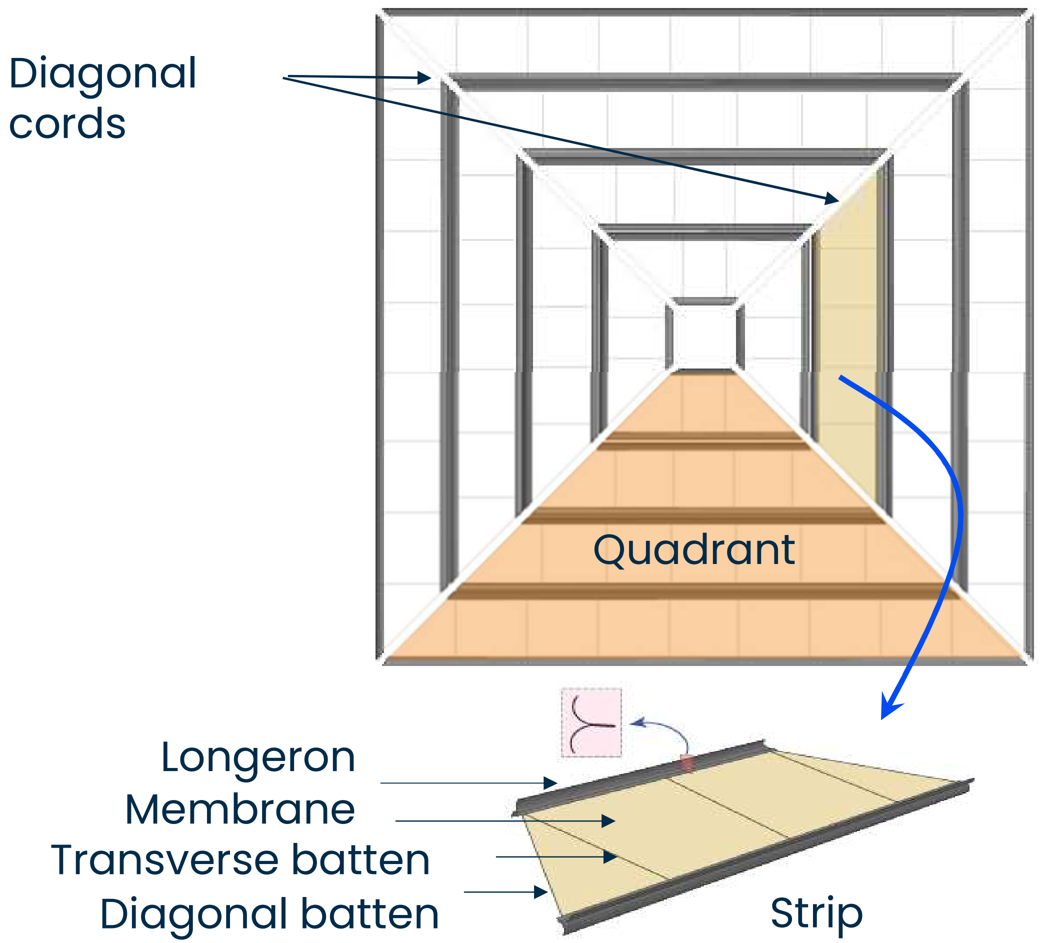
Pedivellano et al. 2020

SSPP Structure

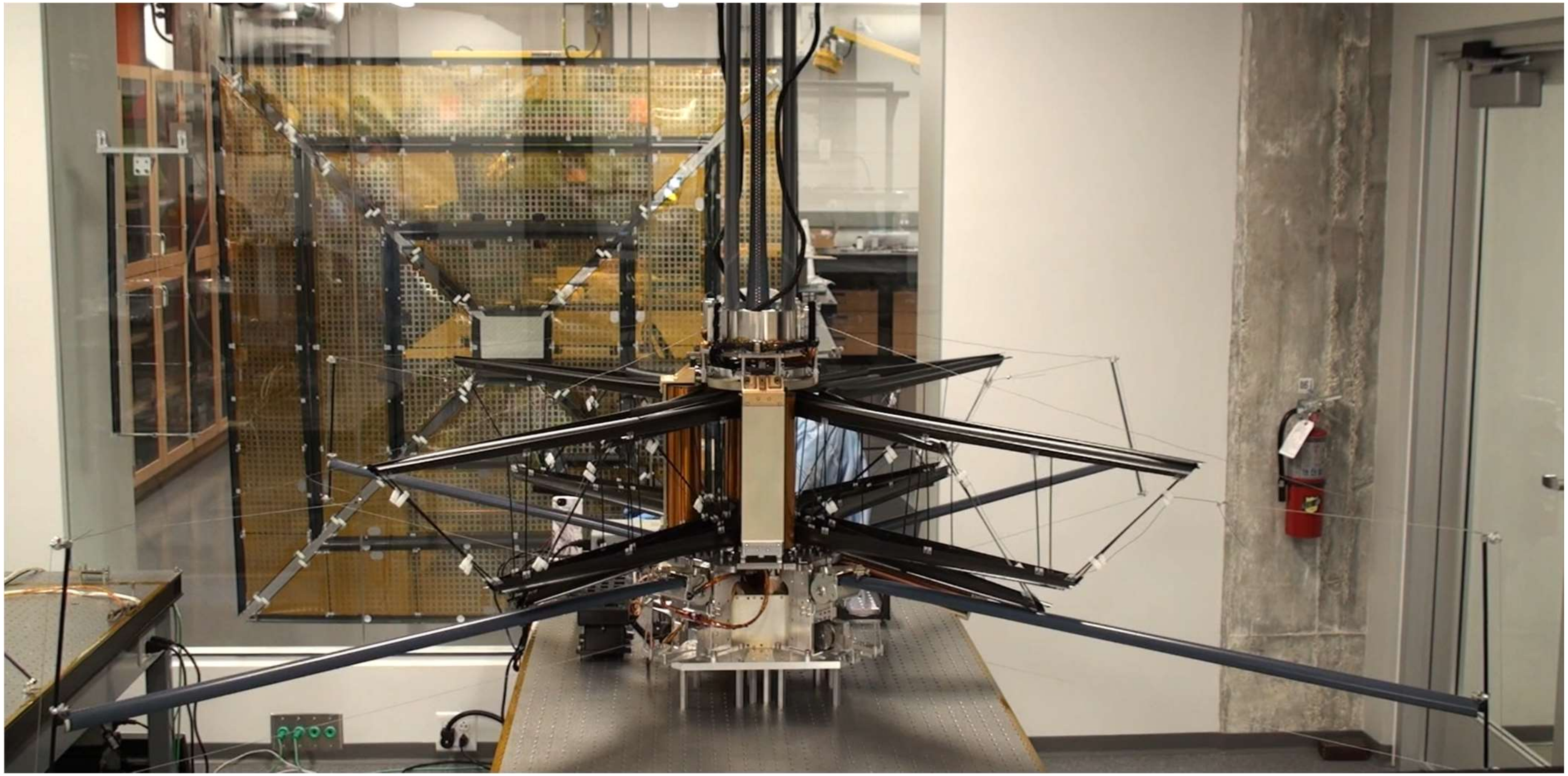
- Even-strip architecture (pairs)
- Repeating square unit
- Strips directly connected to boom (no cords)
- Continuous diagonal tapes
- Central deployable boom/strip mechanism



Boom deployment mechanism



Space Solar Power Project – experimental deployment



See attached File "Video HUMANS IN SPACE - Augello 08_04_25"
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Final Reflections & Next Steps

- Recap of Main Advantages: Low mass, compact stowage, rapid deployment, cost-effectiveness.
- Diverse Applications: Habitats, antennas, telescopes, rovers, terrestrial spin-offs.
- Challenges: Impact resistance, thermal/radiation shielding, stability, robust deployment mechanisms.
- Ongoing Projects: BEAM, JWST, plus numerous R&D initiatives.
- Significance: These technologies are enabling more ambitious missions and new commercial opportunities.

Future Opportunities

- Innovations in materials science, robotics, and partial ISRU.
- Potential for synergy with commercial space stations and lunar gateway.
- Demand for new skill sets in inflatable design, advanced simulation, structural testing, etc.
- Encouraging students and professionals to get involved.

QUESTIONS?

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