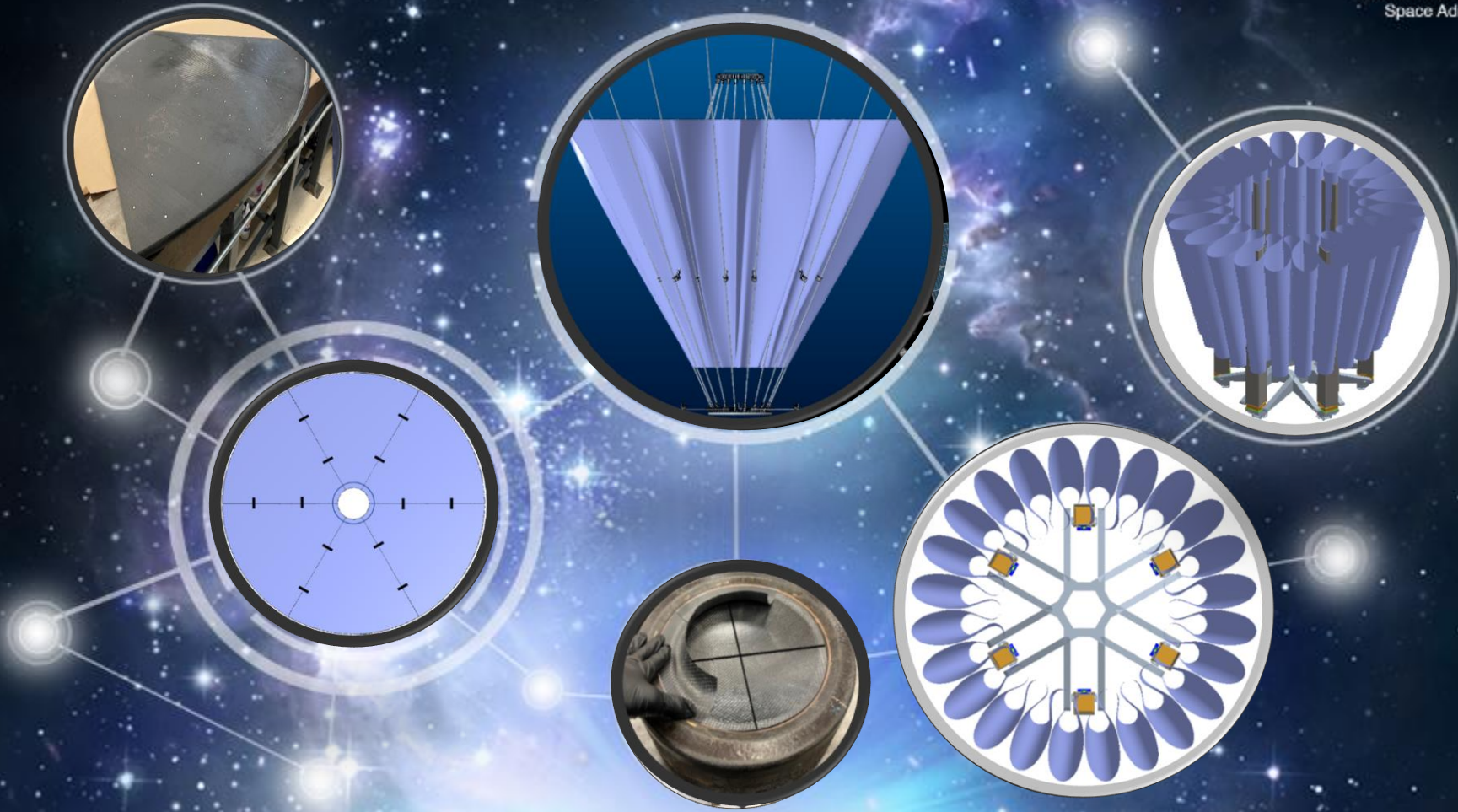




Segmented, Pleat-Folded and Rib-Supported Thin-Shell Composite Antenna Reflector

Juan M. Fernandez, Andrew F. Paddock, Kevin P. Roscoe, Kevin Demarco | NASA Langley Research Center

Introduction



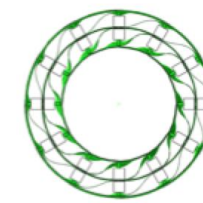
➤ Background and State-of-the-art (SoA)

- Fixed solid surface antenna radiofrequency (RF) reflectors < 4 m-size can target higher RF bands than Ka. Deployable versions with rigid panels target < 10-m class due to mechanical complexity, stowed volume, and mass.
- Deformable versions using mesh or thin-shell composite reflective surface construction can target > 10-m scale but have size limitation due to surface accuracy requiring deep backbone or perimeter ring structures to scale up.
- In-space assembly is an alternative approach for > 10-m scale but maturity is low.

➤ Technical capability goals

- Develop dimensionally and thermally stable deformable composite reflective material that enables efficient packaging of solid surface segmented reflectors.
- Create a folding scheme and architecture that enables self-deployment of at least 10-m reflectors to support S-band and above RF (≥ 4 GHz) with requirements:
 - Surface accuracy better than 3.175-mm root mean square (RMS) error
 - Deployed first natural frequency ≥ 1 Hz
 - Total mass ≤ 50 kg (> 80% improvement over SoA)
 - Stowed volume ≤ 3 m³ (> 25% improvement over SoA)
 - Survival temperature limits: -185°C to +163°C; and +/-100°C for operation

Multi-arm Radial Composite (MARCO) reflector by Air Force Research Laboratory (AFRL).



Gores store by spiral overlapping folds



Deployed by double-hinged arms

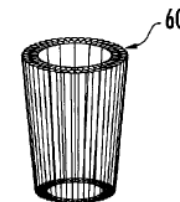
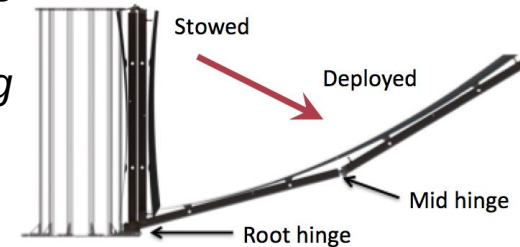


FIG. 6.

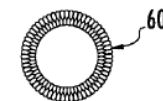


FIG. 7.

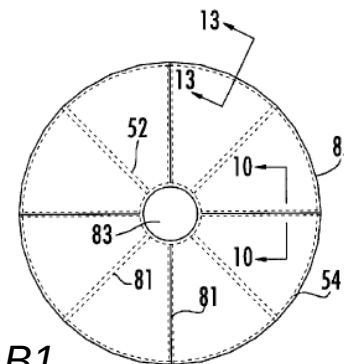


FIG. 8.

U.S. Patent 6,344,835 B1 by Harris Corporation

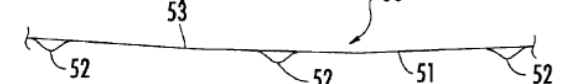
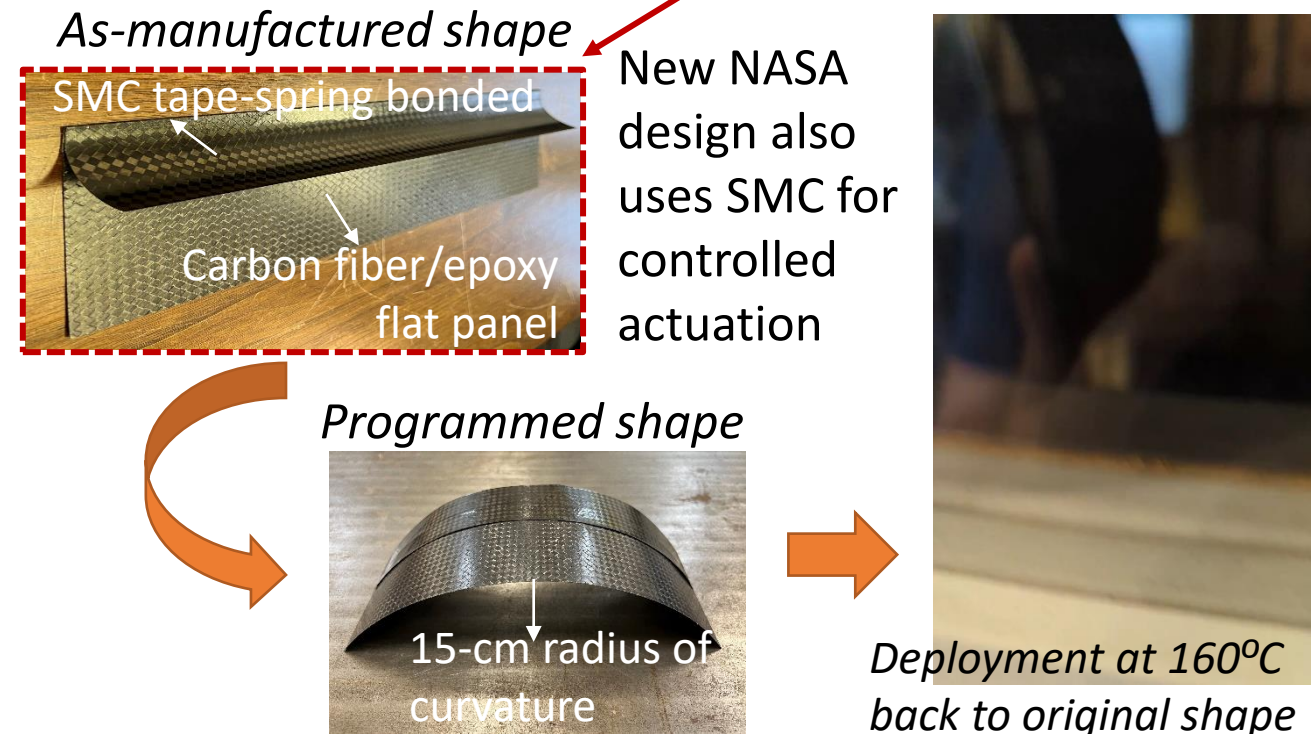
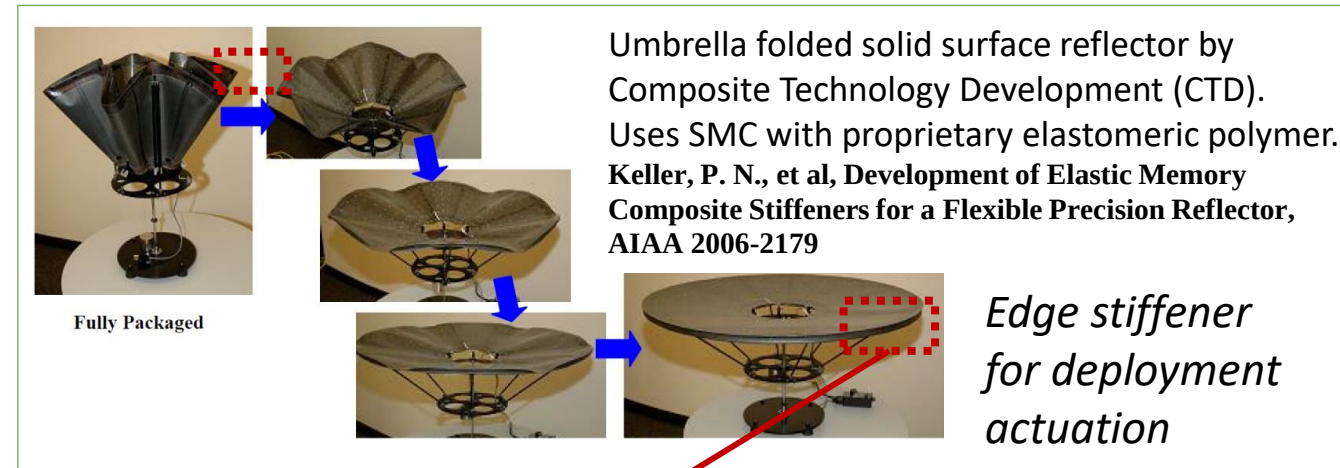


FIG. 9.

Thin-Shell Composite Umbrella-Folded Reflector



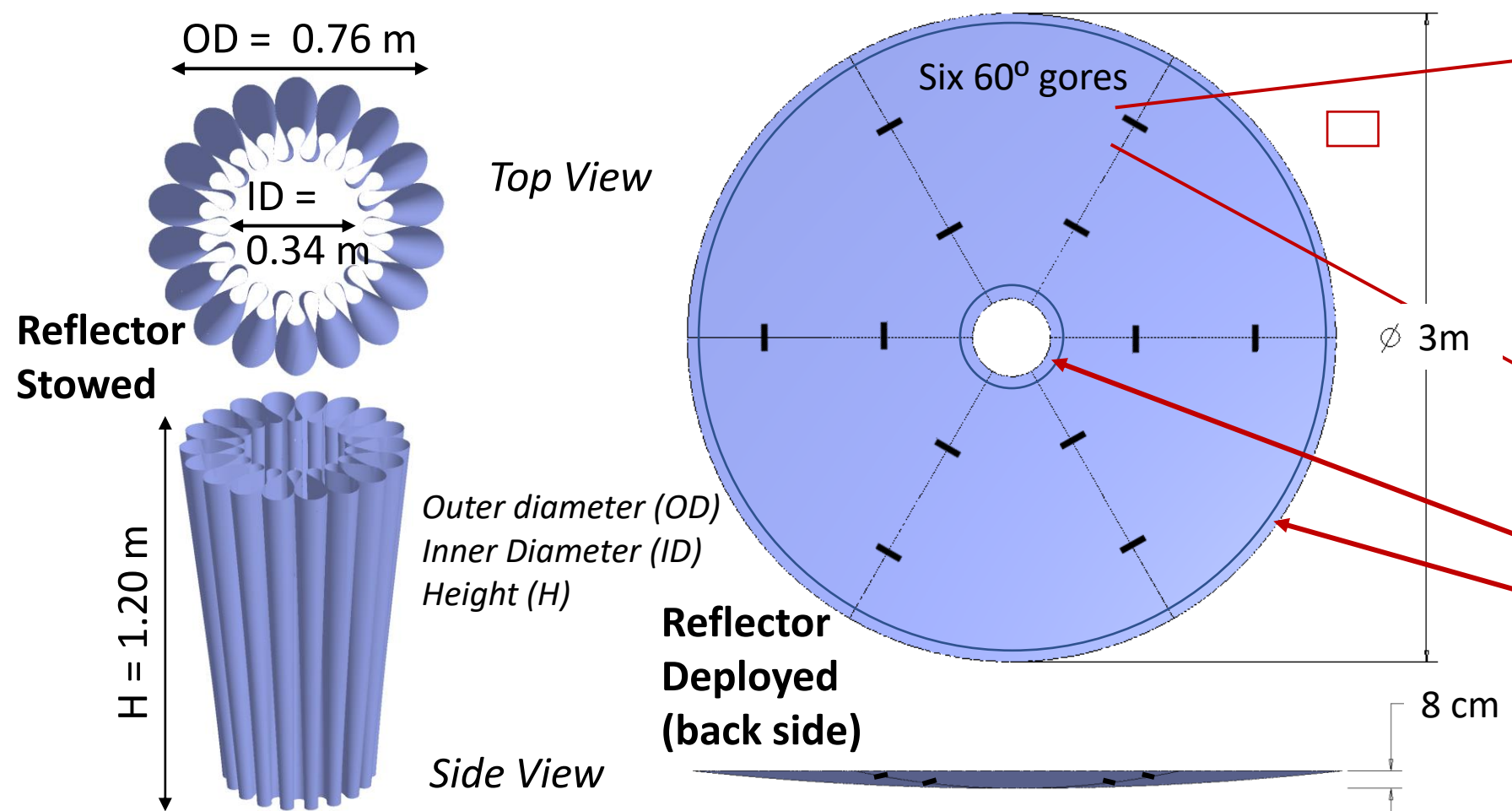
- Investigated thin-shell construction of the foldable reflector using High Strain Composite (HSC) materials and Shape Memory Composites (SMC) to enable a solution that has high packaging efficiency and low mass, while simplifying stowage and deployment via low part count.
- Umbrella-folding of solid surface thin-shell composite reflectors have been demonstrated at small scales (< 2-m diameter). Given the small size, the reflector was not segmented.
- Scaling up the architecture to > 5-m diameter requires advancements in composite materials, structural design, bonding technology, and manufacturing tooling, as well as the need to split the reflective surface into segments.



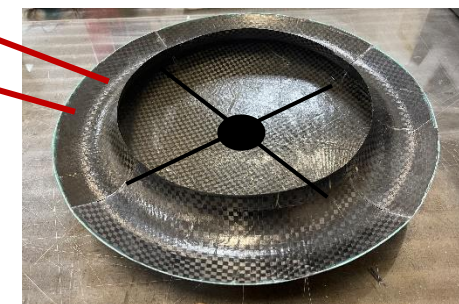
Umbrella Folded Reflector Concept

- 3-m diameter thin-shell composite paraboloid segmented into a number of radial gores connected on the back side by a number of flexible tape-spring hinges and inner and outer tape-spring skirts for out-of-plane stiffness.
- Gore stows into a series of serpentine-shaped folds resembling an umbrella.

Manufacturing trial of doubly-curved tape-spring hinges post-bonded to the paraboloid shell connecting adjacent gores



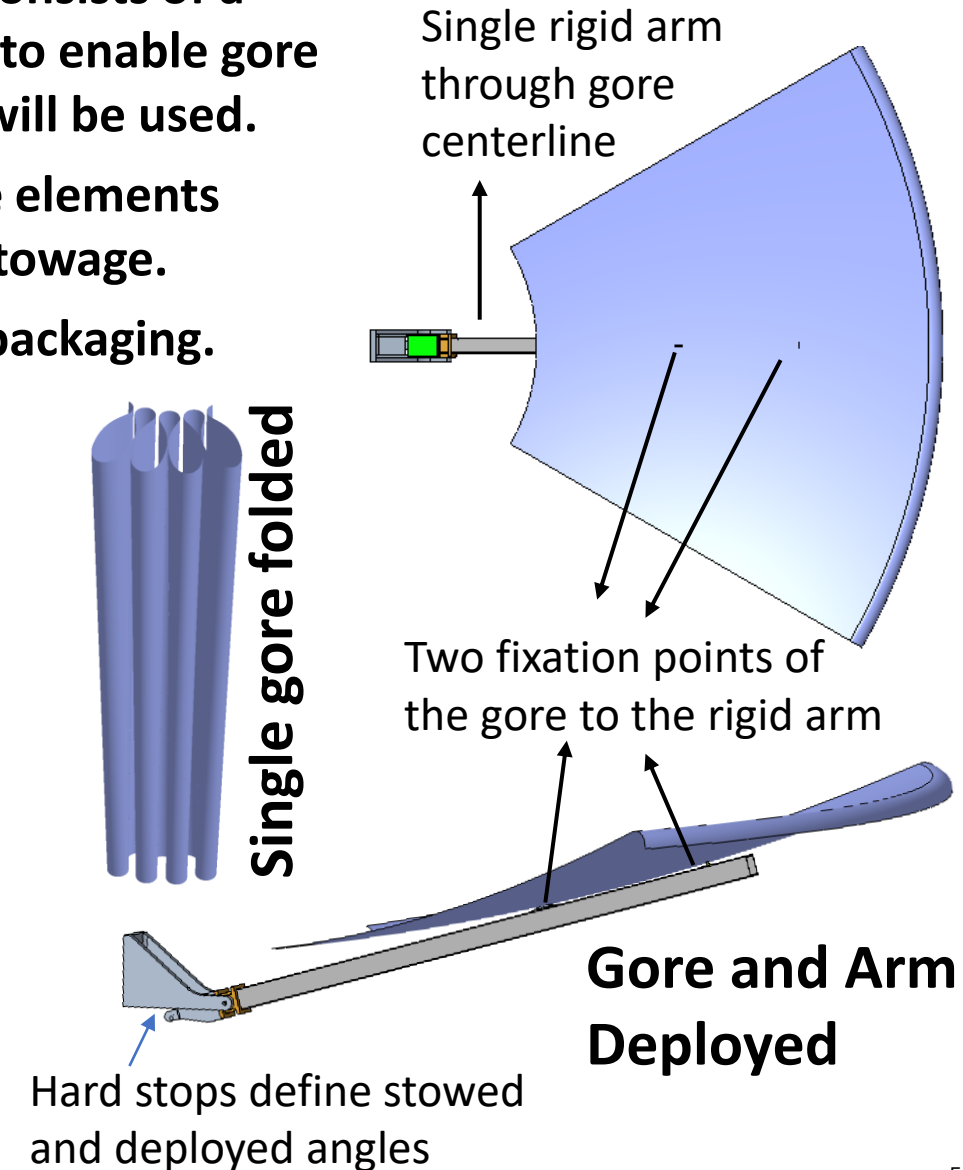
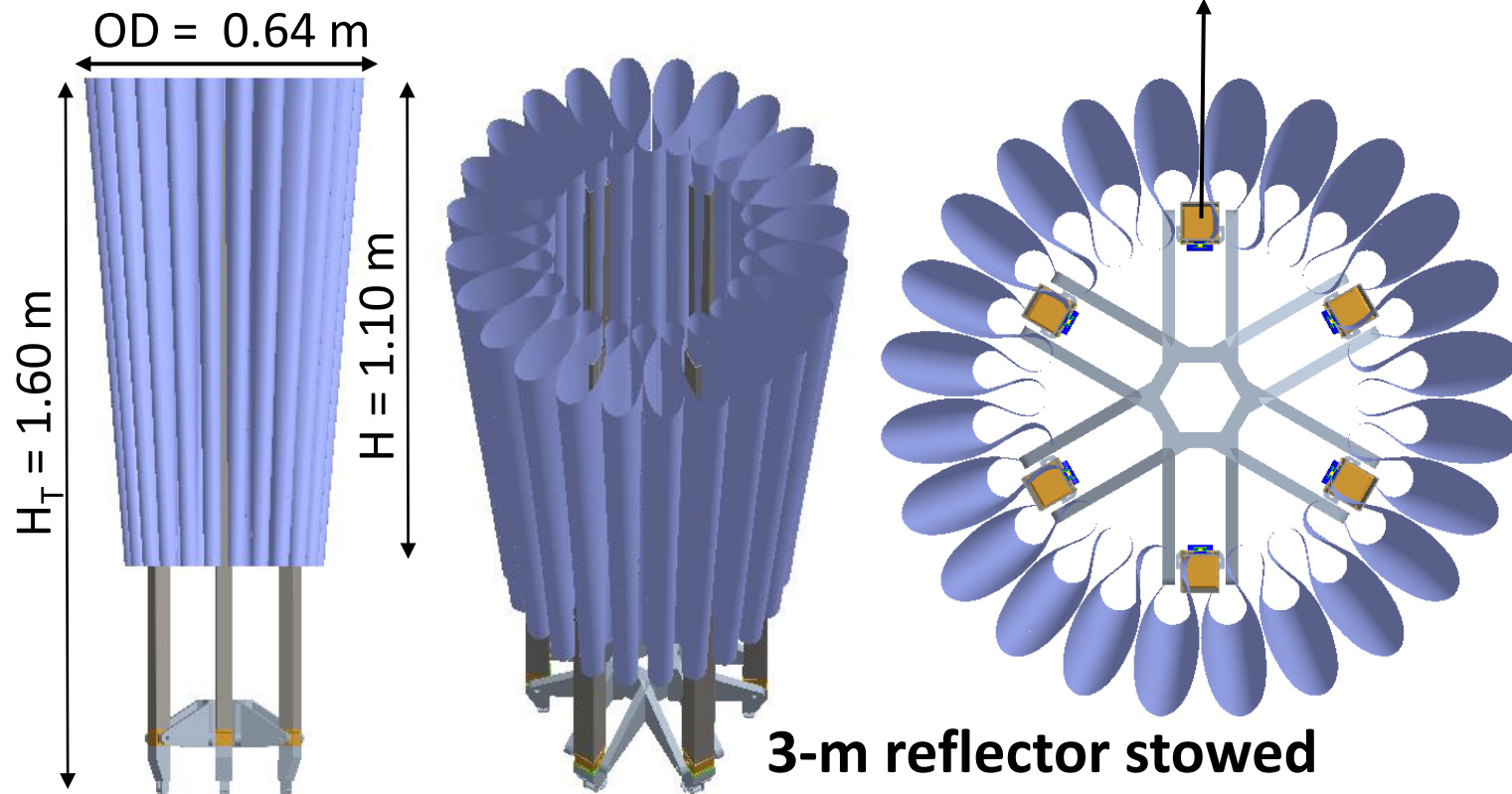
Outer and inner tape-spring skirt for additional stiffness



Reflector Backbone Structure



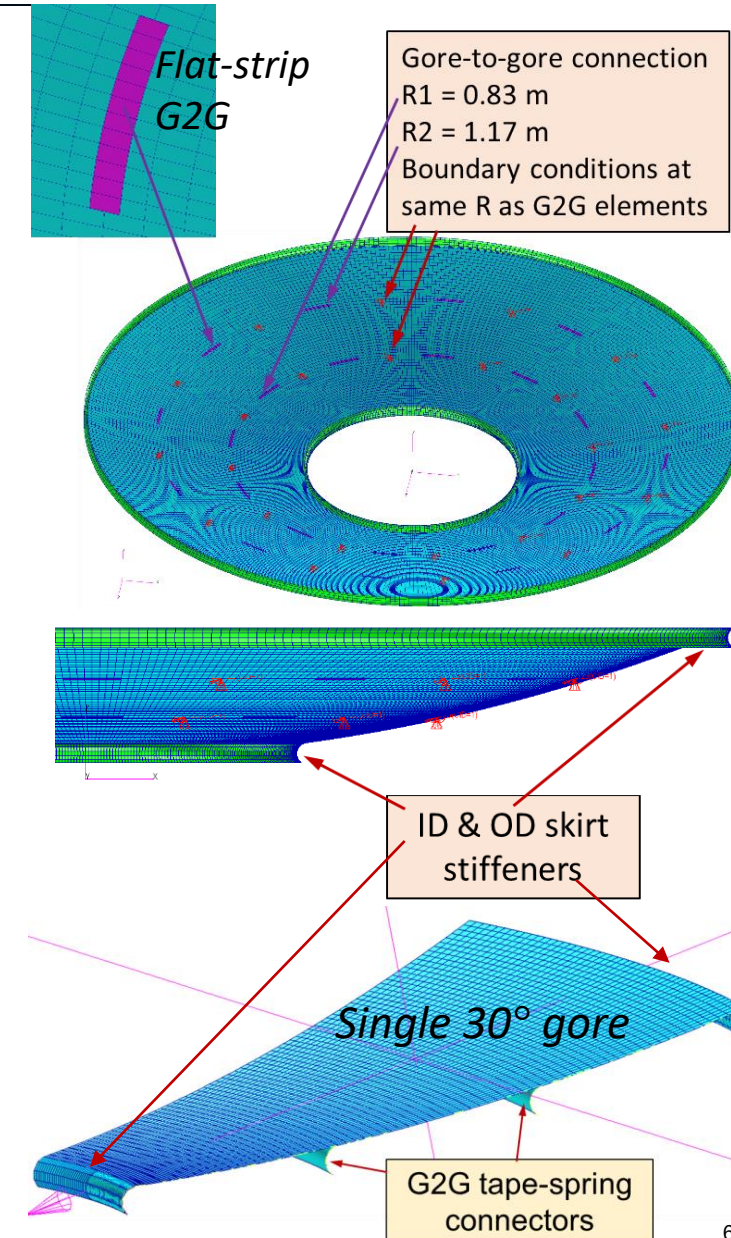
- Deployable rigid backbone for the segmented thin-shell reflector consists of a high modulus composite square tubing arms hinged from the root to enable gore rotation. For scaled up versions, double-hinged arms like MARCO will be used.
- Gore-to-backbone connections along gore centerline by composite elements provide rigid and flexible boundary conditions (BC) to allow gore stowage.
- Rigid arms stow within the pleats of the folded gores for efficient packaging.



Parametric Study of Deployed Reflector

Finite element model (FEM): 3-m OD, IR = 0.5 m, twelve 30° gores with two G2G and one flexible and fixed BC.

- **Objective:** Study how design parameters affect the deployed stiffness of the thin-shell segmented reflector to drive design.
- **Main goal:** 1st mode at 10-m scale ≥ 1 Hz. Parameters traded:
 1. Reflector size or OD: 3 m (breadboard demonstrator) vs 10 m (desired size).
 2. Gore subtended angle (total number of gores): 30° (12 gores) vs 60° (6 gores).
 3. Number of plies of the gore composite laminate: three or four plies at the 3-m scale, and four, five or six plies at the 10-m scale.
 4. Number and degrees of freedom (DoF) of boundary conditions: one, two or three fixation points at each gore and constraint translation vs all-fixed DoF.
 5. Outer rim/skirt shell design: concave vs convex.
 6. Number of 20-cm long gore-to-gore (G2G) connections per gore.
 7. Provide a curved tape-spring as the G2G connector or just a flat strip.
 8. Circumferentially split outer skirt or continuous.
 9. Align circumferentially the skirt joint locations to the BCs or have them staggered.
 10. Provide pad-up boundary condition at the gore-to-backbone fixation points.
 11. Radial location of gore-to-backbone connections.
 12. Inner radius (IR) of the deployed gore, i.e. central hole size: 0.50 m (large) vs 0.375 m (medium) vs 0.25 m (small).
 13. Split 10-m reflector into two radially connected ~5-m reflectors or have single unit.

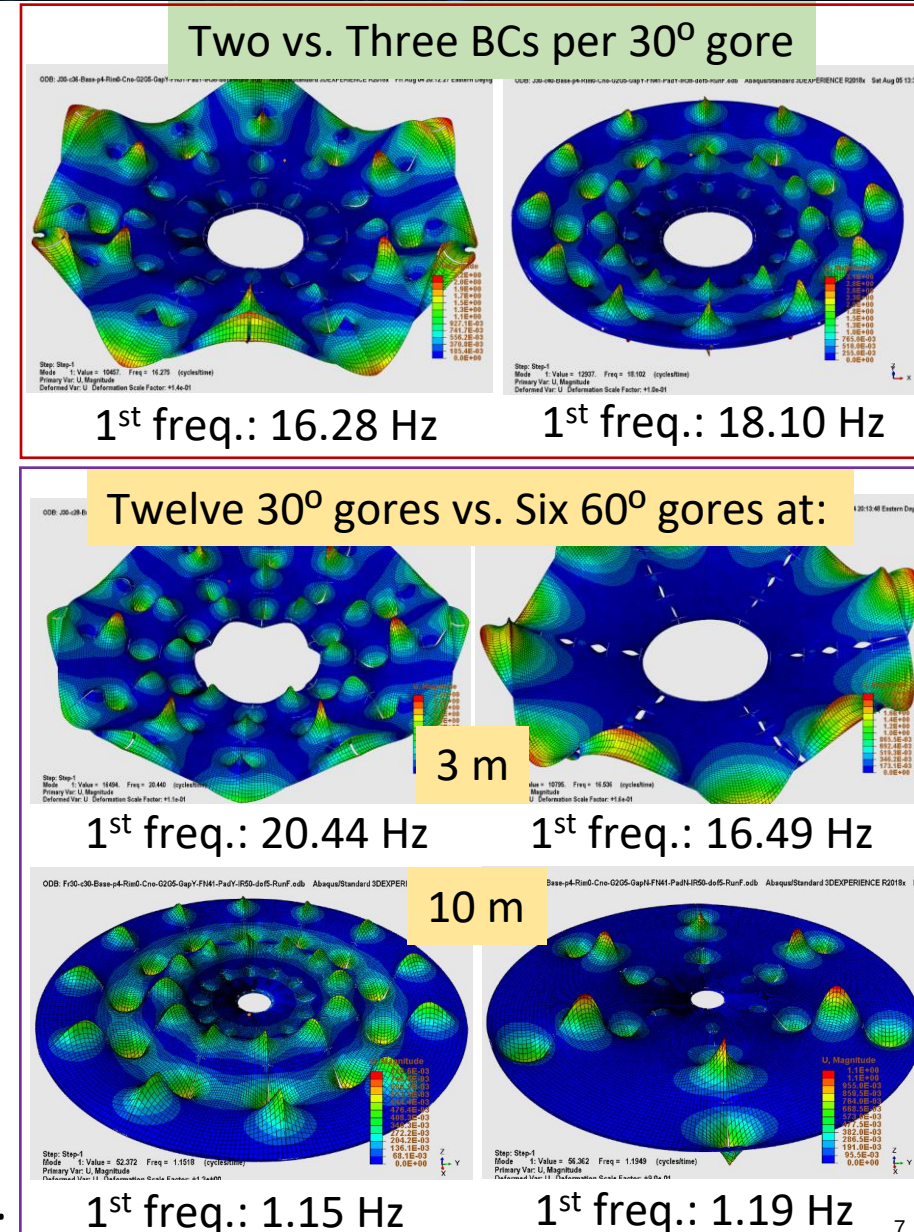


Parametric Study of Deployed Reflector: Results



➤ Main conclusions:

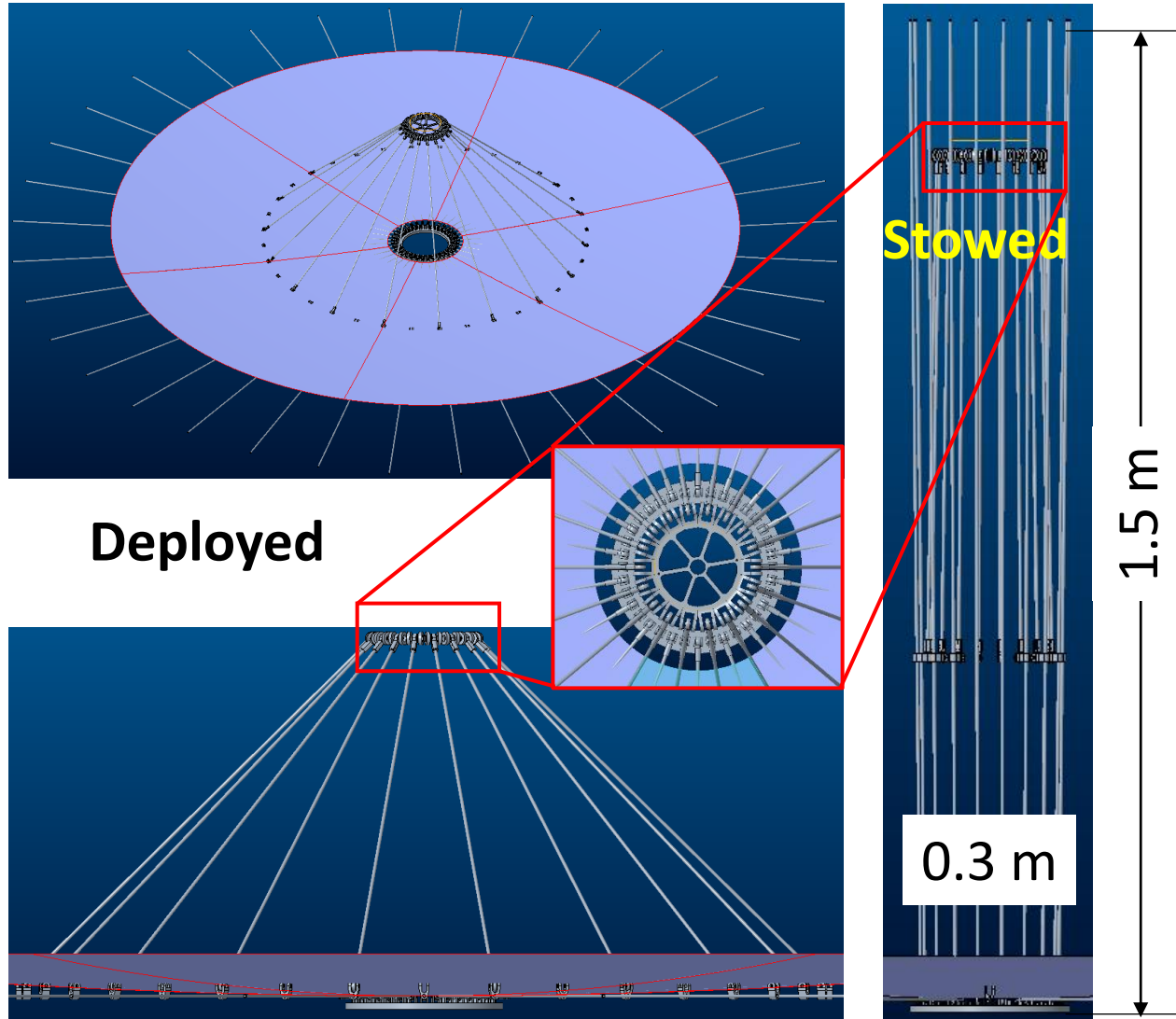
1. Increasing number of G2Gs has the most influence on stiffness. 40% to 50% improvement in the lowest frequency at both size scales.
2. Providing more gore-to-backbone supports stiffens the assembly. 10% to 20% frequency improvement from two to three BCs.
3. Moving the innerboard BCs from the 1/3rd to the 1/6th radial stations only influence significantly the 3-m, 30° gore cases.
4. Number of gores do no influence when the free-edge panel modes dominate. 12-gore cases show $\leq 20\%$ stiffness increase over six gore.
5. Continuous skirts stiffen the reflector but cannot be made to scale. Two flat strips connecting outboard and inboard edges of the nearby skirts provide 40% to 60% stiffness increase vs. partial disconnect.
6. Once gore free edge is stiffened, the skirt stiffness limits frequency. Skirt stiffness is influenced by:
 - a) Moving the gore-to-backbone BCs closer to the skirts.
 - b) Skirt size (bending moment of inertia).
7. Concave or convex skirt shape: no stiffness effect. Concave preferred.



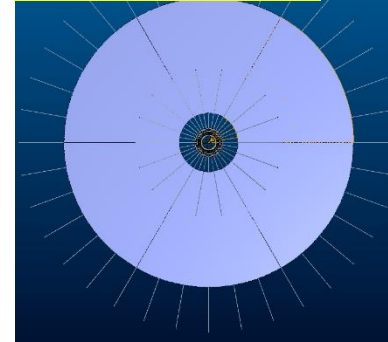
Umbrella-Folded Reflector Packaging Scheme



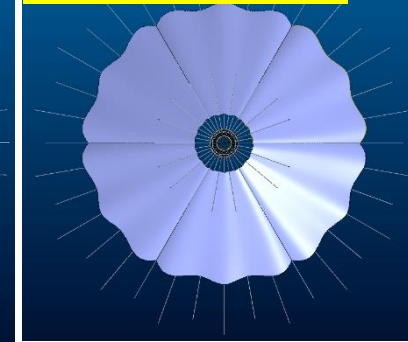
- 3-m diameter thin-shell reflector with ground support equipment (GSE) push rods for folding like an umbrella



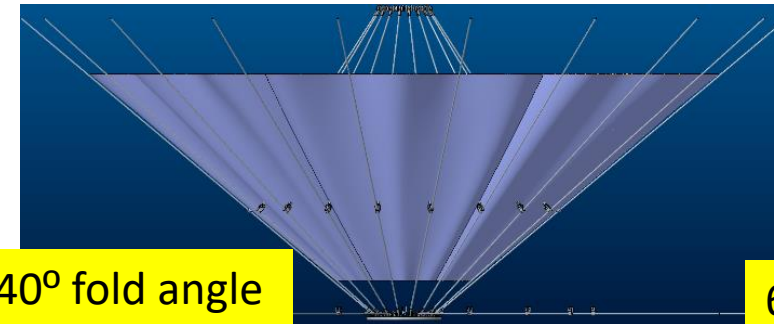
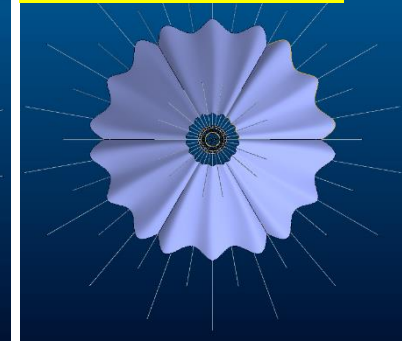
0° fold angle



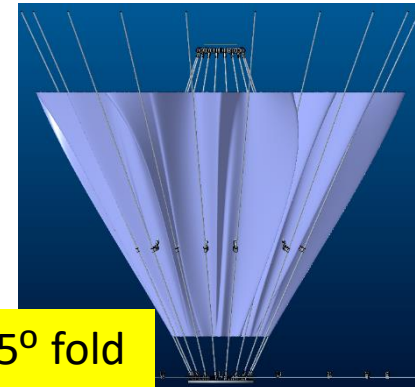
20° fold angle



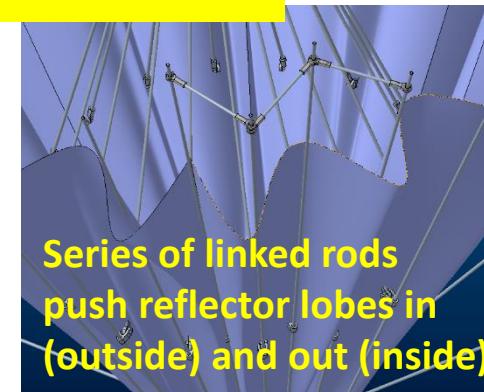
40° fold angle



40° fold angle
– back side



65° fold angle

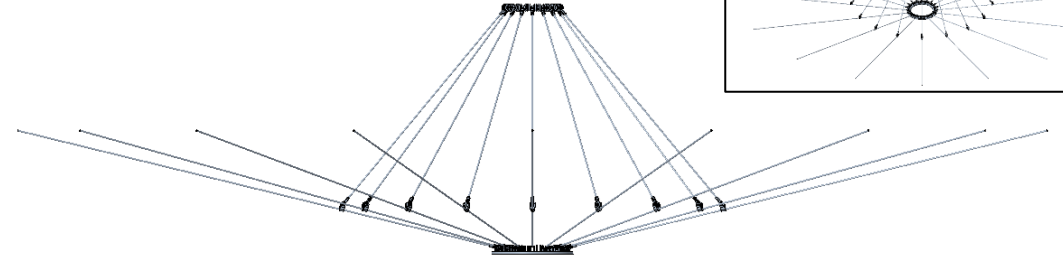
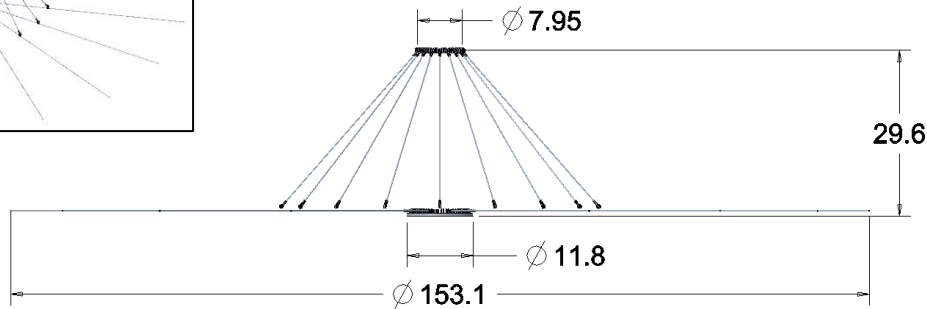


GSE Design for Folding the Umbrella Reflector

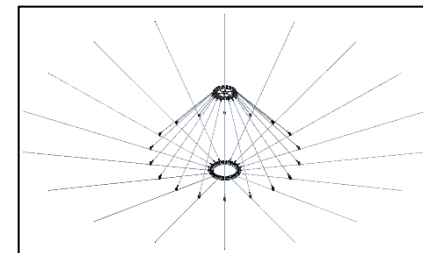
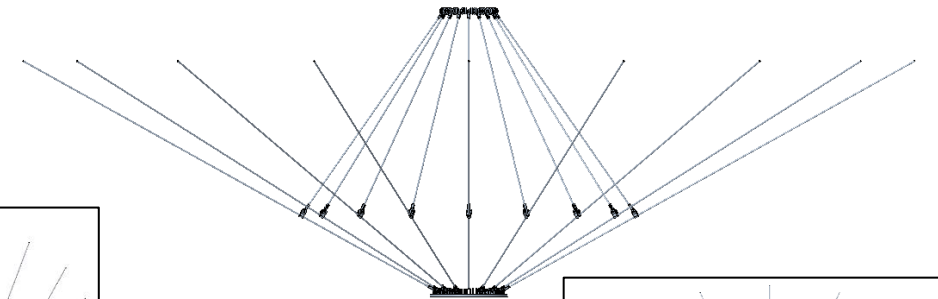
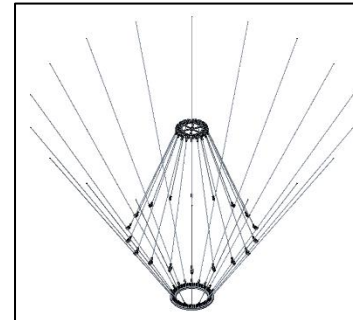
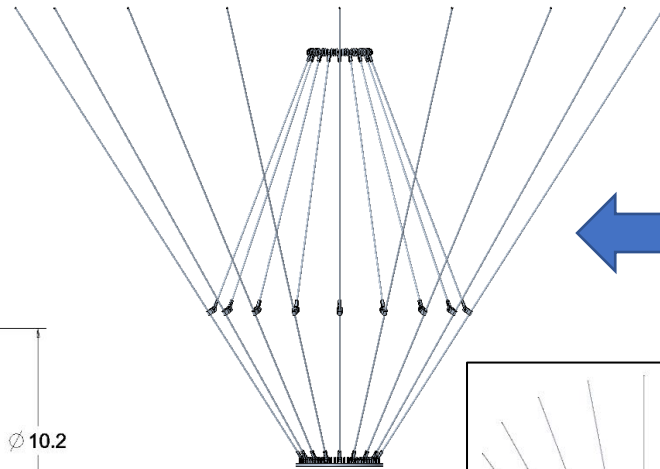
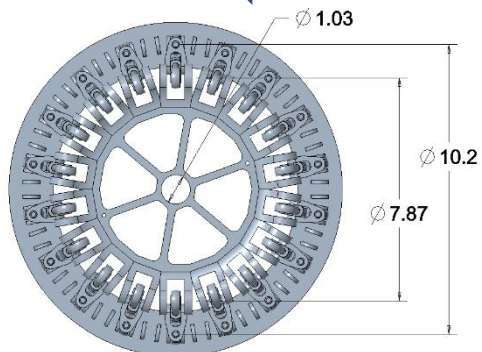
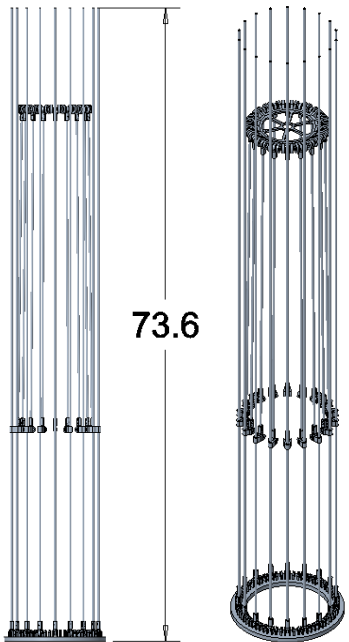


Reflector Deployed

**Dimensions are in inches*



Reflector Stowed

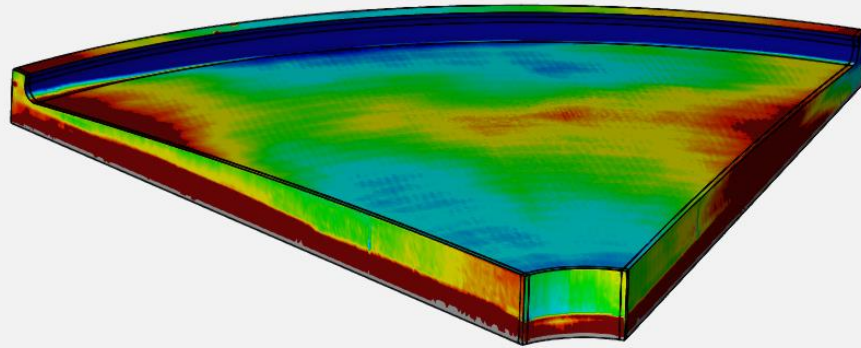


1/6 Gore of 3-m Diameter Dish Tooling

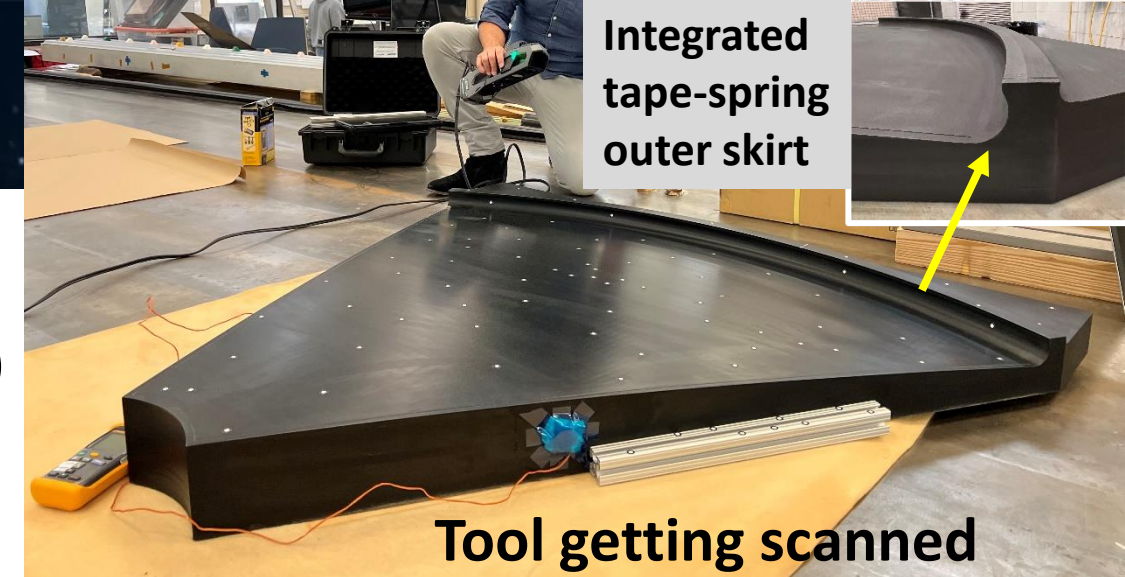
- A 1/6 gore (60°) mold of the inner 3-m diameter disk of a 10-m paraboloid reflector with a $F/D = 0.7$ (shallow curve) was produced for Manufacturing Development Units (MDU)

Surface error of the as-manufactured mold vs nominal (desired) design

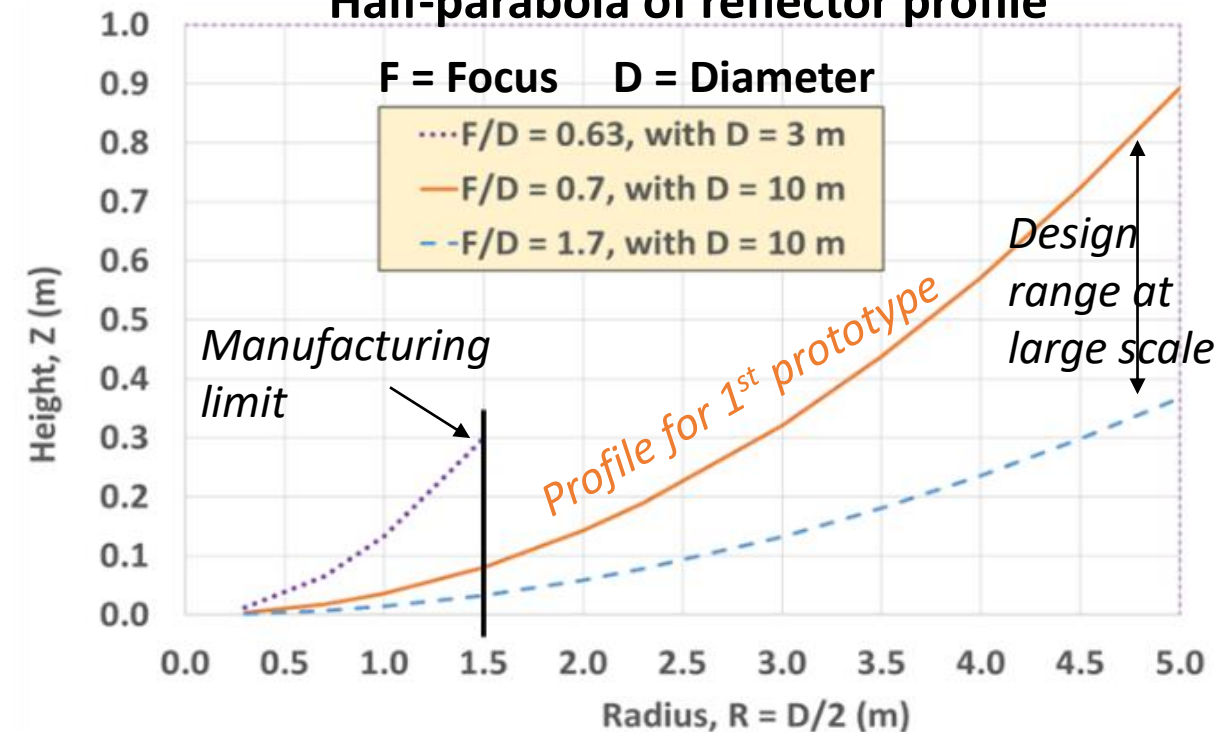
Most of the paraboloid surface is within ± 0.25 mm. Outer skirt has ~ 1 mm error but is less dimensionally critical.



- Surface error after curing the first gore part showing tool deformation up to ± 0.8 mm.
- Subsequent cure cycles continued to deform the tool surface requiring resurfacing to bring back to nominal



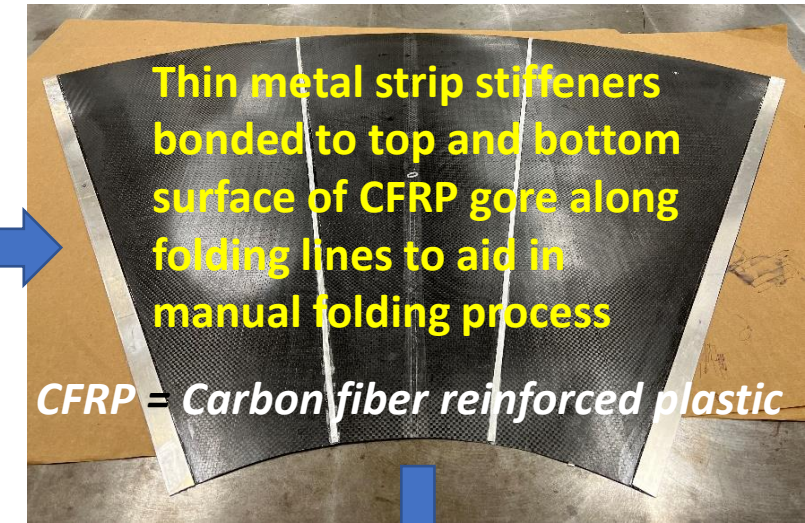
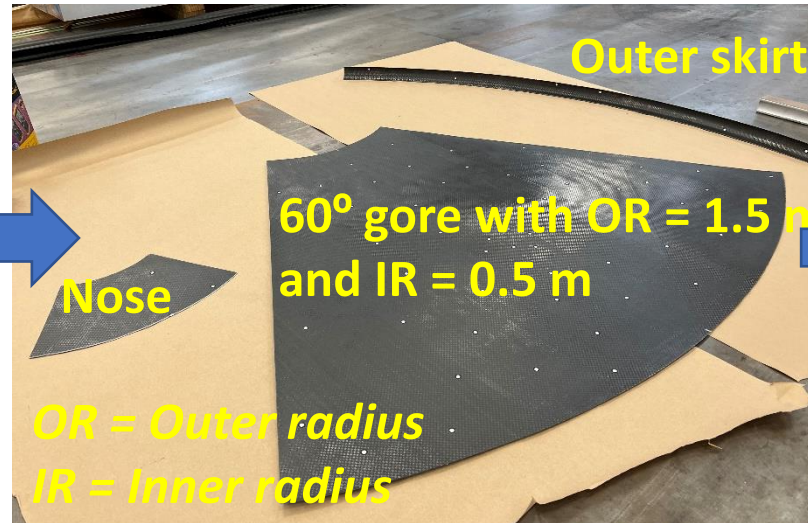
Half-parabola of reflector profile



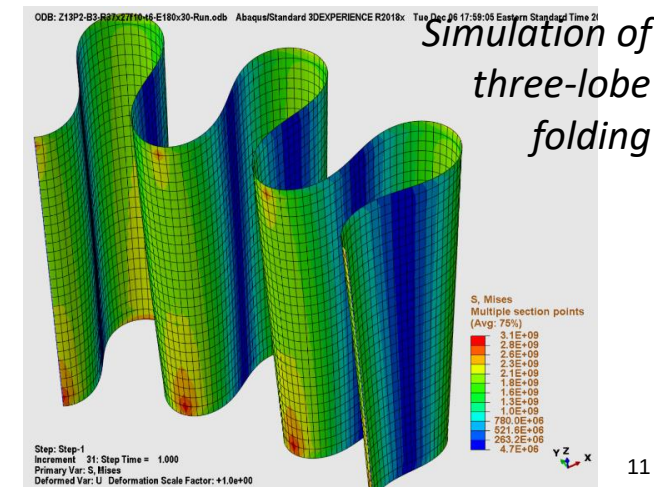
1/6 Gore of 3-m Dish Manual Folding Test



Slit

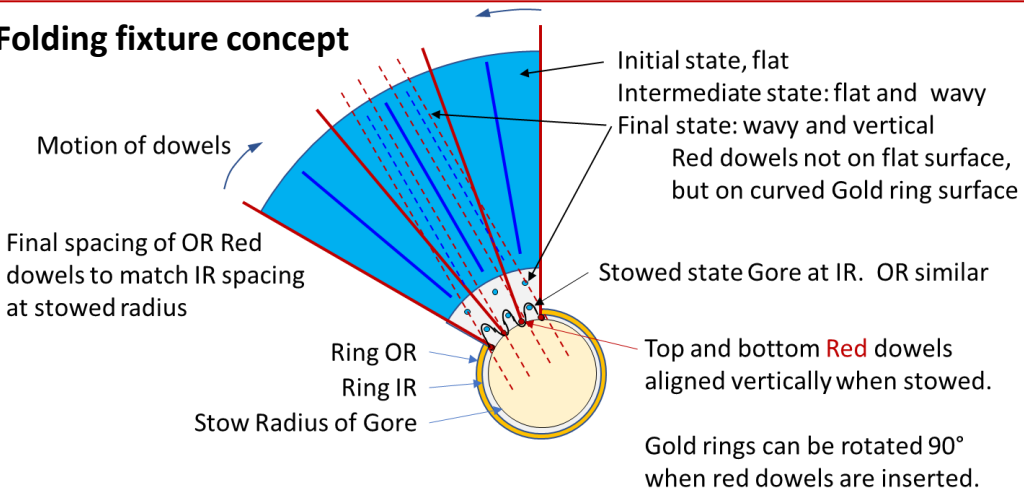


Target of folding the 60° gore into a three-lobe configuration with IR = 0.25 m and OR = 0.45 m

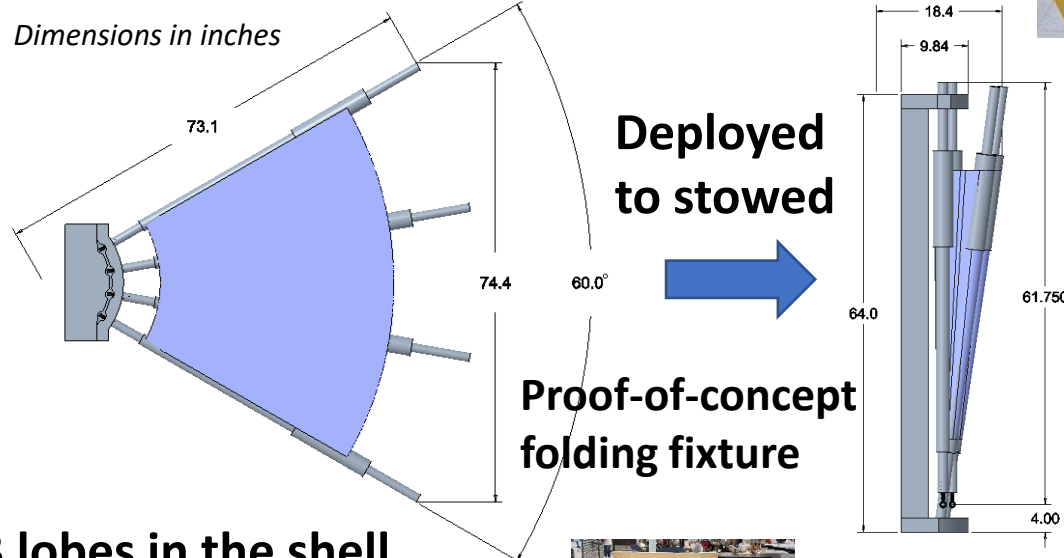


1/6 Gore of 3-m Dish Folding Test with Wood Fixture

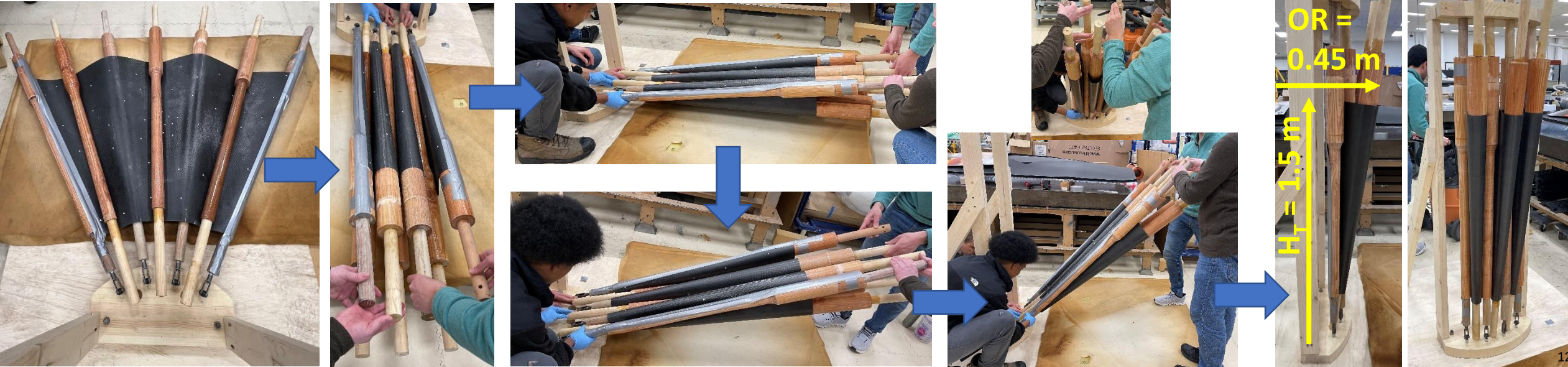
Folding fixture concept



Dimensions in inches



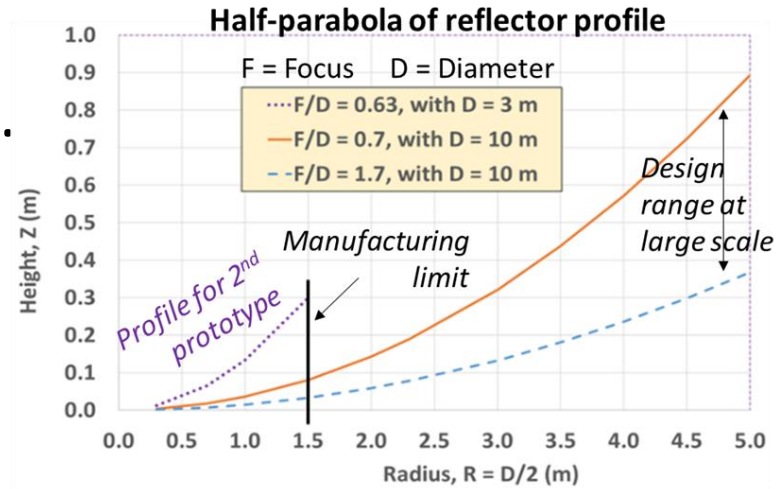
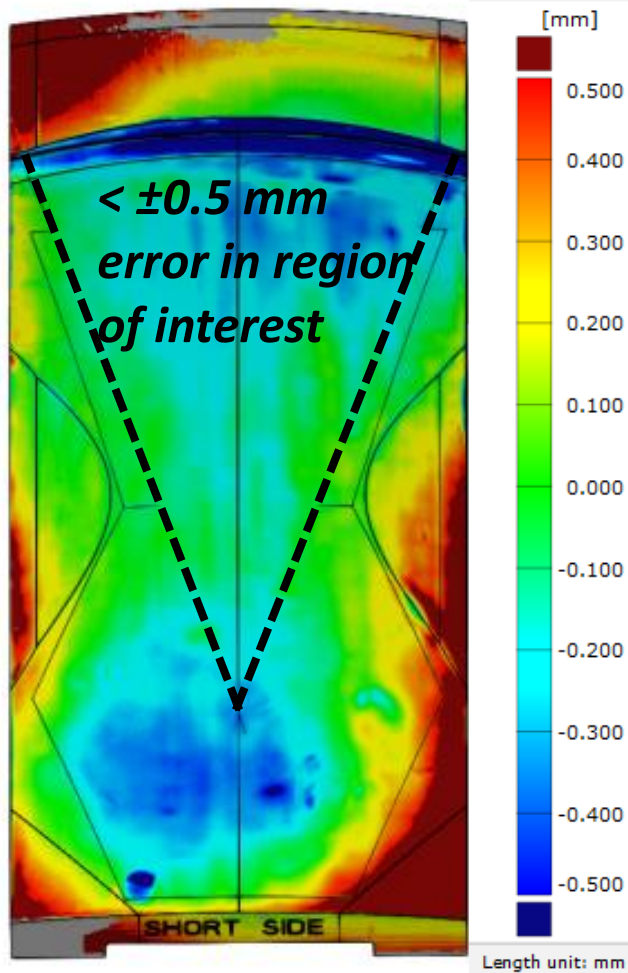
7 rods (4 on outside and 3 on inside) create the 3 lobes in the shell. Outside rods are hinged at the bottom to enable upwards rotation.



30° Gore Breadboard Composite Substrate Fabrication

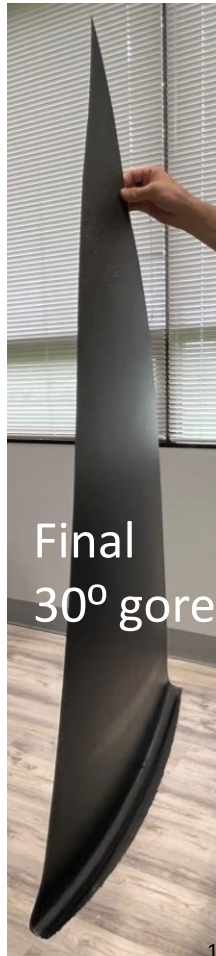


- Existing FR47-18 foam tool with high coefficient of thermal expansion (CTE) was resurfaced to fabricate MDUs of 3-m OD, 30° gores and assess ability to fold.



Demolded part hanging under gravity

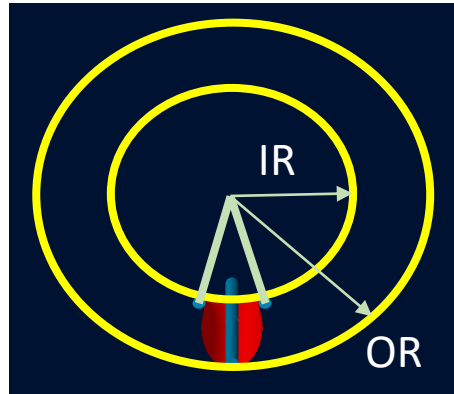
Fabricated sample with deeper paraboloid keeps shape well under gravity



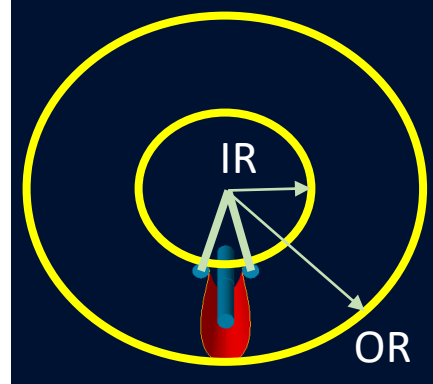
Folding Simulations of $\leq 30^\circ$ Thin-Shell Reflector Gores



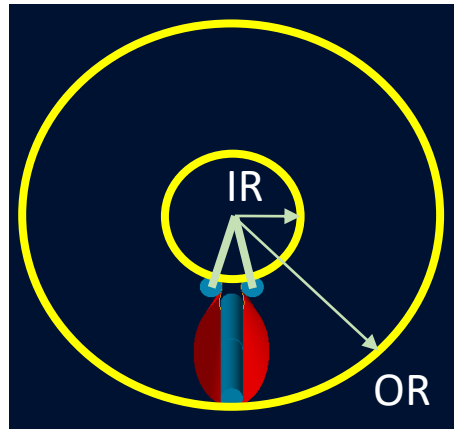
- Folding simulation: Three rods remain at 0° , 15° , and 30° and move inward to center. Gore remains within 30° sector during folding.



IR = 0.474 m
OR = 0.771 m

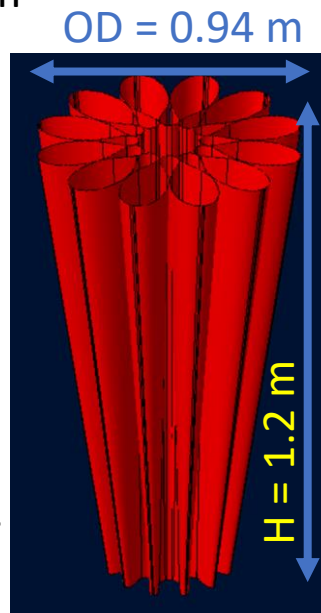
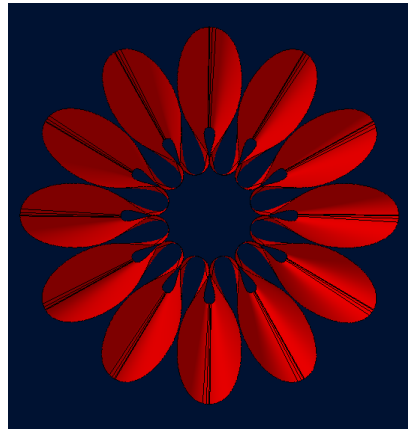


IR = 0.261 m
OR = 0.593 m



IR = 0.155 m
OR = 0.471 m

Entire 360° reflector under this stowed configuration



- Analysis assumes a GSE sawhorse-like fixture with three rods is used to progressively fold the gore by sliding the two outer horizontal rods along the A frame slotted legs while middle angled rod makes gore sag under gravity. Arc segments define folding steps with fixed IR as shown on left images.

Folding GSE for 30° Gore

5X Arc Segments

Inner radius (IR)

Hinge

A frame legs (adjustable angle = gore angle)

Gore sagging under gravity

Slots

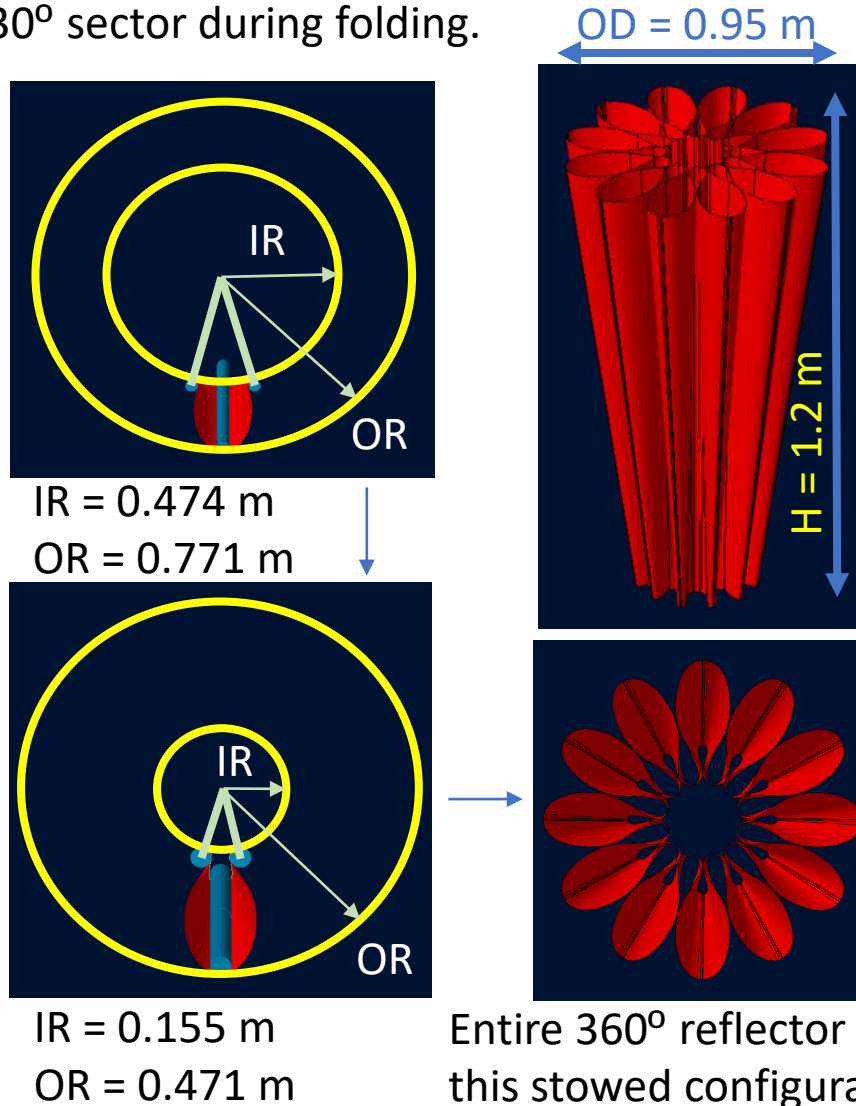
3X Rods

Not Fabricated – Just used for simulation purposes

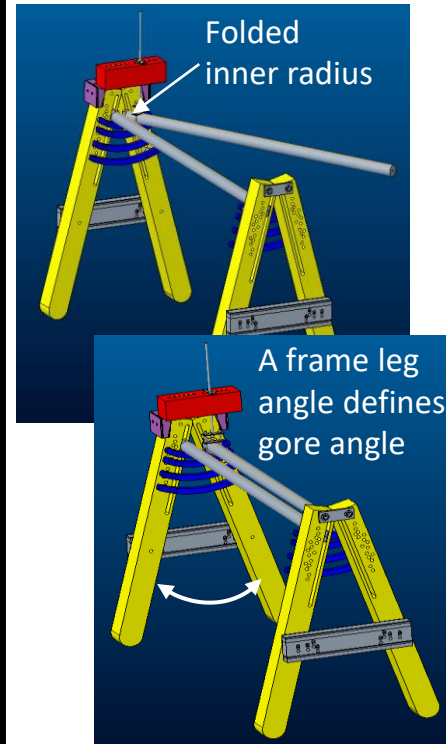
Folding of $\leq 30^\circ$ Thin-Shell Reflector Gore – Folding GSE Fixture and Tests



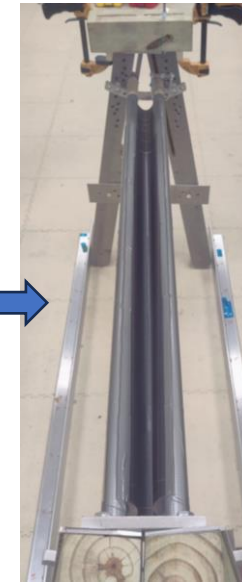
Folding simulation: Rods remain at 0° , 15° and 30° and move inward to center. Gore remains within 30° sector during folding.



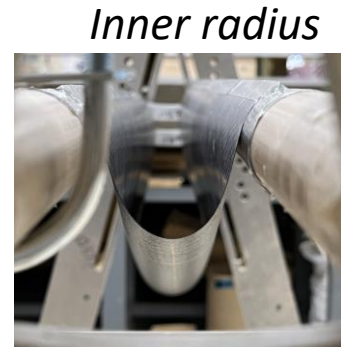
- GSE test fixture with two rods taped to the ends of the gore are used to progressively fold the gore by moving one rod horizontally while the other is fixed at the desired inner folding radius. The gore naturally sags under gravity providing a realistic folded shape. Arc segments define folding steps with fixed IR, as shown on left images.



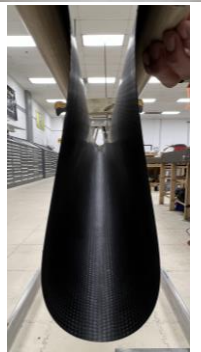
Gore deployed



Gore stowed



Inner radius



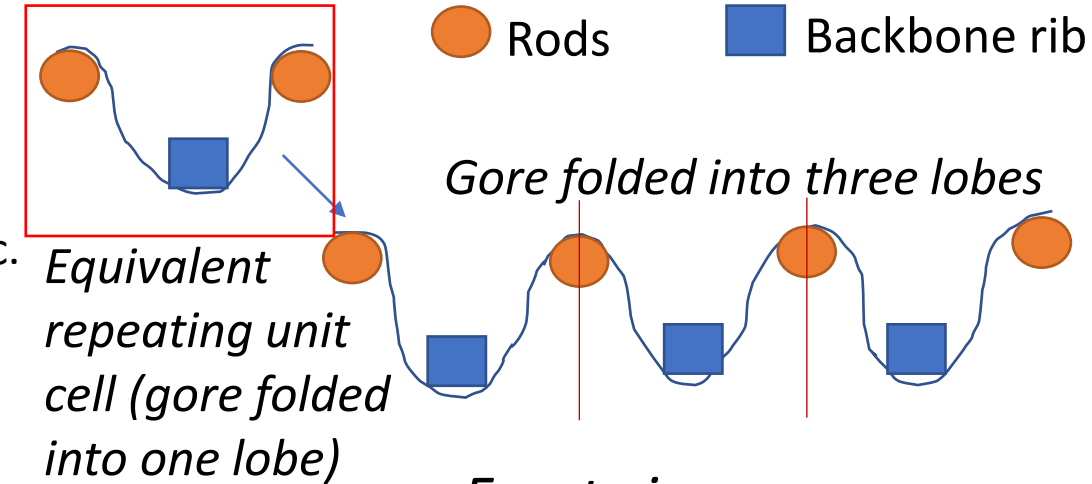
Outer radius

- Tested gores with different gore angles (30° , 22.5° , 18° , and 15°) and deployed inner radius (IR = 0.5 m to 0.25 m) using 3.8-cm and 5.0-cm rods to assess best packaging efficiency achievable in reflector designs.

Folding of $\leq 30^\circ$ Thin-Shell Reflector Gore – Test Results Summary



- Each gore case was folded into a single lobe configuration.
- Objective: Evaluate folding in an equivalent repeating configuration with a proportionally larger number of lobes, e.g., the 15° gore cases assess folding 30° gores into two lobes, 45° gores into three lobes, etc.
- The folding strains in the gore IR region increased from Cases #1 - 8.
- No visual damage was observed on gores during the folding process.
- All 8 cases tested were successful. Multiple reflector designs are possible with combination of gore number and stowed configuration.



Case # / Measurement	1	2	3	4	5	6	7	8
Gore subtended angle ($^\circ$)	30	30	22.5	22.5	18	18	15	15
Deployed Gore IR (m)	0.30	0.30	0.30	0.40	0.40	0.50	0.50	0.50
Folded Gore IR (m)	0.17	0.13	0.17	0.23	0.23	0.30	0.30	0.23
Rod diameter (cm)	5.0	3.8	3.8	5.0	3.8	5.0	3.8	3.8

Front view



Case #2 folded

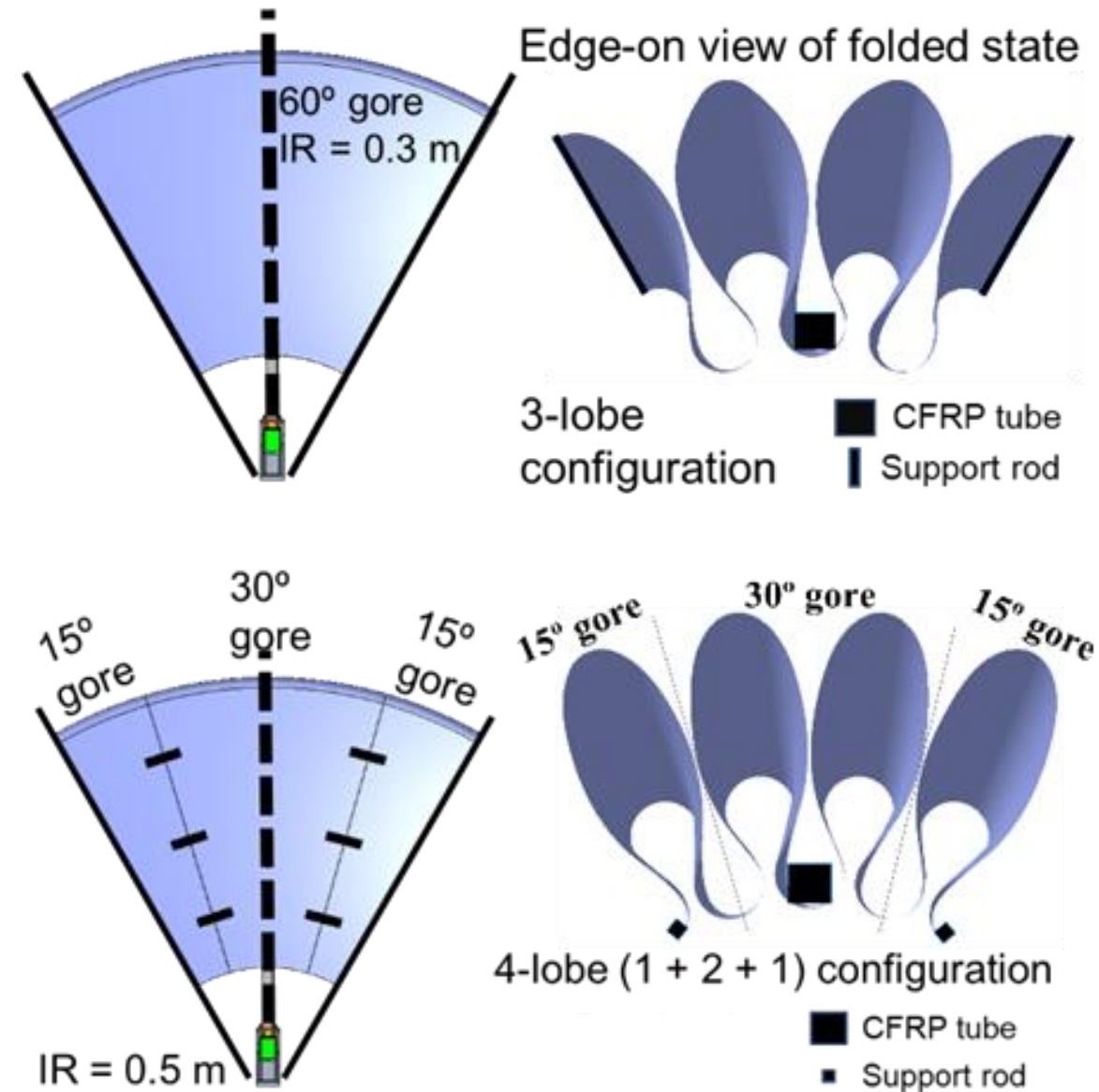


Side view

Full-scale test articles to manufacture and test



- Two full-scale test articles of 3-m OD thin-shell reflector gores will be fabricated and tested inside thermal chamber with gravity offloading system for concept validation:
- One 60° gore with cutout IR = 0.3 m to be packaged as:
 - Three-lobe config. with central CFRP tube connected via fixed and flexible BC at centerline at 1/3rd and 2/3rd radial stations.
 - Arm tucked into central inside radius lobe.
 - Two smaller GSE rods will support gore free edges.
 - Gore stowed with 5-cm rods as per Case #1, but with a folded gore IR = 0.17 m and OR = 0.39 m.
- One central 30° gore with two 15° side gores attached to it via inner/outer skirts and three flat-strip gore-to-gore connectors. All gores with cutout IR = 0.5 m to be stowed as:
 - four-lobe configuration with two lobes on 30° gore and one lobe on each 15° gore.
 - Arm housed inside inner lobe symmetry line of 30° gore.
 - Two smaller GSE rods will support gore free edges.
 - Gore stowed with 3.8-cm rods as per Case #8, but with a folded gore IR = 0.15 m and OR = 0.32 m.



Concluding Remarks



- New architecture for solid surface deployable antenna reflector presented, where the thin-shell reflective surface is divided into a series of backside interconnected gores, each folding into a serpentine pattern and supported by radial arms resembling an umbrella.
- Focus has been on design, analysis and manufacturing of reflective surface and SMC elements with embedded actuators, demonstrating feasibility.
- Parametric study helped in reflector design with baseline case showing acceptable folded strains, sufficient deployed stiffness, and low deployment dynamics via SMC control.
- Several 3-m scale gore prototype test articles of increasing fidelity and dedicated test fixtures used to assess new features to be implemented in designs at ≥ 10 -m scale.
- Final 3-m scale test article and test configuration presented will be used to demonstrate:
 - Efficient stowage with minimal constraints via folding fixture and backbone lightweight arms.
 - Controlled deployment via SMC elements.
 - Maintain shape accuracy of < 3.175 -mm RMS error pre-and-post-deployment in a relevant environment.

Questions

juan.m.fernandez@nasa.gov

Backup Slides

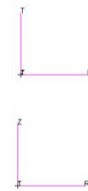
Folding Structural Analysis of Umbrella Reflector



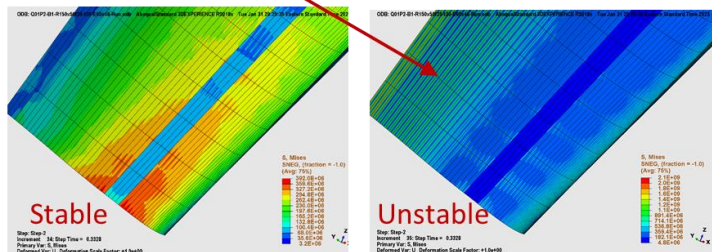
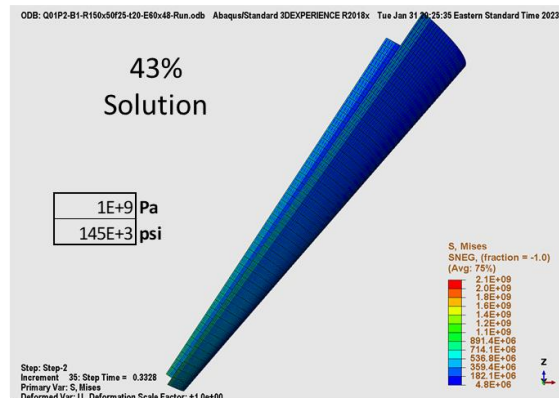
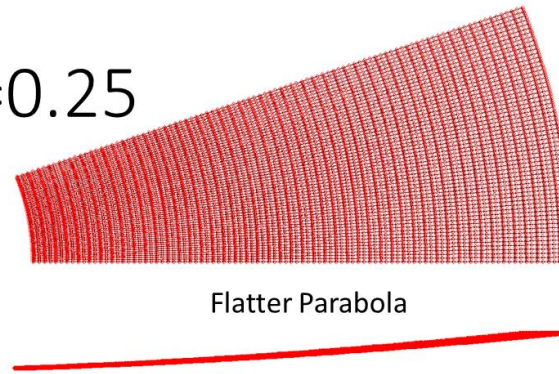
- Recently focused on folding simulations of 20° gore segments to converge to a solution. Still showing unstable buckling events in the thin shell (now confirmed during testing). Need to move to a dynamic solver with heavy damping to better model post-buckling behavior.
- Given modeling challenges, project dedicated to move to full-scale specimen fabrication for experimental validation.

20° Gores (18 for Reflector)
OR=1.5m, IR=0.5m, Fold to IR=0.25

- Static non-linear solution limit requires thicker material
 - In-plane loads cause the thinner material to buckle
 - Post buckling stiffness allows the solution to continue
 - Eventually the buckling become unstable



Center and edges
twice as thick



60° Gores (6 for Reflector)
OR=1.5m, IR=0.5m

- Demonstration gore fabricated
- As-is, too flexible for Static analysis solution
- Likely too flexible for final product
- Susceptible to permanent deformation at creases and small radius folds. Needs GSE for folding.
- Possible solution would be selective stiffening (ribs) on back side of reflector
 - Example: layers used to stiffen:



Folding Structural Analysis of Umbrella Reflector



- Parametric finite element analysis (FEA) tool developed to analyze different reflector designs and packaging schemes for the umbrella-folded architecture.
- Complete folding states challenging achievable using static nonlinear solver due to convergence issues from buckling events.
- Need to move to a dynamic solver with heavy damping to better model post-buckling behavior.

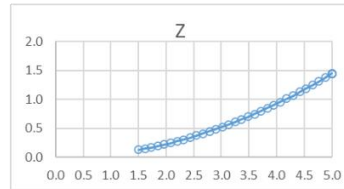
Umbrella FEM

Two Parabola efforts:

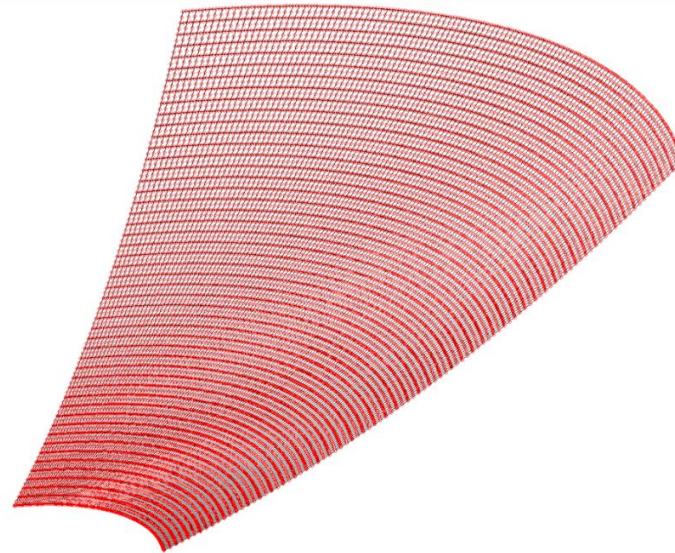
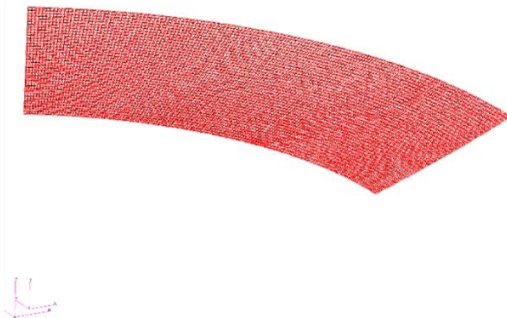
1. A strip: OR 3.7m, IR 2.7m
2. Full: OR 5.0m, IR 1.5m

Multiple cases on strip to study variables:

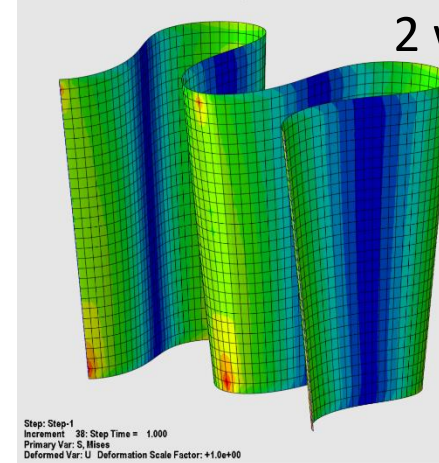
- Mesh density
- Thickness
- Solution parameters
- Number of waves (blisters)



2nd Order Mesh

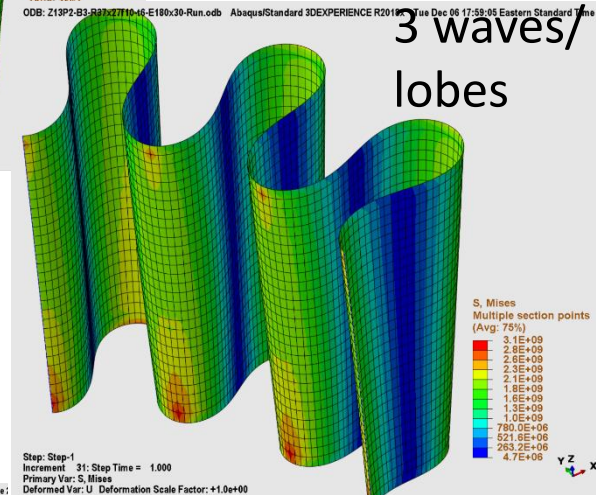


ODB: 20P2-B2-R37x2710-46-E120x30-Run.odb Abaqus/Standard 3DEXPERIENCE R2018x Tue Dec 06 17:13:08 Eastern Standard Time



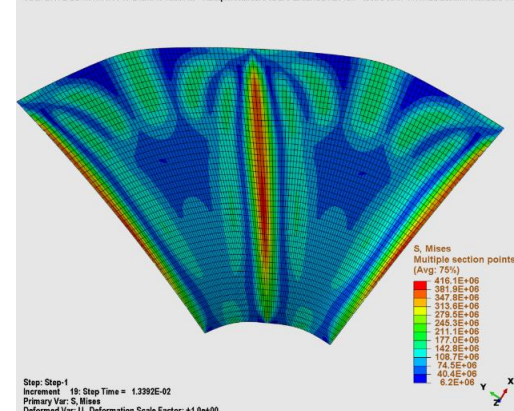
2 waves/lobes

Strip solutions to folded inner radius (IR) = 1m



3 waves/lobes

ODB: Z13P2-B1-R37x2710-46-E180x30-Run.odb Abaqus/Standard 3DEXPERIENCE R2018x Wed Dec 07 11:03:22 Eastern Standard Time

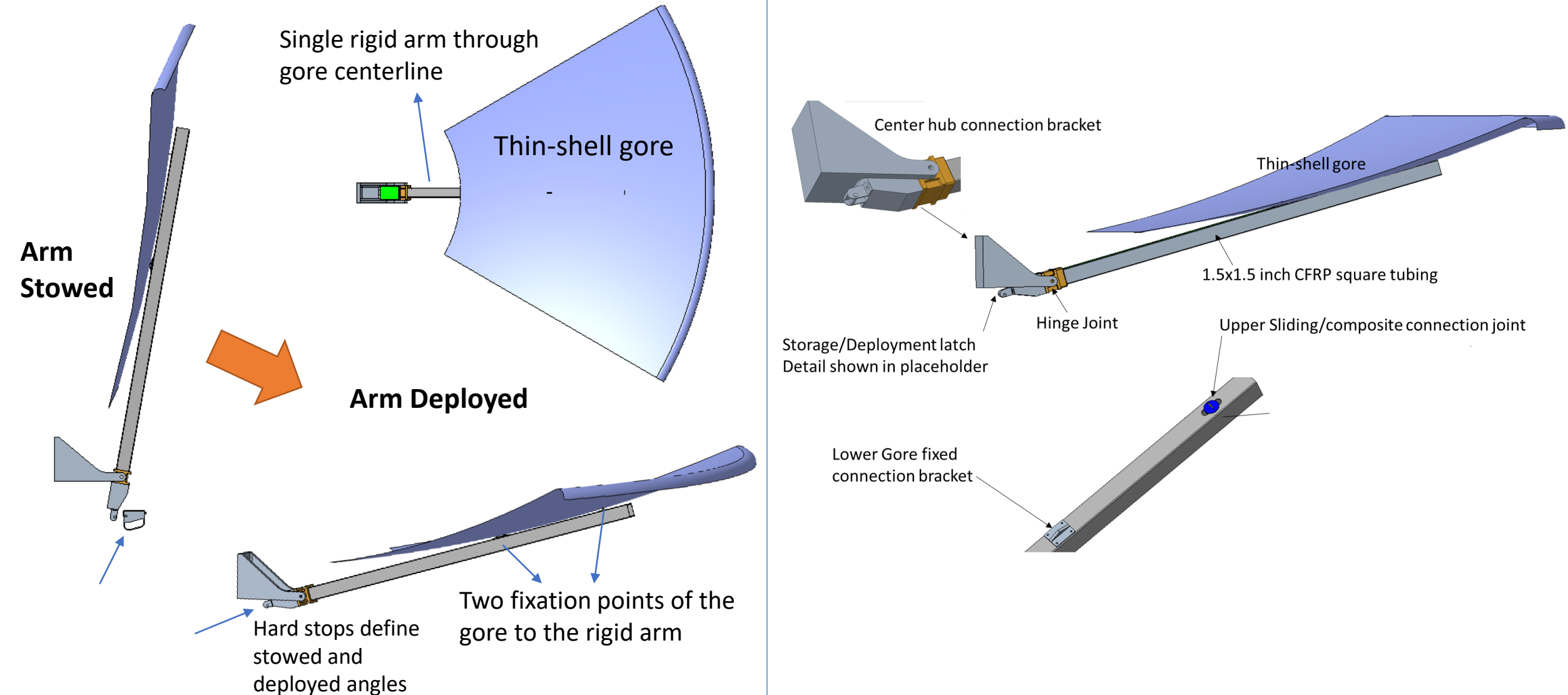


Partial solution of full gore.
Trying different boundary conditions to enable convergence of folding solution

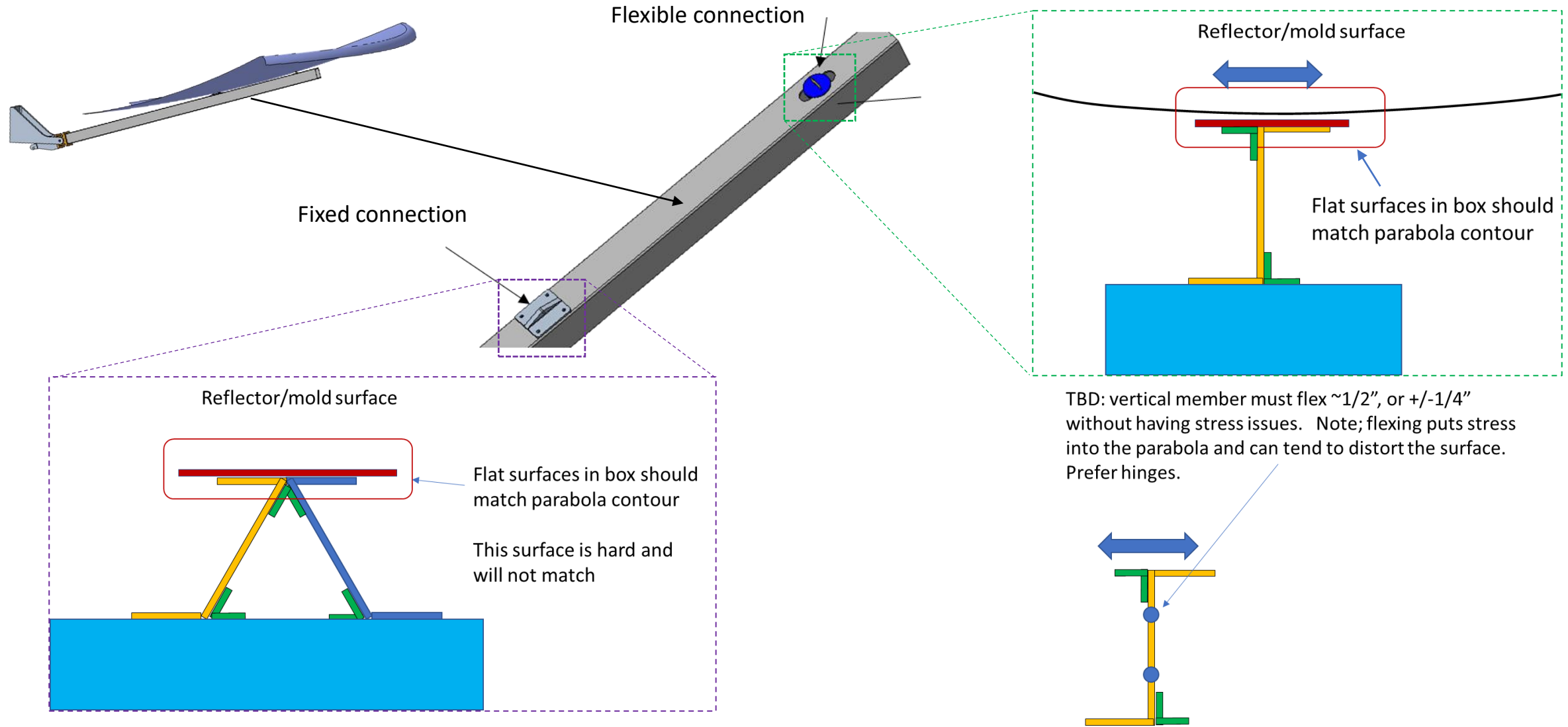
Thin-Shell Reflector Deployable Backbone Preliminary Design



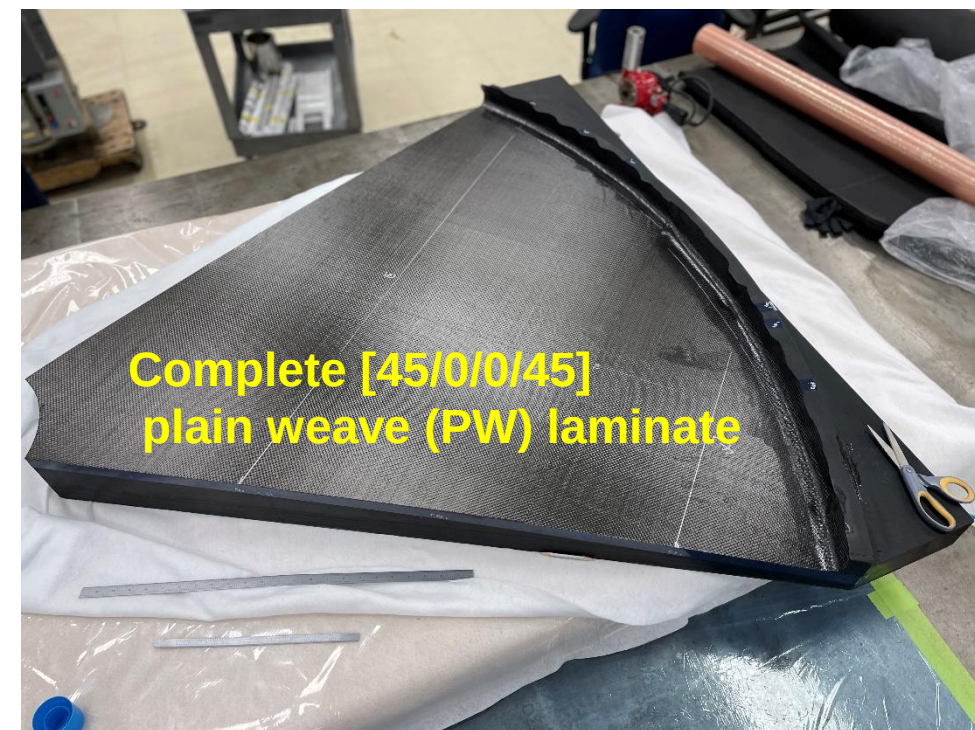
- Preliminary design of deployable rigid backbone for the segmented thin-shell reflector



- Gore to rigid backbone connections



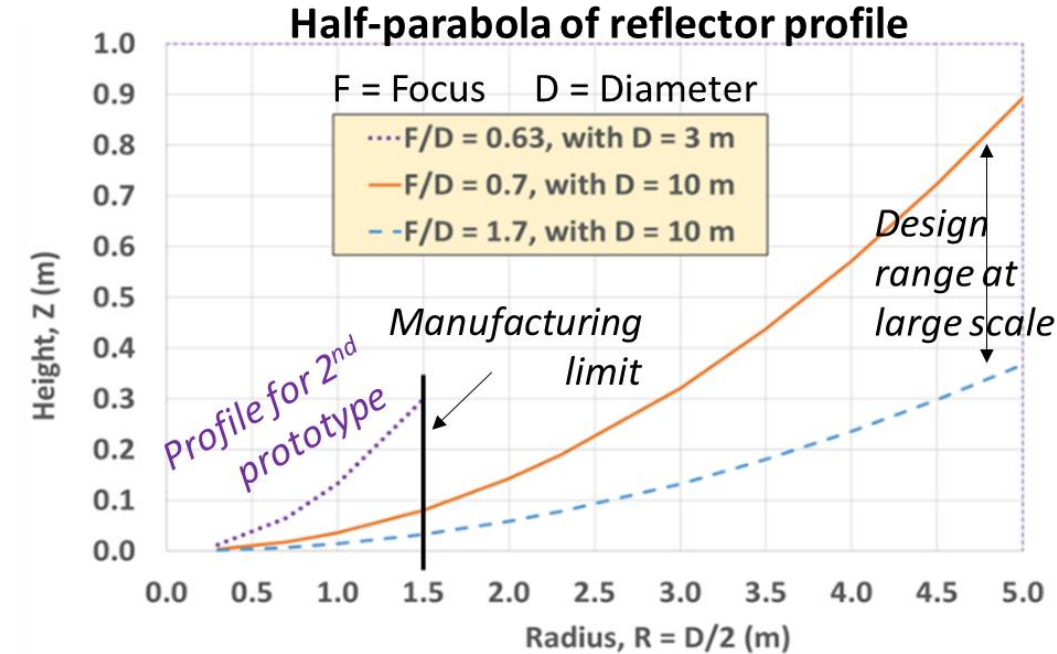
- [illegible]



Adopting a new paraboloid design: SPIDER



- After the initial testing with the prototype 60° gore shown, which followed the orange curve parabola in the graph, it became obvious that getting a good shape measurement under gravity for such thin and large surface was going to be very challenging.
- To compare to on-going SPIDER reflector effort at Maxar, it was decided to adopt the much deeper parabola of that design (purple dotted curve) for both the thin-shell umbrella-folded architecture and the rigid hexagonal panel architecture.
- A prototype 30° gore mold with the SPIDER parabola was manufactured to fabricate proof-of-concept gores with the deeper shape and assess their ability to fold up as desired.

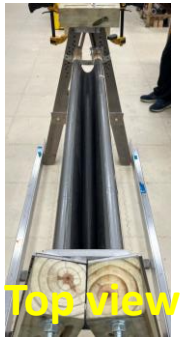


Fabricated 30° gore mold with SPIDER paraboloid

Folding of $\leq 30^\circ$ Thin-Shell Reflector Gore – Test Results Summary



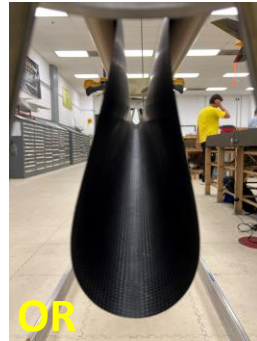
Case #1



Top view



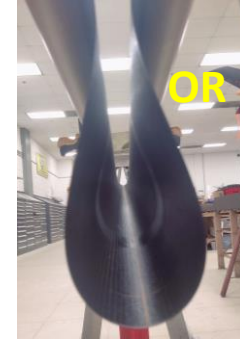
Case #2



OR



IR

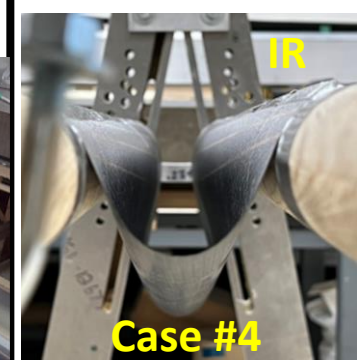


OR

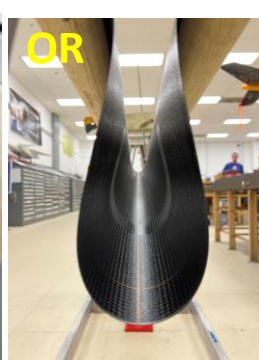


Case #3

Iso View



IR



OR

Case #4



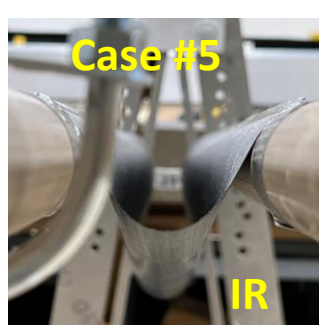
Side View



Side View



Side View

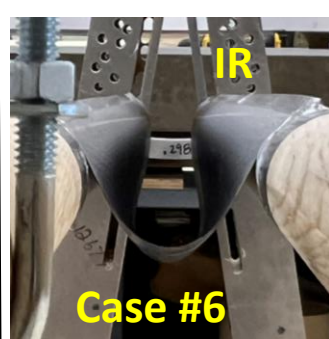


Case #5

IR



OR



IR

Case #6

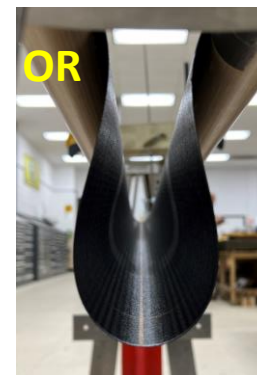


OR

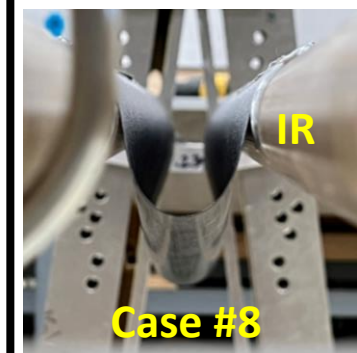


IR

Case #7

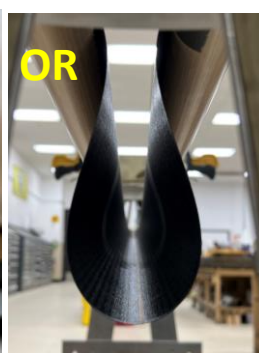


OR



IR

Case #8



OR



Side View



Side View



Side View



Side View

Offloading System for Final Test



- Concept validation via functional test of two-panel assembly of 3-m diameter scale reflector.
- Deployment testing of both the SMC hinge self-deployment and secondary locking mechanism inside thermal chamber at 80°C.
- Gravity offloading of side panel via pulley system with hanging mass traveling along chamber axis on overhead conveyor track.
- Side panel can swing on hexagonal frame that allows panel rotation on bearings about axis connecting two opposing corners.
- Shape measurement scans of the reflective surface pre-and-post deployment used to assess feasibility to support S-band and above RF (≥ 4 GHz) for large-scale antenna applications.
- Goal to demonstrate novel features that would be used in designs at ≥ 10 -m scale to enable efficient stowage with minimal constraints, controlled deployment, and maintain necessary shape accuracy in space of < 3.175 mm RMS error.

