Design and analysis of the Rocket Experiment Demonstration of a Soft X-ray (REDSoX) polarimeter mirror module assembly

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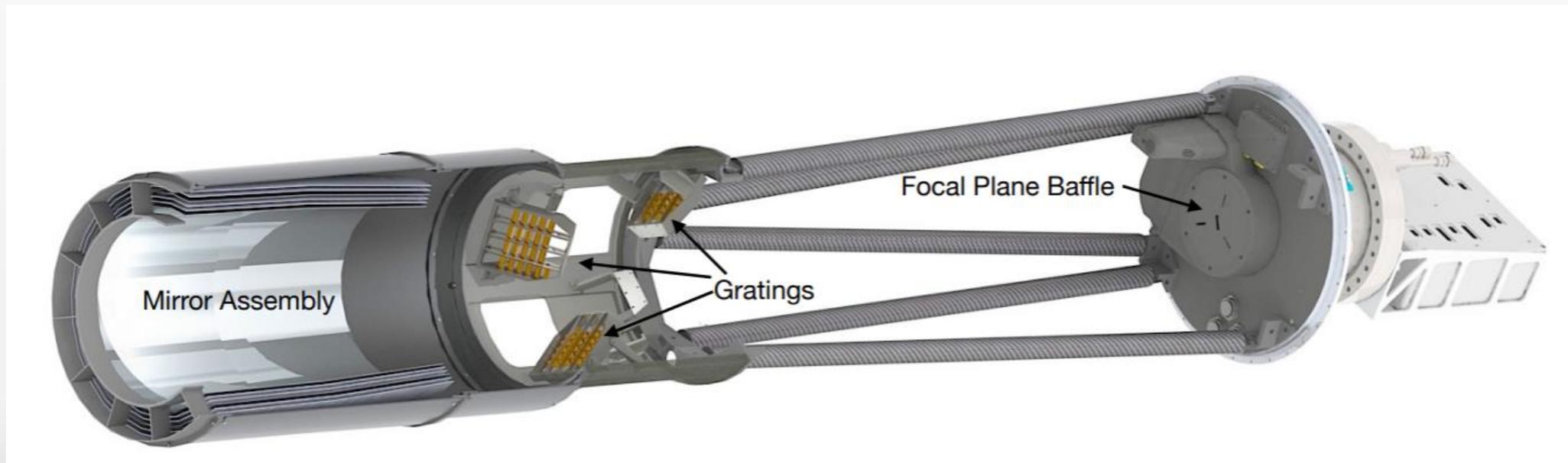
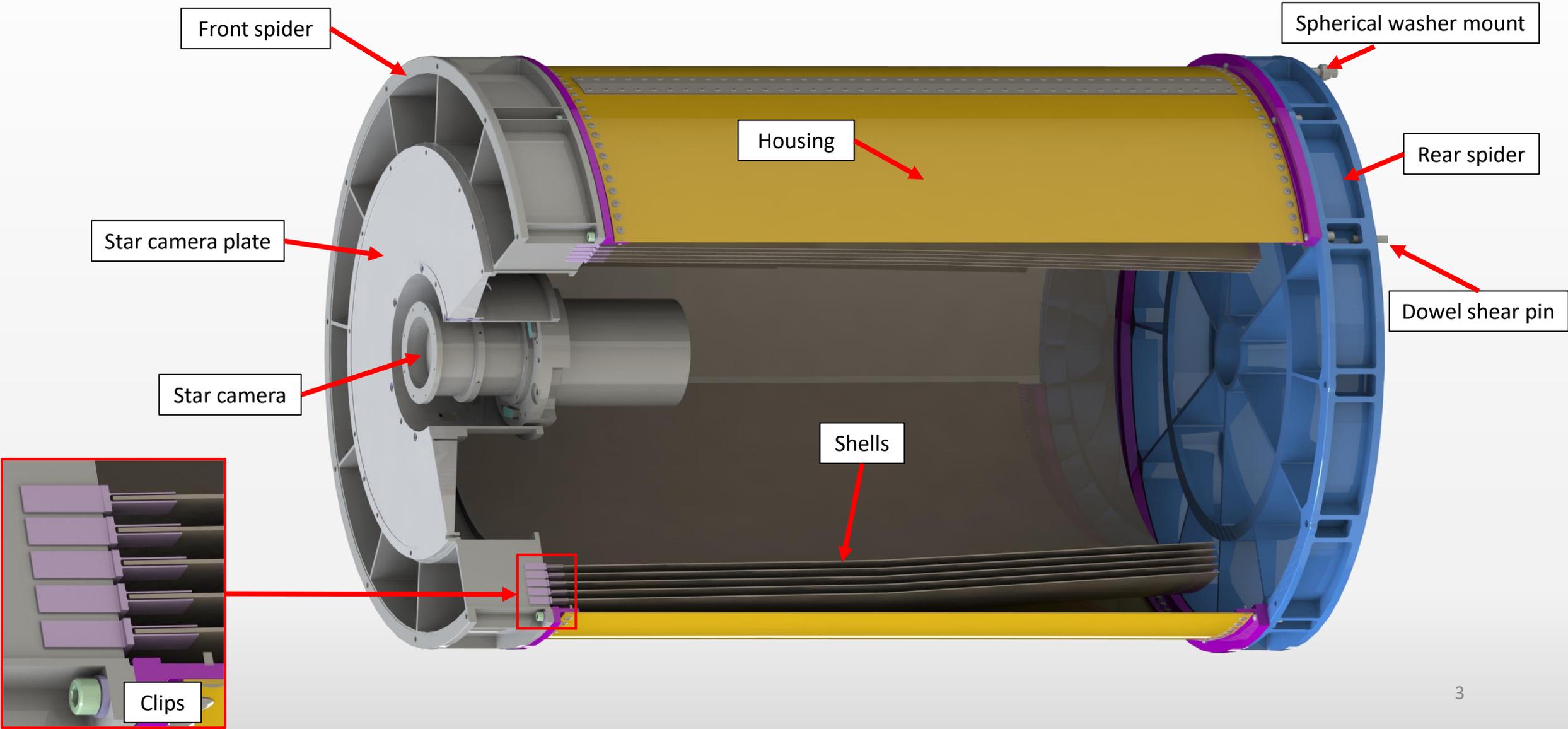Stephen D. Bongiorno, NASA MSFC – ST12

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REDSoX Experiment

- The Rocket Experiment Demonstration of a Soft X-ray (REDSoX) Polarimeter

- NASA sounding rocket experiment that is designed to demonstrate the technology necessary for measuring linear X-ray polarization as a function of energy below 1 keV.

- In astrophysics, soft X-ray spectropolarimetry will be used to probe the nature of acceleration mechanisms in quasar jets and to test models of neutron star structure.
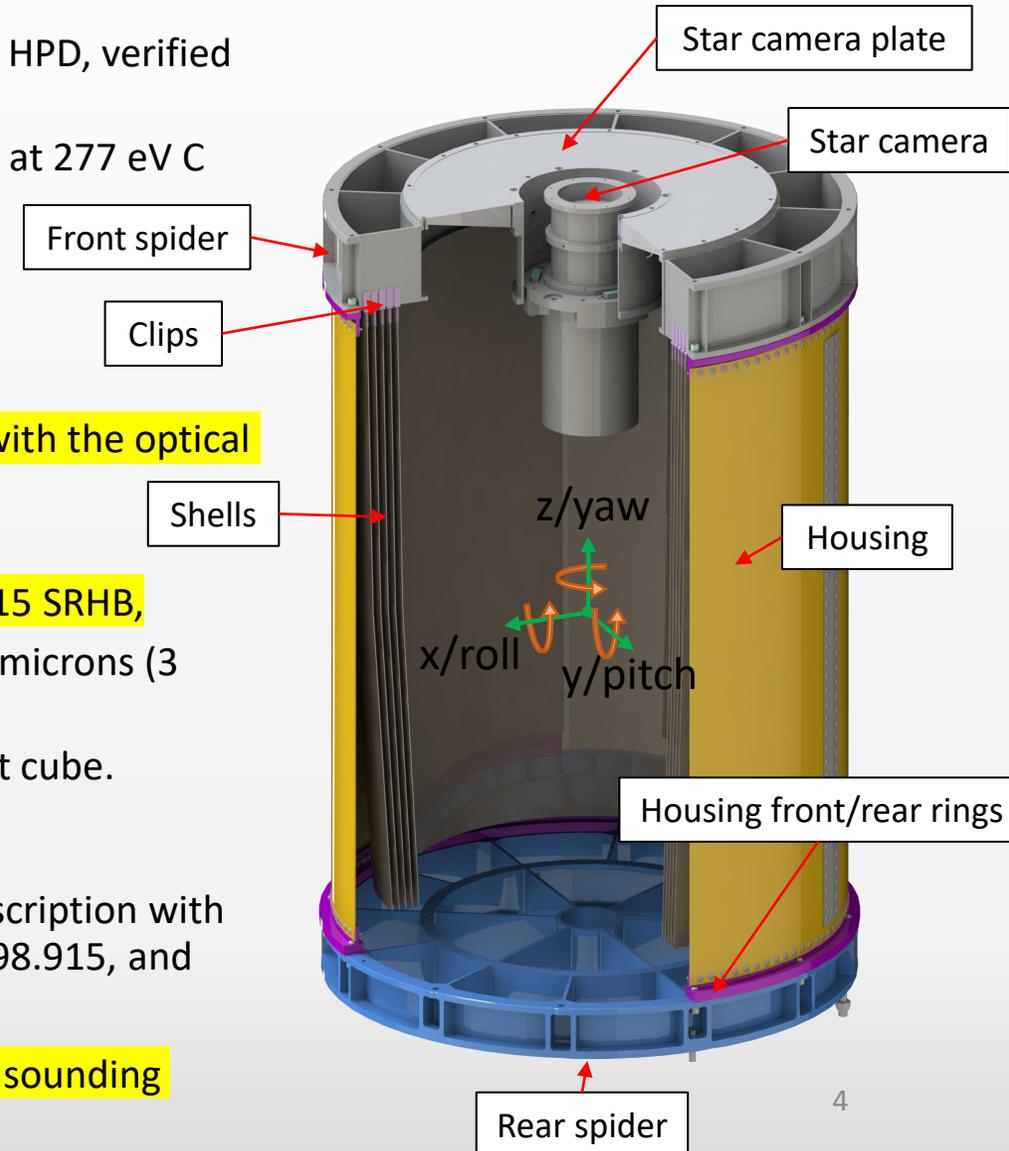
MMA Design

Front spider

Spherical washer mount

Housing

Rear spider

Star camera plate

Dowel shear pin

Star camera

Shells

Clips

MMA Requirements

- The REDSoX Mirror Module Assembly (MMA) shall:
  - have an angular resolution less than or equal to approximately 30 arcseconds HPD, verified by test at 1.5 keV Al Kα,
  - have an effective area of greater than approximately 291 cm^2, verified by test at 277 eV C Kα,
  - have structural occultations with 6-fold symmetry,
  - have mass less than approximately 50 kg,
  - fit inside the 22 inch sounding rocket skin,
  - have features to mount the ST-5000 star camera forward looking and in line with the optical axis,
  - have a focal length of 2500 +/- 5 mm,
  - be vibration tested before X-ray calibration to levels specified in the NASA 2015 SRHB,
  - have knowledge of the optical node position +/-0.5 mm (3 sigma) in Z, +/- 50 microns (3 sigma) in X and Y, relative to the alignment cube, and
  - have knowledge of the optical axis +/- 30 arcseconds relative to the alignment cube.
- ❖ Optics will be made with the MSFC electroformed nickel replicated optics process
- ❖ MMA design will be based on the five Micro-X mandrels which have a Wolter-I prescription with 2.5 m focal length, 301.28 mm segment lengths, and 222.190, 214.203, 206.447, 198.915, and 191.601 mm intersection radii. Shell thickness will be 1 mm.
- ❖ Prescription was designed to be the largest X-ray optic that would fit into a 22 inch sounding rocket skin.

Star camera plate

Star camera

Front spider

Clips

Shells

z/yaw

x/roll

y/pitch

Housing

Housing front/rear rings

Rear spider

4

Design choices

- Front spider
  - Spider manufactured from 17-4PH stainless steel via electrical discharge machining (EDM). (IXPE)
  - Spider thickness scaled up from FOXSI-4 aspect ratio, which resulted in a 3 inch thick spider.
  - Front spider required to contain 6, 12, or 18 spokes. Six is too few for launch loads, 12 has sufficient bond area and minimizes effective area occlusion.
  - Alignment cube mounted to front spider for alignment during integration with REDSoX payload. Position of cube center wrt optical node will be measured with combination of CMM and shell alignment station metrology. Cube axis wrt optical axis will be measured with laser and X-ray measurements during X-ray calibration.

- Clip design successfully used on FOXSI- 1,2,3, and 4. Enables active correction of shell circularity during shell assembly.

- Star camera is recessed inside MMA. Cabling will be routed externally. Assumed the most massive star camera design variant. Mechanical interface is identical for all variants.

- Rear spider
  - Interface to payload will be three shimmed spherical washer bolts with three shear pins. This enables pitch/roll adjustment during payload integration. (IXPE)
  - Rear spider contains radial stiffeners to reduce influence of gratings module on MMA dynamics.

- All MMA component interfaces are separation critical joints and contain pin secondary locking features. Per standard NASA-STD-5020B


Alignment cube

Clips

Spherical washer mount

Dowel shear pin
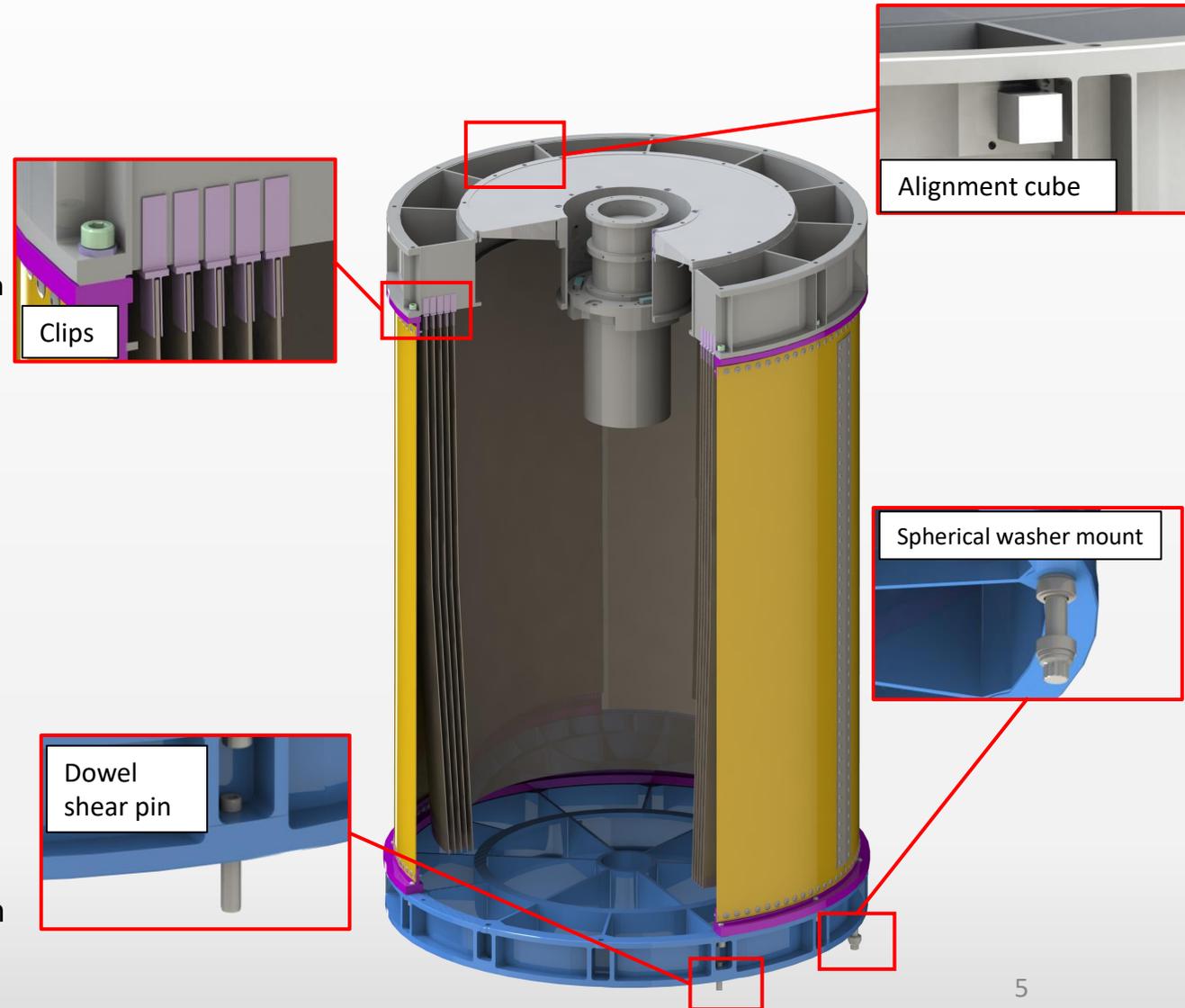
MMA Mass

- MMA mass is approximately 50% shells.
- If needed, we expect that 6 kg could be removed with additional design and simulation work.

Component	Mass (kg)	Mass (lbs)
Front spider	9.14	20.10
Star camera plate	1.00	2.19
Star camera cup	0.36	0.80
Star camera (-9 Mk3 LoPro Mass Model)	1.99	4.37
Clips	0.12	0.26
Shells	34.23	75.30
Housing rivets	0.24	0.53
Housing front ring	1.86	4.09
Housing rear ring	3.05	6.71
Housing sheet metal	9.05	19.92
Rear spider	10.60	23.31
Total	**71.63**	**157.58**

Dynamics simulation

- Solidworks™-generated STEP imported into ANSYS™ 2023

- Small features (fillets, chamfers, etc.) simplified to sharp corners to reduce computation time. Housing and shells modeled with shell elements. Remainder modeled with solid elements.

- Rivets and screws modeled as spring elements rigidly connected to nearby nodes to reduce stress concentration artifacts. Spring rate of fasteners taken from https://mechanicalc.com/.

- Based on lessons learned during IXPE test, damping of 0.7% applied to entire model. This is conservative compared to standard 2.5% for metal structures.

- SRHB 12.7 gRMS random excitation in three axes.

- Constrained by three mounting points (6 dof) and 3 shear pins (4 dof) at rear spider interface to payload.

- FEA solved with implicit solver, ~1M node mesh.

- Results:
  - Factors of safety
  - Shell displacement at free edge
  - Housing buckling
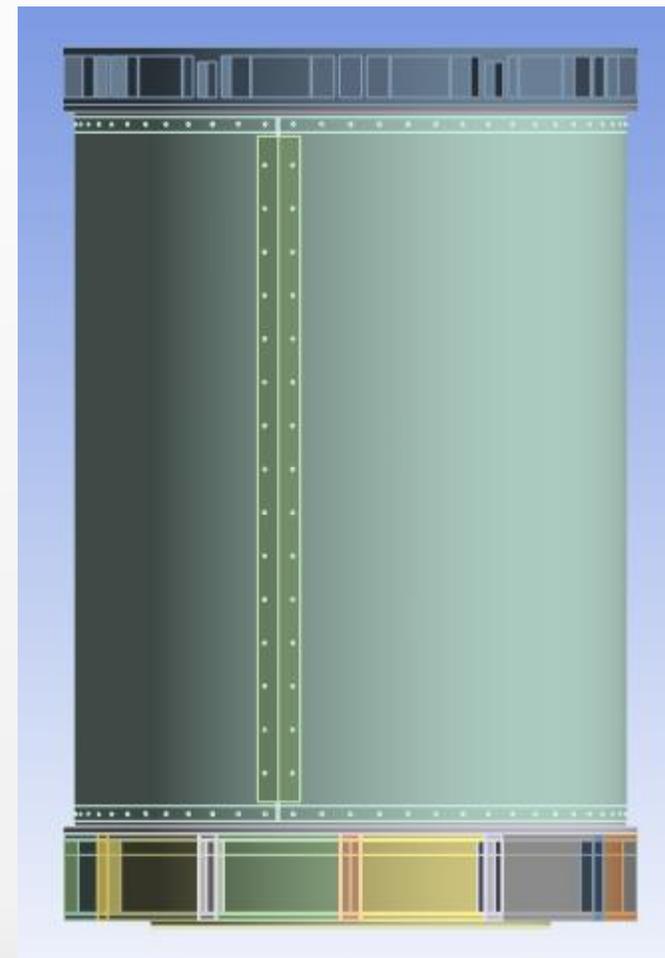
REDSoX MMA FEA model

Dynamics simulation results

	Shell displacement (in.)	Equivalent stress (psi)						Force (max., lbf.)		
	Radial	Mirror Shells	Rear Spider	Outer Housing	Front Spider	Clips	Star camera plate	Mirror Bond	Clip Bond	Rivets
Lateral	0.008	12000	35000	50000	67000	32000	6150	294	174	150
Axial	0.001	9000	26000	40000	55000	36000	15000	228	222	90
Yield strength (A-basis allowable)	27000	145000	93000	145000	145000	26000	752	755	350	
FOS	2.25	4.14	1.86	2.16	4.03	1.73	2.56	3.40	2.33	

- Two dominant modes in both axial and lateral excitation:
  - 130 Hz Lateral Mode Participation 66%
  - 134 Hz Lateral Mode Participation 10%
  - 270Hz Axial Mode Participation 38%
  - 340Hz Axial Mode Participation 22%
- GSFC-STD-7000B requires FOS>1.9 for epoxy bonds and FOS>1.6 for metals.
  - A-basis = 1% fail at 95% confidence. Shown mirror bond force is the worst case. All other bonds are lower.
- No shell contact expected – Harmonic analysis at dominant mode frequencies showed displacement of 0.008" after removing the in-phase displacement of 0.022". Assuming 1 mm shell thickness, minimum shell separation is 0.287 inch between shell 4 and 5 at the H end, indicating no contact. Harmonic analysis is justified by high mass participation and enables quantifying separation between shells because it computes amplitude and phase.
- For FOS calculation near stress concentrations caused by rigid elements, stress values were chosen one node away from rigid element, per MSFC ES22 Flight Structures group guidance.
- ANSYS™ **linear buckling analysis showed that the MMA has >20 FOS** against local buckling and shows no structural buckling.

Analysis methods

- IXPE bond analysis method
  - Pull test data gives A-basis force allowable. Scale force to REDSoX bond area. IXPE testing at smallest and largest bond areas showed that strength scales as area.
  - High-fidelity sub-model used to measure bond displacements.
  - Displacements input into low-fidelity sub-model, which matches MMA dynamic model fidelity, to measure stiffness.
  - Stiffness used in full model bond spring element to measure forces on bonds.
  - FOS is calculated by comparing modeled force to A-basis allowable force.

- Rivet modeling method – High density mesh used to resolve rivet stress concentration artifacts. Apply rigid connection to head OD of rivet, not shank OD.

- Fastener method – Evaluate strength FOS and verify that tensile force does not exceed preload (prevent unclamping misalignment).
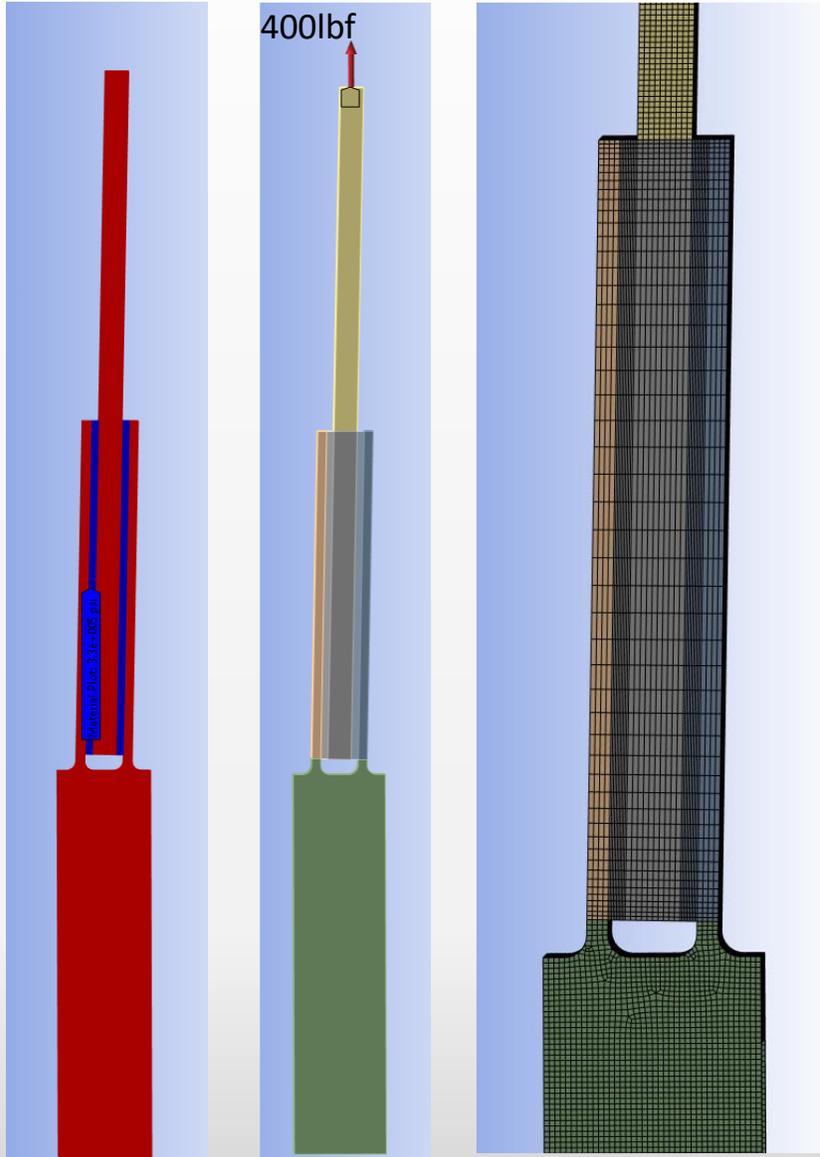

High-density mesh

Rivet spring elements

Rivet head OD
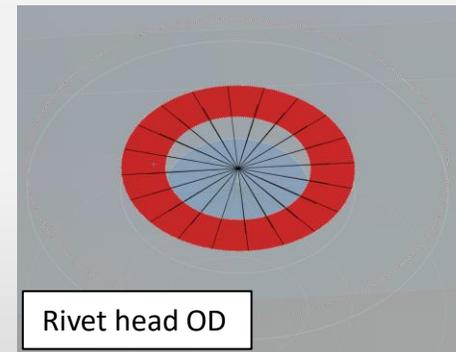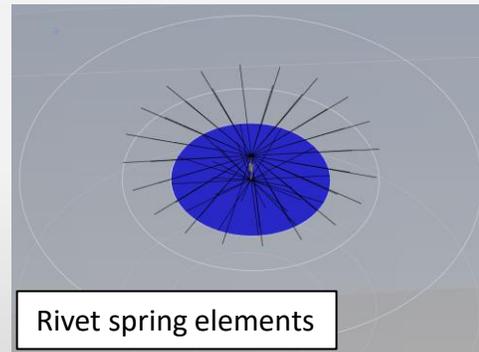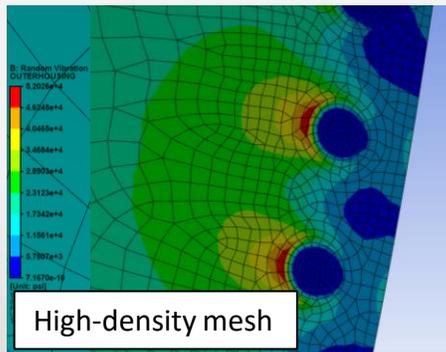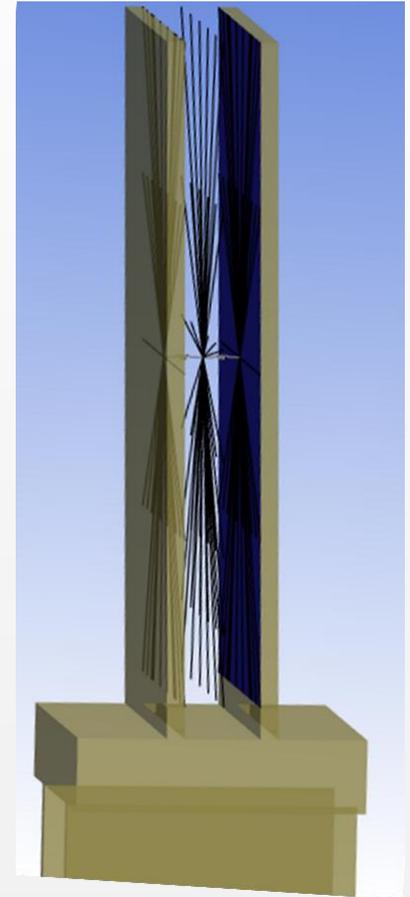
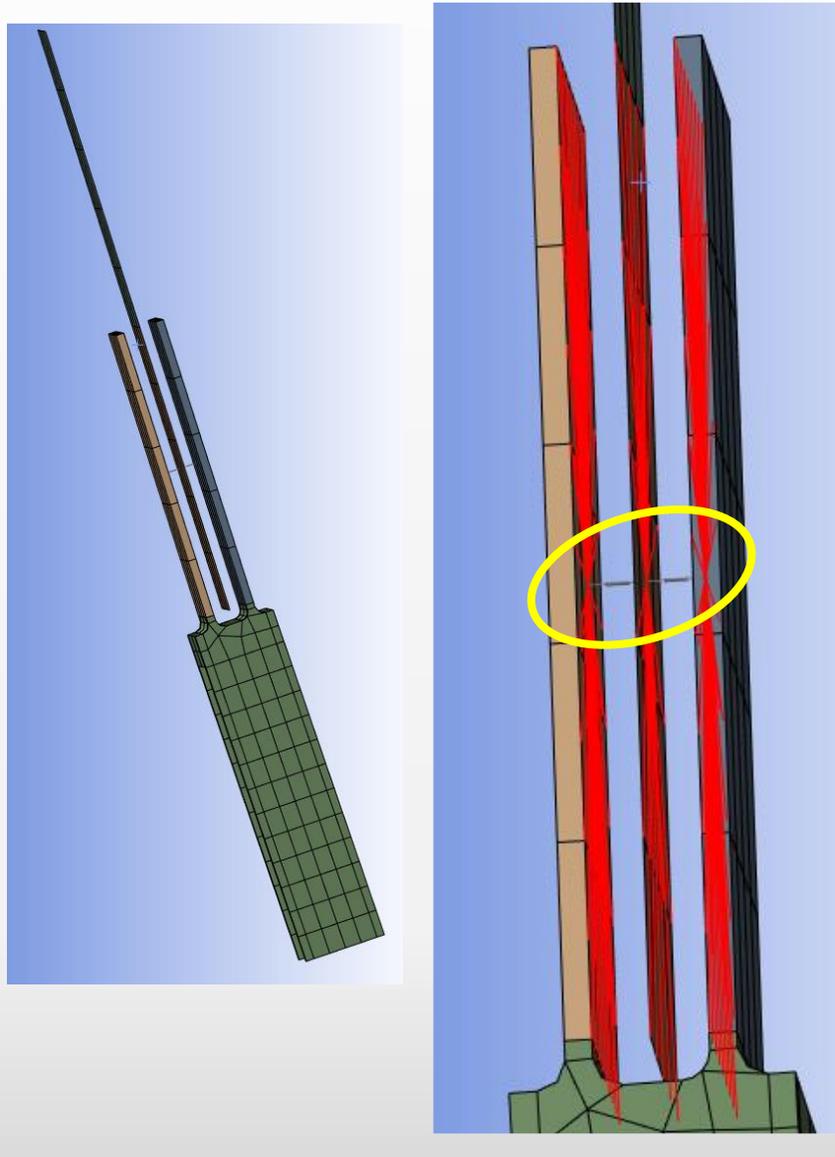Two spring elements connecting a set of rigid elements on the shell and comb

Sub-modelling to derive bond stiffness

SUBMODEL#1

SUBMODEL#2

400lbf

Based on IXPE
bond strength ~2200psi
Bond area = 0.23"(w) x 0.59"(h) x 2 (sides)
Bond area = 0.2714 sq.in
Allowable = 2200psi x 0.2714 sq.in = 597lbf

For REDSoX:
Bond area = 0.177"(w) x 0.59"(h) x 2 (sides)
Bond area = 0.2088 sq.in
Allowable = 2200psi x 0.2088sq.in = 459lbf

BOND JOINT SUBMODELLING

Model 1: Ultra-Mesh Bond Geometry
- Input the book value material property for the bonds
- Apply the pull force of 400lbf
- Calculate the Shell Displacement (0.00127")

Model 2: Simple/coarse model (similar to dynamic model case)
- Apply the shell displacement (0.00127")
- Iterate over different spring stiffness (2E+6 lb/in) to reach the desire shell displacement.

Conclusion

- REDSoX Mirror Module Assembly

  - Preliminary Design Completed and show positive margin of safety

    - All Metallic components have >1.6 FOS

    - All Bonded joints have > 2.5 FOS

  - Future Work:

    - Planning to change the rivet design into a welded joint

    - Reduce the overall mass while maintaining/improving the safety factor

Questions