Demonstration of Deployment Accuracy of the Starshade Inner Disk Subsystem

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Outline

1. Introduction
   - Background
   - Objective
2. Experimental Apparatus
   - Test Article
   - Gravity Compensation
   - Metrology
3. Experimental Procedures
   - Shimming
   - Deployment
4. Test Results
   - Definition of Deployment Error
   - Deployment Accuracy
   - Deployment Repeatability
5. Conclusions

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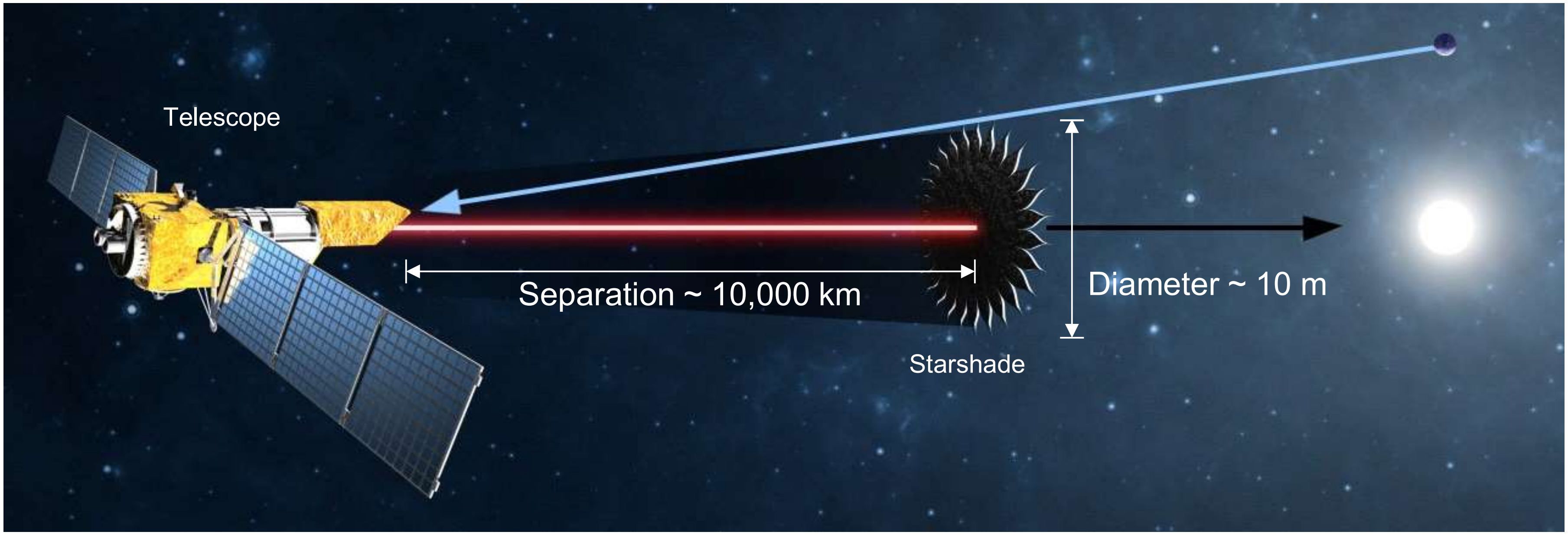
Introduction to Starshades

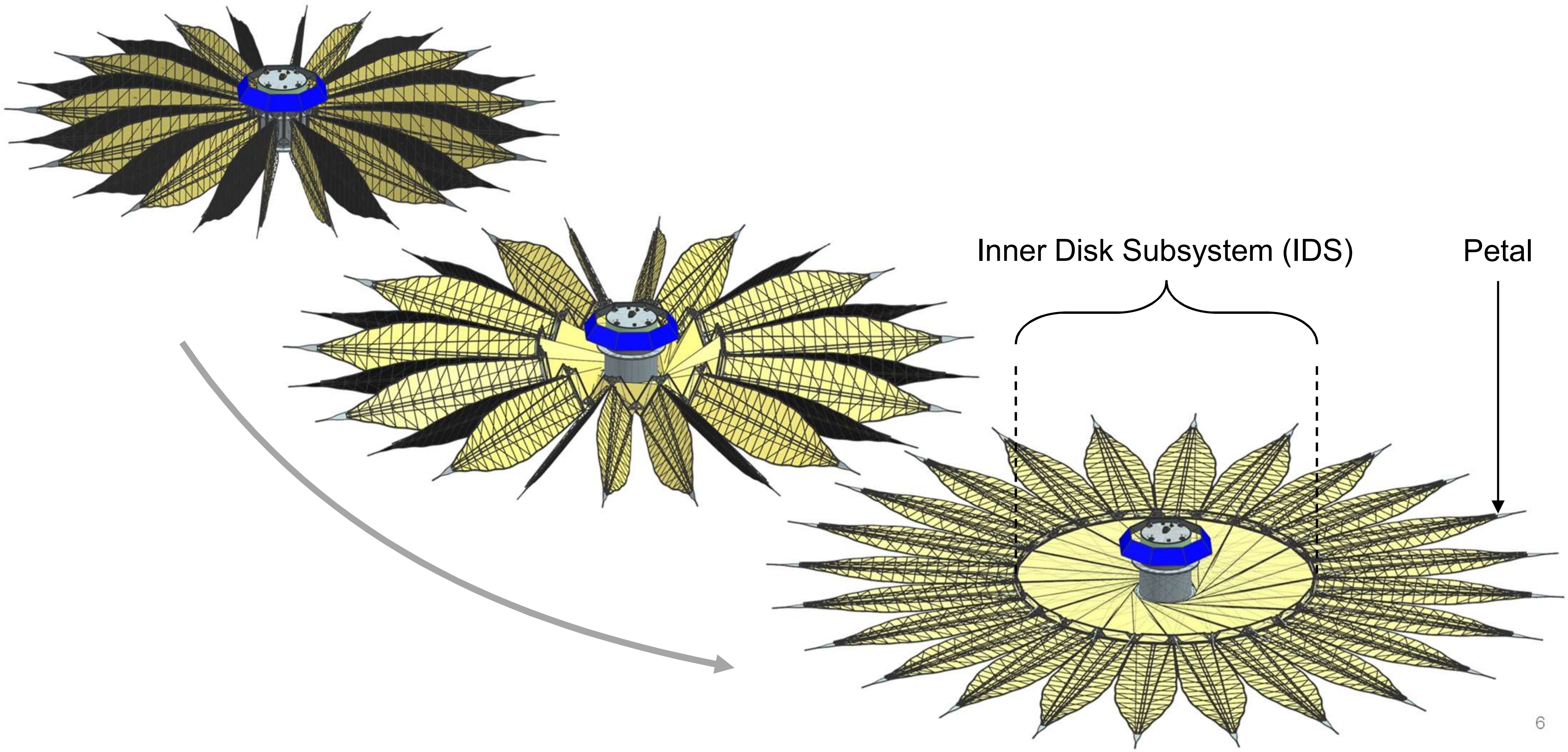
- Starlight suppression for exoplanet imaging using an external occulter
  - Independent spacecraft, formation flying with a space telescope
  - Desired starshade diameters ~ 10s of meters ⇒ deployable system



Starshade Deployment Concept

https://exoplanets.nasa.gov/resources/1015/flower-power-nasa-reveals-spring-starshade-animation/

Starshade Inner Disk Unfolding Concept

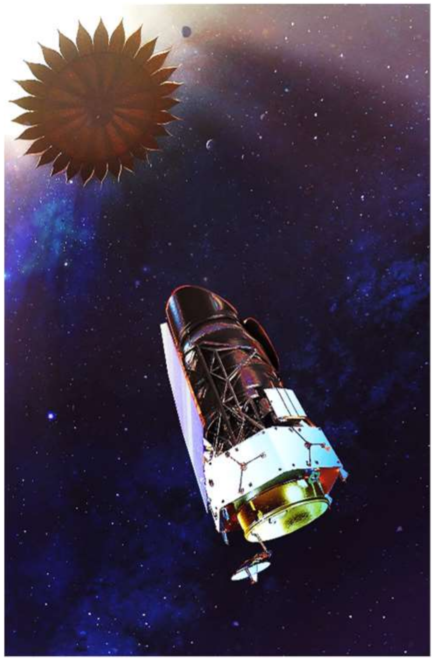


Reference Mission Concepts for Starshade Technology

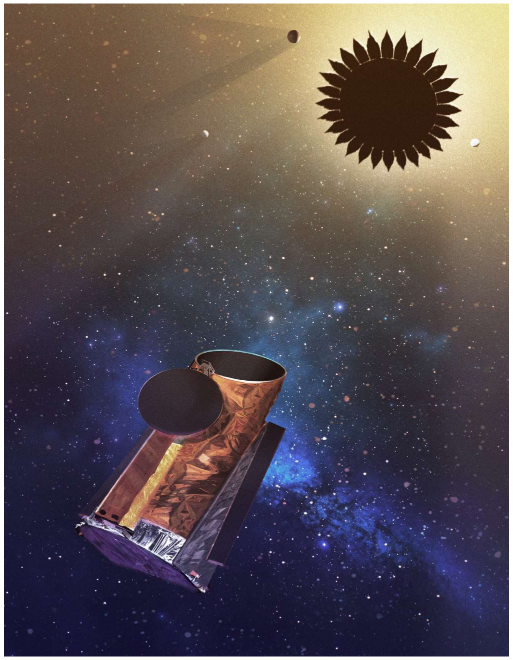
- WFIRST Rendezvous Probe concept – Starshade Rendezvous Mission (SRM):
  - Starshade: 26 m diameter, 8 m-long petals, 10 m-diameter inner disk
  - Telescope diameter: 2.4 m
  - Separation: 26,000 km

- Habitable Exoplanet Observatory (HabEx) concept starshade:
  - Starshade: 52 m diameter, 16 m-long petals, 20 m-diameter inner disk
  - Telescope diameter: 4 m
  - Separation: 76,600 km

- This work is relevant to SRM at full-scale and to HabEx at half-scale



WFIRST SRM



HabEx starshade

Background

- S5 (Starshade-to-TRL5) activity within NASA's Exoplanet Exploration Program will bring starshade technology to Technology Readiness Level 5 (TRL5)

- 15 milestones across 3 technology areas:
    1. Optical testing and modeling of starlight suppression
    2. Formation flying between a space telescope and a starshade
    3. Stable and accurate deployable mechanical system

- We address Milestone 7C, related to the mechanical deployment accuracy of the starshade Inner Disk Subsystem (IDS)

Objective

- Milestone 7C: Inner Disk Subsystem with optical shield assembly that includes deployment critical features demonstrates repeatable deployment accuracy consistent with a total pre-launch petal position accuracy within ± 300 μm

- Petal position accuracy errors applied at the petal attachment interfaces

Petal position error component	Allocation, 3σ (μm)
Radial bias	35
Radial random	150
Tangential random	120

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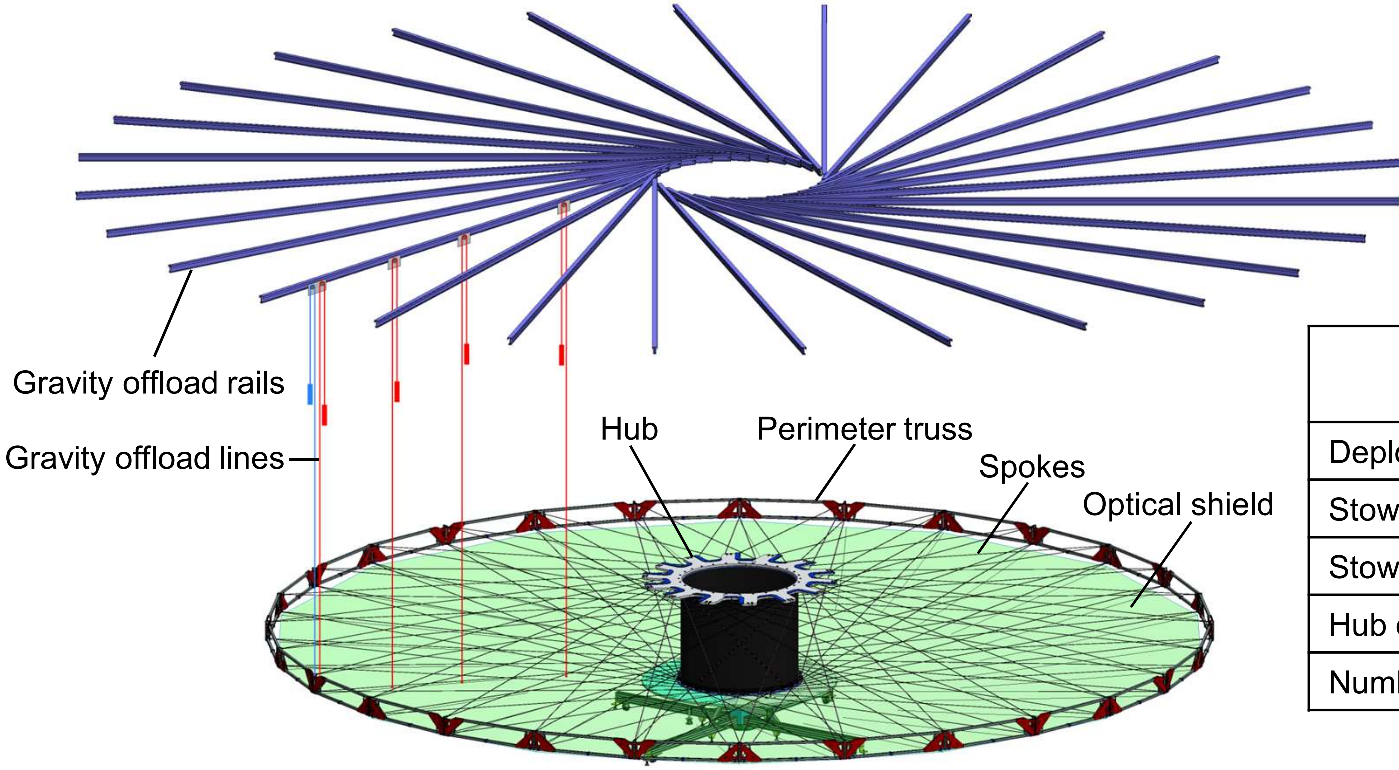
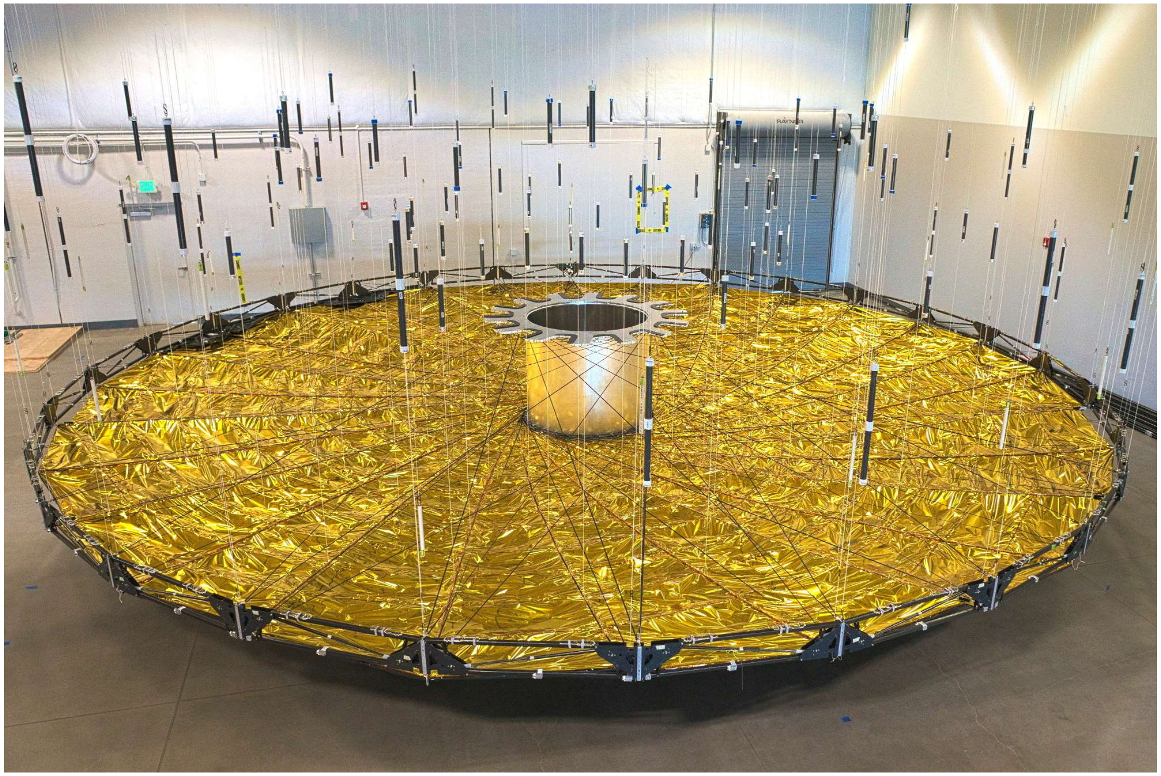
Experimental Apparatus



	Test Article	SRM IDS
Deployed diameter	10.6 m	9.8 m
Stowed diameter	2.3 m	2.3 m
Stowed height	1.2 m	1.4 m
Hub diameter	1.3 m	1.6 m
Number of petals	28	24

- Full-scale IDS test article was fabricated, along with gravity offload system
- Housed in air at Tendeg facility at Louisville, Colorado

Test Article

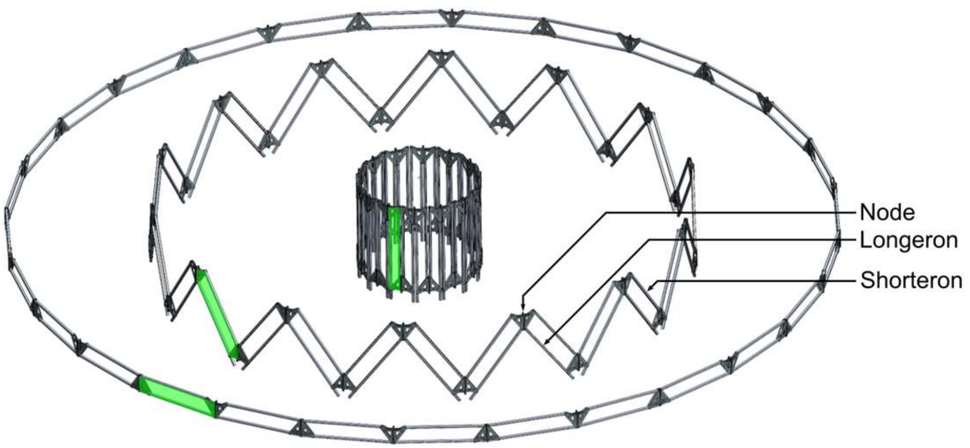


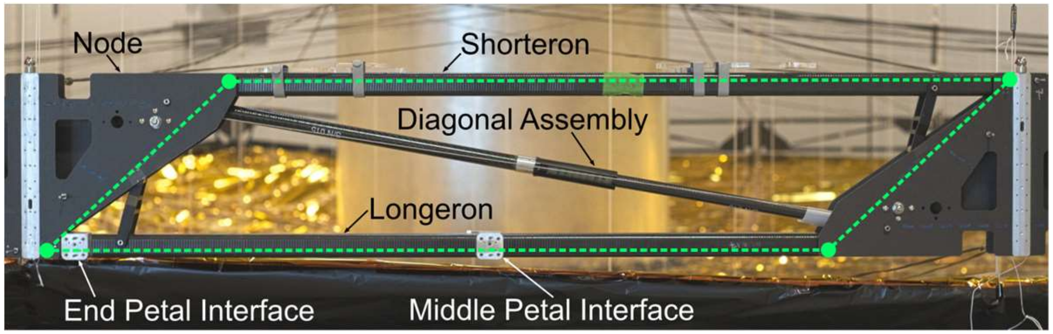
Deployed

Stowed

Perimeter Truss

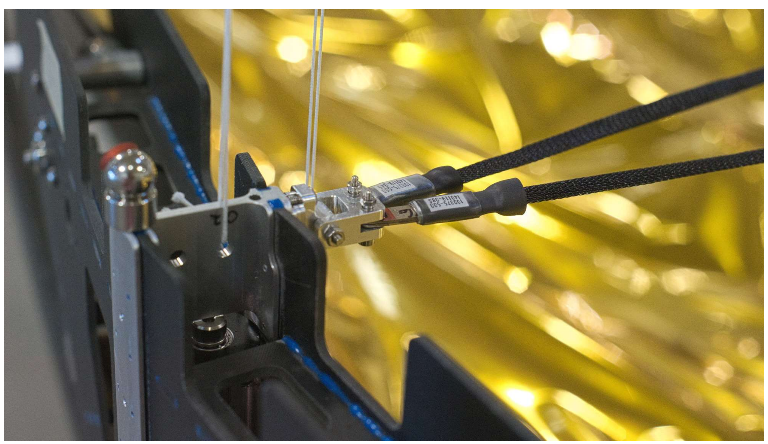
- Stowed barrel form → deployed ring
- 4-bar linkage of each truss bay enables stowage and deployment
- Driven by a single cable, routed along the diagonals of all bays
  - Cable gets reeled by a drive node
- Longerons and shorterons: CFRP with epoxy resin
- Nodes: CFRP plates bonded to aluminum center beam using epoxy

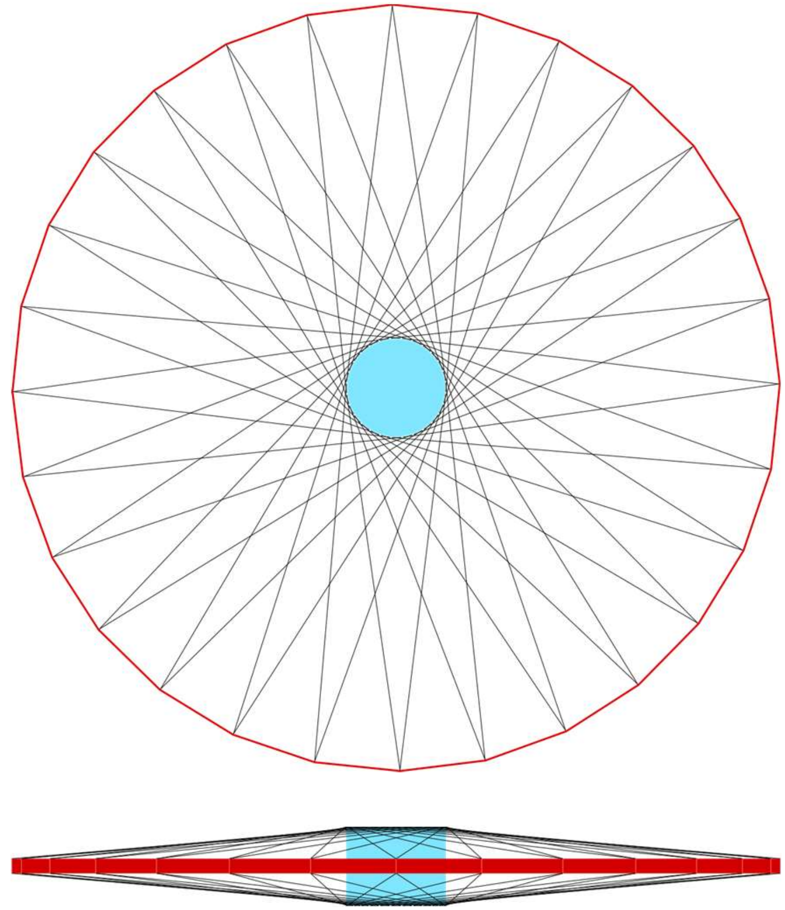




Spokes

- 4x 5 m-long spokes per node, 112 total
- Nominal spoke preload: 71 N (16 lbf)
- Comprised of unidirectional CFRP tape 6.35 mm wide, 0.10 mm thick
  - CFRP: IM7 carbon fiber in a PEKK matrix
  - Protected by flexible braided PEEK sheath
- Manufactured in custom precision jig; standard deviation of prestressed length: 54 μm

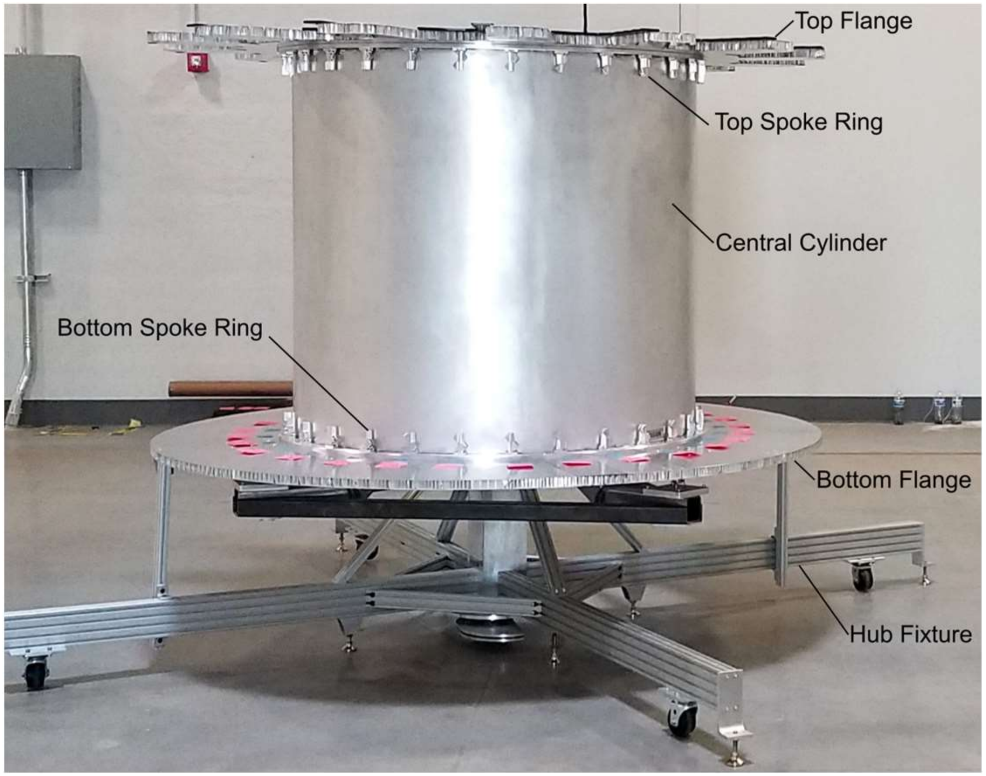




Hub

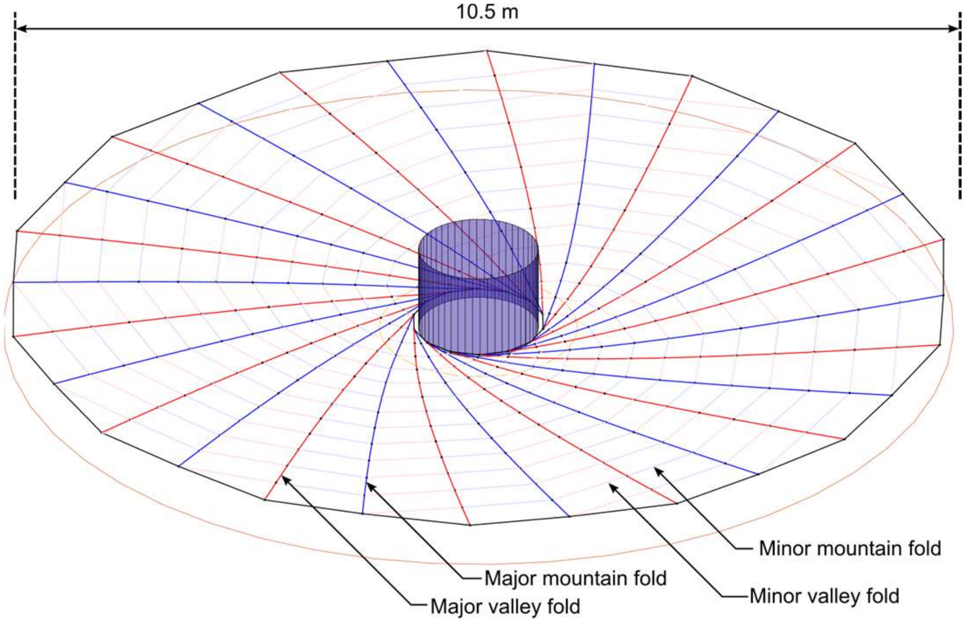
- Aluminum components bonded together:
  - 2x spoke rings
  - 1x central cylinder
  - 2x flanges

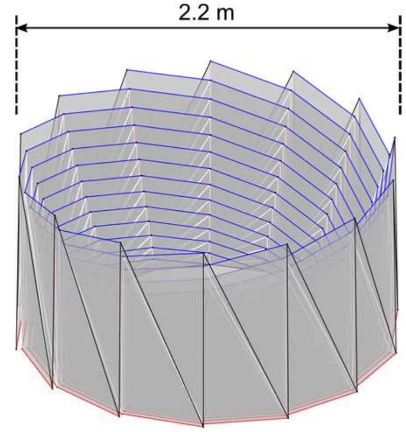
- Spoke interfaces on the hub were shimmed after complete assembly



Optical Shield (OS)

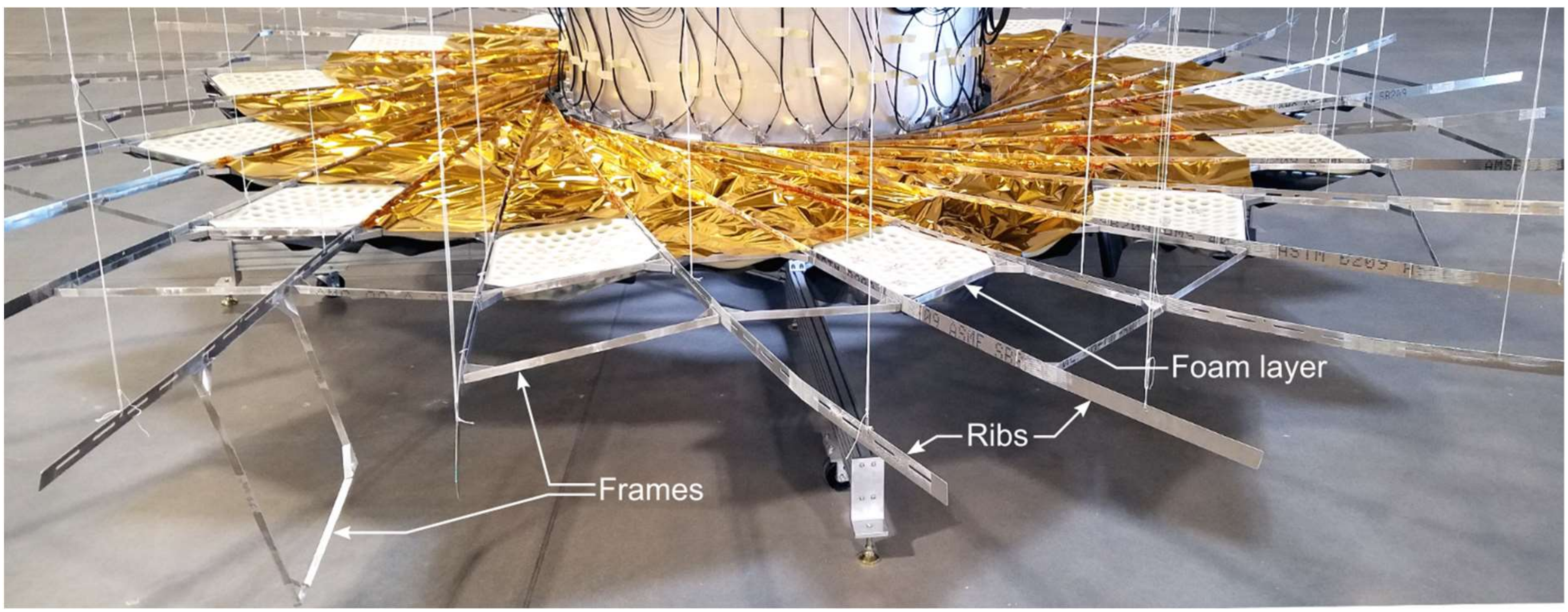
- Primary light-block element of the IDS
- Planar panels hinged together with revolute joints
    - Hinge placement (fold pattern) designed using modified origami algorithm
    - Deployed conical surface wraps while accounting for material thickness
    - Nominally unstrained when fully stowed and fully deployed





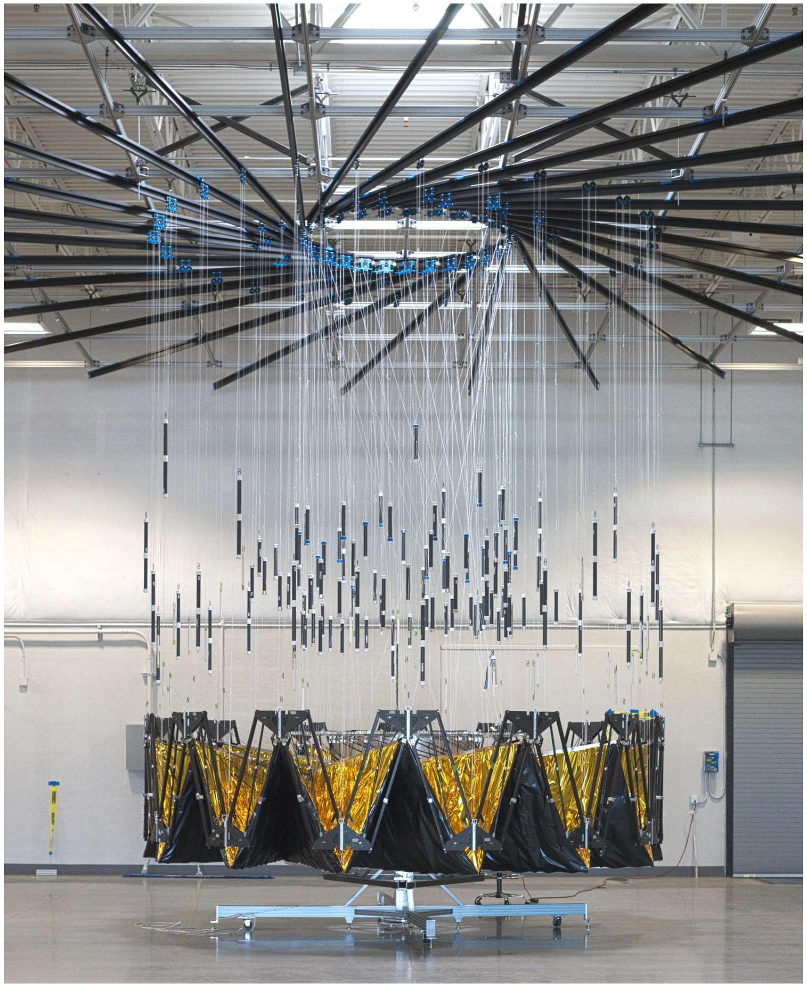
Optical Shield (OS)

- Planar panels made from aluminum “picture frames”; members: 1 mm thick, 16 mm tall
- Frames filled with opaque blankets: 2x Kapton layers + 16 mm-thick foam separator
- 32 mm-tall foldable aluminum ribs along major fold lines for out-of-plane bending stiffness
- Out-of-plane bending stiffness is important for offloading, decoupling the OS from truss



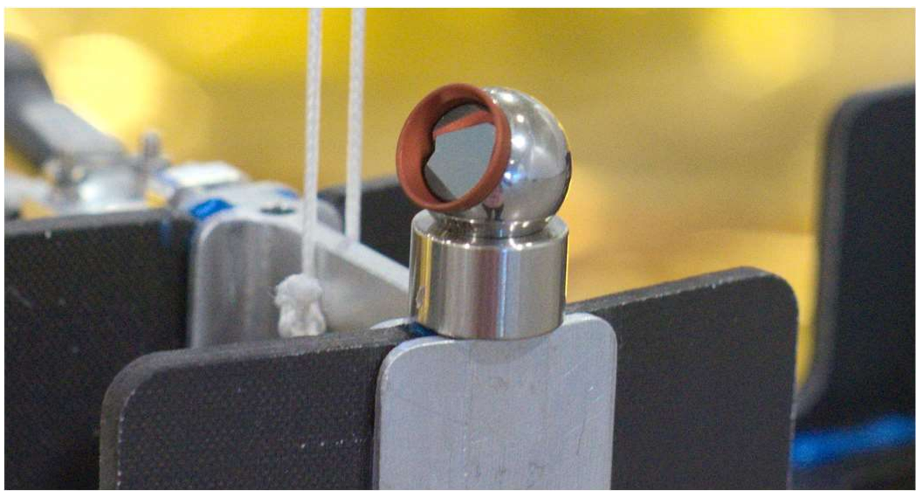
Gravity Compensation

- Counterweighted at 140 discrete locations
  - 4 offload points at each OS major fold line
  - 1 offload point at each perimeter truss node
- Counterweight pulleys on wheeled carts, free to move along 28 overhead rails
  - ~5 m above the perimeter truss (when deployed)
- Hub held by a fixture
  - x, y, z translational degrees of freedom fixed
  - Rotation about the x, y axes fixed
  - Rotation about z-axis free; the hub needs to rotate relative to the perimeter truss during deployment as the OS is unwrapped

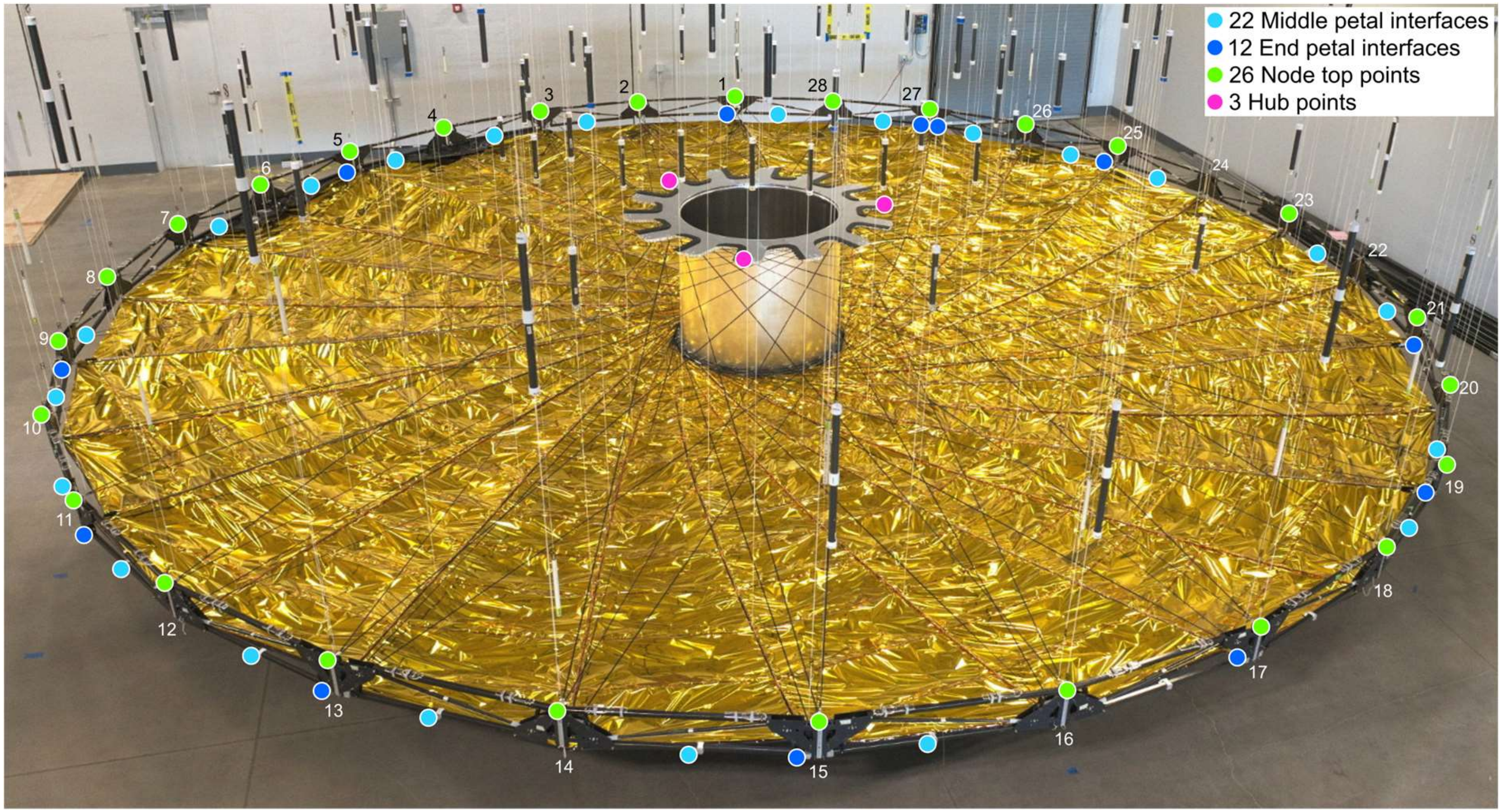


Metrology

- Leica AT402 laser tracker used to measure 3D location of the centers of spherically mounted retroreflectors (SMRs) affixed to the IDS prototype
  - Laser-tracker-reported 3σ uncertainty was between 3 μm and 30 μm for the SMR locations



SMR locations



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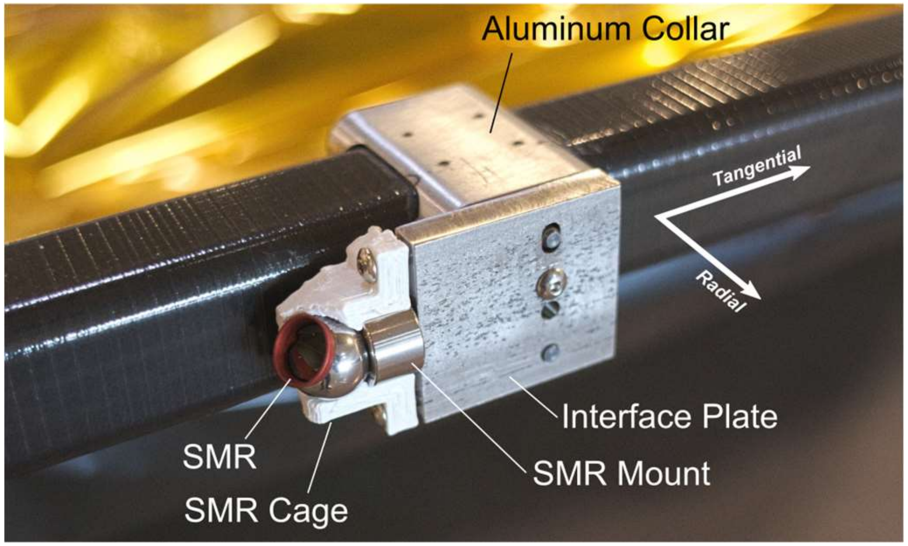
Shimming

- For flight, the petal locations would be shimmed on the ground prior to launch
- Here, the location of SMRs attached to the petal interfaces was shimmed
- 8 rounds shim adjustment were performed; for each round:
  - 3 deployments, SMR locations measured after each deployment
  - Based on this, a mean deployed position for each SMR was established
  - Shim corrections were implemented to reduce deviation between measured and design locations

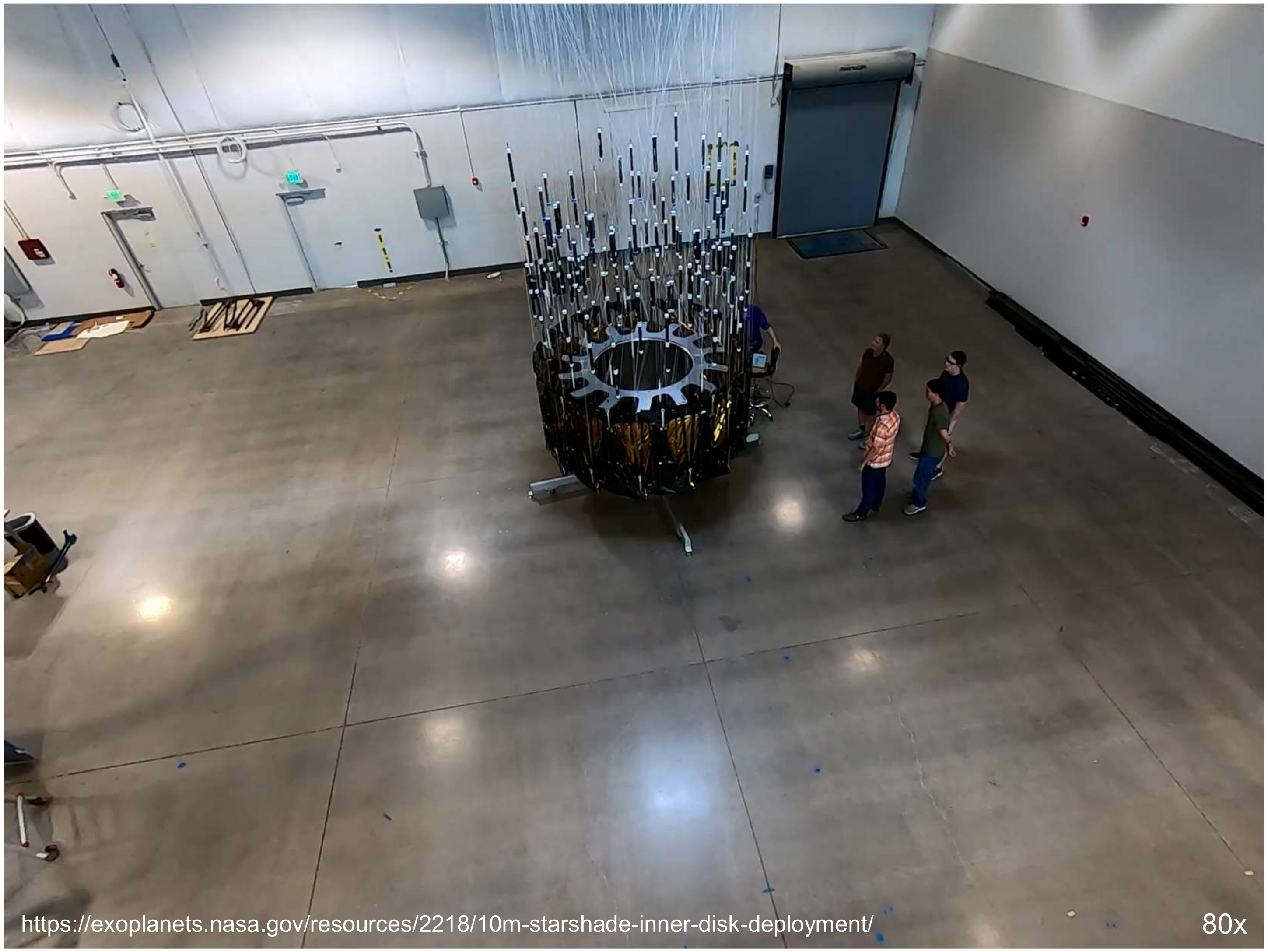


Deployments

- 22 deployments performed at the final shim state
  - 5x from a 96% stowed state
  - 3x from a 82% stowed state
  - 3x from a 49% stowed state
  - 11x from a 8% stowed state

- Stow percent = angle between the longerons when stowed, divided by 180°, which is the angle between the longerons when fully stowed

	Timestamp	Stow %
1	2019.07.17 14:38	8
2	2019.07.17 17:05	8
3	2019.07.17 18:21	8
4	2019.07.17 19:37	8
5	2019.07.18 09:05	8
6	2019.07.18 17:24	82
7	2019.07.22 10:36	8
8	2019.07.22 12:13	8
9	2019.07.22 13:40	8
10	2019.07.22 15:14	8
11	2019.07.23 10:00	8
12	2019.07.24 13:56	82
13	2019.07.25 12:56	82
14	2019.07.25 16:25	49
15	2019.07.26 14:07	49
16	2019.07.29 13:22	49
17	2019.08.08 11:47	8
18	2019.08.12 17:12	96
19	2019.08.15 13:47	96
20	2019.08.16 14:16	96
21	2019.08.20 13:04	96
22	2019.08.21 11:46	96


https://exoplanets.nasa.gov/resources/2218/10m-starshade-inner-disk-deployment/
80x

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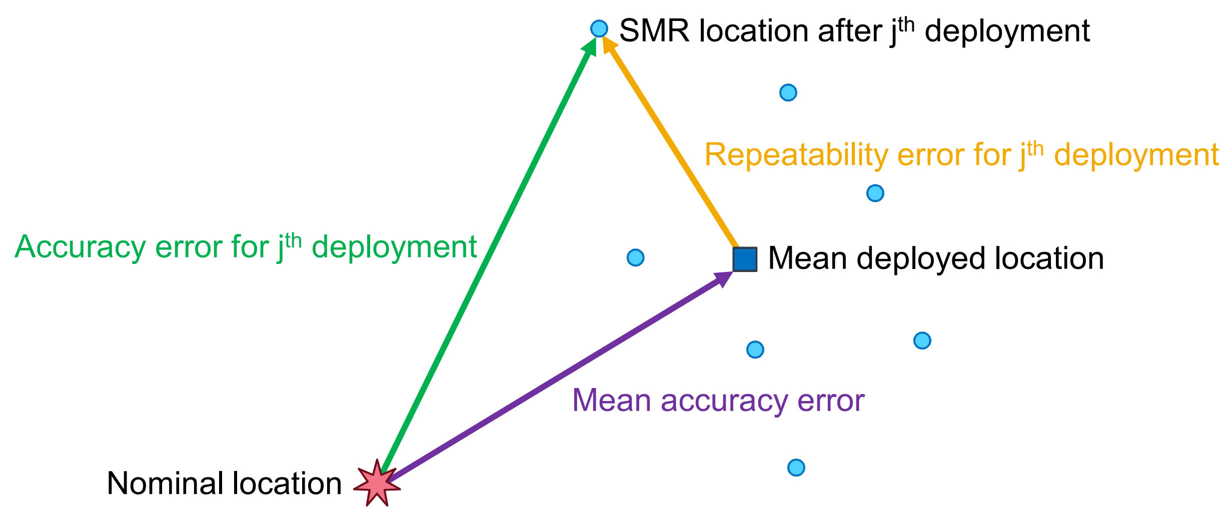
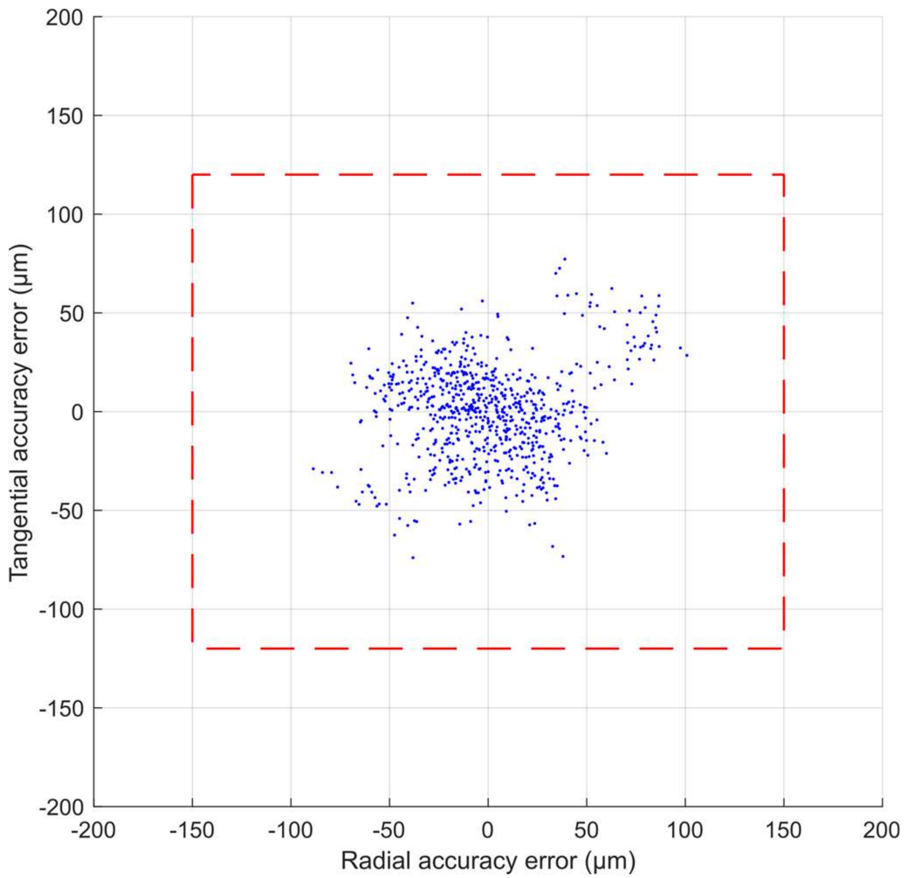
Definition of Deployment Errors

- Accuracy: deviation between measured and nominal SMR location
  - Includes secular shape bias (shimming errors) that does not change between deployments

- Repeatability: deviation between measured and mean (over all deployments) SMR location
  - Zero-mean; neglects contribution of mean accuracy error, i.e., shimming error



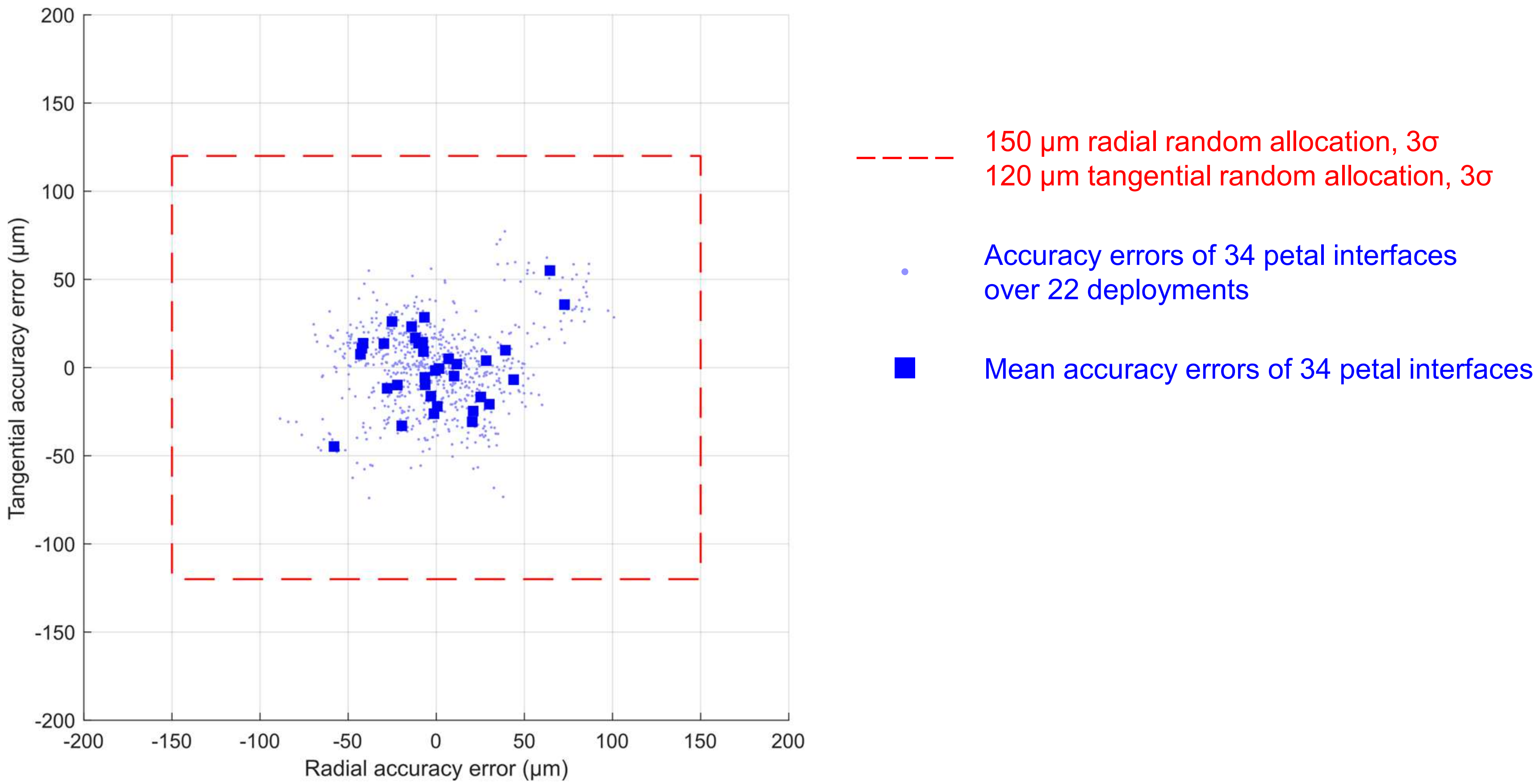
Accuracy Errors at Petal Interfaces



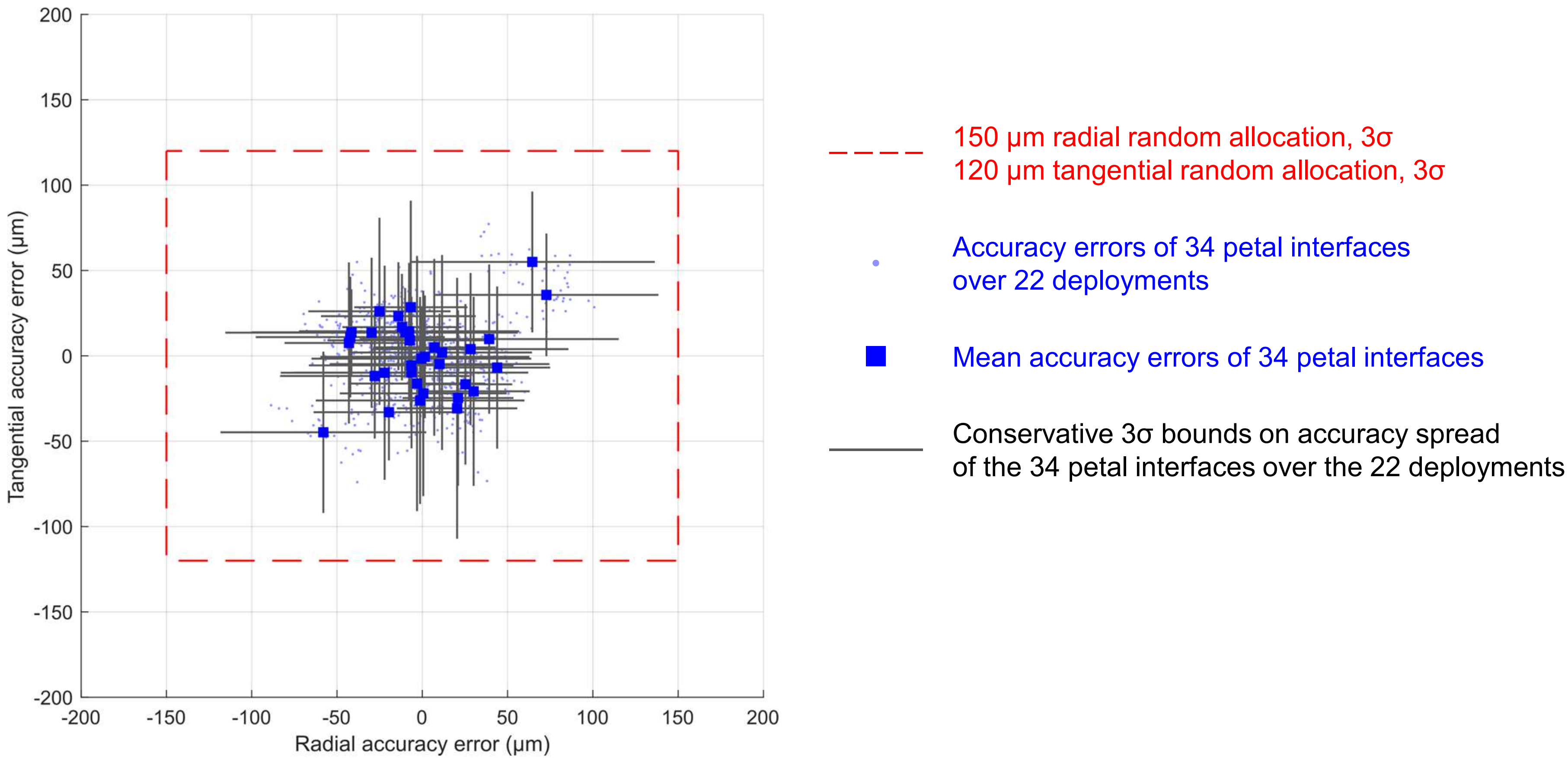
150 µm radial random allocation, 3σ
120 µm tangential random allocation, 3σ

Accuracy errors of 34 petal interfaces over 22 deployments

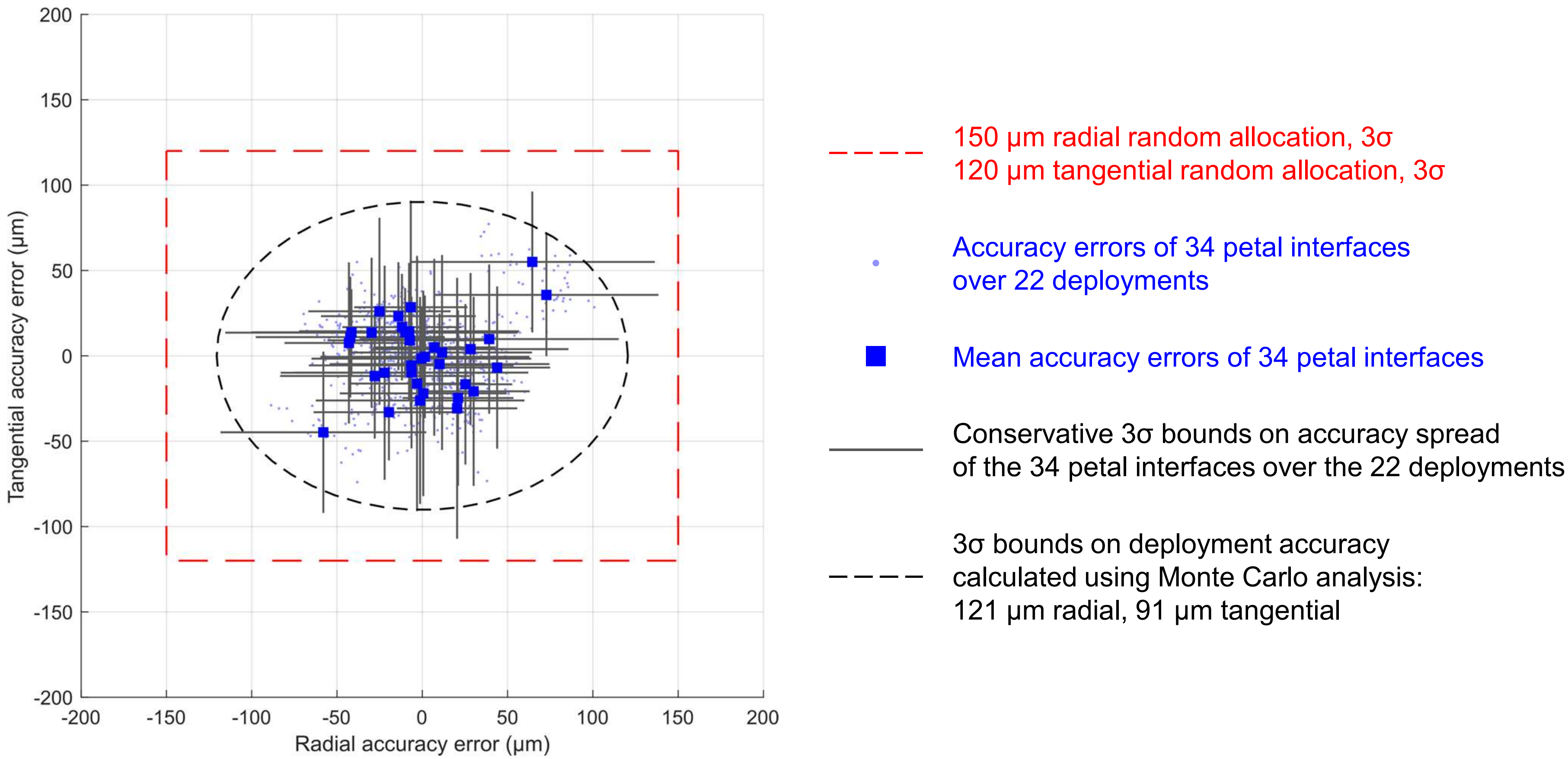
Accuracy Errors at Petal Interfaces



Accuracy Errors at Petal Interfaces



Accuracy Errors at Petal Interfaces

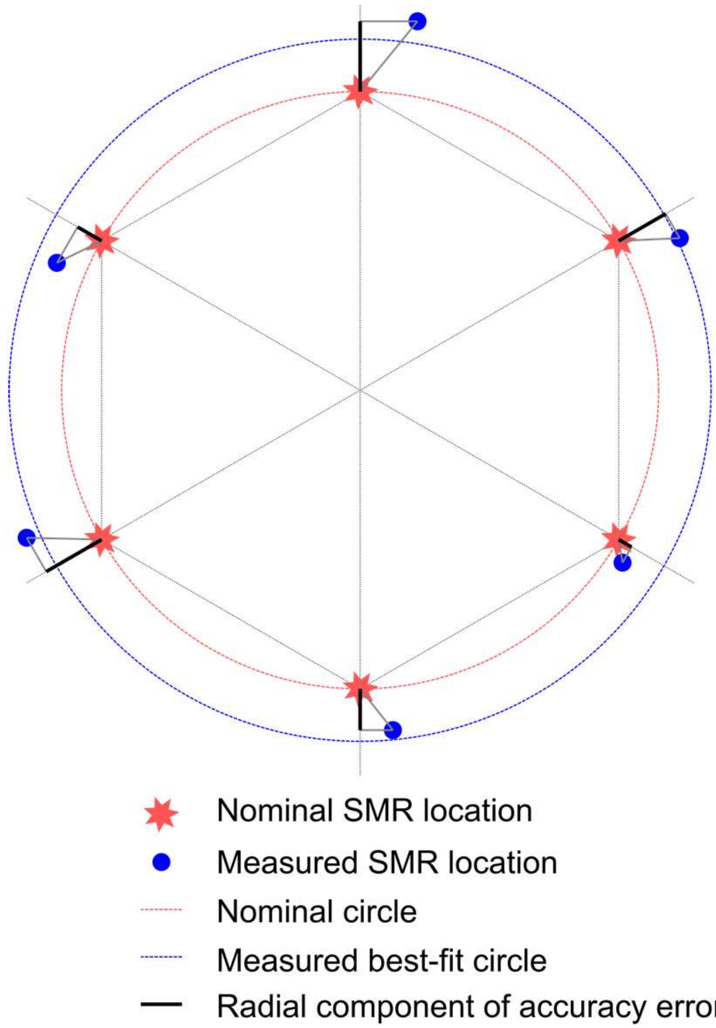


Error component	Allocation, 3σ (μm)	Measured, 3σ (μm)	Margin (% allowable growth)
Radial bias	35	??	??
Radial random	150	121	24
Tangential random	120	91	32

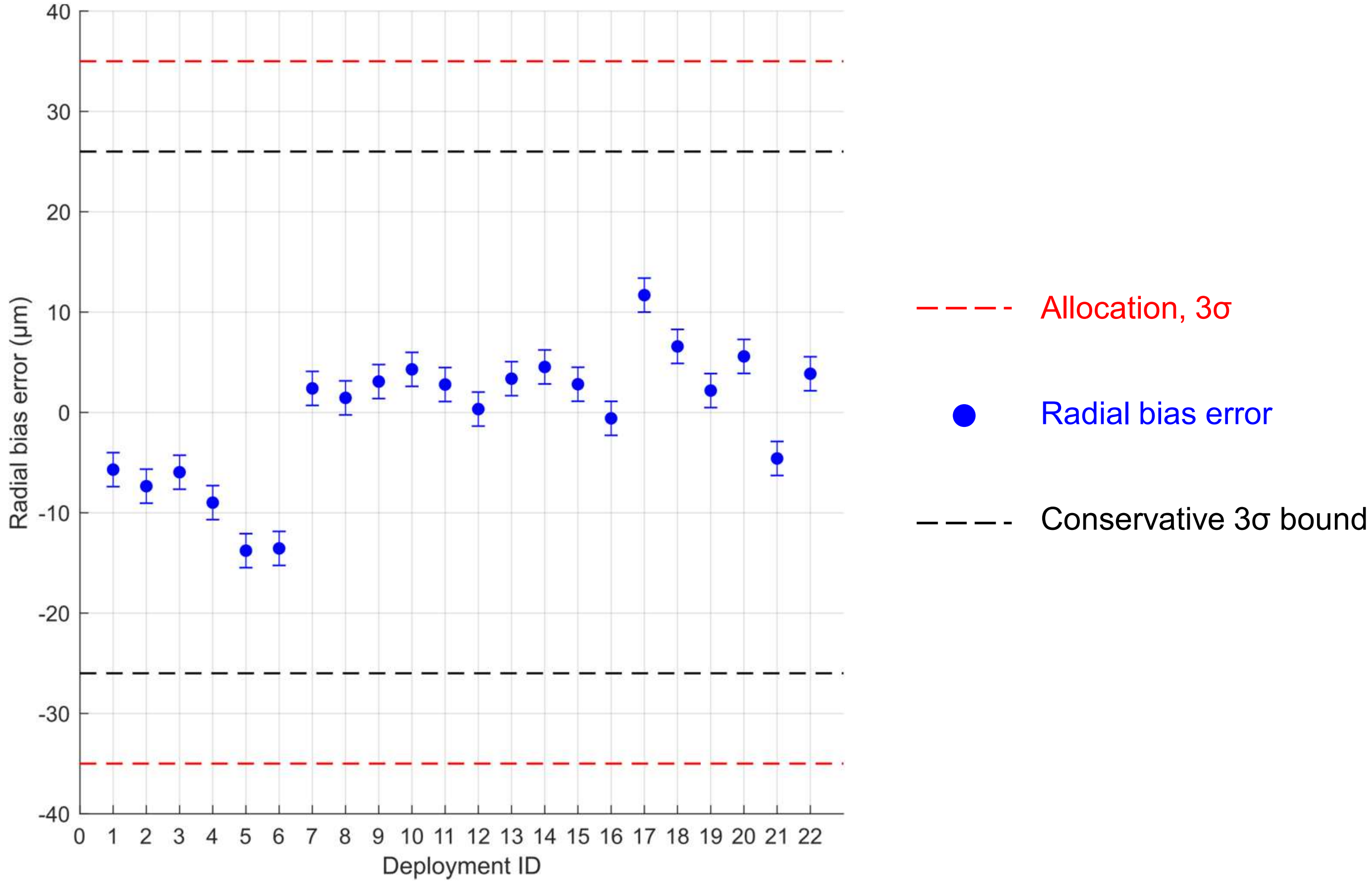
Radial Bias Error

- Radial bias is the difference between nominal radius and measured best-fit radius

- Radial bias = average, taken over all petal hinges after a deployment, of the radial component of accuracy error

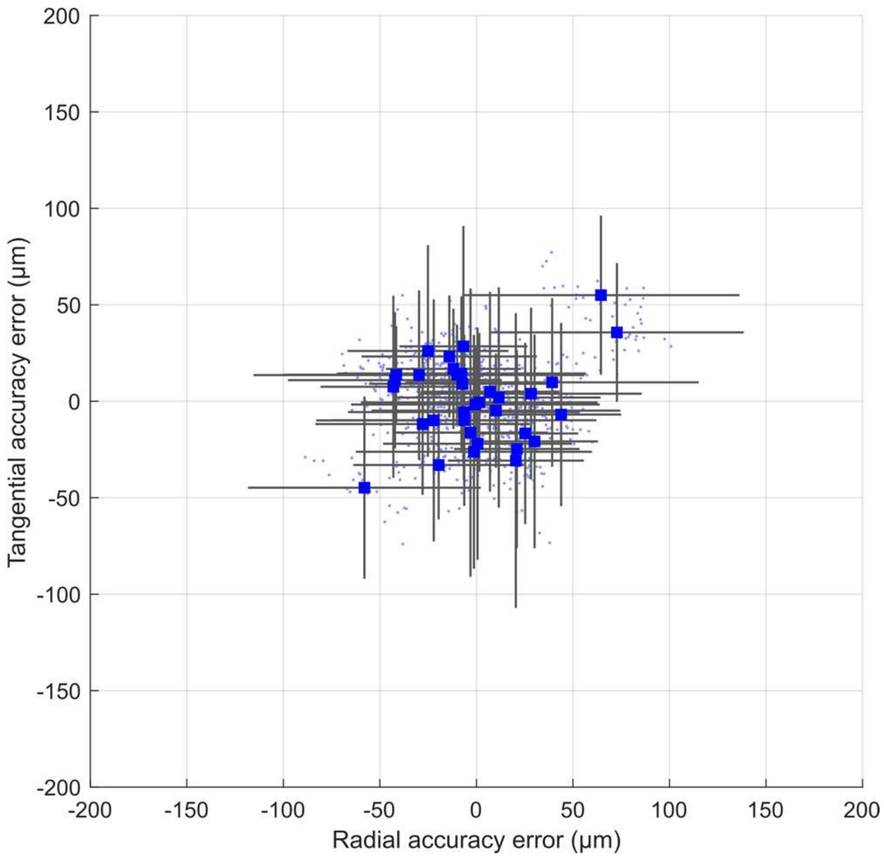


Radial Bias Error



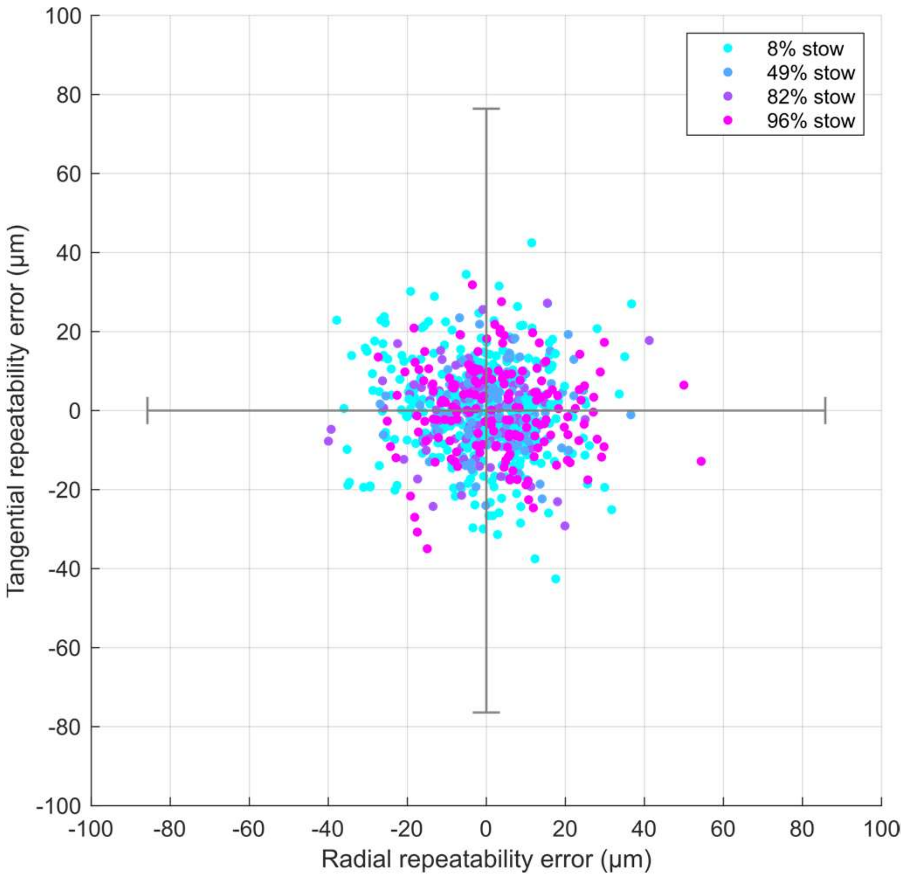
Error component	Allocation, 3σ (μm)	Measured, 3σ (μm)	Margin (% allowable growth)
Radial bias	35	26	35
Radial random	150	121	24
Tangential random	120	91	32

Repeatability Errors at Petal Interfaces



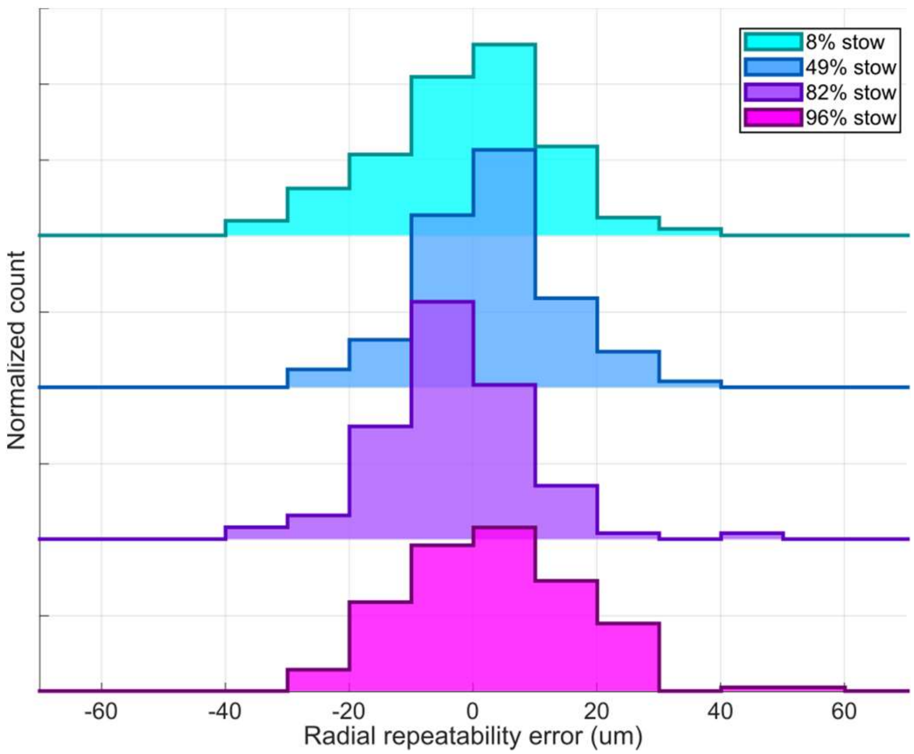
- Accuracy error includes a contribution from shimming errors
- To filter shimming errors, subtract out mean accuracy errors from this data

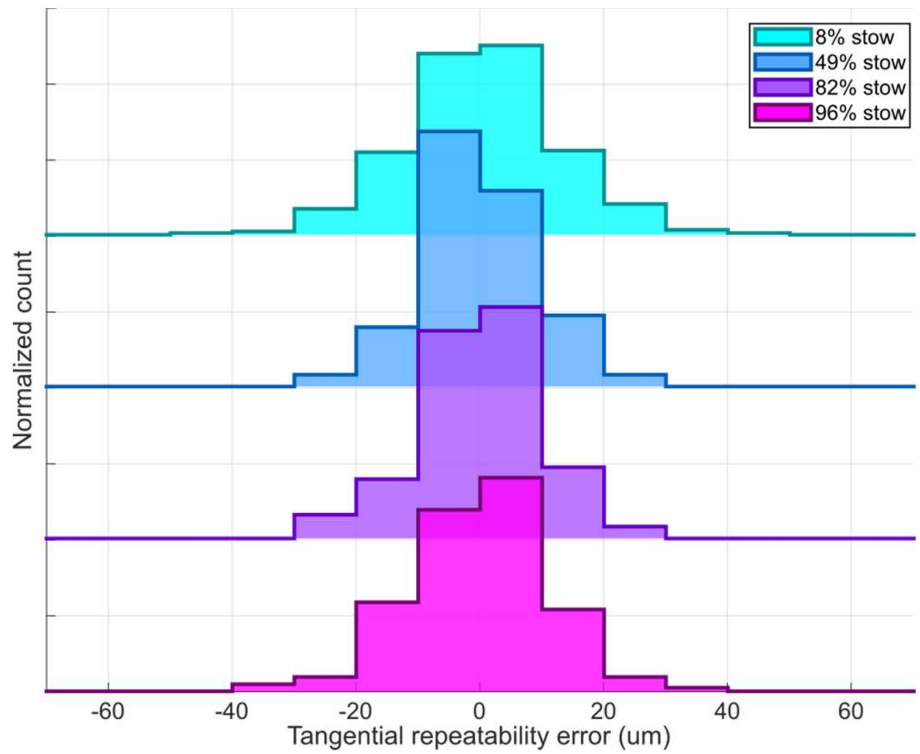
Repeatability Errors at Petal Interfaces



- Repeatability errors from 34 petal interfaces over 22 deployments
- Bars indicate conservative 3σ bounds for repeatability errors:
  - 86 μm radial, 78 μm tangential
- Indicates performance achievable with perfect shimming
- Allows for comparison of data from different stow states

Validity of Partial Stows





Conclusions

- Designed and fabricated 10 m-diameter IDS prototype that is full-scale for SRM
  - Design and implemented gravity compensation, metrology systems
- Deployed 22 times and locations of 34 petal interfaces measured after each deployment

Error component	Allocation, 3σ (μm)	Measured, 3σ (μm)	Margin (% allowable growth)
Radial bias	35	26	35
Radial random	150	121	24
Tangential random	120	91	32

- Demonstrated IDS deployment accuracy with optical shield and thermally-stable spokes
- Meets criteria for Milestone 7C of the Starshade-to-TRL5 plan
  - Will undergo formal review by an independent external committee (ExoTAC) in January 2020
- Follow-on work to meet Milestone 7D will increase hardware fidelity of the optical shield and contribute towards maturing the IDS to TRL5

Acknowledgments

- Many thanks to the interns and engineers at JPL, Roccor, and Tendeg who assisted with the construction of the test hardware and the conduction of the experiments
- The research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration (80NM0018D004)

Questions?

Backup Slides

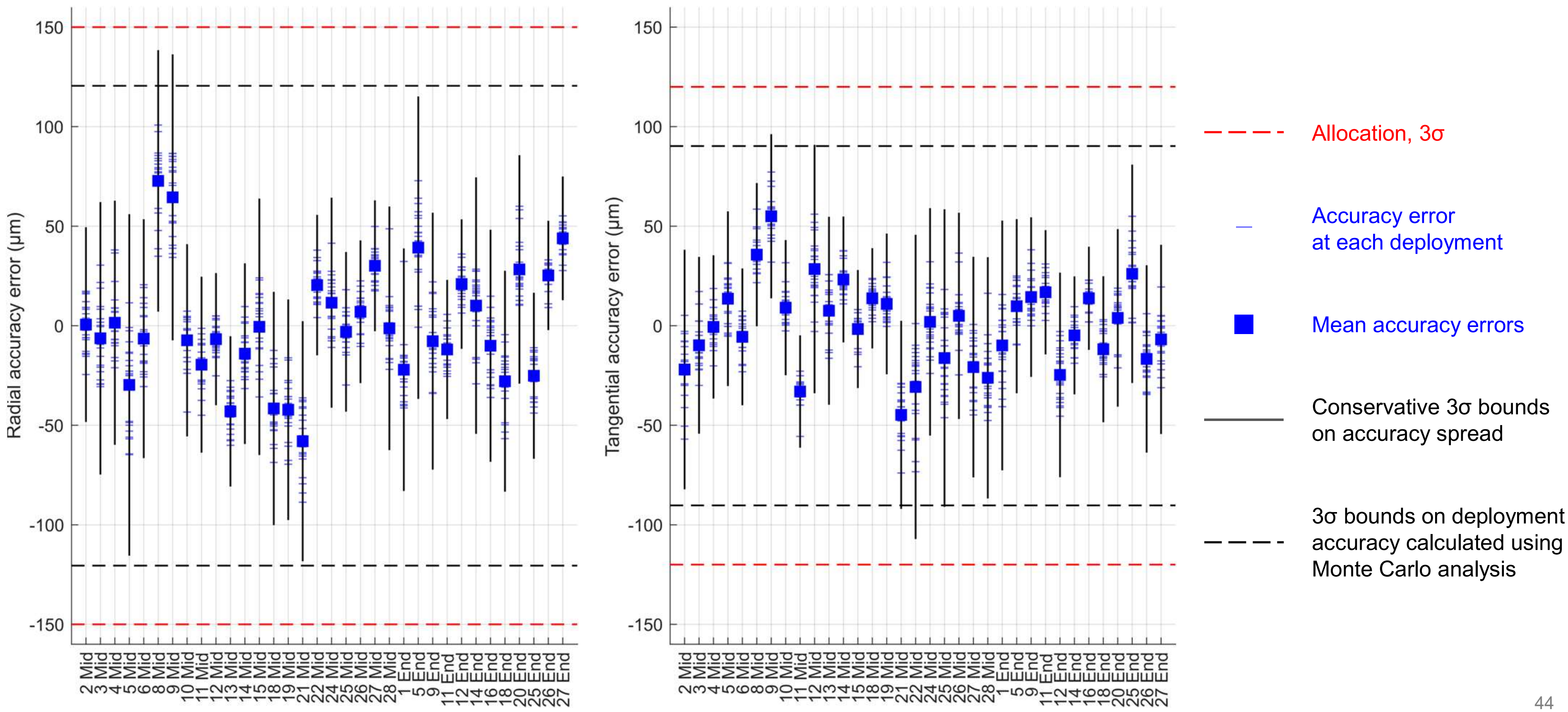
Tolerance Intervals

- We compute the standard deviations of the radial and tangential components of the accuracy and repeatability errors
- Given the low sample size – 22 deployments in total – the standard deviations of the sample may differ greatly from the standard deviations of the underlying population
  - To retire this uncertainty, tolerance intervals are employed
- A tolerance interval is a $\pm k\sigma$ region centered around the mean that will contain a percentage γ of future members of a population with a confidence level defined by $(1-\alpha)$; we use
  - $\gamma = 0.9973$
  - $(1-\alpha) = 0.90$
- For a sample size of 22 deployments, we get a tolerance interval of $\pm 3.8596\sigma$
  - Compare to a well-sampled normal distribution, for which 99.73% of the population falls within $\pm 3\sigma$

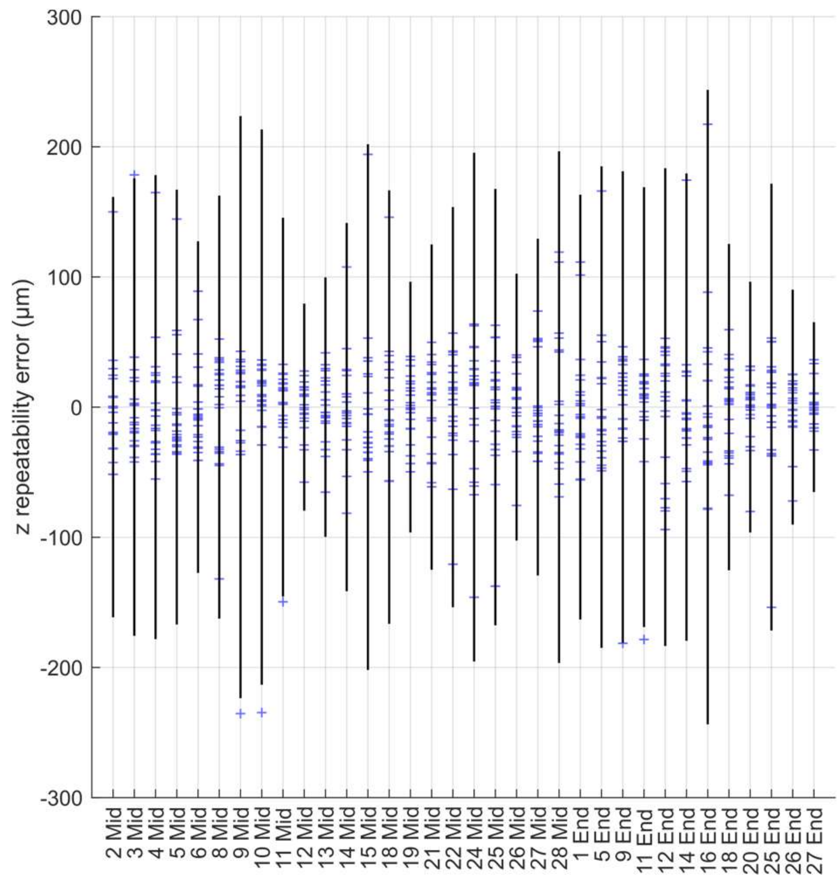
Data Processing

- After each deployment, SMR locations were measured by an automated program
- Automated program run 3 times after each deployment, thus taking 3 independent passes
- Deployed SMR location taken to be the mean of the measurements from the 3 passes
- All SMR locations after a deployment were translated and rotated as a rigid body to best fit (in a least squares sense) the measured petal interface locations to the nominal petal interface locations

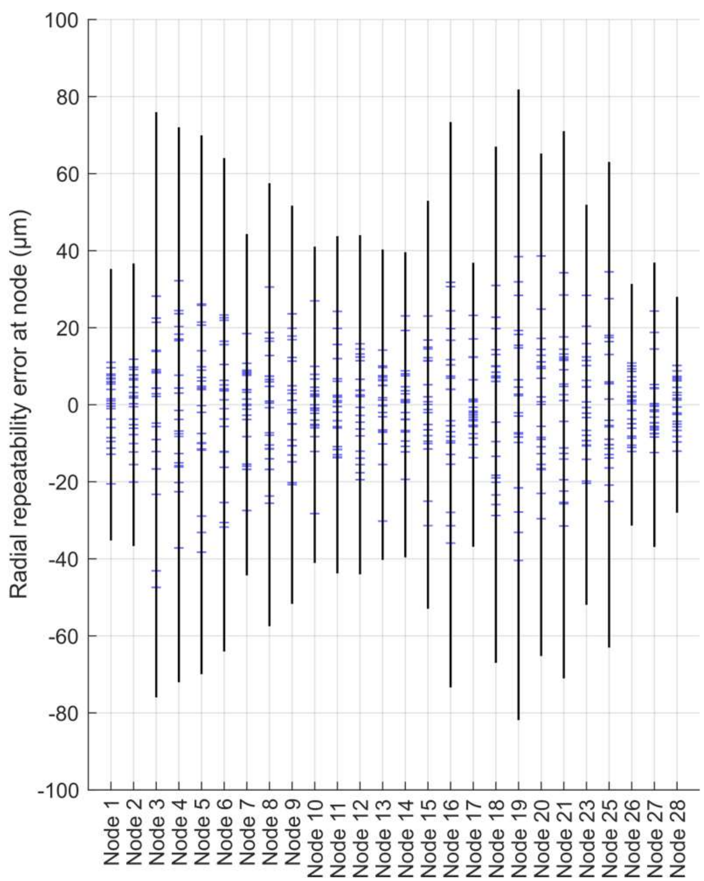
Accuracy Errors at Petal Interfaces

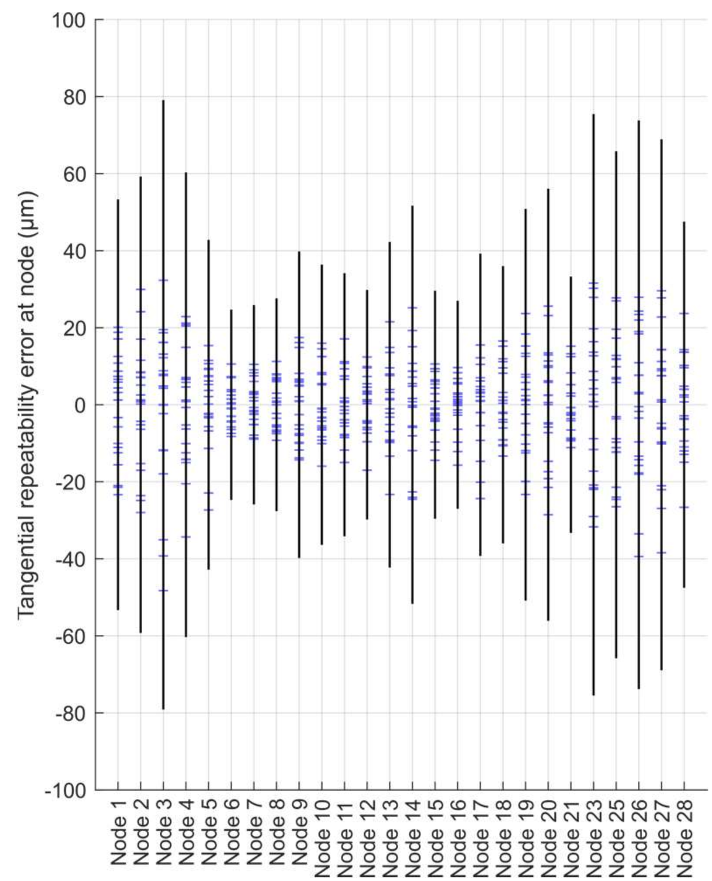


Accuracy Errors at Petal Interfaces

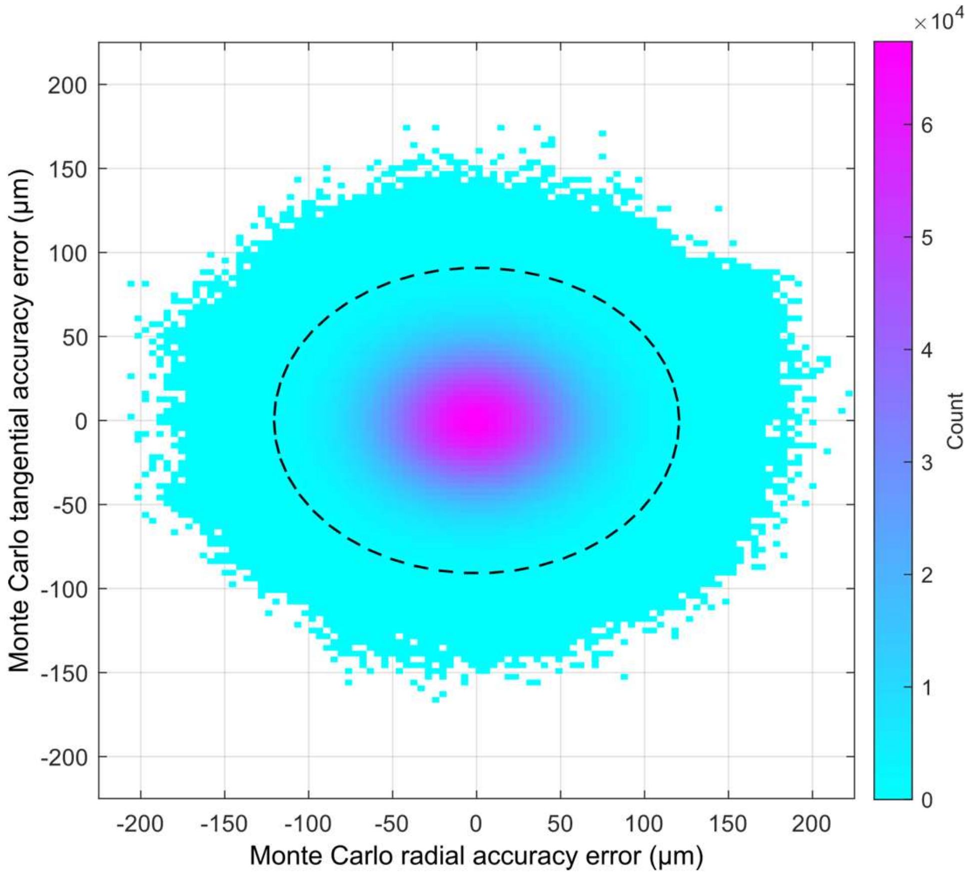


Accuracy Errors at Nodes

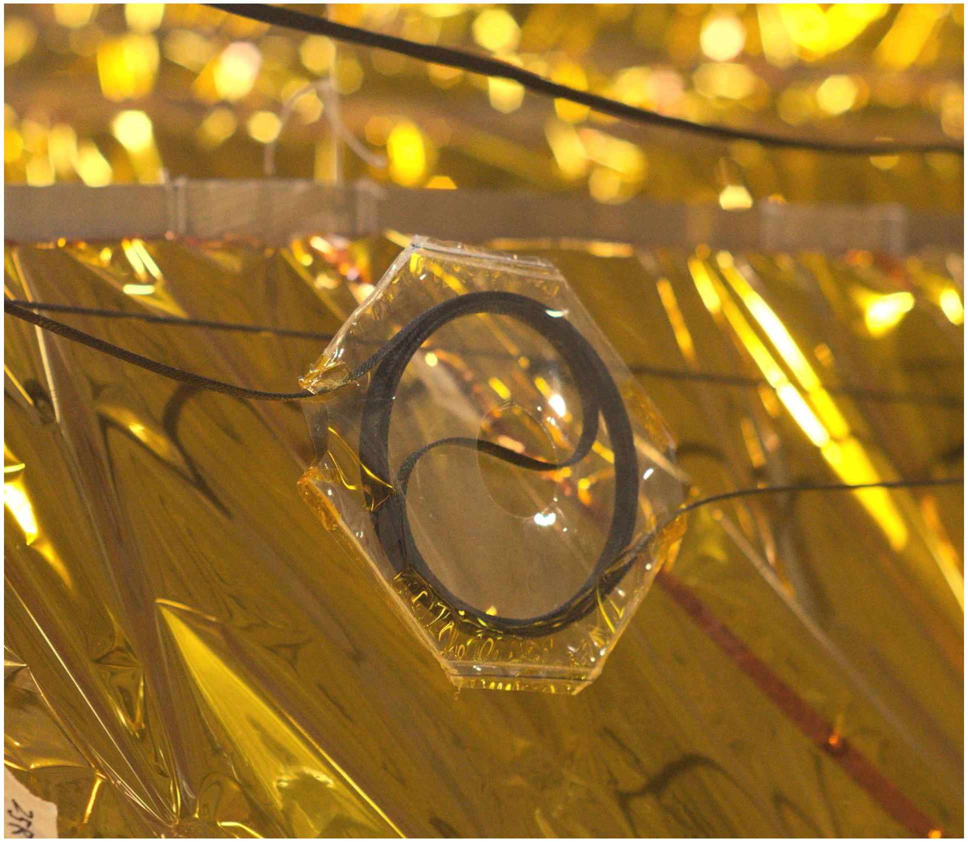




Monte Carlo Study to Determine 3sigma bounds



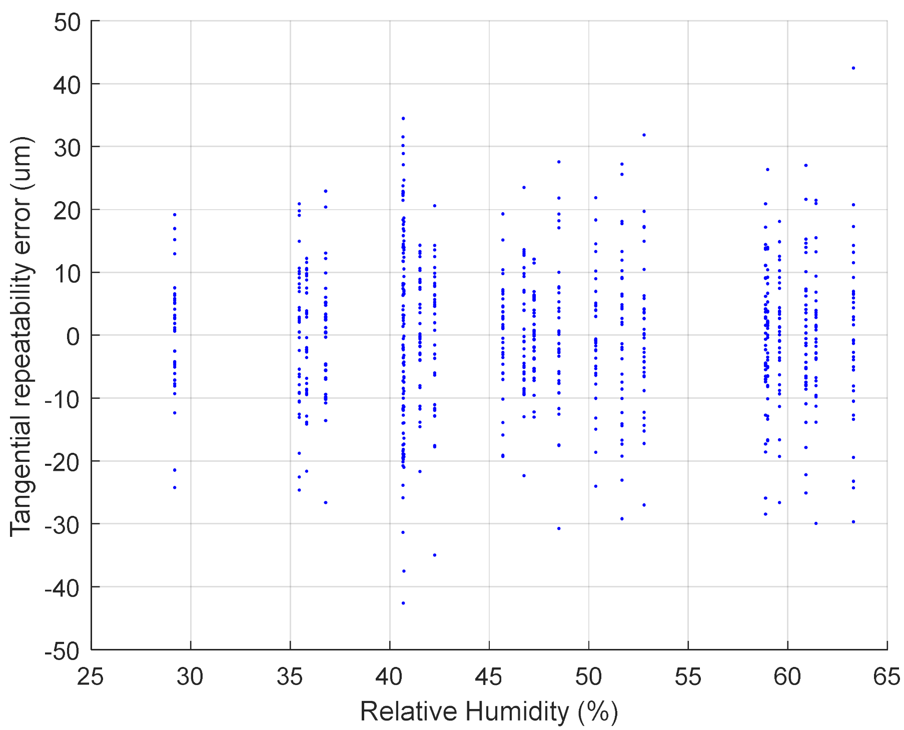
Spoke Bags

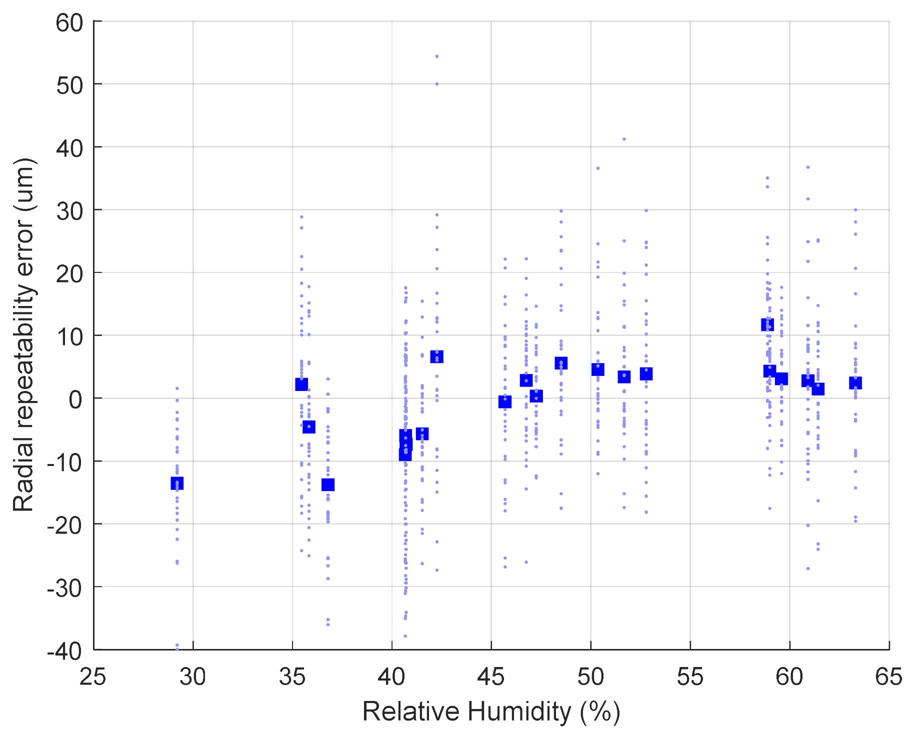


Mass

	Mass (kg)
Optical shield	65.5
Perimeter truss	54.7
Spokes (incl. interfaces)	2.0
Hub (w/o fixture)	79.7

Relative Humidity





Temperature