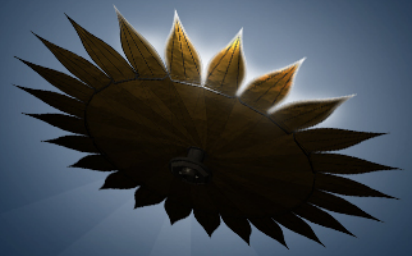
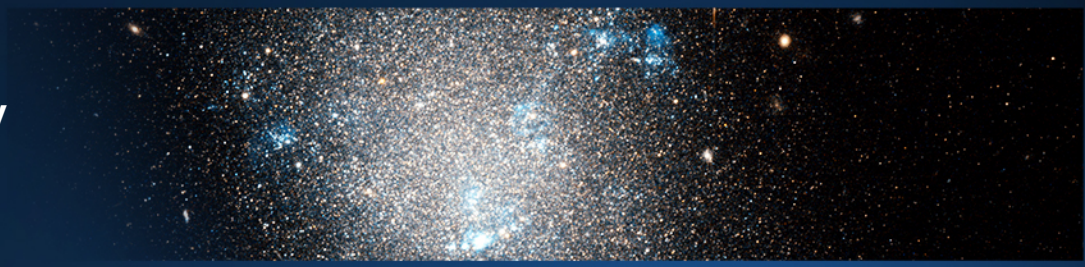


Astrophysics with

# HabEx

## Habitable Exoplanet Observatory

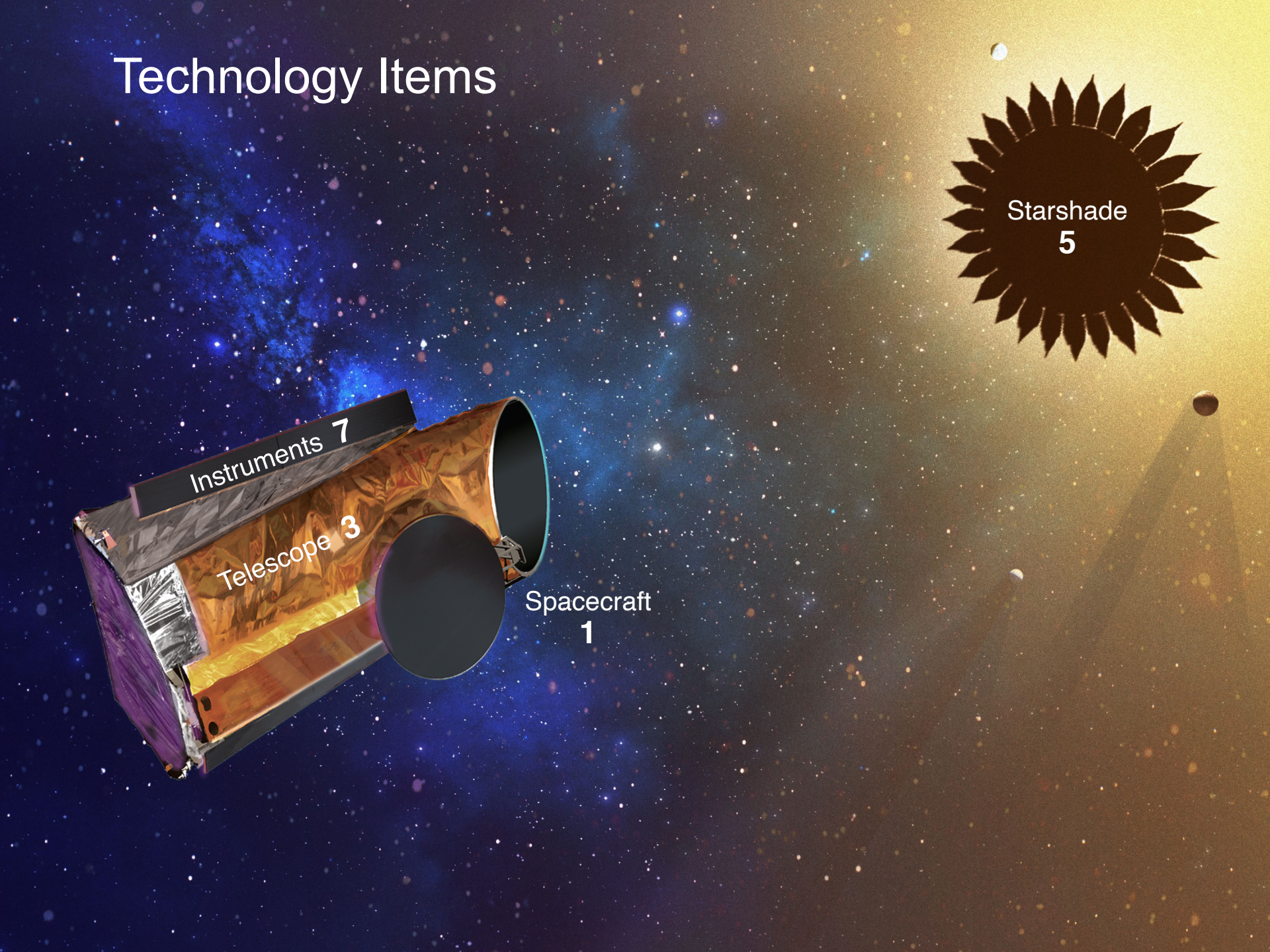


# Technology Maturity for the HabEx Observatory Concept

Rhonda Morgan, Technology Lead
Jet Propulsion Laboratory, California Institute of Technology

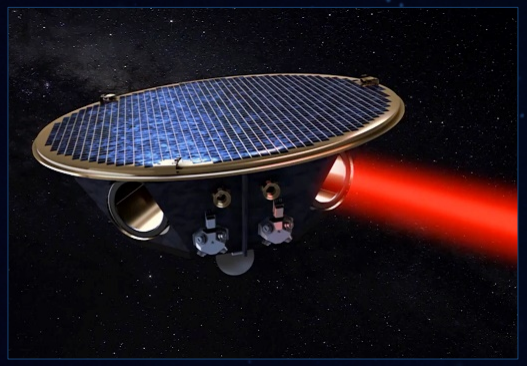
© 2019. California Institute of Technology. Government sponsorship acknowledged

# Technology Items



# Technology Predecessors

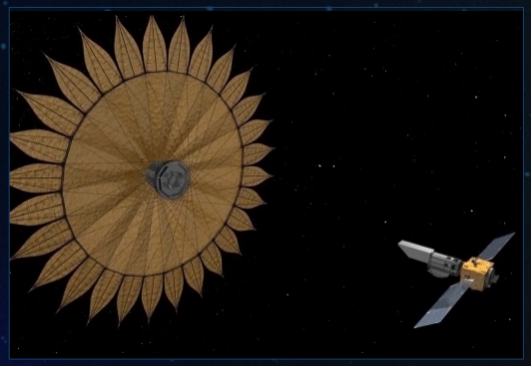
ESA/LISA Pathfinder



Credit: ESA

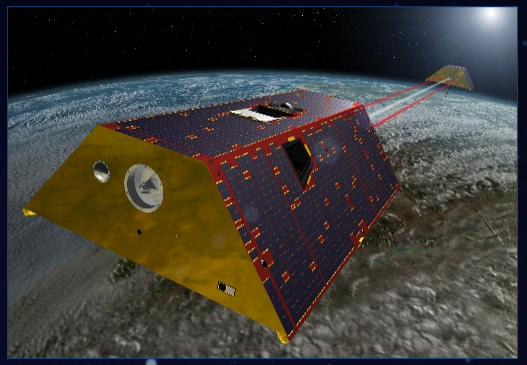
WFIRST Coronagraph Instrument

S5



Credit: NASA

Grace Follow-On



Credit: NASA

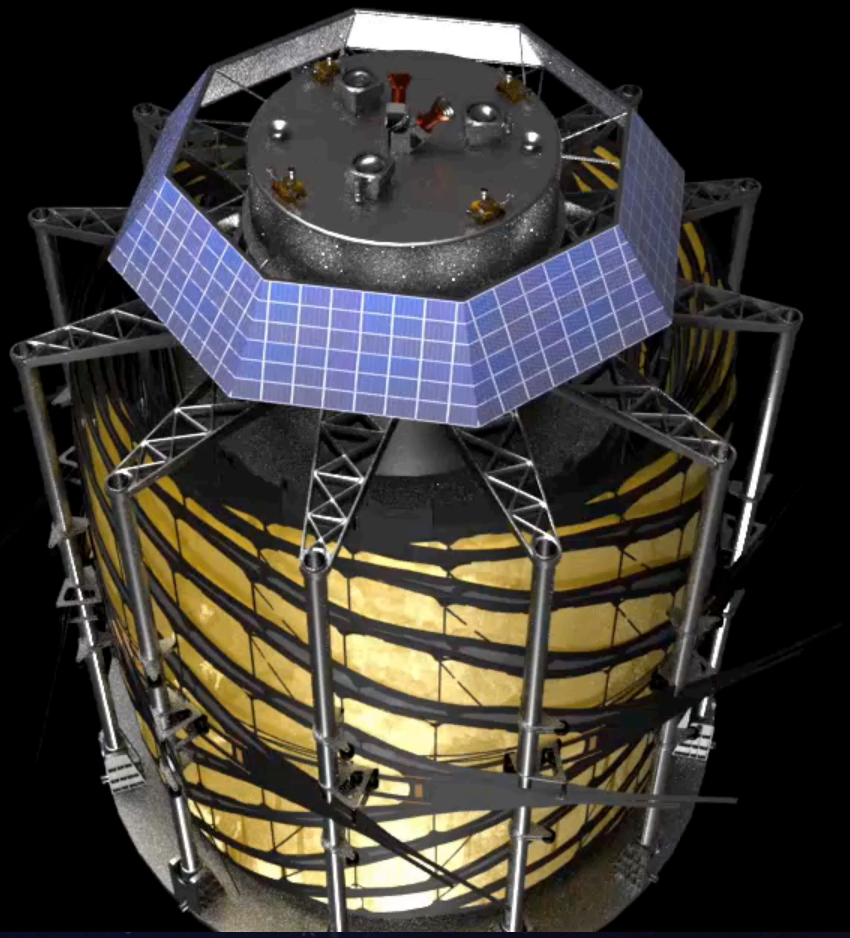
Daniel K Inouye Solar Telescope

Credit: NSO

E-ELT M2

Credit: ESA

# Starshade Deployment



# Truss Deployment Test

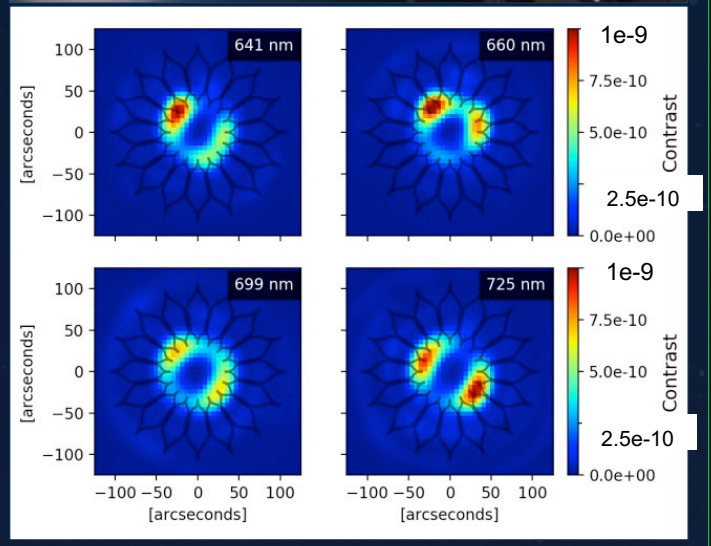
½ scale truss for HabEx

½ scale for HabEx

# Starshade Technology Advances

## TRL 5 March 2020

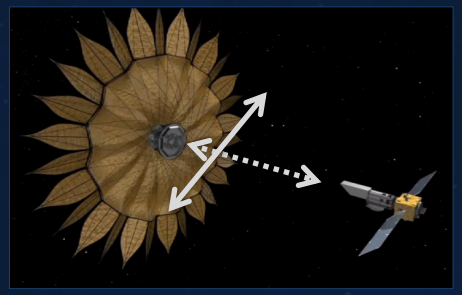
### Starlight Suppression

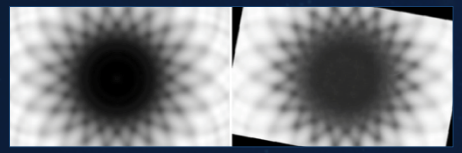


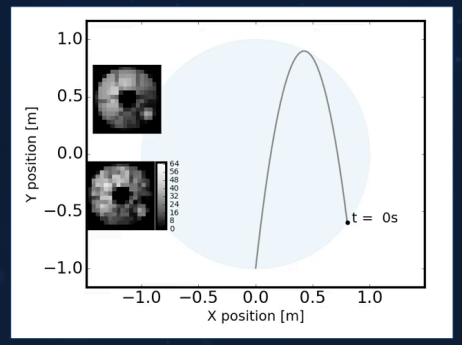

**1 × $10^{-10}$ Contrast over 10% bandwidth**

## TRL 5

### Lateral Formation Sensing



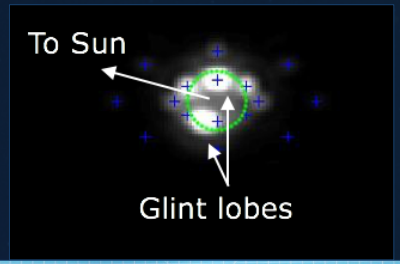


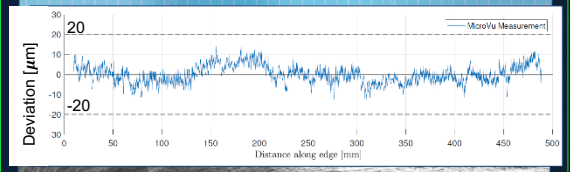


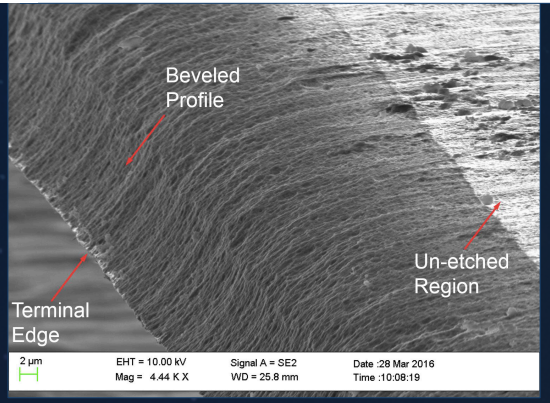

**<1 m lateral displacement**

## TRL 5

### Controlling Scattered Sunlight





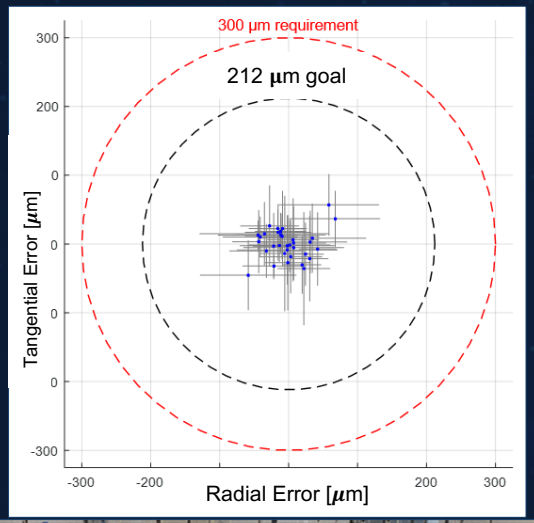



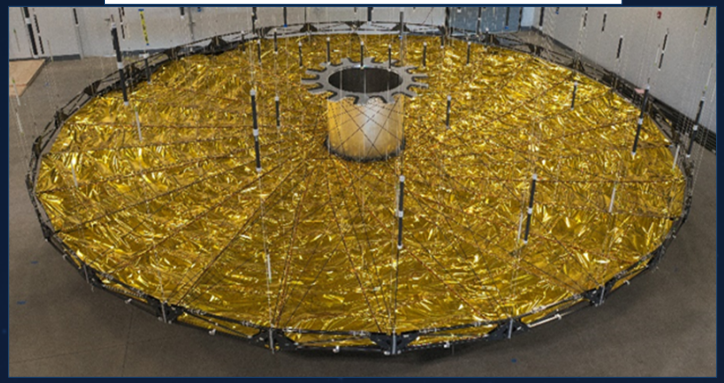

**<20 μm out of plane edge**

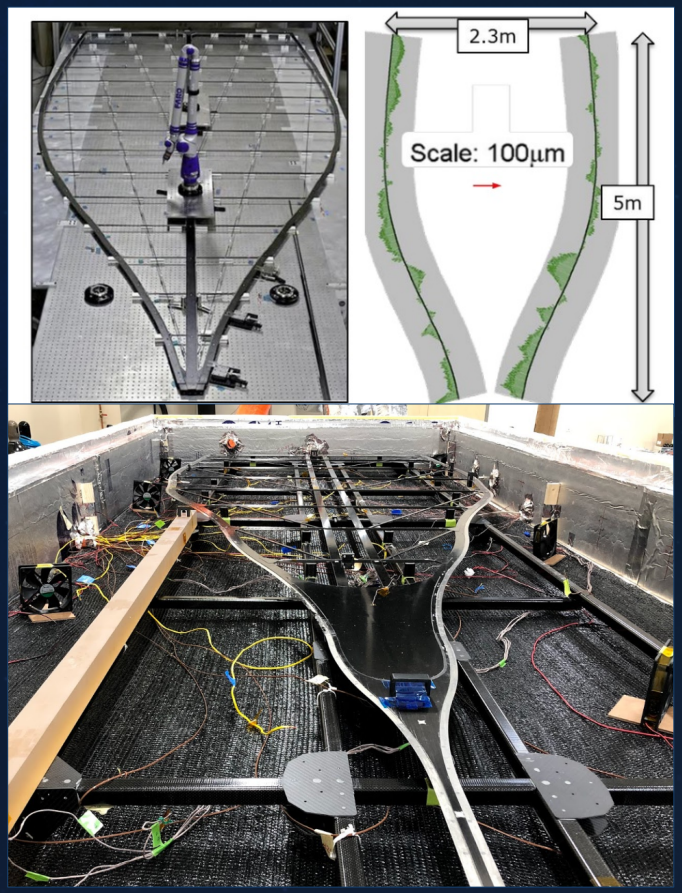
# Starshade Technology Advances

## TRL 4

### Petal Deployment Accuracy and Shape Stability






<300 µm petal deployment accuracy

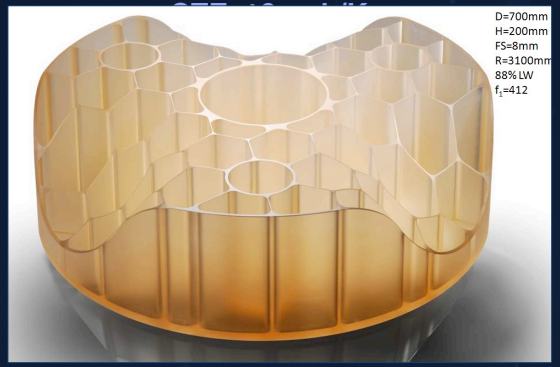
<140 µm petal shape accuracy

# Telescope Technology Advances

## TRL 4

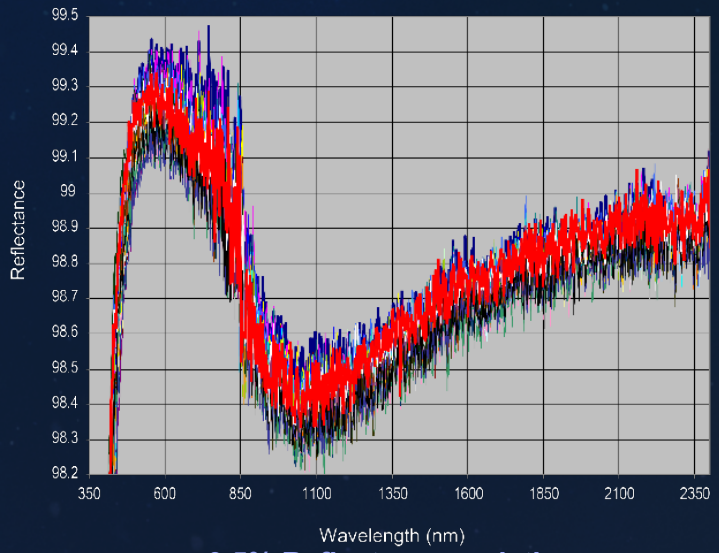
### Large Monolith Mirror Fabrication

**Surface figure error (rms): <19 nm; 5 nm (1–100 mm period), 0.1 nm surface roughness**




**2 mm thick machined ribs**

2.5 Meter Aperture Uniformity Data

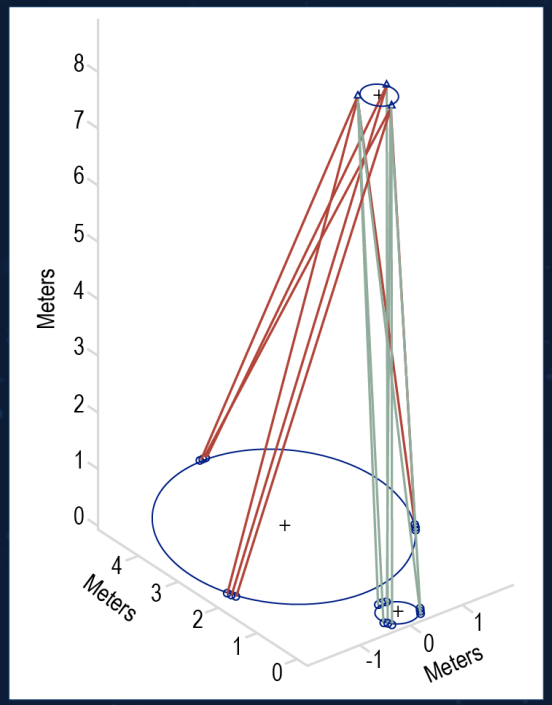


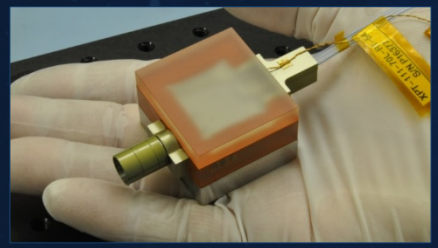

**~0.5% Reflectance variation**
**2.5 m "diameter", 34 samples protected silver**

# Telescope Technology Advances

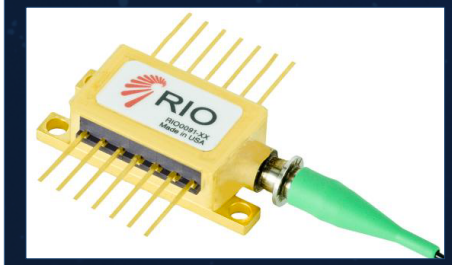
## TRL 5

### Laser Metrology



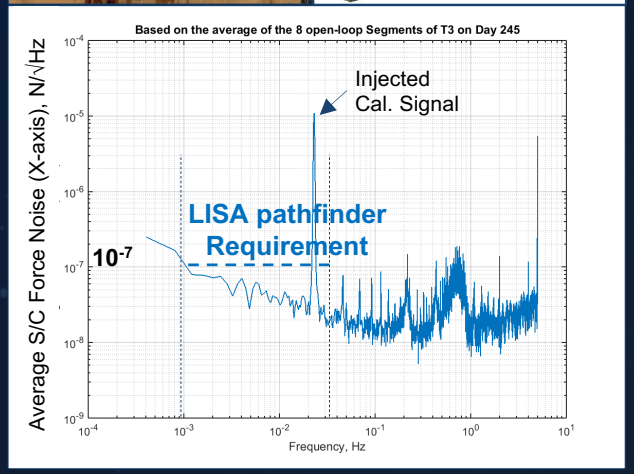
Beam launcher




Phase Stable Laser

## TRL 4

### Microthrusters

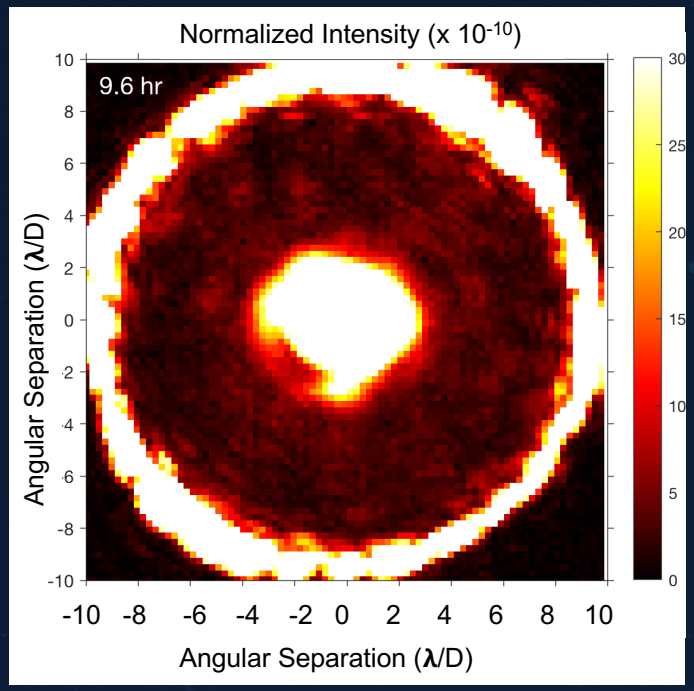



**<0.1 μN/√Hz Noise on orbit**

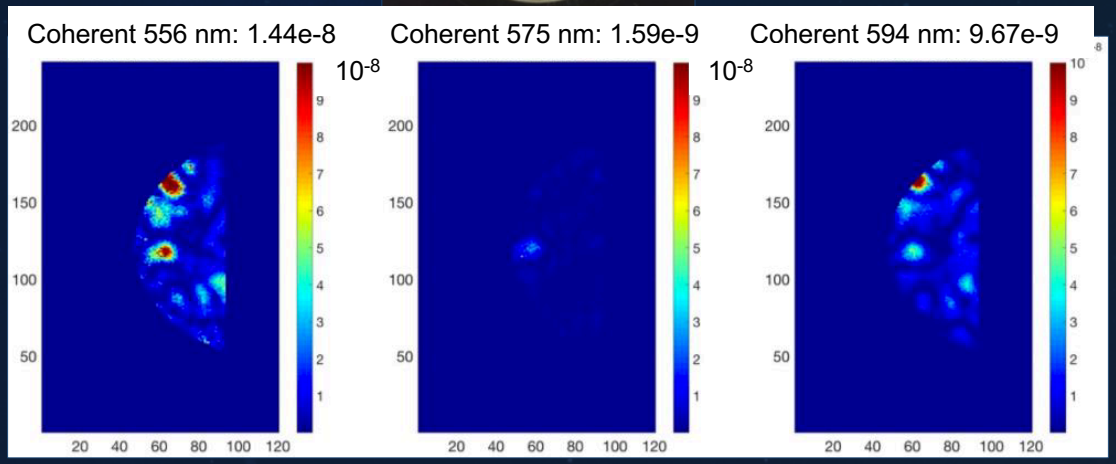
# Instrument Technology Advances

## TRL 4

Coronagraph Architecture




$4 \times 10^{-10}$ raw contrast at 10% bandwidth
Simple Lyot

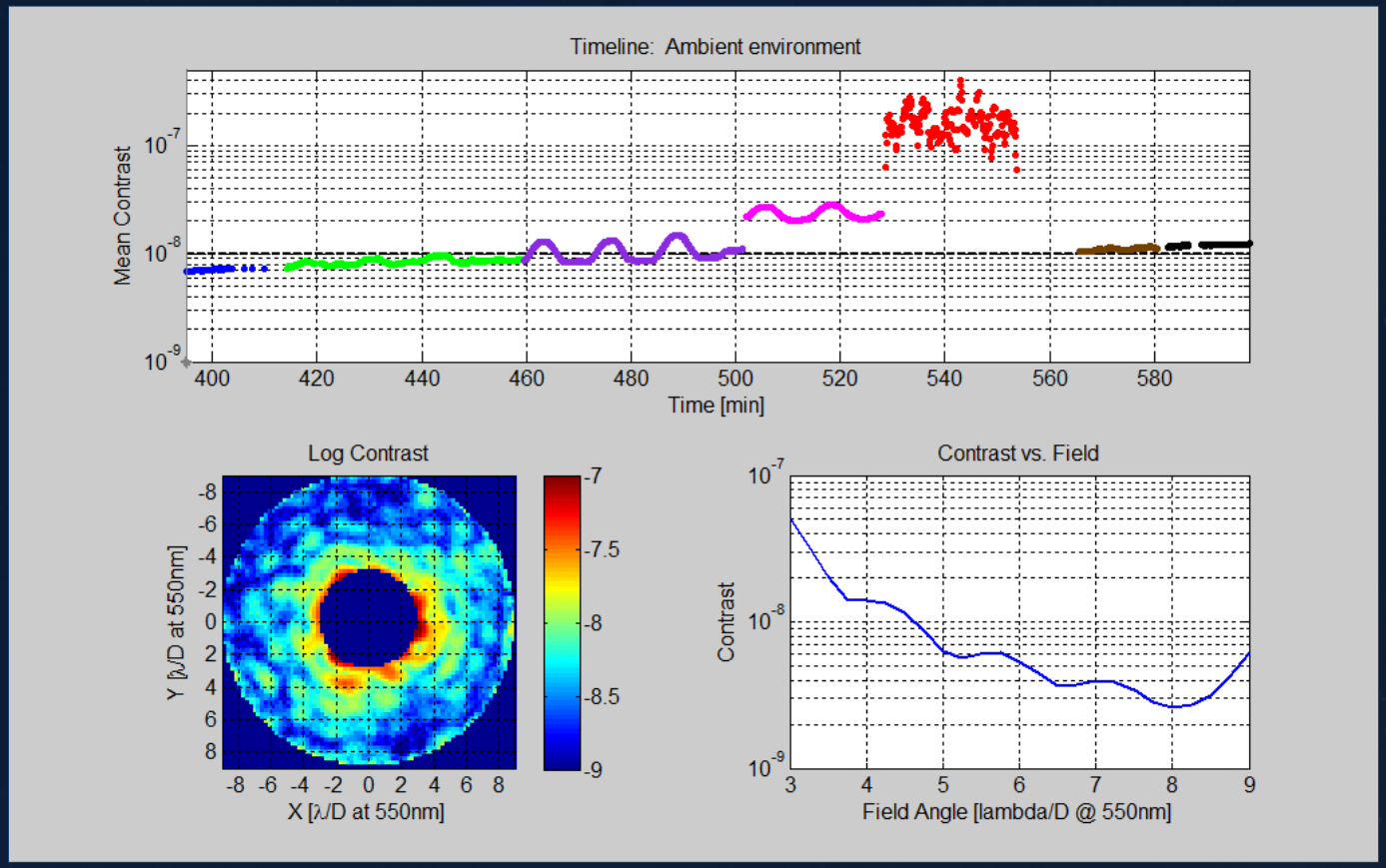



$8.5 \times 10^{-9}$ coherent raw contrast at 10% bandwidth
Vector Vortex

# Instrument Technology Advances

## TRL 4

### Contrast Stability - Zernike Wavefront Sensor




**<0.36 mas rms residual line-of-sight error, ~26 pm rms sensitivity of focus, Mv=5**

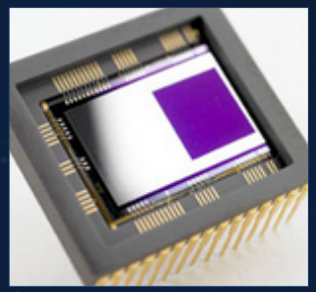
# Instrument Technology Advances

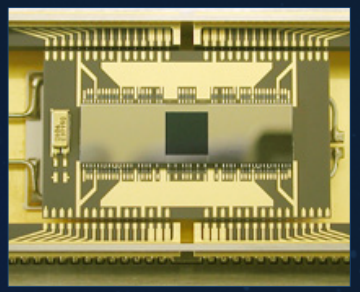
## TRL 4

### Contrast

Deformable Mirrors

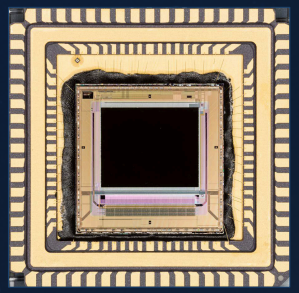
### Detection Sensitivity





Ultra-low Noise UV and Visible EMCCD

Microchannel Plate Detector for UVS



**TRL 5**
320×256

**TRL 4**
1k × 1k

LMAPD NIR photon counting

# Large Mirror Technologies

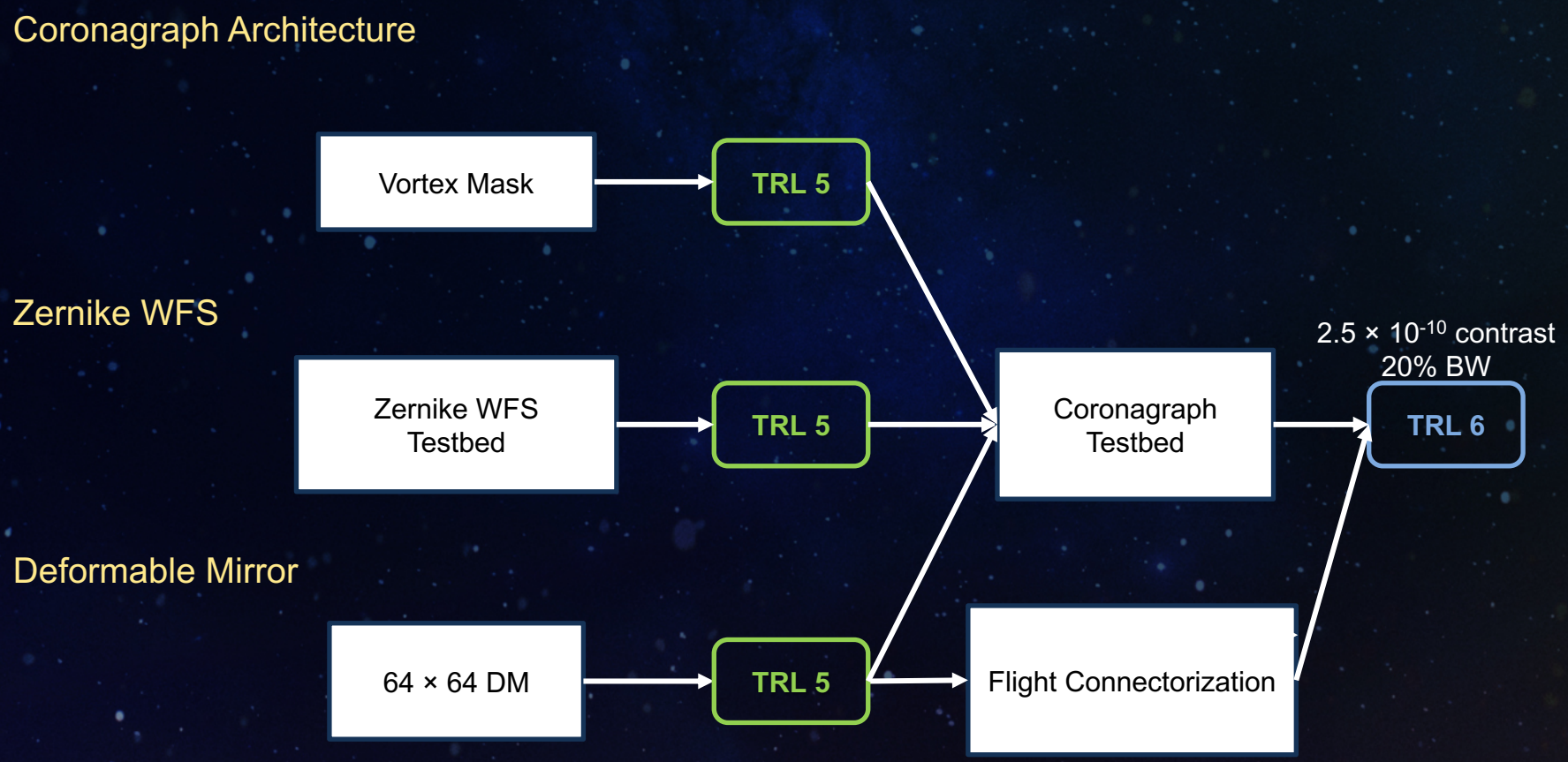
## Large Mirror Fabrication

Thermal uniformity acceptance test → Lightweight → Measure gravity sag *Spherical surface* → TRL 5 → 4 m mirror & mount assembly *protoflight* → TRL 6

## Large Mirror Coating Uniformity

Coating on samples Over 4 m → TRL 5 → Coating on 4 m substrate → TRL 6

# Coronagraph Technologies



# Starshade

The S5 maturation philosophy is applied to mature to high fidelity, full-scale articles and TRL 6.

Petal Shape and Stability
Scattered Sunlight from Petal Edge

TRL 5 → **Full-scale** petal 16 m long ×4 m wide → TRL 6

Petal Unwrapping

TRL 5 → **Full-scale** PLUS 2.25 m stow dia. → GSE stowed truss with 22 med- and 2 high-fidelity petals

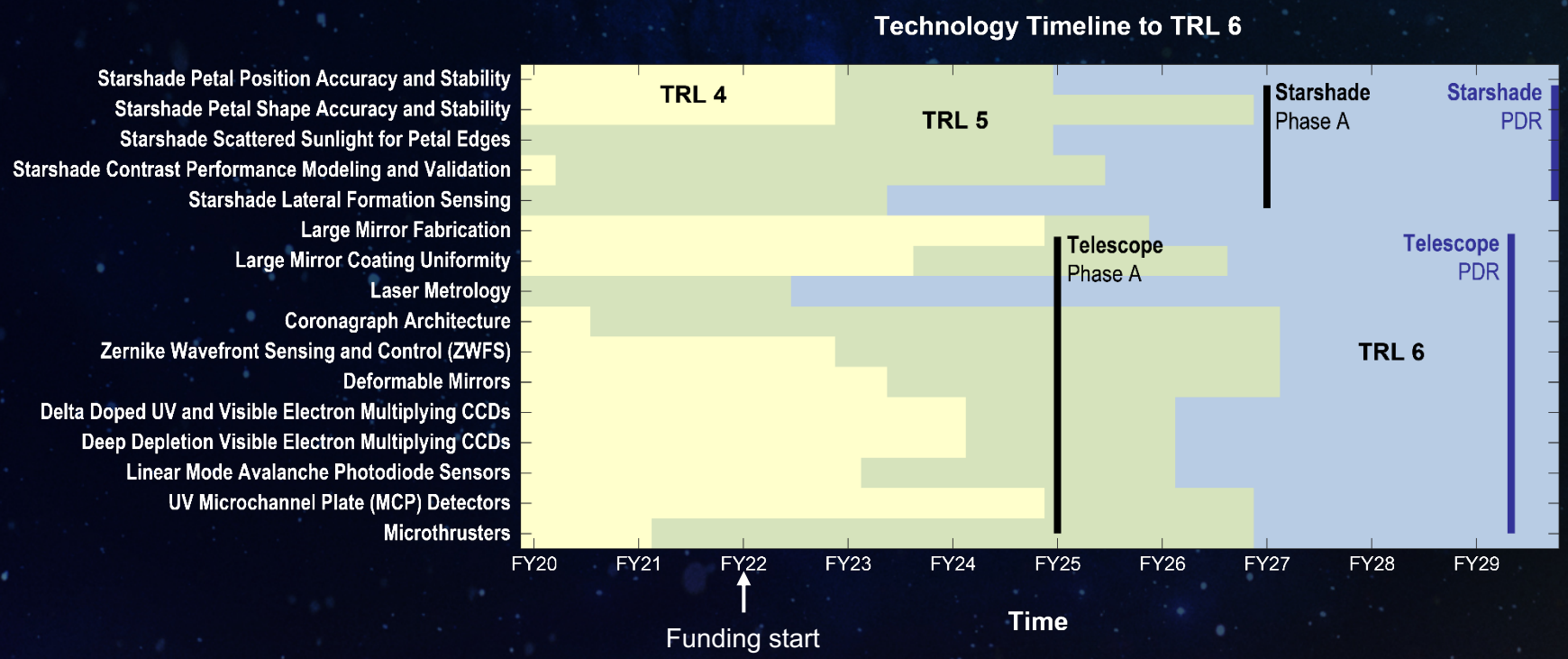
petals

Truss Deploy

TRL 5 → **Full-scale** truss 20 m dia. → **Full-scale** deployable starshade 52 m dia. → TRL 6

*This is the Engineering Model starshade*

# Timeline




TRL 4 TRL 5 TRL 6 Funded

Enabling technologies will be TRL 5 in time for mission start in FY25

# BACKUP

# Technology Maturity Table (1 of 4)

**Table 11.1-1.** HabEx 4 m baseline architecture technology gap list. Note that the cell coloring reflects TRL: TRL 3, *red*; TRL 4, *yellow*; TRL 5, *green*, and TRL 6, *blue*.

| Title | Description | Section | State of the Art | Capability Needed | TRL 2019 | Expected 2023 TRL |
|---|---|---|---|---|---|---|
| **Enabling Technologies** | | | | | | |
| Starshade Petal Position Accuracy and Stability | Deploy and maintain petal position accuracy in L2 environment | 11.2.1.1 | • Petal position deployment tolerance (≤150 μm) verified with multiple deployments of 12 m flight-like perimeter truss and no optical shield<br>• No environmental testing | • Petal position deployment accuracy on 20 m perimeter truss: ±600 μm (3σ) bias<br>• Position stability in operational environment: ±400 μm (3σ) random | 4 | 5 |
| Starshade Petal Shape Accuracy and Stability | Starshade petal shape maintained after deployment, thermal at L2 | 11.2.1.2 | • Manufacturing tolerance (≤100 μm) verified with low-fidelity 6 m long by 2.3 m prototype; no environmental tests<br>• Petal deployment tests conducted on prototype petals to demonstrate rib actuation; no post-deploy cycle and petal shape stability measurements | • Petal 16 m long by 4 m wide<br>• Petal shape manufacture: ±140 μm (3σ)<br>• Post-deploy cycle and petal shape thermal stability ≤ ±160 μm (3σ) | 4 | 5 |
| Starshade Scattered Sunlight for Petal Edges | Limit edge-scattered sunlight and diffracted starlight with petal optical edges | 11.2.2.1 | • Chemically etched amorphous metal edges limit solar glint flux to 25 visual magnitudes in two main lobes, verified at coupon level<br>• In-plane shape tolerance of ±20 μm met at half meter length after integration onto prototype petal<br>• In plane shape stability demonstrated post-deploy and thermal cycle<br>• Scatter performance on half meter edge verified post environment | • One meter length edges assembled precisely onto petal<br>• Petal edge in-plane shape tolerance: ±66 μm (3σ)<br>• Petal edge in-lane placement tolerance: ±55 μm (3σ)<br>• Solar glint: 26.25 (TBR) visual magnitudes in two main lobes | 5 | 5 |
| Starshade Contrast Performance Modeling and Validation | Validate at flight-like Fresnel numbers the equations that predict the contrasts | 11.2.2.2 | • $1.5 \times 10^{-10}$ contrast demonstrated at Fresnel $\text{Number}_{R=1}$ ~13 (monochromatic)<br>• Expect $1 \times 10^{-10}$ contrast demonstrated at Fresnel $\text{Number}_{R=1}$ ~13 (10% bandwidth) in March 2019 | • Experimentally validated models with scaled flight-like geometry and Fresnel $\text{Number}_{R=1}$ ≥12 across a broadband optical bandpass. Validated models are traceable to $1 \times 10^{-10}$ contrast system performance in space. | 4 | 5 |
| Starshade Lateral Formation Sensing | Lateral formation flying sensing to keep telescope in starshade's dark shadow | 11.2.3.1 | • Simulations have shown centroid to ≤1/10th aperture with ample flux to support control loop<br>• Control algorithms demonstrated control ≤1 m radius within line of sight of the star for durations representative of typical starshade observation times | • Demonstrate sensing lateral errors ≤0.40 m accuracy (≤1/10th aperture) at scaled flight separations<br>• Control algorithms demonstrated with scaled lateral control corresponding to ≤1 m of the line of sight | 5 | 6 |
| Large Mirror Fabrication | Large monolith mirror that meets tight surface figure error and thermal control requirements at visible wavelengths | 11.3.1.1 | • 4.2 m diameter, 420 mm thick blanks standard<br>• Schott demonstrated computer-controlled-machine lightweighting to pocket depth of 340 mm, 4 mm rib thickness on E-ELT M5 and 240 mm deep/2 mm thick rib on Schott 700 mm diameter test unit | • 4.04 m diameter substrate<br>• 3–4 mm ribs, 14 mm facesheet, and pocket depth of 290 mm for 400 mm thick blank<br>• Aerial density 110 $kg.m^2$<br>• <5 ppb/K CTE homogeneity<br>• First mode ≥60 Hz | 4 | 4 |

# Technology Maturity Table (2 of 4)

| Title | Description | Section | State of the Art | Capability Needed | TRL 2019 | Expected 2023 TRL |
|---|---|---|---|---|---|---|
| | | | • State-of-the-practice (SOP) lightweighting has yielded large mirrors of aerial density 70 kg/m$^2$<br>• Zerodur® can achieve 2.83 parts per billion/K CTE homogeneity (DKIST mirror)<br>• Wavefront stability: 25 nm rms for HST in LEO<br>• Wavefront error of WFIRST-like primary mirror (spatial frequency cycles/beam diameter: nm RMS):<br>▪ 0–7 cy/D: 6.9 nm RMS<br>▪ 7–100 cy/D: 6.0 nm RMS<br>▪ >100 cy/D: 0.8 nm RMS | • Wavefront stability of 100s to a few picometers rms (depending on spatial frequency) over 100s of seconds<br>• Wavefront error (spatial frequency cycles/beam diameter: nm RMS):<br>▪ 0–7 cy/D: 6.9 nm RMS<br>▪ 7–100 cy/D: 6.0 nm RMS<br>▪ >100 cy/D: 0.8 nm RMS | | |
| Large Mirror Coating Uniformity | Mirror coating with high spatial uniformity over the visible spectrum | 11.3.1.2 | • Reflectance uniformity <0.5% of protected Ag on 2.5 m TPF Technology Demonstration Mirror<br>• IUE, HST, and GALEX used $MgF_2$ on Al to obtain >70% reflectivity from 0.115 µm to 2.5 µm<br>• Operational life: >28 years on HST | • Reflectance uniformity <1% over 0.45–1.0 µm<br>• Reflectivity comparable to HST:<br>▪ 0.115–0.3 µm: ≥70%<br>▪ 0.3–0.45 µm: ≥88%<br>▪ 0.45–1.0 µm: ≥85%<br>▪ 1.0–1.8 µm: ≥90%<br>• Operational life >10 years | 4 | 5 |
| Laser Metrology | Sensing for control of rigid body alignment of telescope front-end optics | 11.3.2.1 | • Nd:YAG ring laser and modulator flown on LISA-Pathfinder<br>• Phase meters flown on LISA-Pathfinder and Grace Follow-On<br>• Sense at 1 kHz bandwidth<br>• Thermally stabilized Planar Lightwave Circuit at TRL 6. Thermal stability measured, which could provide uncorrelated per gauge error of 0.1 nm | • Sense at 100 Hz bandwidth<br>• Uncorrelated per gauge error of 0.1 nm | 5 | 6 |
| Coronagraph Architecture | Suppress starlight by a factor of ≤1E-10 at visible and near-IR wavelengths | 11.4.1.1 | • Hybrid Lyot: $6 \times 10^{-10}$ raw contrast at 10% bandwidth across angles of 3–16 λ/D demonstrated with a linear mask and an unobscured pupil in a static vacuum lab environment<br>• Vector vortex charge 4: $5 \times 10^{-10}$ raw contrast monochromatic across angles of 2–7 λ/D<br>• Lyot: $3.6 \times 10^{-10}$ raw contrast at 10% bandwidth over 3–7 λ/D in a static lab environment (DST)<br>• Vector vortex charge 6: $8.5 \times 10^{-9}$ coherent contrast at 10% bandwidth across angles of 3–8 λ/D demonstrated with an unobscured pupil in a static lab environment | • Vortex Charge 6<br>• Raw contrast of $\leq 1 \times 10^{-10}$<br>• Raw contrast stability of $\leq 2 \times 10^{-11}$<br>• Inner working angle (IWA) ≤ 2.4 λ/D<br>• Coronagraph throughput ≥10%<br>• Bandwidth ≥20% | 4 | 5 |

# Technology Maturity Table (3 of 4)

| Title | Description | Section | State of the Art | Capability Needed | TRL 2019 | Expected 2023 TRL |
|---|---|---|---|---|---|---|
| Zernike Wavefront Sensing and Control (ZWFS) | Sensing and control of low-order wavefront drift; monitoring of higher order Zernike modes | 11.4.2 | • <0.36 mas rms per axis LoS residual error demonstrated in lab with a fast-steering mirror attenuating a 14 mas LOS jitter and reaction wheel inputs on Mv = 5 equivalent source; ~26 pm rms sensitivity of focus (WFIRST Coronagraph Instrument Testbed)<br>• WFE stability of 25 nm/orbit in low Earth orbit (HST). Higher low-order modes sensed to 10–100 nm WFE rms on ground-based telescopes | • LoS error <0.2 mas rms per axis<br>• Wavefront stability:≤~100 pm rms over 1 second for vortex<br>• WFE <0.76 nm rms | 4 | 5 |
| Deformable Mirrors | Flight-qualified large-format deformable mirror | 11.4.3 | • Micro-electromechanical DMs available up to 64 × 64 actuators, 400 µm pitch with 6 nm RMS flattened surface; 3.3 nm RMS demonstrated on 32 × 32 DM<br>• $8.5 \times 10^{-9}$ coherent contrast at 10% bandwidth in a static test achieved with smaller 32 x 32 MEMS DMs<br>• Contrast drift of ~$1 \times 10^{-12}$/hour over 4 hr, ~$1 \times 10^{-8}$ drift over 42 hr<br>• Drive electronics in DST provide 16 bit resolution, which contributes ~$1 \times 10^{-10}$ to contrast floor | • 64 × 64 actuators<br>• Enable coronagraph raw contrasts of ≤$1 \times 10^{-10}$ at ~20% bandwidth and raw contrast stability ≤$2 \times 10^{-11}$<br>• <3.3 nm RMS flattened surface figure error (SFE)<br>• Drive electronics of at least 18 bits | 4 | 5 |
| Delta Doped UV and Visible Electron Multiplying CCDs | Low-noise UV and visible detectors for exoplanet characterization | 11.5.1.1 | • 1k × 1k EMCCD detectors (WFIRST)<br>▪ Dark current of $7 \times 10^{-4}$ e-/px/s<br>▪ CIC of $2.3 \times 10^{-3}$ e-/px/frame<br>▪ Read noise ~0 e- rms (in EM mode)<br>▪ Irradiated to equivalent of 6-year flux at L2<br>▪ Updated design for cosmic ray tolerance under test<br>• 4k × 4k EMCCD dark current $1.5 \times 10^{-4}$ e-/px/s | • 0.45–1.0 µm response;<br>• Dark current <$10^{-4}$ e-/px/s<br>• CIC <$3 \times 10^{-3}$ e-/px/frame<br>• Effective read noise <0.1e rms<br>• Tolerant to a space radiation environment over mission lifetime at L2<br>• 4k × 4k format for Starshade IFS | 4 | 5 |
| Deep Depletion Visible Electron Multiplying CCDs | Low-noise detectors with improved QE at 940 nm for exoplanet characterization | 11.5.1.1 | • Under investigation. e2V claims dark current is on boundary surface and not throughout volume<br>• CCD-201 is not currently made in deep depletion<br>• CCD-220 (regular CCD) dark current < 0.02 e-/px/s | • QE >80% at 940 nm<br>• thicker silicon (up to 200 µm thick layer), deep depletion devices<br>• 4k × 4k format for starshade IFS | 4 | 5 |
| Linear Mode Avalanche Photodiode Sensors | Near infrared wavelength (0.9 µm to 2.5 µm), extremely low noise detectors for exo-Earth IFS | 11.5.1.2 | • HgCdTe photodiode arrays have read noise <~2 e rms with multiple non-destructive reads; dark current <0.001 e-/s/pix; very radiation tolerant (JWST)<br>• HgCdTe APDs have dark current ~10–20 e-/s/pix, read noise <<1 e- rms, and < 1k × 1k format<br>• LMAPD have 0.0015 e-/pix/s dark current, <1 to 0.1 e rms readout noise (SAPHIRA) for 320×256, 24 µm pixels. This format is TRL 5. | • Read noise <<1 e- rms<br>• Dark current <0.002 e-/pix/s<br>• In a space radiation environment over mission lifetime<br>• 320 × 256 format array, 24 µm pixels | 4 | 5 |
| | | | • LMAPD 1k × 1k formats of 15 µm pixels have 0.04 e rms dark current at gain of 25 | • 1k × 1k pixel array, 15 µm pixels | | |

# Technology Maturity Table (4 of 4)

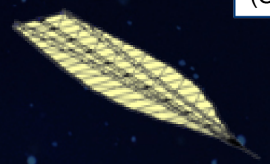
| Title | Description | Section | State of the Art | Capability Needed | TRL 2019 | Expected 2023 TRL |
|---|---|---|---|---|---|---|
| UV Microchannel Plate (MCP) Detectors | Low-noise detectors for general astrophysics as low as 0.115 µm | 11.4.4 | • MCPs: QE 44% 0.115–0.18 µm with alkalai photocathode, 20% with GaN; dark current ≤0.1–1 counts/cm$^2$/s with ALD activation and borosilicate plates | • Dark current <0.001 e-/pix/s (173.6 counts/cm$^2$/s), in a space radiation environment over mission lifetime,<br>• QE>50% (TBR) for 0.115–0.3 µm wavelengths | 4 | 4 |
| Microthrusters | Jitter is mitigated by using microthrusters instead of reaction wheels during exoplanet observations | 11.6.1.1 | • Colloidal microthrusters 5–30 µN thrust with a resolution of ≤0.1 µN, 0.05 µN/√Hz, 100 days on-orbit on LISA-Pathfinder<br>• Colloidal microthrusters with 100 µN thrust and 10-year lifetime under development<br>• Cold-gas micronewton thrusters flown on Gaia (TRL 9), 0.1 µN resolution, 1 mN max thrust, 0.1 µN/sqrt (Hz), 4 years of on-orbit operation | • Thrust capability: 350 µN with 16 thruster cluster<br>• Thrust resolution 4.35 µN<br>• Thrust noise: 0.1 µN/√Hz<br>• Operating life: 5 years | 4 | 6 |
| **Enhancing Technologies** | | | | | | |
| Far-UV Mirror Coating | General astrophysics imaging as low as 0.1 µm | 11.7.1.1 | • For a ~0.1 µm cutoff, Al + LiF + AlF3 has been demonstrated at the lab proof-of-concept level with test coupons achieving reflectivities<br>▪ for >0.2 µm: 80%<br>▪ for 0.103–0.2 µm: 70%<br>▪ Lifetime: no loss of reflectivity after 3-year lab storage | • Reflectivity from 0.3–1.8 µm: >90%<br>• Reflectivity from 0.115–0.3 µm: >80%<br>• Reflectivity from 0.103–0.115 µm: >50%<br>• Operational life: >10 years | 3 | 3 |
| Delta-Doped UV Electron Multiplying CCDs | Low-noise detectors for general astrophysics as low as 0.1 µm | 11.7.3.1 | • Delta-doped EMCCDs: Same noise performance as visible with addition of high UV QE ~60–80% in 0.1–0.3 µm, dark current of 3 × 10$^{-5}$ e-/pix/s beginning of life. 4k × 4k EMCCD fabricated. Dark current <0.001 e-/pix/s, in a space radiation environment over mission lifetime, ≥4k × 4k format fabricated | • Dark current <0.001 e-/pix/s, in a space radiation environment over mission lifetime,<br>• ≥4k × 8k format for spectrograph run in full frame mode,<br>• High QE for 0.1–0.3 µm wavelengths | 4 | 4 |
| Microshutter Arrays | An array of apertures for the UV spectrometer | 11.7.2 | • 171 × 365 shutters with electrostatic and magnetic actuation (JWST NIRSpec, TRL 7)<br>• 128 × 64 electrostatic actuated array at TRL 4; will fly in FORTIS sounding rocket summer 2019<br>• 840 × 420 electrostatic, buttable array developmental model with partial actuation | • 300 × 300 shutters needed | 3 | 5 |

# Large Mirror Coating Uniformity

| | HST | Kepler | JWST | FUSE | Gemini | Subaru |
|---|---|---|---|---|---|---|
| PM Size | 2.4m monolith | 1.4m monolith; 950mm entrance aperture | 18 hexagonal Be mirror segments (~1.52m wide) with total collecting area of 25m | Four mirrors of 38.7x35.2 cm each | 8m monolith | 8.3m monolith |
| Spectral range | 115 nm to 2500 nm | 300nm to 1200nm | 700 nm to 20µm | 90.5 nm to 118.7nm | 400nm to 20 µm | 300nm to 25 µm |
| Coating | Protected Al ($MgF_2$ on Al) | Protected Ag (multilayer on Ag) | Protected Gold | LiF on Al on 2 mirrors and SiC on other 2 | Ag with SiNx and NiCrNx protective layers | Al primary and protected Ag secondary |
| **Uniformity** | | **<30nm PV; Reflectivity variation <2%** | **<1% thickness variation among the 18 segments. <10nm pv; Reflectance variation <0.5% in the IR** | | **Thickness uniformity required +/- 5%** | **Average thickness 177nm with 20nm pv and 4.1nm stdev. Reflectivity variation ~ 1.2% pv** |

# Starshade Mechanical

## Petal Shape & Stability



FY22

Accelerate S5 TRL 5 milestones (Subscale petal) → 9/2022 TRL 5 → FY23 Fabricate full scale petal, 16 m long, 4 m wide, with TRL-5 *optical edge* attached → Measure 2D edge profile

*Starshade Scattered Sunlight from Petal Edges will be matured with the Starshade Mechanical Technology gaps*

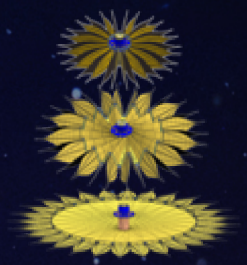
→ Deploy Cycles & verify shape → Thermal Cycles (deployed) & verify shape → Thermal Cycles (stowed) & verify shape → Validate Model of critical dimension vs. temperature → Validate Model of petal shape vs. I/F load → Storage (creep) & verify shape (10/2024) → 10/2024 TRL 6

## Petal Unwrapping

FY22

Accelerate S5 TRL 5 milestones (Subscale petals) → 9/2022 TRL 5 → FY23 Fabricate Petal Launch & Unfurl Subsystem (PLUS) Full scale (2.25m stow dia.) → Fabricate GSE "stowed truss" with 22 med. fidelity petals and 2 high fidelity petals → Verify unwrapping with no edge contact → Validate Model of deployment kinematics → Stowed vibe test, measure position, & validate dynamics model → Storage (creep) & verify position (9/2024)

## Truss Deploy



FY22

Accelerate S5 TRL 5 milestones Half scale (10 m dia.) → 9/2022 TRL 5 → FY23 Design and Fabricate truss Full scale (20 m dia.) → 9/2024 Remove petals from GSE and install on truss to create deployable starshade Full scale (52 m) → Deploy Cycles & verify positions → Thermal Cycles & verify positions

→ Verify opacity at interfaces on subassembly → Validate Model of petal position vs. I/F load → Validate Model of deployement kinematics → Validate Model of deployed structure FEM → Storage (creep) & verify position (9/2026) → 9/2026 TRL 6

# Starshade Optical Performance and Formation Sensing

## Starshade Lateral Formation Sensing

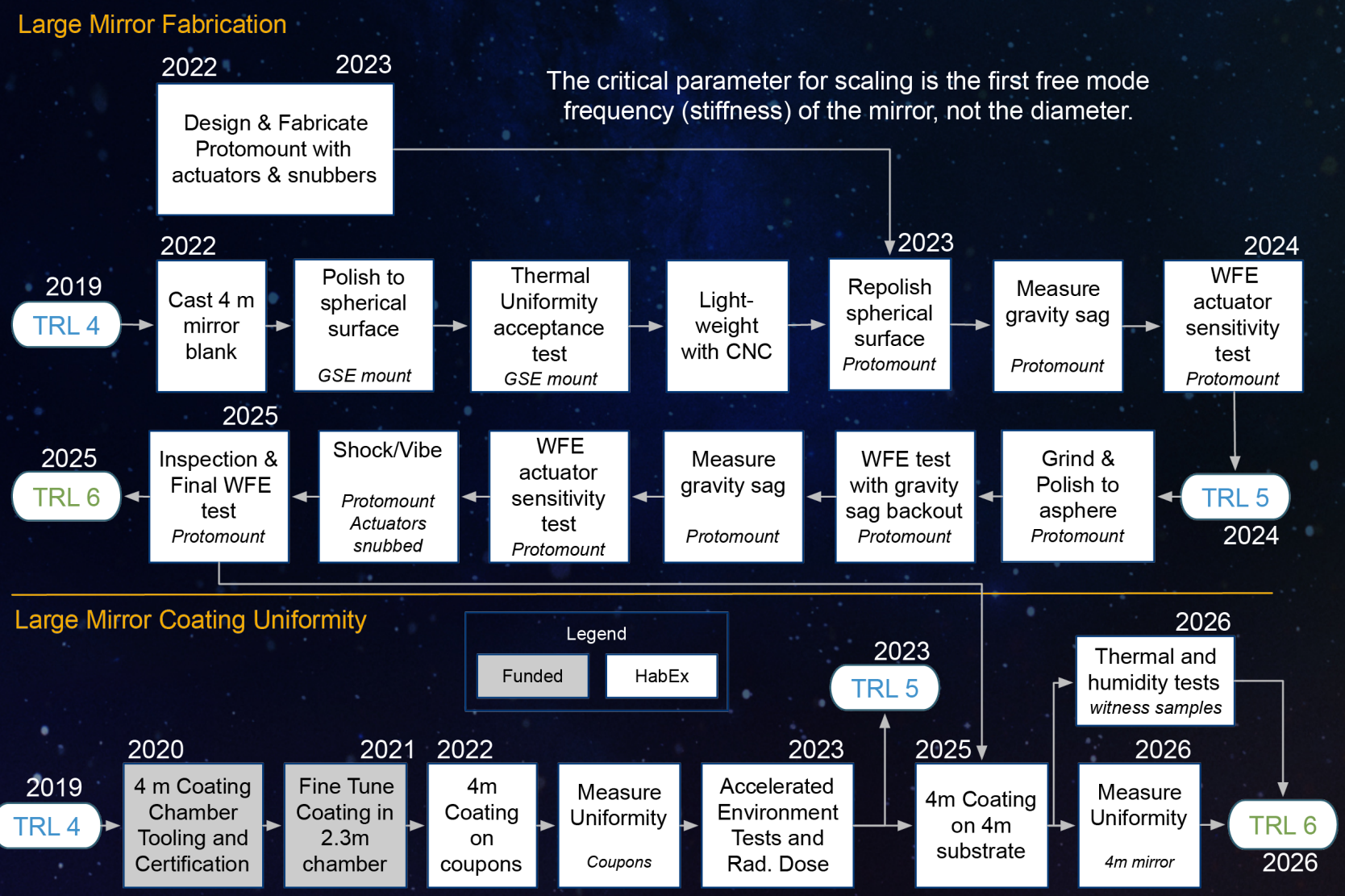
2019 TRL 5 → 2022, 9 months: Upgrade SLATE Testbed optics, add NIR source and sensor → 2 months: NIR Sensing Test & Closed Loop Demo → 2 months: UV source and sensor Integration → 2 months: UV Sensing Test & Closed Loop Demo → 3/2023 TRL 6

## Starshade Contrast Performance and Model Validation

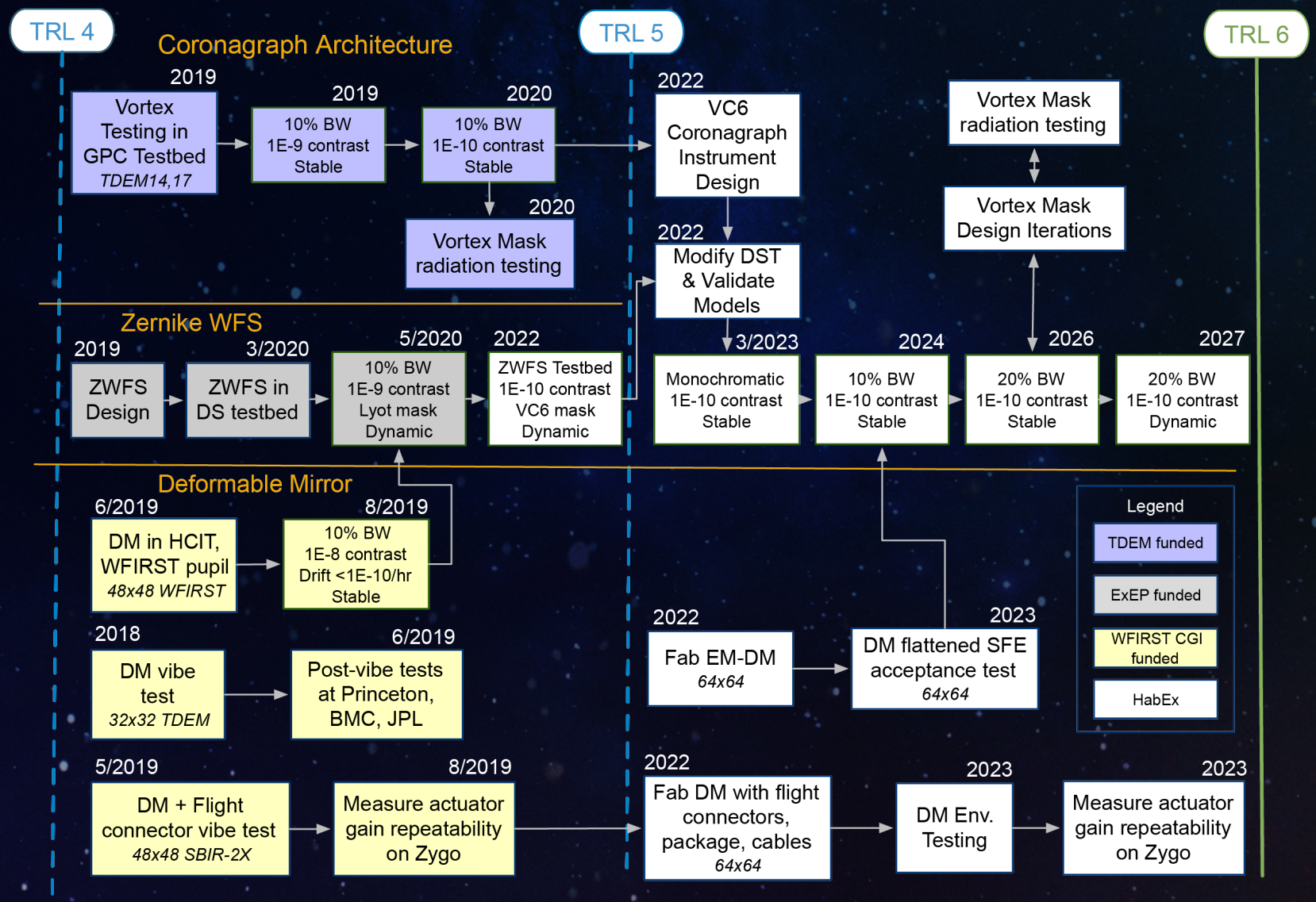
1/2020 TRL 5 → 2022, 16 months: Build Test Facility With 308 m long light-vacuum, thermally stable tunnel → 3 months: Integrate optical elements, sources, detectors → 8 months: Repeat S5 milestone 1A 1E-10 Contrast narrowband *10 cm mask* → 4 months: Repeat S5 milestone 1B 1E-10 20% super continuum source *10 cm mask* → 12 months: Repeat S5 milestone 2 Model Validation with known errors *10 cm mask* → 4/2025 TRL 6

2022, 16 months: Fabricate baseline starshade masks *10 cm mask* → 2024, 16 months: Fabricate known error starshade masks *10 cm mask*

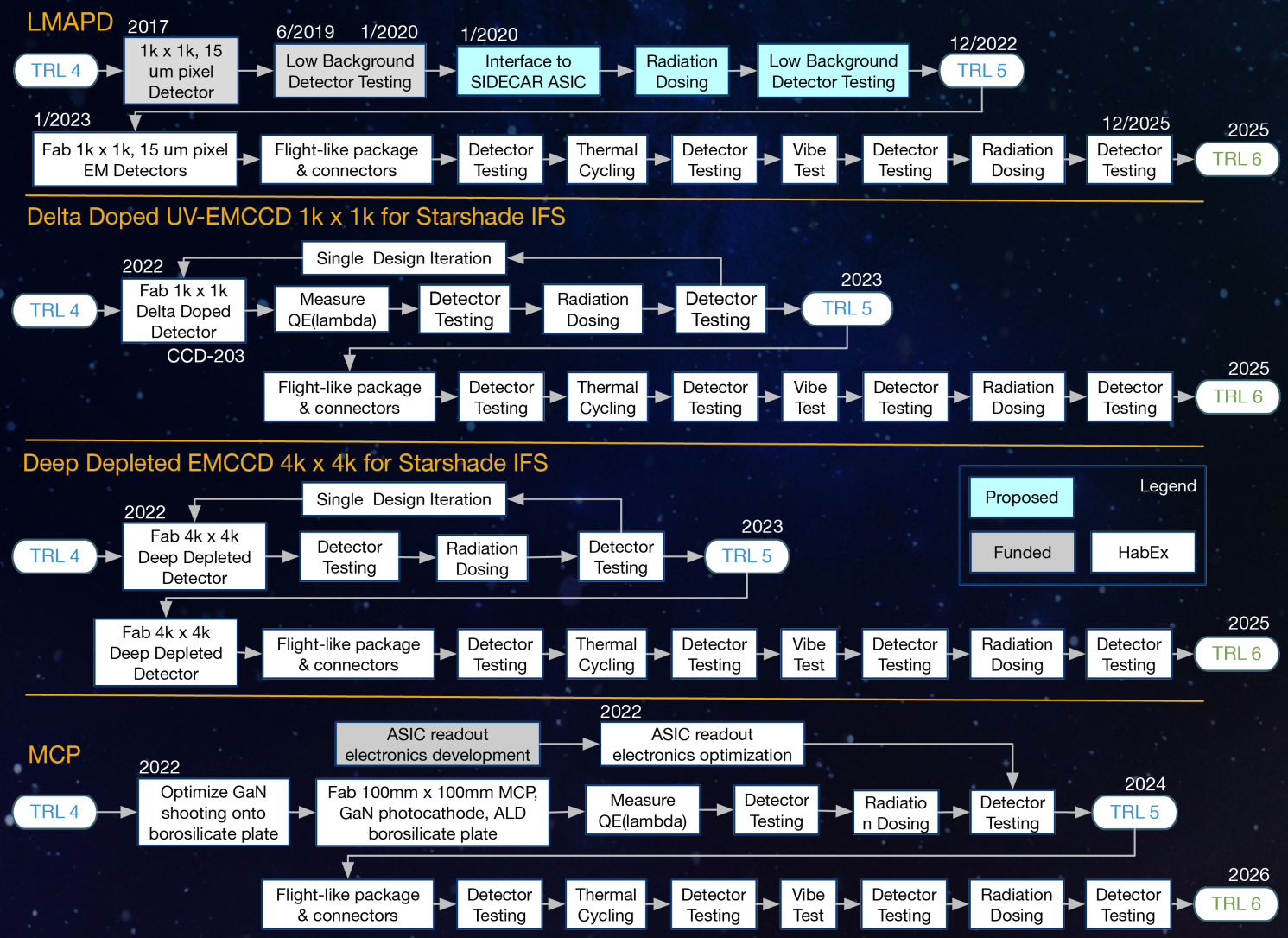
# Large Mirror Fabrication



# Coronagraph Testbed

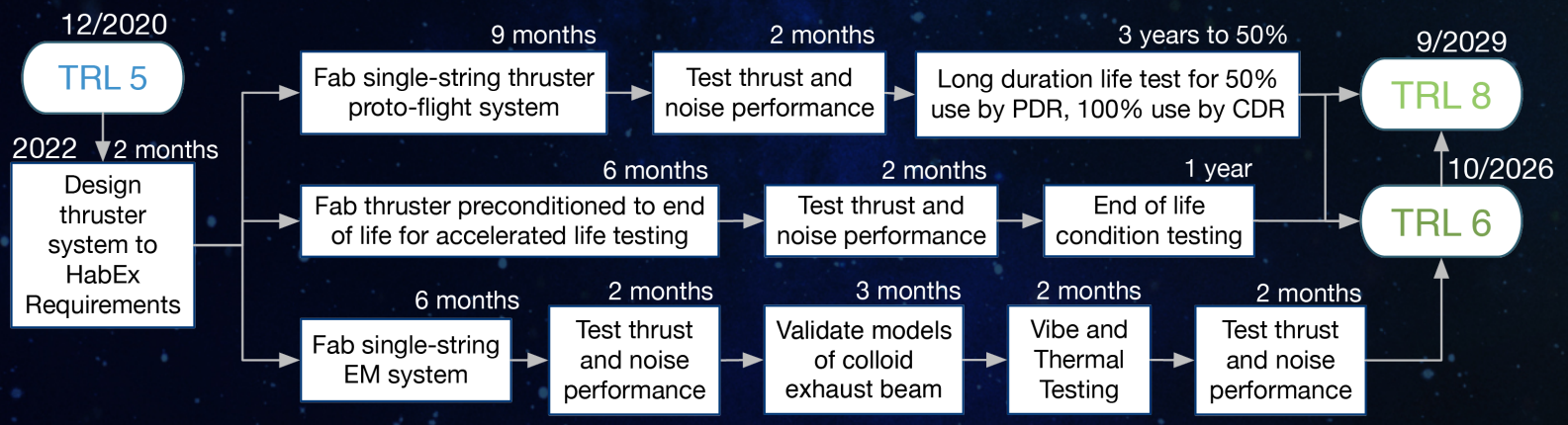


# Detectors

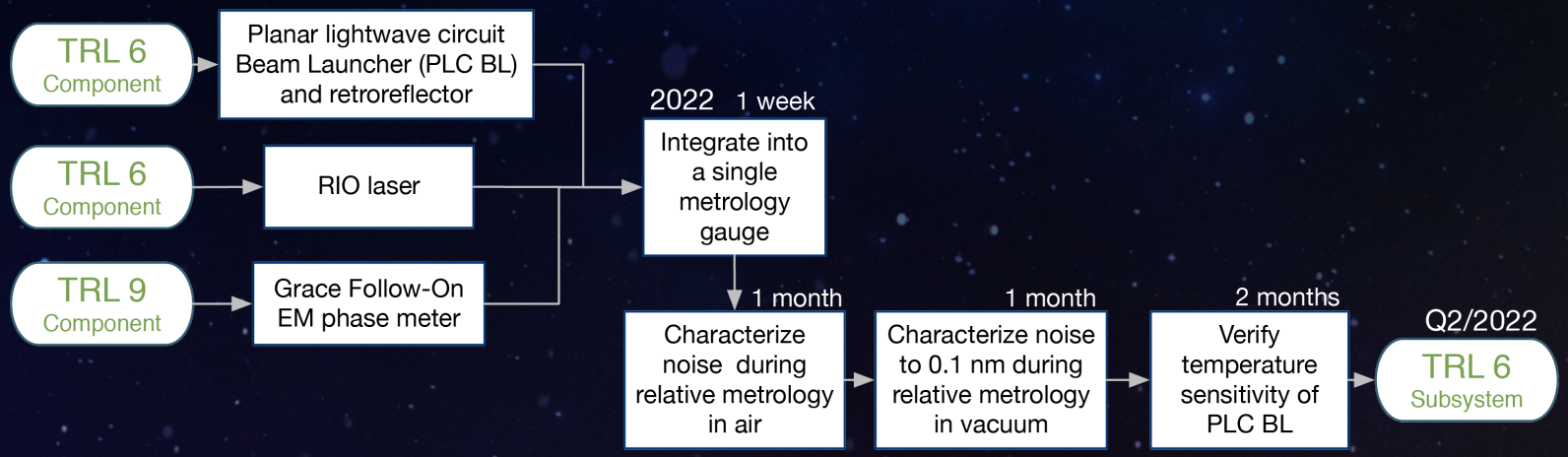

LMAPD
TRL 4
2017
1k x 1k, 15 um pixel Detector
6/2019
1/2020
Low Background Detector Testing
1/2020
Interface to SIDECAR ASIC
Radiation Dosing
Low Background Detector Testing
12/2022
TRL 5
1/2023
Fab 1k x 1k, 15 um pixel EM Detectors
Flight-like package & connectors
Detector Testing
Thermal Cycling
Detector Testing
Vibe Test
Detector Testing
Radiation Dosing
12/2025
Detector Testing
2025
TRL 6
Delta Doped UV-EMCCD 1k x 1k for Starshade IFS
Single Design Iteration
2022
TRL 4
Fab 1k x 1k Delta Doped Detector
CCD-203
Measure QE(lambda)
Detector Testing
Radiation Dosing
Detector Testing
2023
TRL 5
Flight-like package & connectors
Detector Testing
Thermal Cycling
Detector Testing
Vibe Test
Detector Testing
Radiation Dosing
Detector Testing
2025
TRL 6
Deep Depleted EMCCD 4k x 4k for Starshade IFS
Single Design Iteration
2022
TRL 4
Fab 4k x 4k Deep Depleted Detector
Detector Testing
Radiation Dosing
Detector Testing
2023
TRL 5
Legend
Proposed
Funded
HabEx
Fab 4k x 4k Deep Depleted Detector
Flight-like package & connectors
Detector Testing
Thermal Cycling
Detector Testing
Vibe Test
Detector Testing
Radiation Dosing
Detector Testing
2025
TRL 6
MCP
ASIC readout electronics development
2022
ASIC readout electronics optimization
2022
TRL 4
Optimize GaN shooting onto borosilicate plate
Fab 100mm x 100mm MCP, GaN photocathode, ALD borosilicate plate
Measure QE(lambda)
Detector Testing
Radiatio n Dosing
Detector Testing
2024
TRL 5
Flight-like package & connectors
Detector Testing
Thermal Cycling
Detector Testing
Vibe Test
Detector Testing
Radiation Dosing
Detector Testing
2026
TRL 6

# Microthrusters and Laser Metrology

## Microthrusters




## Laser Metrology



# Technology Maturation Cost

**Table E-1.** Technology cost estimates to TRL 5 & 6.

| Technology Gap Title | Cost Estimate ($FY20) | | Basis of Estimate | |
|---|---|---|---|---|
| | To TRL 5 | To TRL 6 | To TRL5 | To TRL6 |
| Starshade Lateral Formation Sensing | N/A | $1.1M | at TRL 5 | Based on S5 SLATE testbed actual costs |
| Starshade Contrast Performance Modeling and Validation | N/A | $10M | Funded by S5 | Based on S5 Contrast Performance testbed actual costs and grassroots estimate |
| Starshade Scattered Sunlight | N/A | N/A | Funded by S5 | Included in starshade mechanical technologies |
| Starshade Mechanical Technologies | N/A | $147M | Funded by S5 | Exo-S report and S5 estimates for TRL5 |
| Large Mirror Fabrication | $40M | $40M | Quote from industry | |
| Large Mirror Coating Uniformity | $5M | $2.5M | Quote from industry | |
| Laser Metrology | N/A | $0.5M | At TRL 5 | based on IRAD testbed actual costs |
| Coronagraph Architecture | N/A | $7M | Funded by TDEM | Based on WFIRST CGI actual costs |
| ZWFS | N/A | $1M | Funded by DST | Included in coronagraph architecture |
| Deformable Mirrors | N/A | $1.5M | Funded by WFIRST | Based on WFIRST DM actual costs |
| On Board Computing | N/A | $4 M | Funded by SAT | Based on SAT planned costs |
| Delta Doped UV EMCCDs | $4.6M | $2.3M | Vendor quote and grassroots estimate | |
| Deep Depletion EMCDDS | $3.8M | $2.3M | Vendor quote and grassroots estimate | |
| Linear Mode Avalanche Photodiode Sensors | $1.5M | $1M | Vendor quote and grassroots estimate | |
| Microchannel Plate Detectors | $3.7M | $2.6M | Vendor quote and grassroots estimate | |
| Microthrusters | N/A | ($10M) | At TRL 5 | Covered by NASA candidate for LISA contribution, pending LISA microthruster requirement definition. |
| **TOTAL** | **$58.6M** | **$232.8M** | | |

**Table E-2.** Technology cost risk estimate for currently funded technologies to TRL 5.

| Technology Gap Title | Cost Estimate ($FY20) | Basis of Estimate | |
|---|---|---|---|
| | To TRL 5 | To TRL5 | To TRL6 |
| Starshade Contrast Performance Modeling and Validation | TRL 5 by 1/2020 | TRL 5 by 1/2020 | S5 Technology Development Plan |
| Starshade Mechanical Technologies | $26M | Funded by S5 | S5 Technology Development Plan |
| Coronagraph Architecture | $1.1M | Funded by TDEM | WFIRST CGI and TDEM plan |
| ZWFS | $0.03M | Funded by DST | DST plan |
| Deformable Mirrors | TRL 5 by 10/2019 | Funded by WFIRST | WFIRST CGI plan and TDEM |
| **TOTAL** | **$27.13M** | | |

The cost information contained in this document is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and/or Caltech.

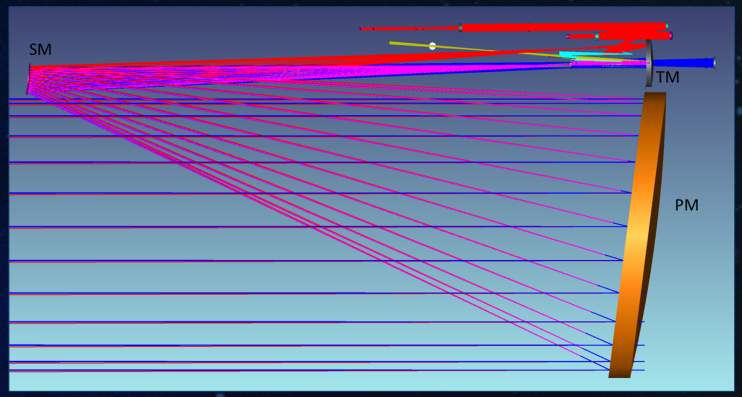
# Required Facilities

Most facilities required by HabEx already exist.

| Technology Title | Facility | Location |
|---|---|---|
| **Starshade Lateral Formation Sensing** | For SLATE testbed lab space and optical bench | JPL |
| **Starshade Contrast Performance Modeling and Validation** | 308 m long, lightly evacuated, thermally stable tube with clean room surrounding mask insertion area | TBD |
| **Starshade Mechanical Technologies** | Vacuum chamber to thermally cycle 2.3 m × 8 m petal | JPL |
| **Starshade Mechanical Technologies** | Room for 10 m perimeter truss deployment | Northrop Grumman, Aerojet |
| **Starshade Mechanical Technologies** | Deployment test of 52 m starshade | NASA Ames, Northrup, Vandenburg AFB, Edwards AF Point Mugu Naval Base |
| **Large Mirror Fabrication** | Mirror blank casting, machining, testing | SCHOTT |
| **Large Mirror Fabrication** | Final mirror figuring and testing | Collins, L3 Harris, AOS |
| **Mirror Coating Uniformity** | 4 m coating chamber | L3 Harris |
| **Coronagraph Architecture** | Coronagraph Testbed in HCIT-1 or HCIT-2 | JPL |
| **ZWFS** | Coronagraph Testbed in HCIT-1 or HCIT-2 | JPL |
| **Deformable Mirrors** | Coronagraph Testbed in HCIT-1 or HCIT-2, Vacuum Surface Gauge | JPL |
| **Delta Doped EMCCD** | Delta doping facility at Microdevices Lab | JPL |
| **Detectors** | Detector testing lab | JPL, Berkeley |

# Optical Telescope Assembly (OTA) Specifications

- OTA is
  - off-axis unobscured
  - F/2.5
  - 3 x 3 arc-sec FOV
  - Three-mirror anastigmatic design

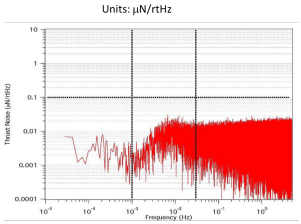


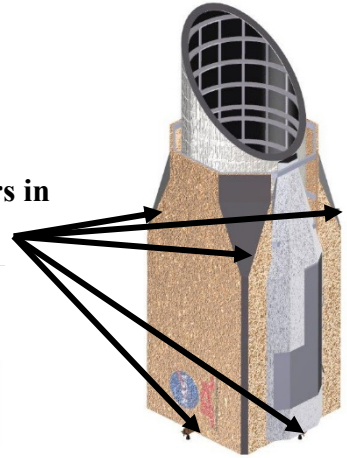

Specifications are within current State of Practice.

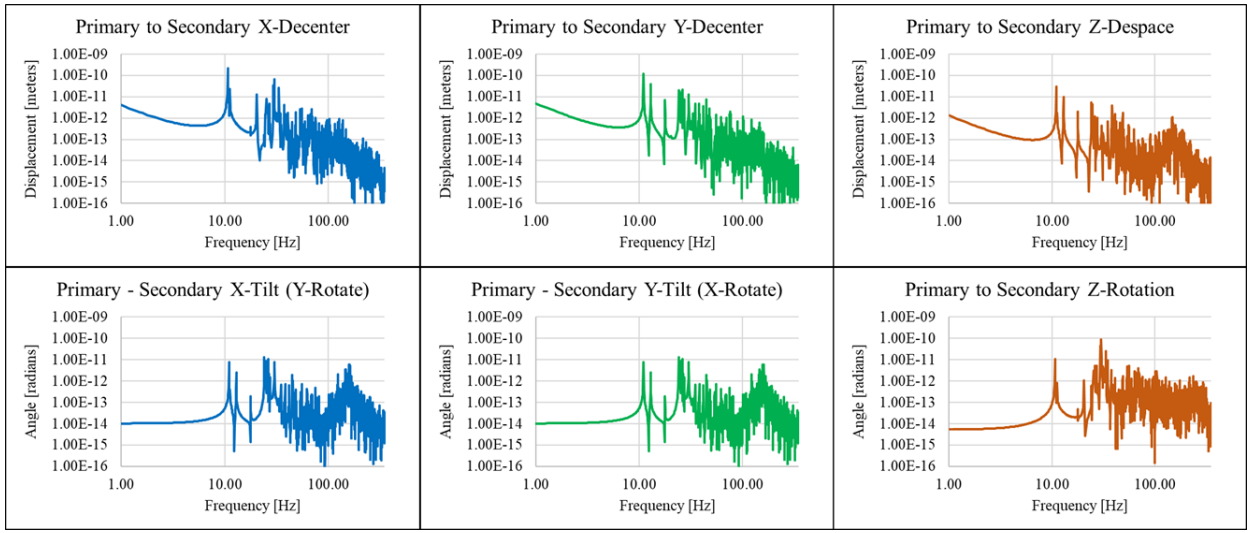
| | |
|---|---|
| Aperture Diameter | 4.0 meters |
| Diffraction Limited Wavelength | 400 nm |
| Total Wavefront Error | 30 nm rms (wavefront) |
| Total Primary Mirror Figure Error | 5.6 nm rms (surface) |
| Low Spatial SFE (< 30 cycles/dia) | 4.3 nm rms |
| Mid Spatial SFE (30 to 100 cycles/dia) | 3.3 nm rms |
| High Spatial SFE (> 100 cycles/dia) | 1.4 nm rms |
| Roughness | 0.3 nm rms |
| Line of Sight Stability (Jitter) | < 0.7 milli-arc-seconds |
| Wavefront Error Stability | 1 to 250 pm (spatial frequency dependent) |
| Spectral Range | 115 nm to 1700 nm |

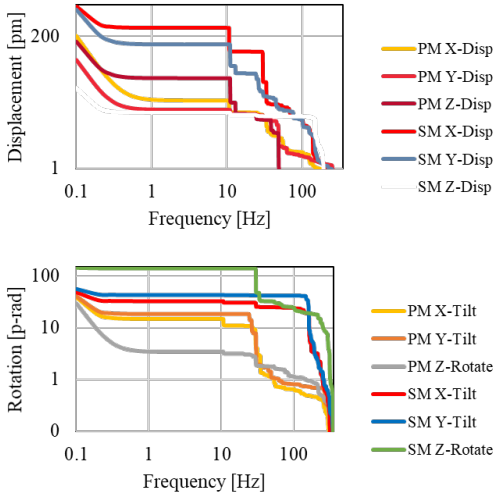
# Predicted LOS Stability: Jitter

Jitter calculated by modeling motion of primary & secondary mirrors relative to tertiary mirror from structure response to micro-thruster noise specification.




**Max rigid-body motion yields < 0.03 mas jitter (20X margin)**

Table 6: Predicted maximum 'jitter' motion of PM and SM from Microthruster Noise

| DOF | Δx (nm) | Δy (nm) | Δz (nm) | Θx (nrad) | Θy (nrad) | Θz (nrad) |
|---|---|---|---|---|---|---|
| Primary | 0.20 | 0.08 | 0.16 | 0.04 | 0.04 | 0.03 |
| Secondary | 0.67 | 0.58 | 0.03 | 0.05 | 0.06 | 0.15 |