Telescope Technology Needs for HabEx and LUVOIR

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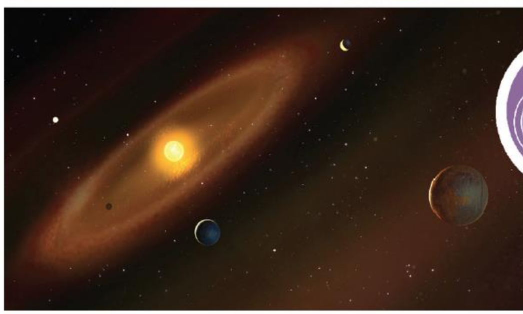
2019 Mirror Technology Days in the Government Workshop

HabEx Science Mission

EXPLORING PLANETARY SYSTEMS *AROUND NEARBY SUNLIKE STARS AND ENABLING OBSERVATORY SCIENCE FROM THE UV THROUGH* **NEAR-IR**

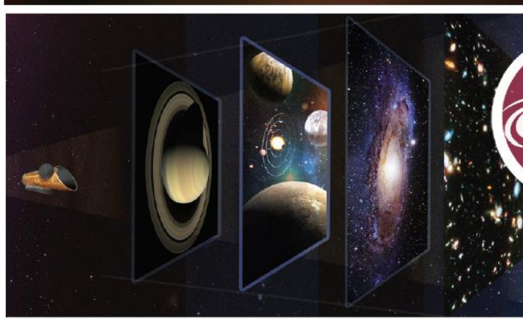
GOAL 1

To seek out nearby worlds and explore their habitability, *HabEx* will search for habitable zone Earth-like planets around sunlike stars using direct imaging and will spectrally characterize promising candidates for signs of habitability and life.



GOAL 2

To map out nearby planetary systems and understand the diversity of the worlds they contain, *HabEx* will take the first “family portraits” of nearby planetary systems, detecting and characterizing both inner and outer planets, as well as searching for dust and debris disks.



GOAL 3

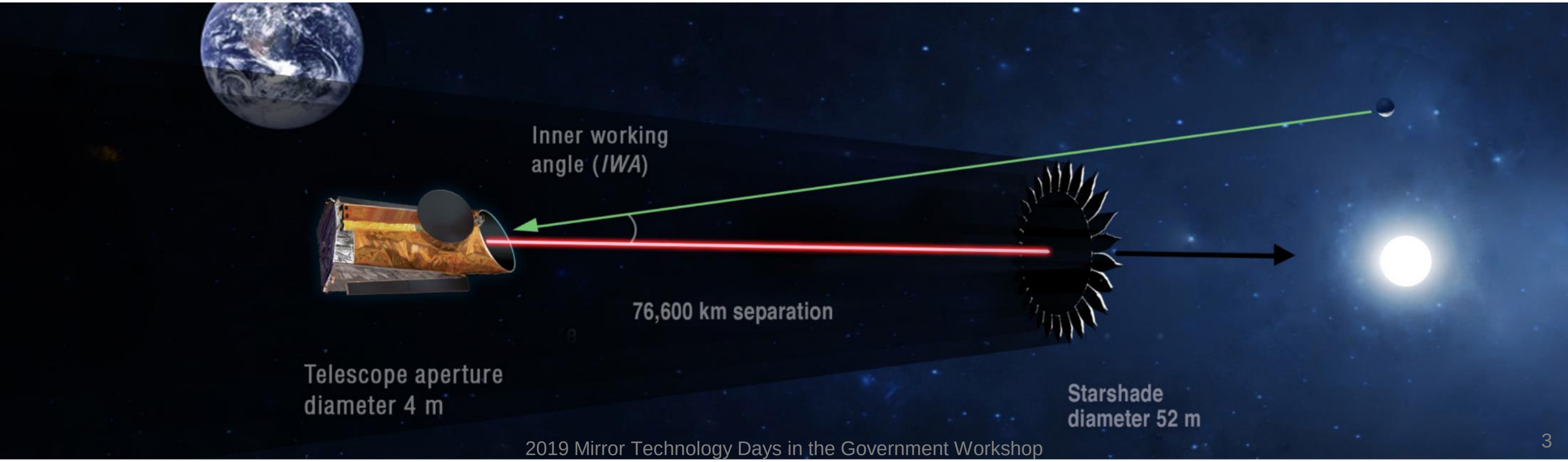
To carry out observations that open up new windows on the universe from the UV through near-IR, *HabEx* will have a community driven, competed Guest Observer program to undertake revolutionary science with a large-aperture, ultra-stable UV through near-IR space telescope.

from HabEx interim report URS273294

Architecture A Concept

The HabEx STDT chose these parameters for Architecture A:

- Telescope with a 4m aperture
- 52-m diameter, formation flying external Starshade occulter
- Four instruments:
  - Coronagraph Instrument for Exoplanet Imaging
  - Starshade Instrument for Exoplanet Imaging
  - UV– Near-IR Imaging Multi-object Slit Spectrograph for General Science
  - High Resolution UV Spectrograph for General Observatory Science

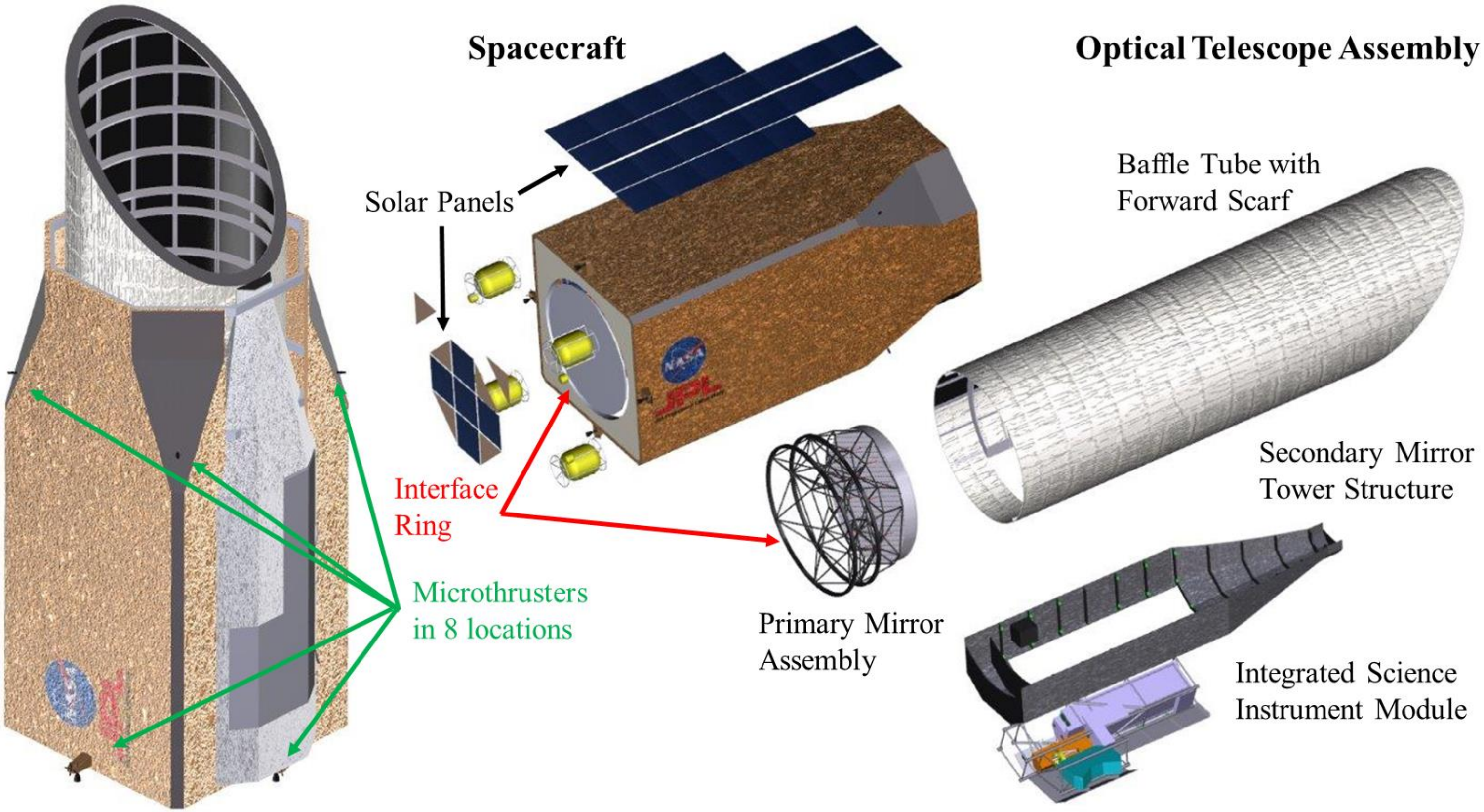


Baseline Design

Baseline Observatory is Telescope surrounded by Spacecraft.

Only connection between two is Interface Ring.

Interface Ring is also where Observatory attaches to SLS PAF.

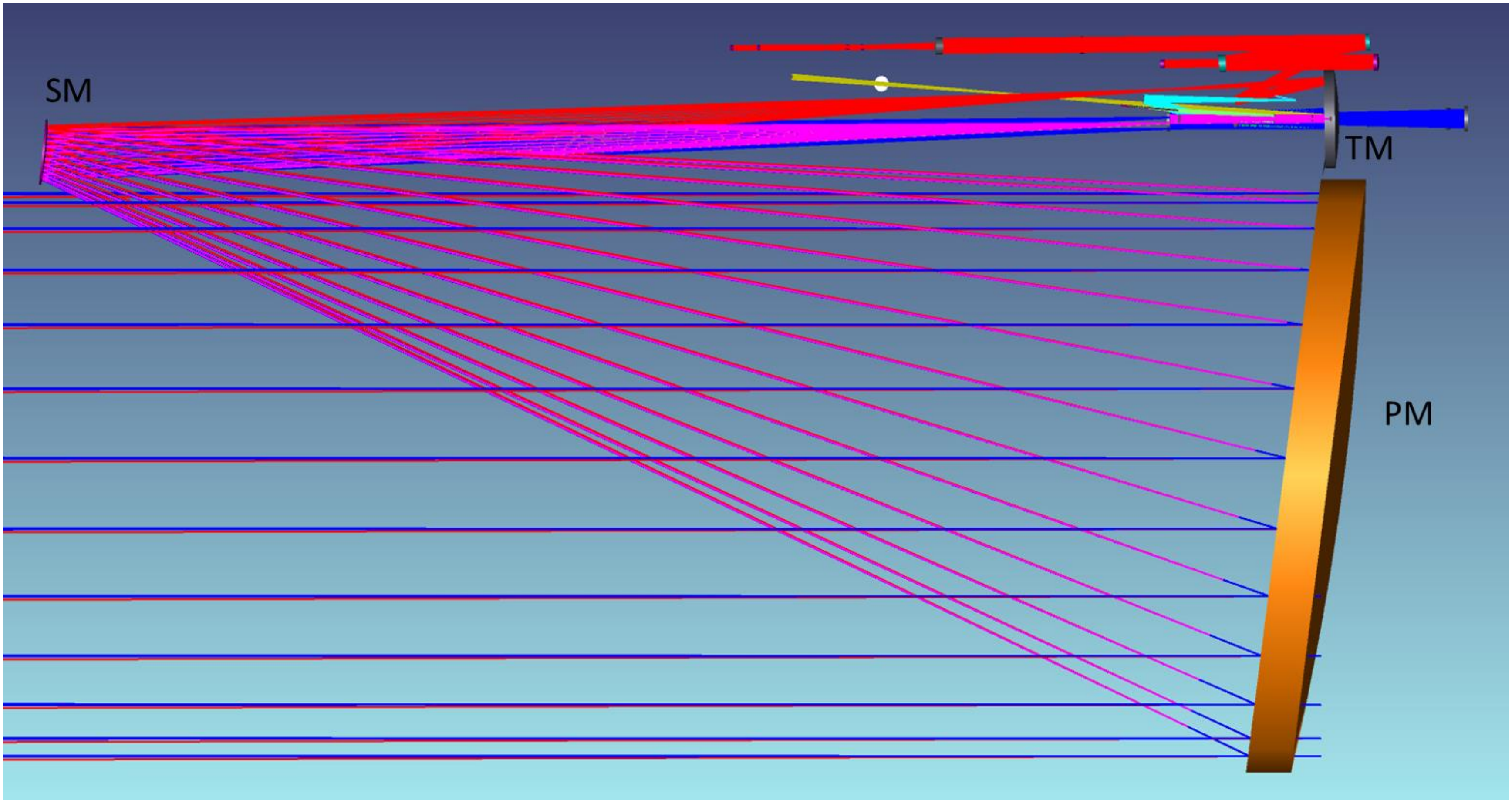


Optical Telescope Assembly (OTA) Specifications

Architecture	Unobscured Off-Axis F/2.5 TMA
Aperture Dia	4-meters Monolithic (Minimum)
LOS Stability	< 2.5 mas on-sky jitter (< 10 Hz) for astrophysics & starshade < 0.3 mas on-sky jitter (> 10 Hz) for coronagraph
Diffraction Limit	400 nm
Wavefront Error	30 nm rms Total
Primary Mirror	Total SFE < 5.6 nm rms Low-Order (< 30 cpd) < 4.3 nm rms Mid-Spatial (30 to 100 cpd) < 3.3 nm rms High-Spatial (>100 cpd) < 1.5 nm rms
WFE Stability	< 5 nm rms (astrophysics and starshade) < 1 to 200 pm rms per spatial frequency (coronagraph)

Telescope Optical Design

HabEx telescope optical design is off-axis TMA.



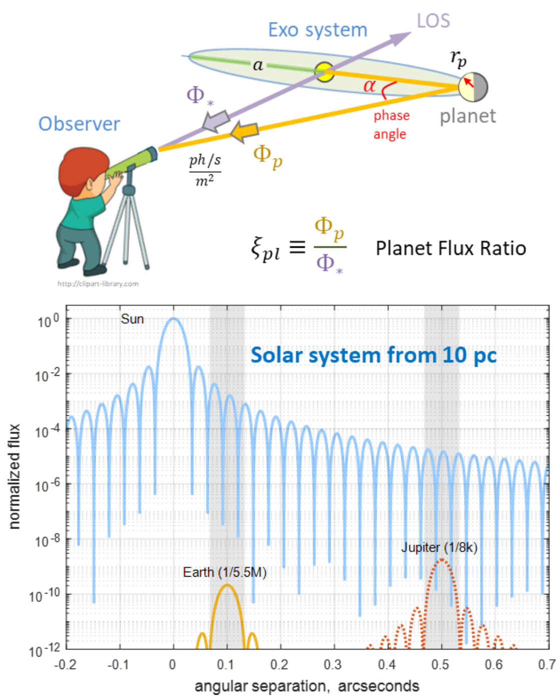
HabEx Baseline Telescope

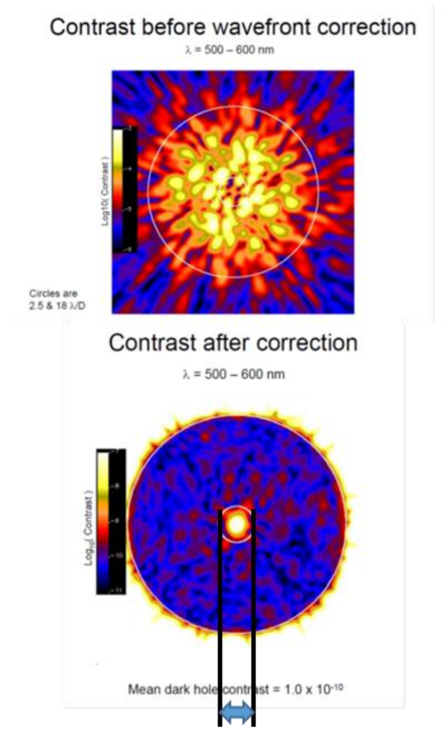
Science Driven Systems Engineering

‘The’ System Challenge: Dark Hole

Imaging an ‘exo-Earth’ requires blocking 10^{10} of host star’s light.

Internal coronagraph (with deformable mirrors) can create a ‘dark hole’ with < 10^{-10} contrast.



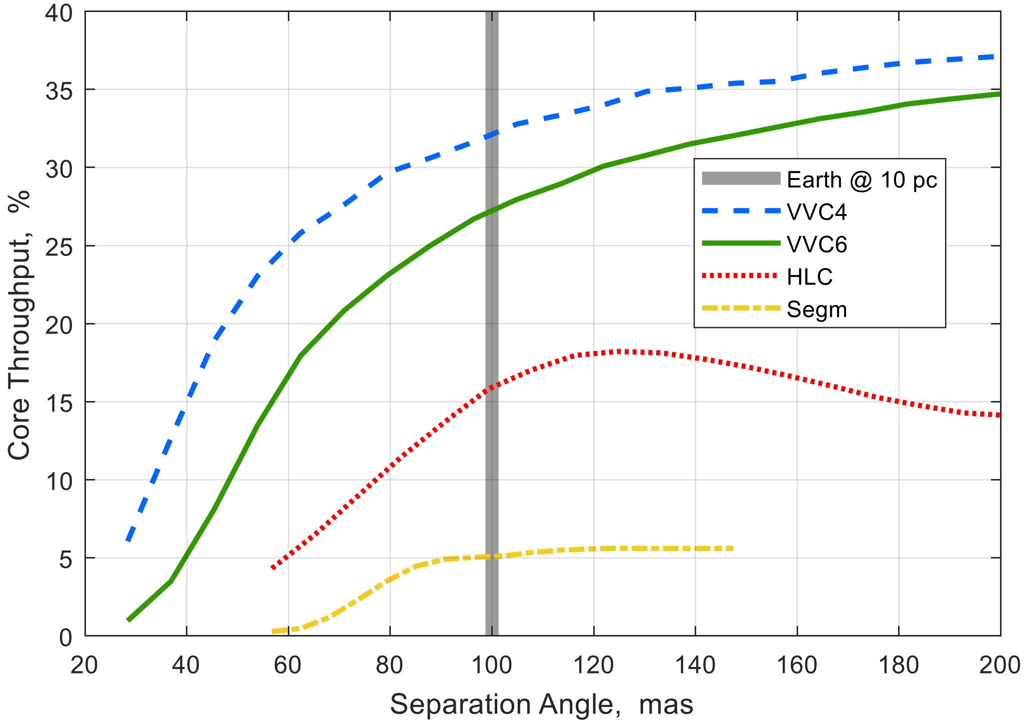


Inner Working Angle
(John Krist, JPL)

Krist, Trauger, Unwin and Traub, “End-to-end coronagraphic modeling including a low-order wavefront sensor”, SPIE Vol. 8422, 844253, 2012; doi: 10.1117/12.927143

IWA and Core Throughput

The greater the core throughput at the smallest possible IWA, the larger the number of habitable zones that can be searched.



IWA is driven by

- PSF Size — Aperture Diameter & Off-Axis Architecture
- PSF Stability — LOS Jitter and WFE Stability Specification

Why Off-Axis

Science depends on the telescope Point Spread Function (PSF) and the angular size of the 80% Encircled Energy (EE) circle:

- Inner Working Angle (IWA) Expolanet Science
- Angular Resolution General Astrophysics

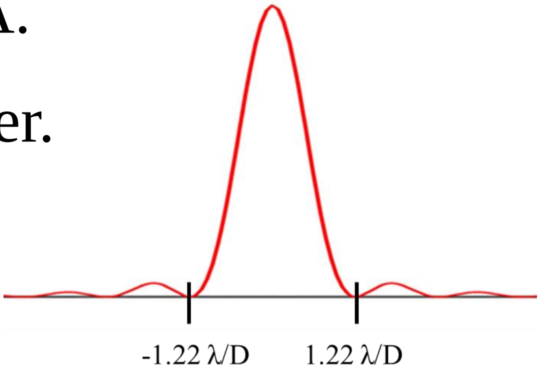
IWA is how close to a host star the coronagraph can detect an exo-planet – based on its ability to block light from the host star.

The more compact the PSF, the smaller the IWA.

PSF size depends on Telescope aperture diameter.

PSF central lobe angular radius = 1.22 λ/D.

83% of the energy is in the central lobe.



The larger the telescope aperture, the smaller the PSF and IWA.

Why Off-Axis

But, PSF is also affected by central obscuration and spiders.

Diffraction from central obscuration and spiders broaden the PSF and move energy out of the central core.

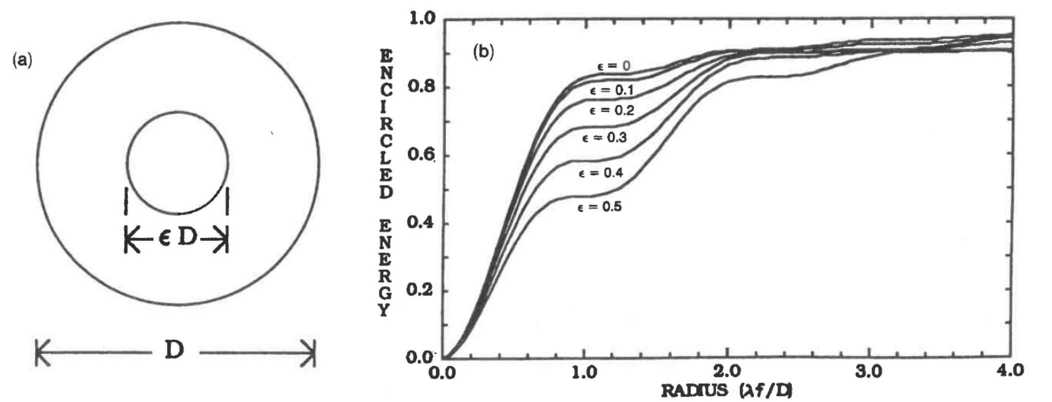


Fig. 6. Encircled energy caused by the diffraction-limited annular apertures. This figure can be used as a set of characteristic curves from which to obtain values of $EE_{annulus}(r)$, which are necessary when the empirical equation is applied to various aperture configurations.

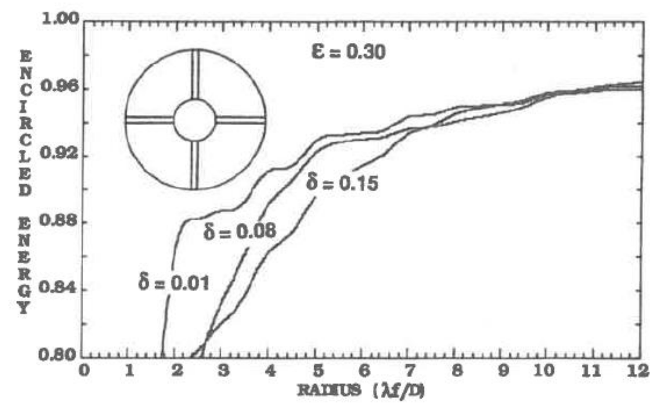


Fig. 13. Corresponding fractional encircled energy curves providing insight into the image-degradation effects of secondary mirror spiders of varying widths.

Thus, an off-axis unobscured aperture has a smaller IWA than an on-axis centrally obscured aperture.

Harvey, James E. and Christ Ftaclas, "Diffraction effects of telescope secondary mirror spiders on various image-quality criteria", Applied Optics, Vol.34, No.28, p.6337, 1 Oct 1995.

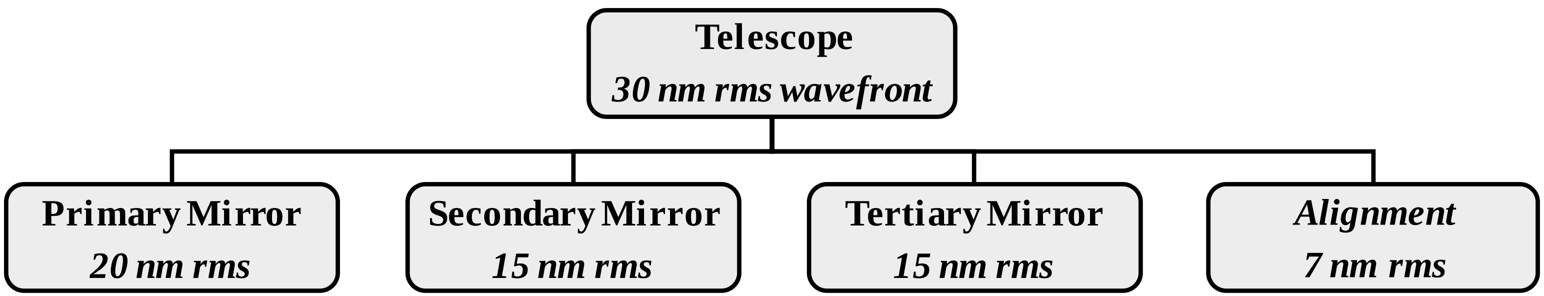
Diffraction Limited Performance

Diffraction limited performance (in addition to aperture) drives PSF size:

- General Astrophysics Resolution
- Coronagraphy Inner Working Angle

Diffraction limit drives transmitted wavefront error (WFE).

Primary Mirror requirements flow from transmitted WFE.



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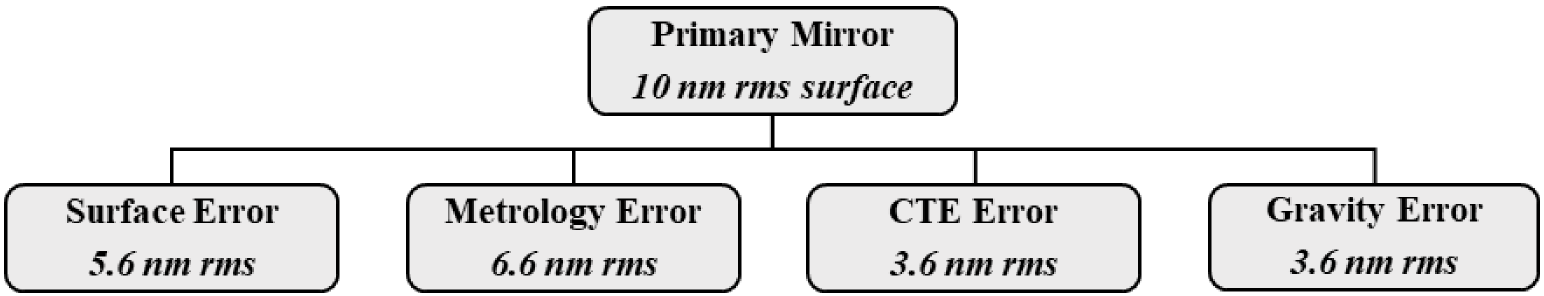
Primary Mirror Total Surface Figure Requirement

PM must have < 10 nm rms surface.

PM Specification depends on thermal behavior & mounting



PM must be very smooth.

Mid-spatial frequency errors move light from core into ‘hole’

- DM moves that light back into the core.

High-spatial errors (3X OWA) ‘fold’ or ‘scatter’ light into ‘hole’

- Errors above DM range produce speckles whose amplitude varies as $1/\lambda^2$

Spatial Frequency vs Science

Low spatial frequency specification is driven by General Astrophysics (not Exoplanet) science.

Exoplanet instruments have deformable mirrors to correct low-spatial errors and General Astrophysics instruments typically do not.

Mid/High spatial frequency specification is driven by Exoplanet because of 'leakage' or 'frequency folding'.

For exoplanet, the spatial band is from the inner working angle (IWA) to approximately 3X the outer working angle (OWA).

Theoretically, a 64 x 64 DM can correct spatial frequencies up to 32 cycles per diameter (N/2), therefore, the maximum mid-spatial frequency of interest is ~ 90 cycles.

Since mirrors are smooth & DM controllability rolls-off near N/2 limit, a conservative lower limit is ~N/3 or ~20 cycles.

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Risks to Diffraction Limited Performance

Assuming that mirrors are made to their prescription, biggest potential WFE source is ability to align mirrors and maintain that alignment on-orbit.

- Mitigate risk by designing hexapod actuators range.
- Mitigate risk by using laser position metrology system.

Another potentially error source is ability to quantify and back-out gravity effects.

Because mirrors are made in 1-G and operated in 0-G, G-release is a risk.

- Mitigate risk by active mirror control with actuator placement optimized to control most likely error modes.

Line of Sight (LOS) In-Stability

LOS in-stability causes PSF smear and beam-shear WFE.

LOS in-stability has two causes:

- Jitter – response of structure to mechanical accelerations
- Drift – response of structure to changes in thermal environment

Specification of < 0.3 mas rms per axis is uncorrectable Jitter and residual Drift after correction by Laser-truss system.

Wavefront In-Stability

WFE Drift cause speckles which can produce a false exoplanet measurement or mask a true signal.

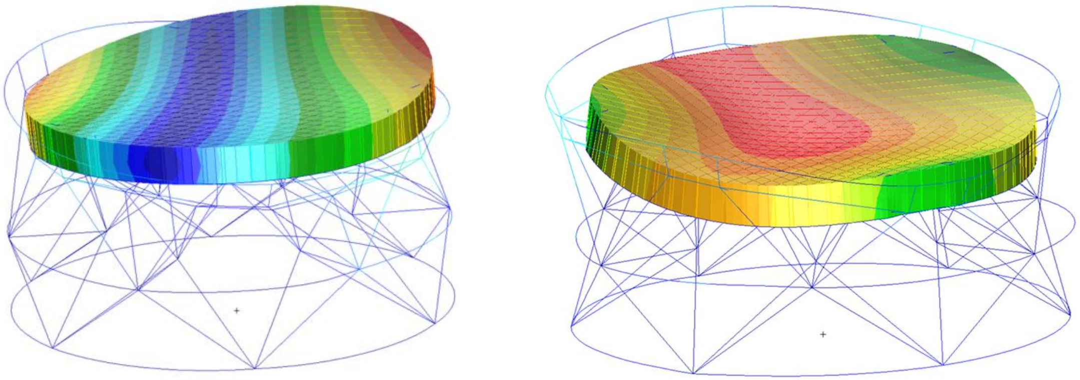
Spatial frequency of that error is important.

Three sources of WFE in-stability:

- LOS: Rigid body motions of optical components on their mounts causes beam-shear – this is mostly low-order.
- Inertial: Shape change of primary or secondary mirror reacting against its mount due to mechanical accelerations.
- Thermal: Shape changes of telescope structure or individual optical components due to thermal environment.

Wavefront In-Stability: Inertial

Inertial WFE is caused by the Primary Mirror reacting against its mount (i.e. rocking or bouncing) in response to accelerations (i.e. from the microthrusters).



To minimize Inertial WFE:

- Design the PM Substrate to be as stiff as possible
- Consider the Mount stiffness and location.

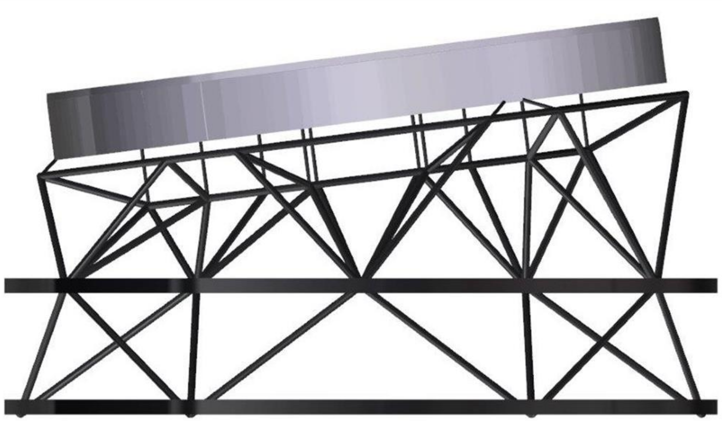
NOTE: Inertial WFE is not caused by resonant motion.

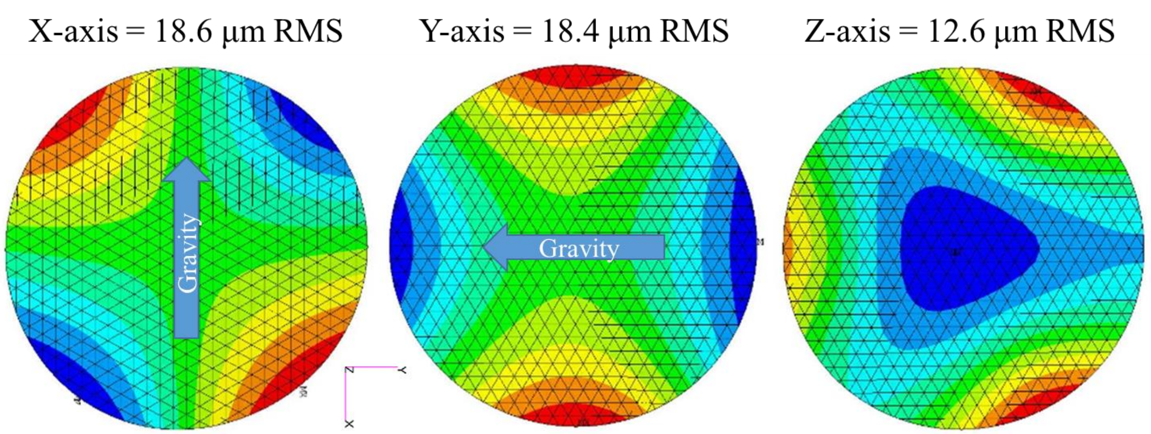
Primary Mirror Assembly

Dozens of Zerodur® and ULE® mirror designs were considered.

Baseline Zerodur® mirror design balances mass and stiffness.

- Substrate has a flat-back geometry with a 42 cm edge thickness and mass of approximately 1400 kg.
- The mirror's free-free first mode frequency is 88 Hz. And, its mounted first mode frequency is 70 Hz.
- The mirror is locally stiffened to minimize gravity sag.





Wavefront In-Stability: Thermal

Thermal WFE instability occurs when the primary mirror's bulk temperature or temperature gradient changes.

If the mirror's coefficient of thermal expansion (CTE) is completely homogeneous and constant, then a bulk temperature should only result is a defocus error.

But any inhomogeneity in the mirror's CTE will result in a temperature dependent WFE.

Additionally, because CTE is itself temperature dependent, any change in the mirror's thermal gradient will also result in a WFE.

The best mitigation strategy is to actively control the mirror's thermal stability.

PM Thermal Stability

Thermal WFE stability depends on the primary mirror's thermal sensitivity and the thermal system's controllability.

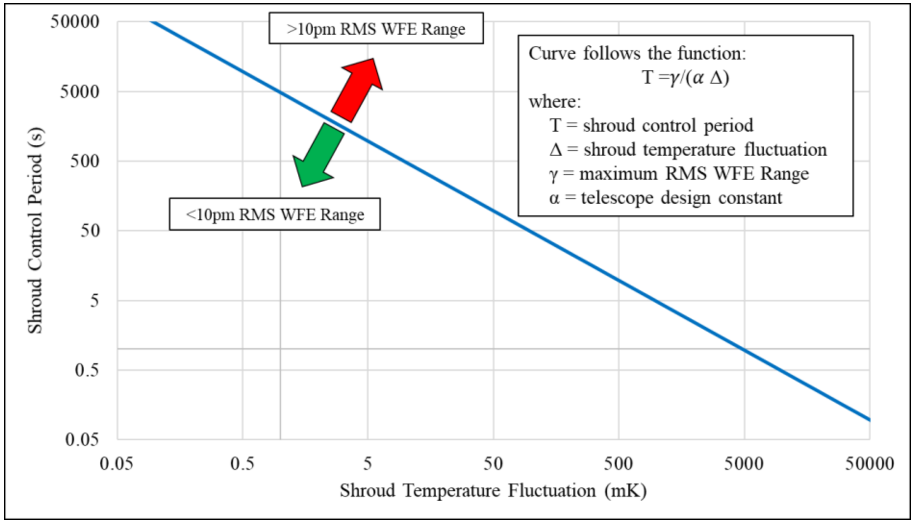
Rate at which the PM's RMS WFE changes depends on CTE, mass and specific heat (c_p):

$$\frac{\delta SFE}{\delta t} \sim \frac{CTE}{M\ c_p}$$

The larger a mirror's mass and smaller it's CTE, the smaller and slower its thermal response.

Thus want a zero CTE material.

Also want zero CTE homogeneity



Wavefront In-Stability: Thermal

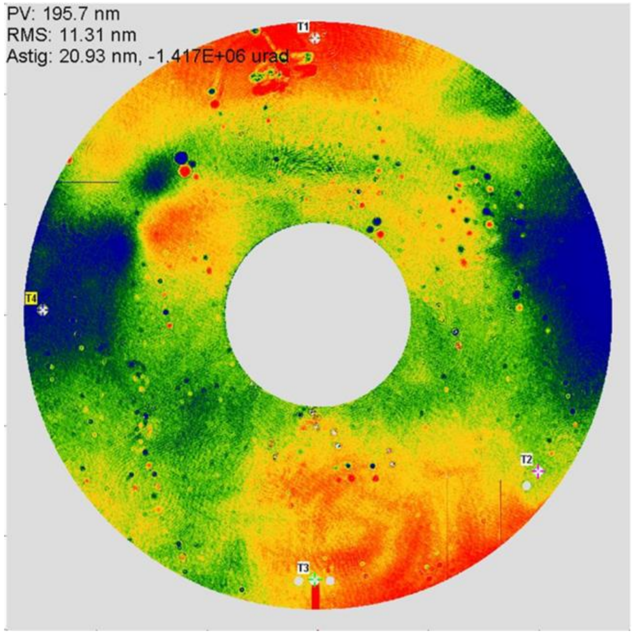
CTE homogeneity causes WFE as a function of thermal variation.

Again, this WFE is minimized by thermal control. BUT, the required control precision is proportional to CTE homogeneity.

The more homogeneous, the less precise the required control.

AMTD tested a 1.2m Zerodur mirror and determined that its CTE homogeneity is approx. +/- 5 ppb/K.

This mirror would meet WFE stability with ~2 mK thermal stability.



Measured Delta-SFE 292-230K			
Index		**TOTAL RMS**	**9.76**
N	M	Zernike Term	nm rms
1	1	Tilt	0.05
2	0	Power	0.24
2	2	Astig	8.55
3	1	Coma	0.90
4	0	Spherical	0.27
3	3	Trefoil	2.15
4	2	Secondary Astig	0.72
5	1	Secondary Coma	0.75
6	0	Secondary Spherical	0.40
4	4	Tetrafoil	1.73
5	3	Secondary Trefoil	1.39
6	2	Tertiary Astig	0.93
7	1	Tertiary Coma	0.77
8	0	Tertiary Spherical	0.24
5	5	Pentafoil	0.53
6	4	Secondary Tetrafoil	0.29
7	3	Tertiary Trefoil	1.72
8	2	Quaternary Astig	0.04
9	1	Quaternary Coma	0.81
10	0	Quaternary Spherical	0.57
6	6	Hexafoil	1.28
7	5	Secondary Pentafoil	0.49
8	4	Tertiary Tetrafoil	0.48
9	3	Quaternary Trefoil	1.20
10	2	Quinary Astig	0.58
11	1	Quinary Coma	0.45
12	0	Quinary Spherical	0.73

TRL Assessment

Technology Readiness Level (TRL)

NASA requires that the technology to manufacture and test the HabEx primary mirror must be:

- TRL-5 before start of Phase A
- TRL-6 before by PDR & start of Phase C.

TRL	Abridged definition
1	Basic principles observed and reported
2	Concept and/or application formulated
3	Proof of concept hardware or model validation; critical properties demonstrated
4	Low-fidelity component or breadboard in lab demonstrates functionality and validates models that predicts performance in relevant environment
5	Medium fidelity component or breadboard demonstrate overall performance in relevant environment
6	High fidelity system/subsystem demonstrates critical performance in operational environment; scaling is understood
7	High fidelity engineering unit demonstrates performance in operational environment
8	System is flight qualified
9	System flight performance successful

HabEx Technology Gaps

Assessed TRL assessment to identify Enabling Technology Gaps (i.e. < TRL4):

- Star-Shade
  - Petal Position Accuracy and Stability
  - Petal Shape Accuracy and Stability
  - Contrast Model Validation
- **Large Mirror Fabrication**
- **Large Mirror Coating Uniformity**
- Coronagraph Architecture
- Zernike Wavefront Sensing & Control
- Deformable Mirrors
- Detectors
- Micro-Thrusters

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 • No environmental testing	• Petal position deployment accuracy on 20 m perimeter truss: ±600 μm (3σ) bias • 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 • 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 • Petal shape manufacture: ±140 μm (3σ) • 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 • In-plane shape tolerance of ±20 μm met at half meter length after integration onto prototype petal • In plane shape stability demonstrated post-deploy and	• One meter length edges assembled precisely onto petal • Petal edge in-plane shape tolerance: ±66 μm (3σ) • Petal edge in-lane placement tolerance: ±55 μm (3σ)	5	5
Starshade Contrast Performance Modeling and Validation						
Starshade Lateral Formation Sensing						
Large Mirror Fabrication			• State-of-the-practice (SOP) lightweighting has yielded large mirrors of aerial density 70 kg/m² • Zerodur® can achieve 2.83 parts per billion/K CTE homogeneity (DKIST mirror) • Wavefront stability: 25 nm rms for HST in LEO • Wavefront error of WFIRST-like primary mirror (spatial frequency cycles/beam diameter: nm RMS): ▪ 0–7 cy/D: 6.9 nm RMS ▪ 7–100 cy/D: 6.0 nm RMS ▪ >100 cy/D: 0.8 nm RMS	• Wavefront stability of 100s to a few picometers rms (depending on spatial frequency) over 100s of seconds • Wavefront error (spatial frequency cycles/beam diameter: nm RMS): ▪ 0–7 cy/D: 6.9 nm RMS ▪ 7–100 cy/D: 6.0 nm RMS ▪ >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 • IUE, HST, and GALEX used MgF_2 on Al to obtain >70% reflectivity from 0.115 μm to 2.5 μm • Operational life: >28 years on HST	• Reflectance uniformity <1% over 0.45–1.0 μm • Reflectivity comparable to HST: ▪ 0.115–0.3 μm: ≥70% ▪ 0.3–0.45 μm: ≥88% ▪ 0.45–1.0 μm: ≥85% ▪ 1.0–1.8 μm: ≥90% • 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 • Phase meters flown on LISA-Pathfinder and Grace Follow-On • Sense at 1 kHz bandwidth • 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 • Uncorrelated per gauge error of 0.1 nm	5	6
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) • 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 • Wavefront stability: ≤~100 pm rms over 1 second for vortex • 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 • 8.5×10^{-9} coherent contrast at 10% bandwidth in a static test achieved with smaller 32 x 32 MEMS DMs • Contrast drift of $\sim 1 \times 10^{-12}$/hour over 4 hr, $\sim 1 \times 10^{-8}$ drift over 42 hr • Drive electronics in DST provide 16 bit resolution, which contributes $\sim 1 \times 10^{-10}$ to contrast floor	• 64 × 64 actuators • Enable coronagraph raw contrasts of $\leq 1 \times 10^{-10}$ at ~20% bandwidth and raw contrast stability $\leq 2 \times 10^{-11}$ • <3.3 nm RMS flattened surface figure error (SFE) • 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) ▪ Dark current of 7×10^{-4} e-/px/s ▪ CIC of 2.3×10^{-3} e-/px/frame ▪ Read noise ~0 e- rms (in EM mode) ▪ Irradiated to equivalent of 6-year flux at L2	• 0.45–1.0 μm response; • Dark current $<10^{-4}$ e-/px/s • CIC $<3 \times 10^{-3}$ e-/px/frame • Effective read noise <0.1e rms • Tolerant to a space radiation environment	4	5
Deep Depletion Visible Electron Multiplying CCDs						
Linear Mode Avalanche Photodiode Sensors						
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/cm²/s with ALD activation and borosilicate plates	• Dark current <0.001 e-/pix/s (173.6 counts/cm²/s), in a space radiation environment over mission lifetime, • 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 • Colloidal microthrusters with 100 μN thrust and 10-year lifetime under development • 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 • Thrust resolution 4.35 μN • Thrust noise: 0.1 μN/√Hz • 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 ▪ for >0.2 μm: 80% ▪ for 0.103–0.2 μm: 70% ▪ Lifetime: no loss of reflectivity after 3-year lab storage	• Reflectivity from 0.3–1.8 μm: >90% • Reflectivity from 0.115–0.3 μm: >80% • Reflectivity from 0.103–0.115 μm: >50% • 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, • ≥4k × 8k format for spectrograph run in full frame mode, • 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) • 128 × 64 electrostatic actuated array at TRL 4; will fly in FORTIS sounding rocket summer 2019 • 840 × 420 electrostatic, buttable array developmental model with partial actuation	• 300 × 300 shutters needed	3	5

Primary Mirror TRL Assessment

HabEx assesses that the technology to manufacture a 4-m class flight mirror is currently TRL-4 because of 3 key technologies:

- Ability to Certify that Zerodur Blank has CTE Homogeneity
- Ability to Certify that Mirror has Wavefront Error
- Ability to Certify that Mirror will achieve Wavefront Stability

Large Mirror Fabrication			
Technology	**Need**	**State of the Art**	**TRL**
Mirror Substrate Diameter	4.04 meter	Schott Corp manufactures blanks that are 4.2 m diameter x 420 mm thick	6
Mirror Substrate CTE			
• Bulk CTE	0 at 270 K	Schott Corp can tune CTE to be 0 at a specific temperature.	6
• CTE Homogeneity	< +/- 5 ppb/K over 100 x 100 spatial sampling	Schott Corp demonstrated < +/- 3 ppb/K over limited spatial sampling on DKIST	4
Substrate Machining	3–4 mm ribs, 14 mm facesheet, and pocket depth of 290 mm for 400 mm thick blank	Schott Corp 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	6
Areal Density	110 kg.m^2	State-of-the-practice lightweighting has made large glass mirrors with aerial density of 70 kg/m^2	6
First Mode Frequency	≥ 60 Hz	By design, if the baseline Zerodur® mirror substrate can be machined to its specified dimensions using demonstrated Schott Corp machining capability, it will achieve the required first mode frequency. Also, sub-scale WFIRST 2.4-m Primary Mirror has ~ 200 Hz first mode.	6
Wavefront Error	0-7 cy/D: 6.9 nm RMS 7-100 cy/D: 6.0 nm RMS >100 cy/D: 0.8 nm RMS	Demonstrated on sub-scale WFIRST 2.4-m Primary Mirror	4
Wavefront Stability	1 to 100 pm rms	By design, baseline Zerodur® mirror will achieve required wavefront stability with active zonal thermal control stability of < 5-mK. Sub-scale active thermal control has been demonstrated by Harris Corp to TRL-9 on 1.1-m Spaceview™	4

Mirror Material

A key metric for selecting the HabEx primary mirror material is coefficient of thermal expansion (CTE).

- CTE and CTE homogeneity are important because they determine how the mirror's shape deforms as a function of bulk temperature or thermal gradient changes.
- Such deformations impacts the telescopes ability to meet its diffraction limited performance and wavefront stability specifications.

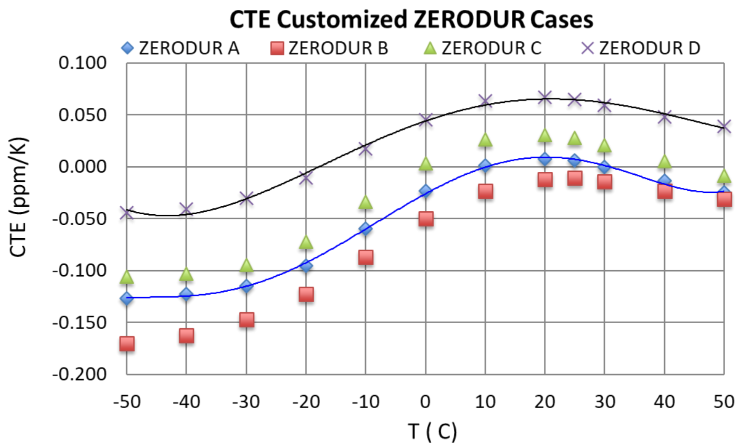
Typical approaches for mitigating this risk are

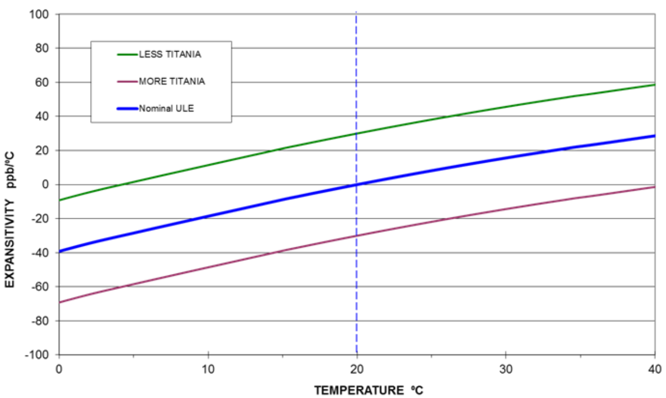
- Select a material with zero CTE and extreme homogeneity.
- Measure the mirror's shape change between its manufacture and operational temperatures and 'cryo-null figure' the mirror
- Actively control the mirror's on-orbit shape or its thermal environment.

Mirror Material

Both Zerodur® and ULE® are TRL-9 with multiple mirrors flying.

Both Schott and Corning can tailor their material’s zero CTE temperature.





And both claim similar CTE homogeneity (i.e. +/- 5 ppb).

Thus, a mirror manufactured from either material should have similar thermal performance.

Mirror Material

A significant difference between ULE® and Zerodur® is the design architecture enabled by each.

As a glass, ULE® can be assembled to enable closed-back mirror architectures. Such mirrors are stiffer.

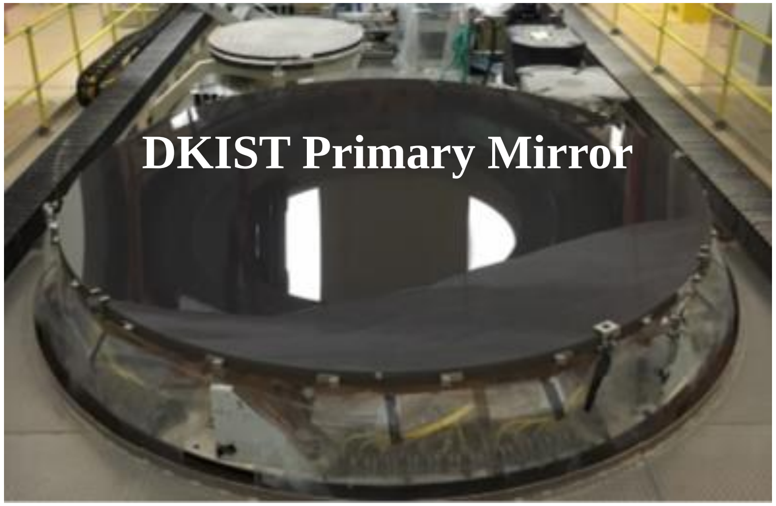
As a ceramic, Zerodur® must be machined from a single blank. Thus, Zerodur® mirrors required an open-back architecture.

However, because Zerodur® mirrors are machined from a single boule, they may have a smoother and more homogeneous CTE.

Primary Mirror Material Selection

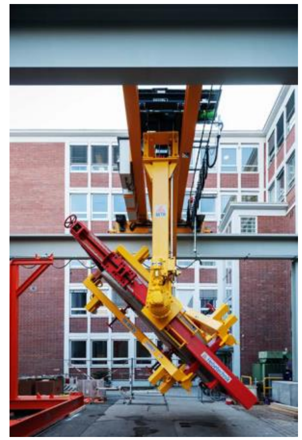
Zerodur® was selected as the baseline HabEx primary mirror material because Schott has demonstrated a routine ability to manufacture 4-m class mirror blanks.

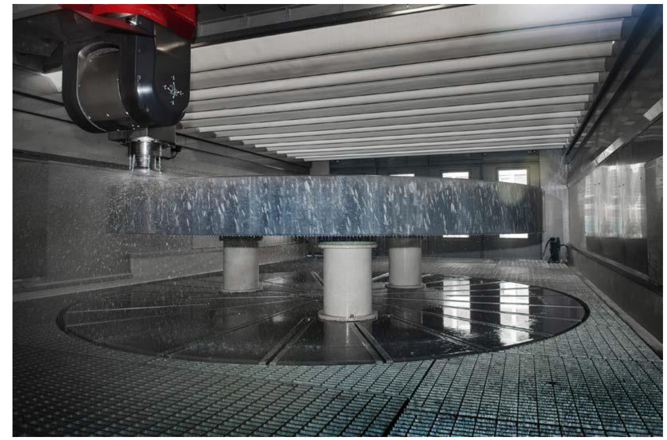
This demonstrated capability enables HabEx to assess the ability to make 4-m class mirror blanks to be TRL-6.



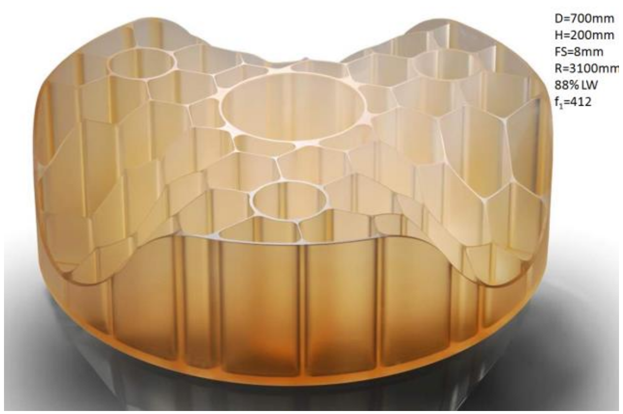
Substrate Machining

Schott Corp has the infrastructure (including a 5-m 5 axis CNC Machine) to machine deep core structures as large as 4.5-meters.

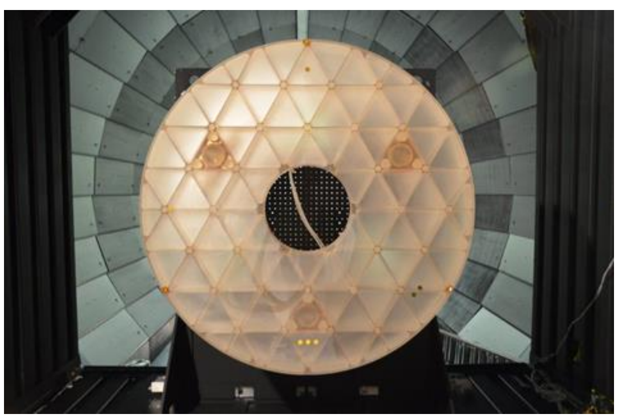




Machining high-fidelity sub-scale mirrors has capability at TRL-6



0.7-m diameter, 200 mm thick mirror with 2 mm machined walls.



1.2-m diameter, 125-mm thick mirror with 2 mm machined walls.

Polishing Infrastructure

Multiple organizations have existing infrastructure to grind and polish 4-m class substrates into space mirrors, including: Collins Aerospace, L3/Brashears, Harris Cor., Arizona Optical Systems, University of Arizona, and REOSC.

Wavefront Stability

Schott's ability to provide a 4-m substrate with < +/-5 ppb/K CTE homogeneity is assessed at TRL-4 because they do not have a non-destructive process for validating CTE homogeneity on a 4-m class mirror over 100 x 100 spatial sampling.

CTE Homogeneity State of Practice

Schott Corp has a dilatometer process that can measured CTE of test samples with a reproducibility of ~ +/- 1 ppb/K.

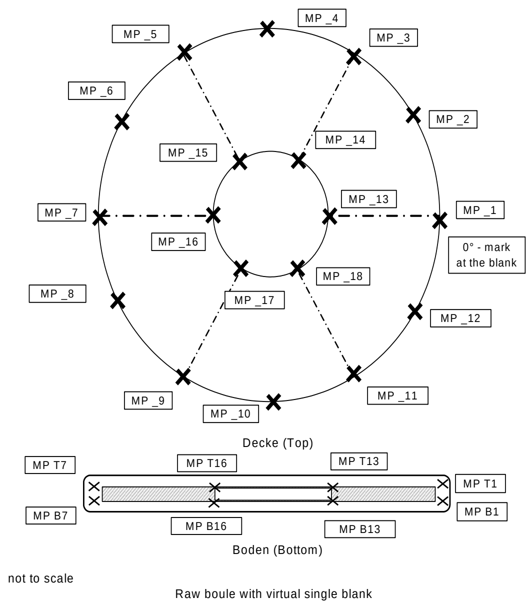
Since 20010, Schott has produced seven 4-m mirror substrates with CTE homogeneity < 10 ppb/K. And one with 3 ppb/K.

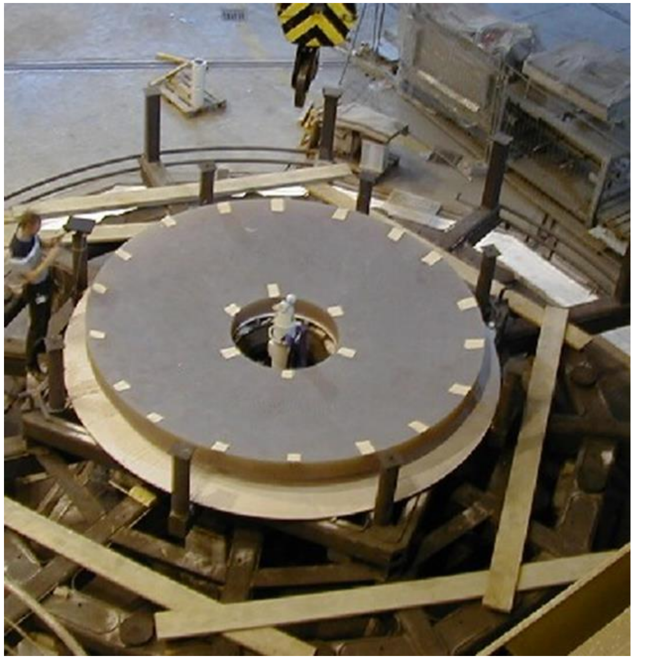
	Dimension	Number of Samples	CTE (0°; 50°) absolute value [ppb / K]		CTE (0°; 50°) homogeneity [ppb / K]	
Year	**[mm]**	**#**	**Specification**	**Achieved**	**Specification**	**Achieved**
2003	4100 x 171	18	+/- 50	66	20	18[1]
2005	3610 x 370	12	+/- 100	80	30	25[1]
2009	3700 x 163	36	+/- 150	54	40	9
2010	3400 x 180	12	+/- 100	42	30	5
2012	4250 x 350	16	+/- 30	60	40	5
2014	4250 x 350	16	+/- 30	0	40	3
2016	4060 x 103	16	+/- 50	36	20	7
2016	4000 x 100	12	+/- 150	15	20	4
2019	4250 x 100	20	+/- 20*	-9*	20*	8*

R. Jedamzik, T. Westerhoff, "Homogeneity of the coefficient of linear thermal expansion of ZERODUR®: A Review of a decade of evaluations" Proc. SPIE Vol. 10401, (2017)
Westerhoff, Thomas, and Tony Hull, "Production of 4 m diameter Zerodur® mirror substrates", HabEx White Paper Contribution, 2018.

CTE Homogeneity State of Practice

But, because acquiring CTE samples is destructive, data sampling is limited to perimeters and holes.





Thus, HabEx requires a ‘validated’ non-destructive process to certify CTE homogeneity of the primary mirror blank over at least a 100 x 100 spatial sampling as part of the primary mirror blank acceptance process.

Tony Hull Private Communication

CTE Homogeneity Characterization

Schott has mapped CTE homogeneity of meter class blanks, but this mapping has not been correlated with Cryo-Deformation.

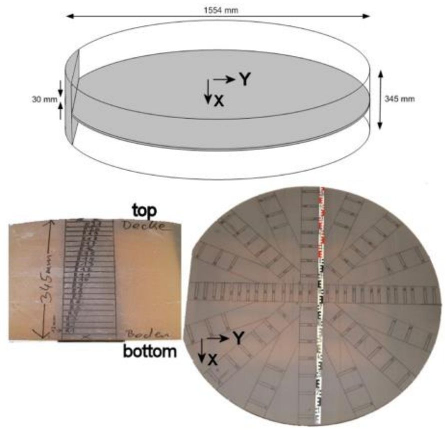


Figure 4: Top: schematic view on how the sample sections were cut out of the disc shaped blank. Lower left: vertical section with sample markings, lower right: horizontal section with sample markings.

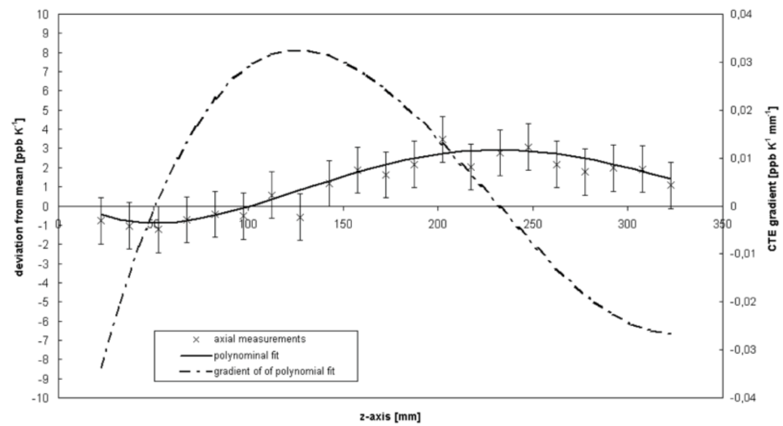
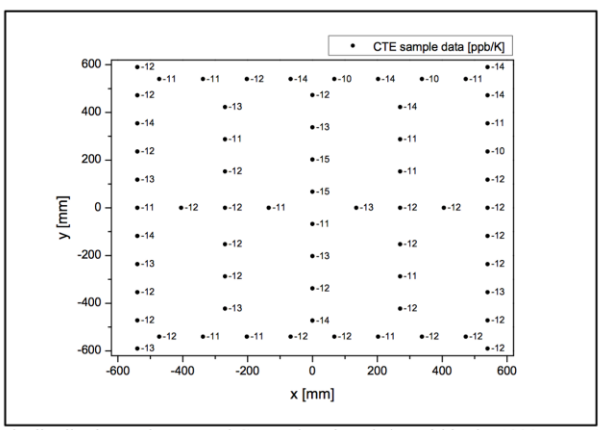


Figure 9: Variation of the CTE deviations from the mean value and gradient in axial direction



Sample distribution and measured CTE values in ppb / K within the 1200 mm x 1200 mm plate

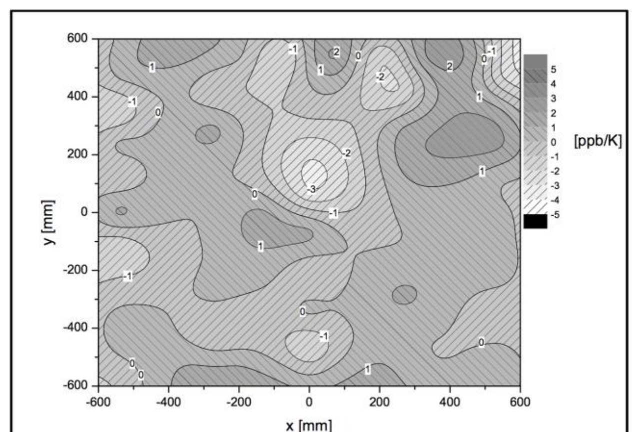


Figure 7: Two dimensional contour plot of CTE homogeneity value delta to the mean absolute value of 12.2 ppb / K of the 1.2 m x 1.2 m ZERODUR® blank. The peak to valley homogeneity is 5 ppb/K.

Surface Figure Error

Polishing mirrors to required specification at 2.4-m is TRL-9.

HabEx specification is same as WFIRST's current surface.

The primary risk is the ability to quantify and back-out gravity induced self-weight deflection to ~ 4 nm rms over a 100 x 100 spatial sampling is assessed to be at TRL-4.

Gravity Deformation State of Practice

Gravity-sag characterization and mitigation have been studied extensively since the 1960s.

Mitigation approaches:

- Minimize Gravity Sag by making the mirror as stiff as possible and optimizing its mounting
- Off-load Gravity during fabrication and test
- Analytically removed Gravity Sag during test
- Actively correct mirror shape on-orbit

Minimize Gravity Sag

Design the mirror to be as stiff as possible

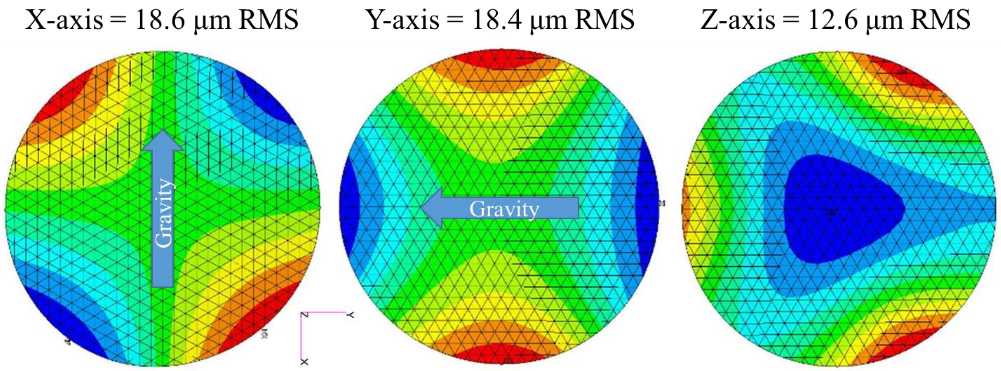
$$1G\ Gravity\ Sag \sim C_{SP}\left(\frac{D^4}{t^3}\right)\rho_{AD} \sim 1/(2\pi f)^2$$

And optimize its mounting

Support Constant	C_{SP}	Factor of Reduced Deflection Compared to 3-Pt Support
Ring at 68% of Diameter	0.028	11
6 Points Equal Spaced at 68.1% of Diameter	0.041	8
Edge Clamped	0.187	1.5
3 Points, Equal Spaced at 64.5% of Diameter	0.316	-
3 Points, Equal Spaced at 66.7% of Diameter	0.323	~1
3 Points, Equal Spaced at 70.7% of Diameter	0.359	0.9
Edge Simply Supported	0.828	1/3
Continuous Support along the Diameter	0.943	1/3
"Central Support" (Mushroom or Stalk Mount; r = radius of stalk)	1.206	1/4
3 Points Equal Spaced at Edge	1.356	1/4

Yoder, Paul and Danial Vukobratovich, Opto-Mechanical Systems Design, Fourth Edition, Two Volume Set, CRC, 2015

Yields Baseline Zerodur® mirror designed to minimize gravity sag

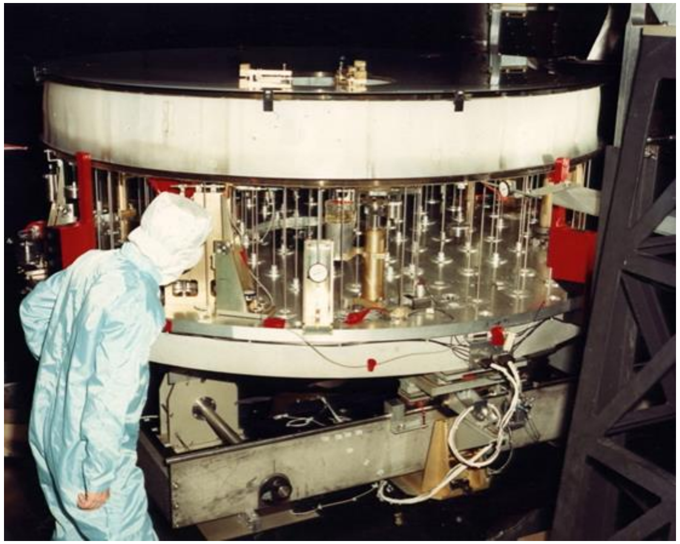


Gravity Off-Loading

Gravity off-loading is typically done via:

- Multipoint Mount
- Air Bag Support

Hubble PM's 7.6 micrometer G-sag was characterized to an accuracy of 1.4 nm rms using a 135 point metrology mount.



Yoder, Paul and Danial Vukobratovich, Opto-Mechanical Systems Design, Fourth Edition, Two Volume Set, CRC, 2015 ISBN-10: 1439839778
https://www.hexagonkh9.com/blog/2019/1/19/hexagon-looked-at-the-earth-the-hubble-looked-at-the-stars

Analytical Removal

Gravity Sag can be estimated via an orientation test:

- Face-up/Face-down Test
- Horizontal Rotation Test

JWST segments were tested using rotation test to < 10 nm rms.

Kepler Gravity Sag

Kepler primary mirror was tested using an air bag, a 108 point metrology mount, and a face-up/face-down orientation test.

Air bag was estimated to off-load gravity sag to 5.6 nm rms.

Difference between air bag & multi-point mount was 16.4 nm rms

Difference between air bag & face-up/face-down was 18.4 nm rms

Largest component of difference was spherical aberration.

By inference, difference between multipoint mount and up/down test should be 8.3 nm rms.

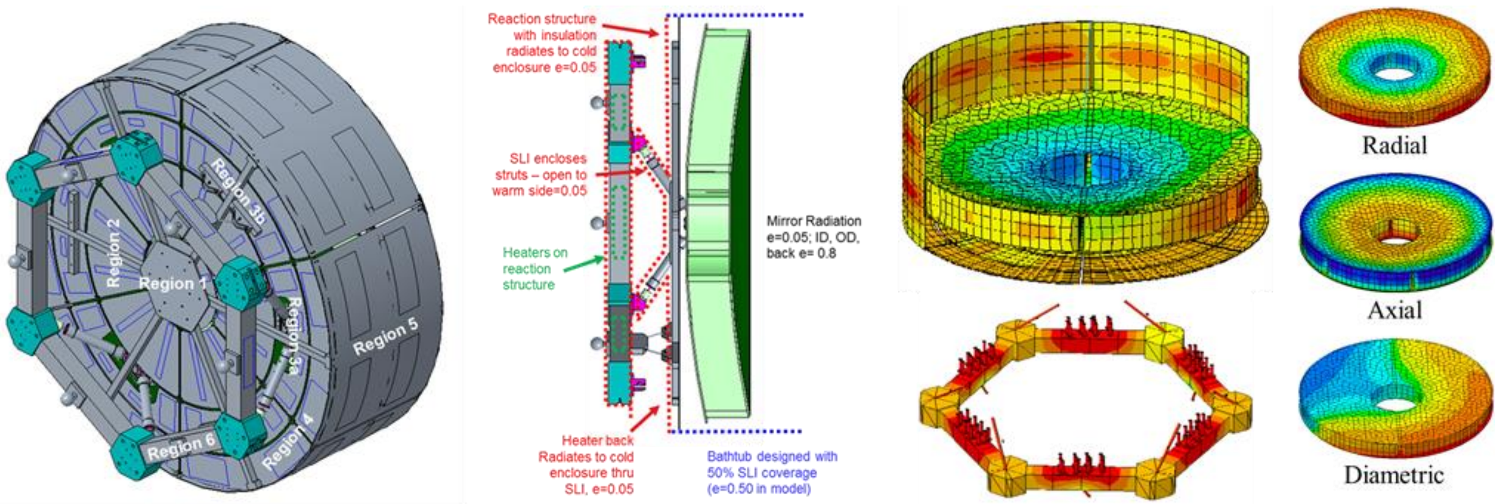
Zinn, John W., George W. Jones, "Kepler primary mirror assembly: FEA surface figure analyses and comparison to metrology," Proc. SPIE 6671, Optical Manufacturing and Testing VII, 667105 (14 September 2007)

Thermal Control System TRL

Baseline HabEx thermal control system is assessed to be TRL-4.

System is scale-up of TRL-9 system built by Harris Corp.

- Harris is flying 0.7 & 1.1-m systems on its Spaceview™ telescopes.
- Harris built 1.5-m system built with 37 thermal control zones for MSFC Predictive Thermal Control Study.



Analysis indicates that, because of PM thermal mass, system with 0.5-Hz, 50-mK sensors will keep PM stable to ~1-mK.

Proc. SPIE 11116, Astronomical Optics: Design, Manufacture and Test of Space and Ground Systems, August 2019

Primary Mirror Coating TRL Assessment

HabEx assesses that to:

- Achieve TRL-5 requires demonstrated on coupons, representing a 4-m diameter mirror, ability to coat with required reflectivity and uniformity.
- Achieve TRL-6 requires a full-scale 4-m mirror demonstration.

Description	State of the Art	Capability Needed	TRL 2019	2023 TRL
Mirror coating with high spatial uniformity over the visible spectrum	• Reflectance uniformity <0.5% of protected Ag on 2.5 m TPF Technology Demo Mirror • IUE, HST, and GALEX used MgF_2 on Al to obtain >70% reflectivity from 0.115 to 2.5 µm • Operational life: >28 yrs on HST	• Reflectance uniformity <1% over 0.45–1.0 µm • Reflectivity compared to HST: ▪ 0.115–0.3 µm: ≥70 % ▪ 0.3 – 0.45 µm: ≥88 % ▪ 0.45 – 1.0 µm: ≥85 % ▪ 1.0 - 1.8 µm: ≥90 % • Operational life >10 years	4	5

Deformable Mirror TRL Assessment

Description	State of the Art	Capability Needed	TRL 2019	2023 TRL
Flight-qualified large-format deformable mirror	• Micro-electromechanical DMs available up to 64 × 64 actuators, 400 μm pitch with 6 nm RMS flattened WFE; • 3.3 nm RMS demonstrated on 32 × 32 DM • 16 bit resolution drive electronics	• > 64 × 64 actuators • < 3.3 nm RMS flattened WFE • > 18 bit drive electronics	4	5

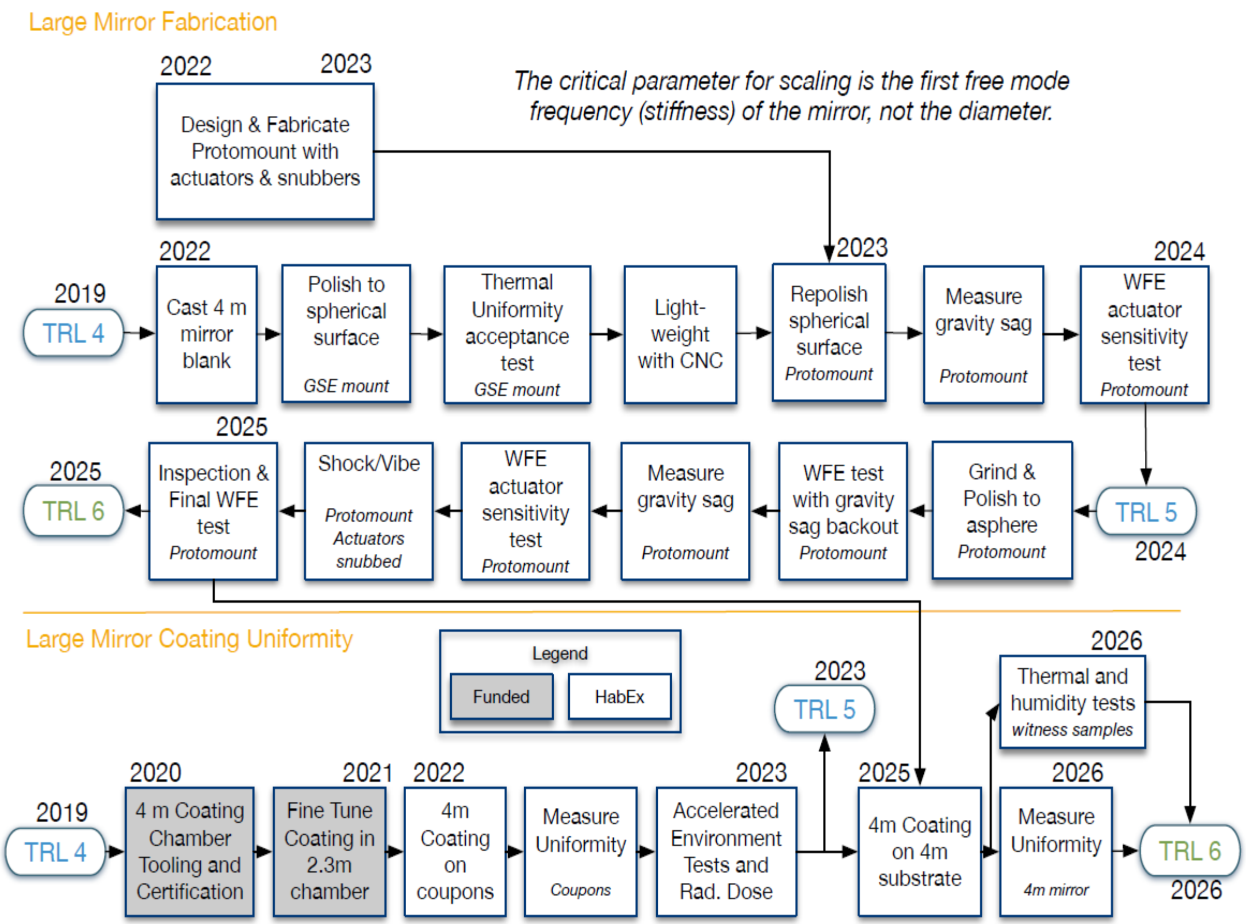
Zernike Wavefront Sense & Control TRL Assessment

Description	State of the Art	Capability Needed	TRL 2019	2023 TRL
Sensing & control low-order wavefront drift; monitoring of higher order Zernike modes	• <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) • 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 • Wavefront stability:≤~100 pm rms over 1 second for vortex • WFE <0.76 nm rms	4	6

Path to TRL-6

HabEx Study has roadmap to mature technology gaps to TRL-6.

But opportunity exists for SBIR contributions.



Star-Shade Only Option

HabEx Starshade-Only Architectures

HabEx mission goals

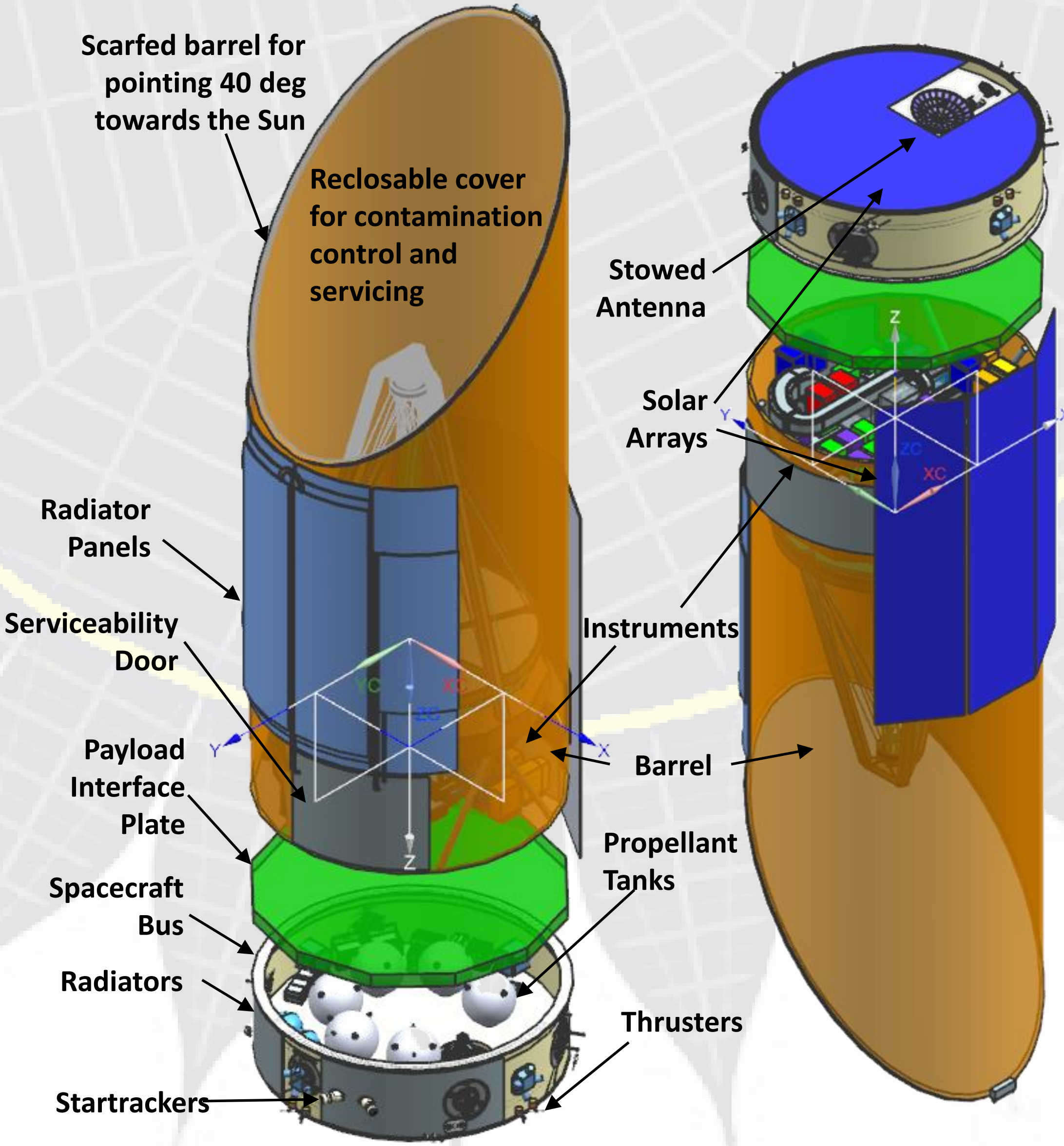
Seek out nearby worlds and explore their habitability.

Map out nearby planetary systems and understand the diversity of the worlds they contain.

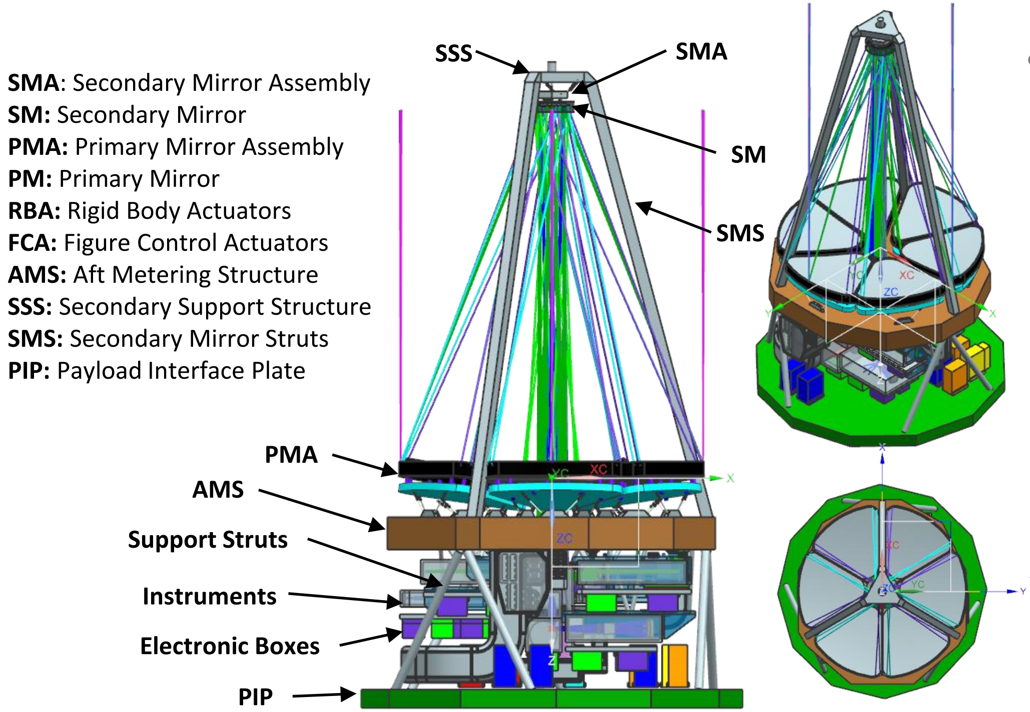
Open up new windows on the universe from the UV through near-IR.

Key Mission Requirements

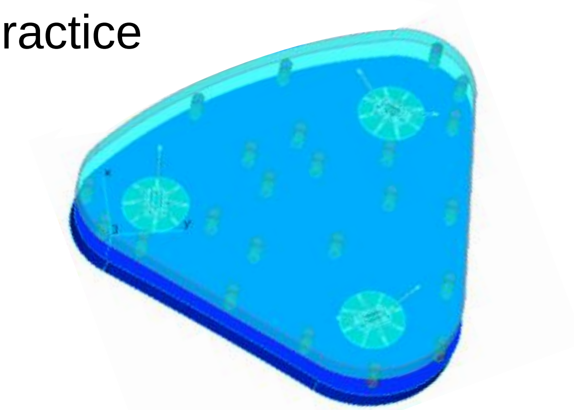
	Parameter	Value
General	Aperture diameter	3.2 to 4 meter
	Bandpass	115–1,700 nm
	Operating temperature	≥270K
	Diffraction limit wavelength	400 nm
	Wavefront error, total	≤30 nm rms
	Pointing accuracy	2 mas/axis
	Pointing stability	2 mas/axis
Exoplanet	Raw contrast	≤10^-10 from IWA
	Inner Working Angle (IWA)	<74 mas
	Spectroscopy resolution	R ≥ 7 (300–450 nm)
		R ≥ 140 (450–1,000 nm)
		R ≥ 40 (1,000–1,800 nm)
Workhorse Camera	Waveband, imaging	150-1,700 nm
	Waveband, spectroscopy	350-1,400 nm
	Field of View	3x3 amin
	Spectral resolution	R ≥2 ,000
UV Spectro -graph	Waveband	115-300 nm
	Field of View	2.5x2.5 amin
	Spectral resolution	R = 1 to 60,000
Starshade Camera	Waveband, imaging	300-1,700 nm
	Waveband, spectroscopy	300-1,700 nm
	Field of View	8x8 asec
	Spectral resolution	R ≥2 ,000

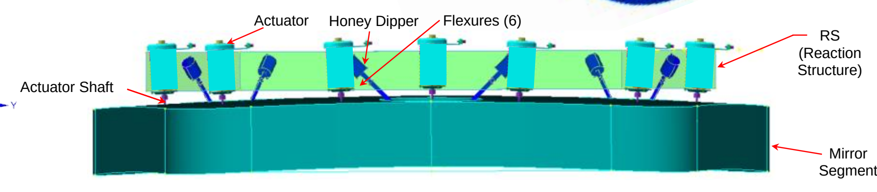


Active Optics Telescope



- Corrects optical errors on-orbit
- Mirror fabrication within current state of practice





- Wavefront Sensing and Control establishes initial 30 nm RMS WF error
  - Rigid-body control of PM segments and SM phase and collimate the telescope
  - PM segment figure control assures performance while relaxing fabrication reqts.
- Laser Metrology is used to continuously maintain optical alignments

Requirement 18.0 nm rms WFE

Nominal	Corrected	
56.0	16.0	nm

Margin		
	8	nm

	Nominal	Corrected	
Segment Figure	108.0	12.0	nm

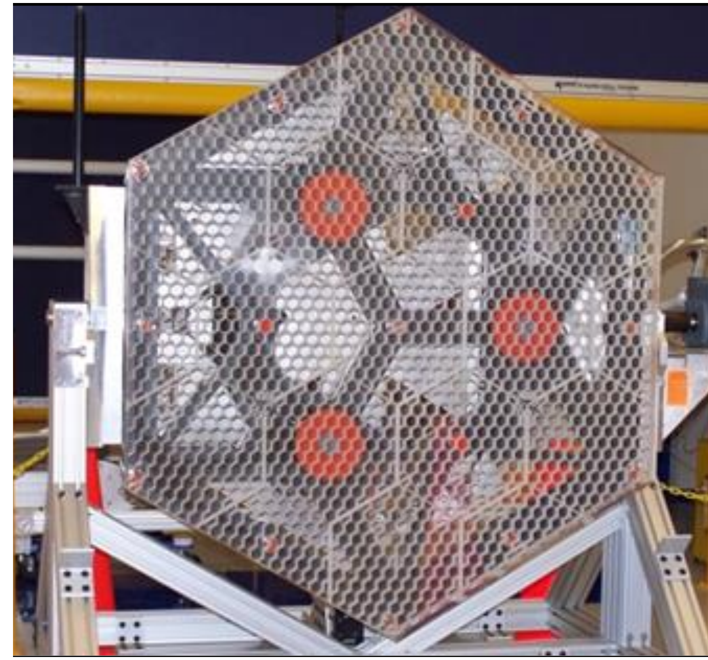
Includes effects of polishing, testing, gravity sag prediction, temperature change, coating, and matching radius of curvature

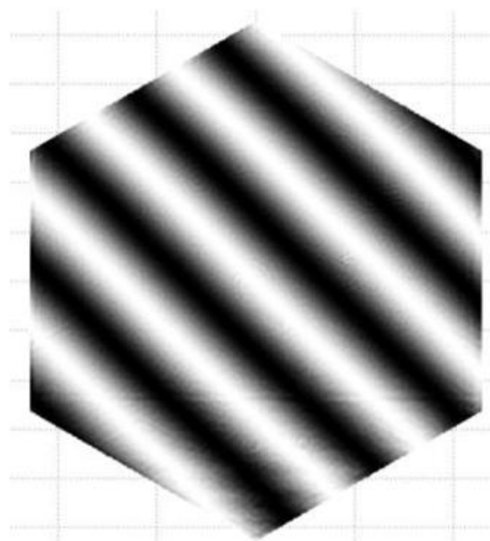
	Nominal	Corrected	
Mounting Errors	26.0	10.0	nm

Includes effects of bonding mounts and devices, material creep, desorption, etc.

ULE Mirrors: Demonstrated Performance

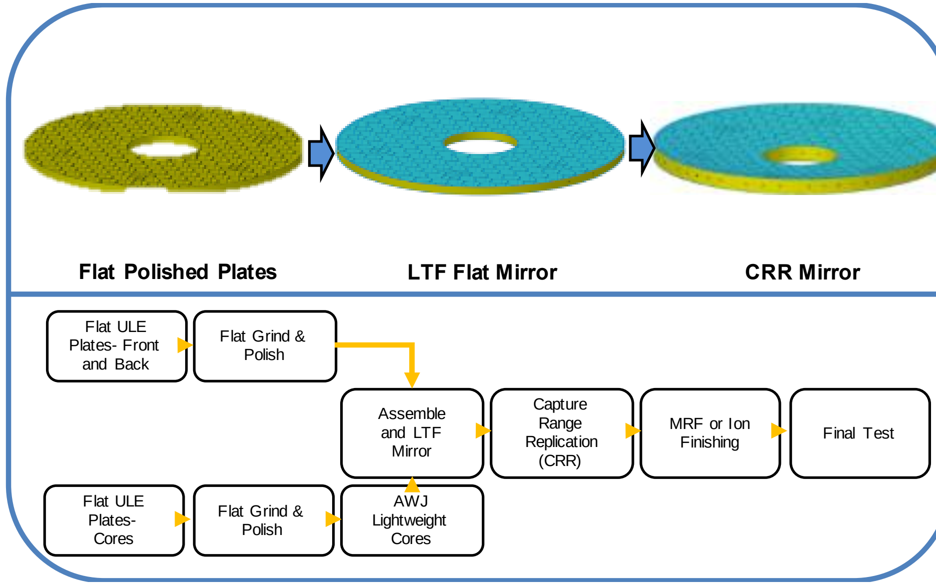
- MMSD low mass: 10 kg/m^2
  - Prefer 20 kg/m^2 for HabEx B
- WF error:
  - 15 nm RMS WFE stand-alone, with backouts
  - 8 nm WFE RMS post-actuation predicted
- Survivability tested to high level
  - Random vibe and shock



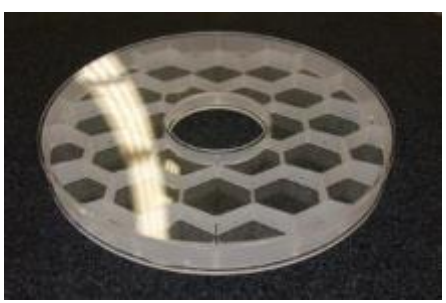


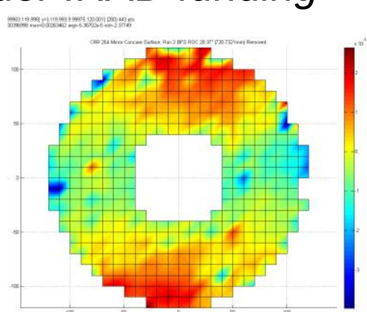
Harris Capture Range Replication

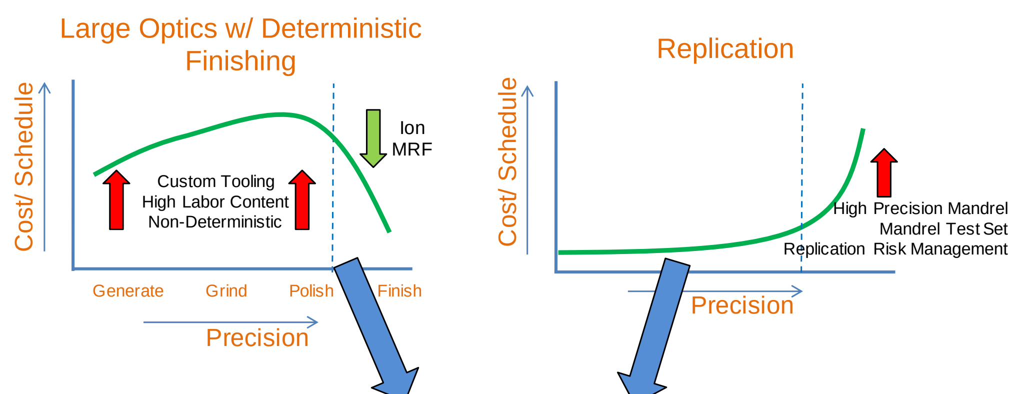
- Capture Range Replication uses precision mandrels and low-temperature slumping to replace traditional generate-grind-polish processes
- CRR finishes a mirror blank to within capture range for final finishing (MRF or Ion Beam)
- Result is a repeatable, efficient process for mirror fabrication, saving time and cost



CRR mirror finished under IRAD funding



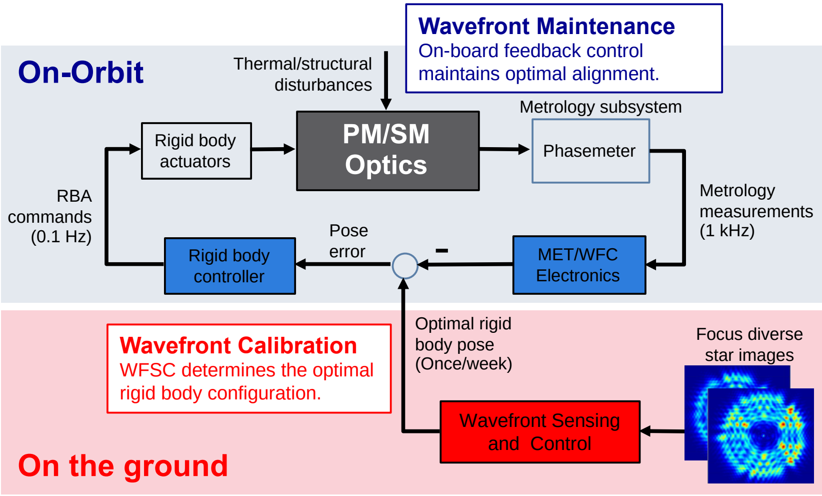




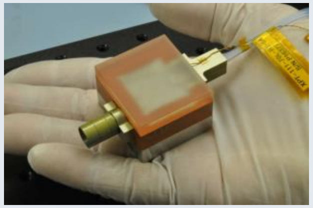
Capture Range Replication (CRR) leverages the strengths of replication to eliminate the high cost/ schedule processes in optical fabrication to provide an optimized solution

Maintaining Alignments

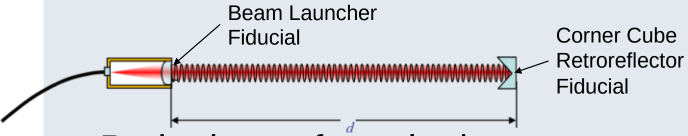
- Laser Metrology (MET) measures SM-PM-Instrument Bench alignments in real time
- Rigid Body Actuators move the SM and PM segments to preserve alignments



Laser Distance Gauge measures distance to <1 nm accuracy

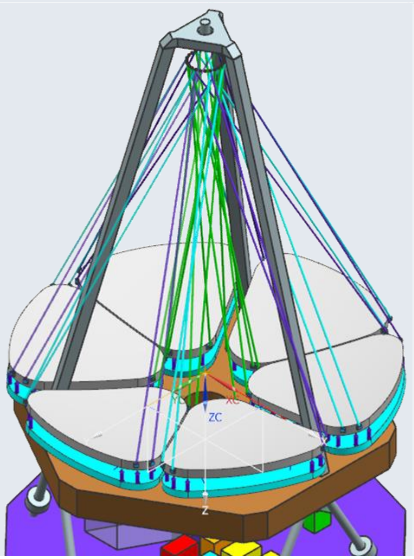


Beam Launcher



- Probe beam from the beam launcher is reflected by corner cube
- Returning probe beam mixes with a reference beam within the beam launcher
- Phasemeter electronics measure phase between the reference and return beams

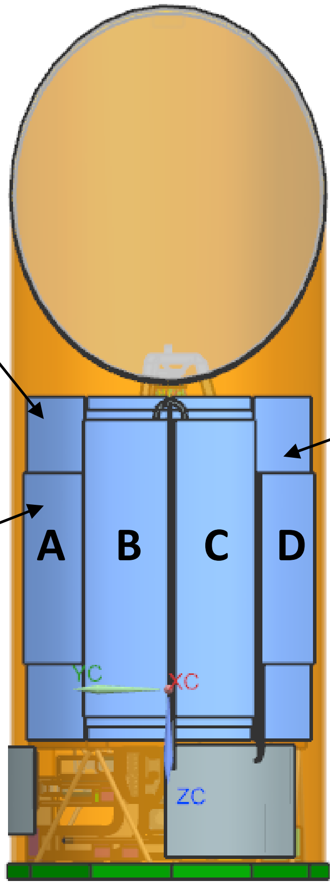
Laser Truss combines gauges to measure 6DOF alignment of all optics wrt corner cubes on the SM



- MET technology originally developed for Space Interferometry Mission
- Elements flown on LISA Pathfinder and GRACE Follow-On
- Requires:
  - Laser frequency stability to <1 MHz
  - Temperature control of all optical elements to <0.2C
  - RBA precision <5 nm

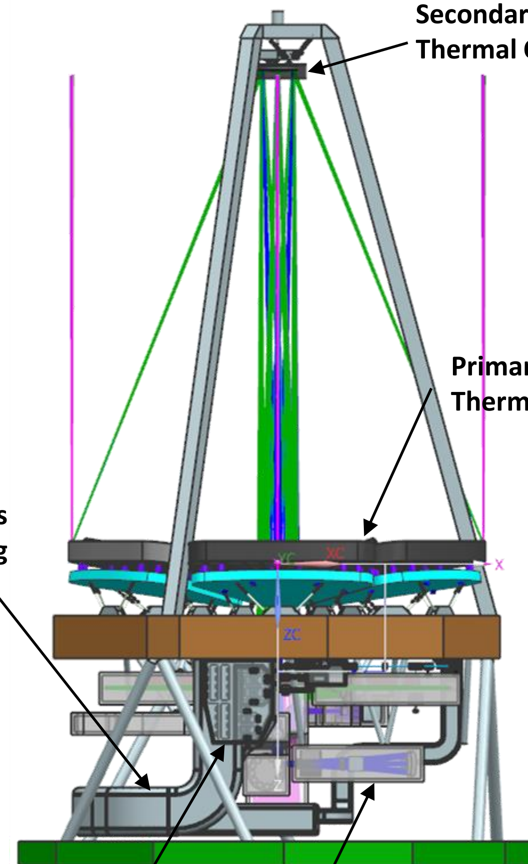
Passive Thermal Design

Passive thermal system design is similar to HabEx 4H Baseline



Radiator panel sets **A** and **D** are equivalent to each other. Both sets consist of two stacked radiator panels that will be used to cool instruments of operating temperatures of **273K** and **150K**

Radiator panel sets **B** and **C** are equivalent to each other. Both sets consist of three stacked radiator panels. The panel closest to space will be used to cool instruments of operating temperatures of **77K**. The panels stacked behind are used as insulators from the hot barrel.



- Heat pipes in isolated routing manifolds channel excess heat from instrument detectors, electronics and structures to the radiator
- Three radiator stages operate at 240K, 130K and 55K, providing purely passive cooling for instrument electronics and detectors
- Heaters in thermal cans stabilize PM segments and the SM at 270K

LUVOIR


LUVOIR
EXOTIC WORLDS
THE SEARCH FOR LIFE
OUR DYNAMIC SOLAR SYSTEM
COSMIC ORIGINS & THE ULTRA-FAINT UNIVERSE

Signature science cases span Astro2020 science

LUVOIR

1. Finding habitable planet candidates
2. Searching for biosignatures and confirming habitability
3. The search for habitable worlds in the solar system
4. Comparative atmospheres
5. The formation of planetary systems
6. Small bodies in the solar system
7. Connecting the smallest scales across cosmic time
8. Constraining dark matter using high precision astrometry
9. Tracing ionizing light over cosmic time
10. The cycles of galactic matter
11. The multi-scale assembly of galaxies
12. Stars as engines of galactic feedback

Mapping to Science Panels

Exoplanets, Astrobiology, and the Solar System

Interstellar Medium and Star and Planet Formation

Cosmology

Galaxies

Stars, the Sun, and Stellar Populations

Compact Objects and Energetic Phenomena

The LUVOIR Mission

Launch in 2039 aboard an SLS Block 1B/2

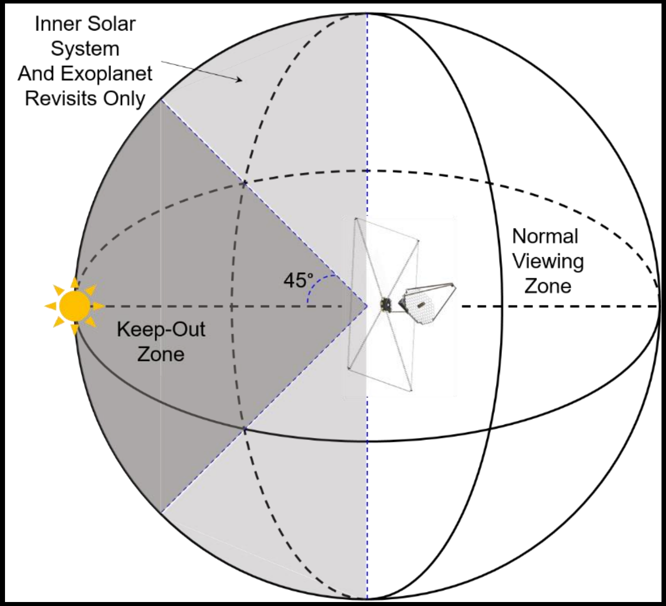
SpaceX Starship and Blue Origin New Glenn are viable alternatives

5-year primary mission, designed to be serviceable for a 25+ year lifetime

Operate in Sun-Earth L2 orbit

Can view entire sky except for a 45° cone about the sun-spacecraft axis

- 3° / min slew rate
- 60 arcsec / sec tracking rate



One Architecture, Two Concepts

Single *scalable* architecture responds to future uncertainties:

- Available launch vehicles
- Budget constraints
- Infrastructure availability
- Technological capability

Two LUVOIR concepts bracket a range of scientific capability, cost, and risk

LUVOIR-A in 8.4-m Fairing

LUVOIR-B In 5-m Fairing

Credit: D. Jones, NASA/GSFC

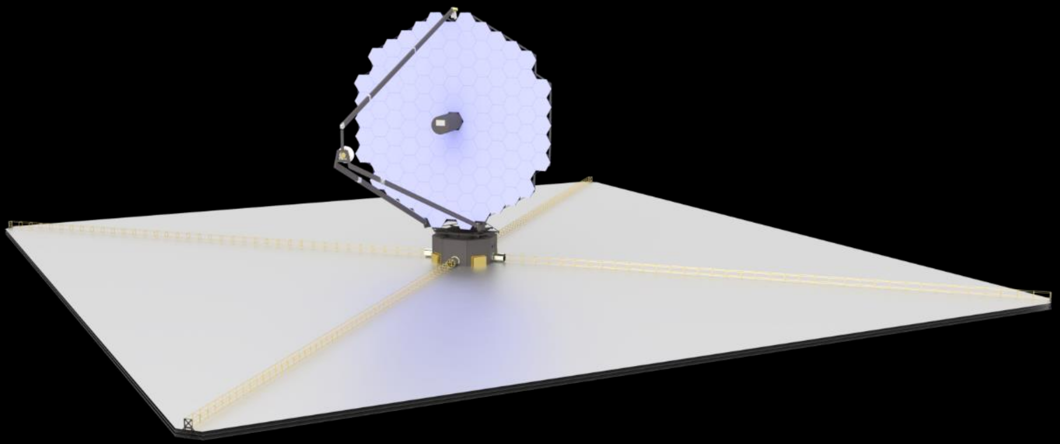
LUVOIR-A

15-m, on-axis telescope

- 120 segments, 1.223-m flat-to-flat
- 155 m^2 collecting area

Four instruments

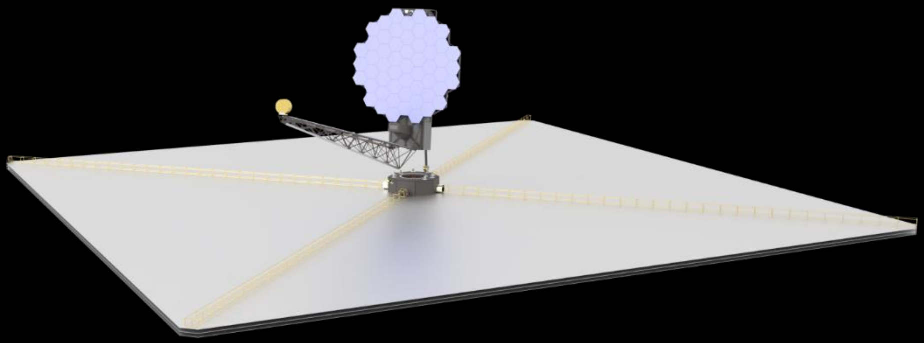
- Extreme Coronagraph for Living Planetary Systems (*ECLIPS*)
- LUVOIR UV Multi-object Spectrograph (*LUMOS*)
- High Definition Imager (*HDI*)
- *Pollux* (CNES-contributed instrument design)



LUVOIR-B

8-m, off-axis telescope

- 55 segments, 0.955-m flat-to-flat
- 43.4 m^2 collecting area

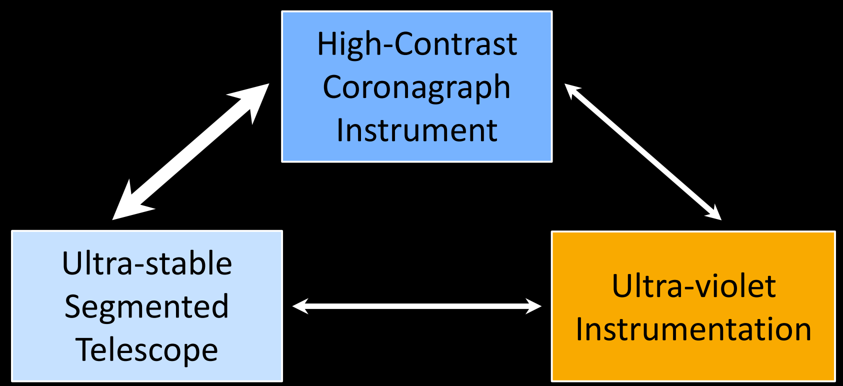


Three instruments

- Extreme Coronagraph for Living Planetary Systems (*ECLIPS*)
- LUVOIR UV Multi-object Spectrograph (*LUMOS*)
- High Definition Imager (*HDI*)

Technology Development

Technologies are organized into three technology systems:



Three development paths mature each of the technologies at the ***system*** level

> Technologies are identified at component level, and validated in assembly-, sub-system-, and system-level demonstrations

Technology systems are coupled, and must be developed in parallel with cross-validation

High-Contrast Coronagraphy - Components

LUVOIR

Technology Component	Implementation Options	State of the Art	Capability Needed	FY19 TRL	In LUVOIR Baseline?
Coronagraph Architecture	Apodized Pupil Lyot Coronagraph (APLC)	6.3×10^{-6} over 6% bandpass in air. Validated models with WFIRST CGI SPC demonstrations	1×10^{-10} raw contrast >10% bandpass <4 λ/D inner working angle 128 λ/D outer working angle Robust to stellar diameter and jitter	4	✓
	Vortex Coronagraph (VC)	8.5×10^{-9} contrast over 10% band with unobscured pupil. SCDA modeling for unobscured, segmented pupil		3	✓
	Phase-Induced Amplitude Apodization (PIAA)	SCDA modeling results for unobscured, segmented pupil		3	
	Hybrid-Lyot Coronagraph (HLC)	3.6×10^{-10} contrast over 10% band in DST. SCDA modeling for unosbcured segmented pupil		3	
	Nulling Coronagraph (NC)	5×10^{-9} narrowband at 2.5 λ/D		3	
Deformable Mirrors	Micro-Electro-Mechanical Systems (MEMS)	Available up to 64 x 64 actuators; 8.5×10^{-9} contrast demonstrated with 32 x 32 actuators	Minimum 64 x 64 actuators (>100 x 100 actuators is enhancing) Stable actuators (low creep) Diffraction-limited surface quality	4	✓
	Lead-Magnesium-Niobate (PMN) Macro-scale	$<1\times10^{-8}$ contrast demonstrated with 48 x 48 actuator Xinetics DMs (WFIRST CGI Testbed)		5	
Wavefront Sensing	Out-of-band Wavefront Sensing	Model predicting <10 pm residual error with nonlinear ZWFS, Mv = 5 source	Wavefront stabililty ~10 pm RMS ~1 Hz bandwidth with Mv < 9 source Able to capture wavefront spatial frequencies on the order of segment-to-segment drift and DM actuators	3	✓
	Low-order Wavefront Sensing	<0.36 mas RMS line-of-sight residual error; <30 pm RMS focus, Mv = 5 source (WFIRST CGI Testbed)		6	✓
	Artificial Guide Star	Concept study for guide star spacecraft and wavefront sensing control loop completed.		3	
UV/VIS Low-noise Detector	Electron-Multiplying CCD	1k x 1k WFIRST Detector: 7×10^{-5} e-pix/s dark current 0 e- read noise 2.3×10^{-3} CIC	3×10^{-5} e-/pix/s dark current 0 e- read noise 1.3×10^{-3} e-/pix CIC >80% QE at all detection wavelengths 4k x 4k array size	4	✓
	Hole-Multiplying CCD	Prototype devices fabricated with gains > 10x (>20x in at least one device)		3	
NIR Low-noise Detector	HgCdTe Photodiode Array	H4RG-10 currently meets needed capability @ 170 K	< 1×10^{-3} e-/pix/s dark current < 3e- read noise 4k x 4k array size	5	✓
	HgCdTe Avalanche Photodiode	1.5×10^{-3} e-/pix/s dark current < 1 e- read noise 320 x 256 array size Requires < 100 K temperatures		4	

Potential SBIR Contributions

Ultra-stable Segmented Telescope - Components

LUVOIR

Technology Component	Implementation Options	State of the Art	Capability Needed	FY19 TRL	In LUVOIR Baseline?
Mirror Substrate	Closed-back ULE (rigid body actuated)	7.5 nm RMS surface figure area with no actuated figure correction < 200 Hz first free mode ~10 kg/m^2 areal density	~5 nm RMS surface figure error > 400 Hz first free mode 19 kg/m^2 areal density	5	✓
	Closed-back ULE (surface figure actuated)			4	
	Open-back Zerodur (rigid body actuated)	Meets wavefront error requirement, but first mode and areal density are challenges		4	
Actuators	Combined piezo/mechanical	JWST mechanical actuators; Off-the-shelf PZT actuator with 5 pm resolution	> 10 mm stroke < 10 pm resolution < 1 pm / 10min creep Long lifetime	3	✓
	All-piezo	20 mm travel with 5 nm coarse resolution and 5 pm fine resolution		3	
Edge Sensors	Capacitive	5 pm in gap dimension, 60 Hz readout	<4 pm sensitivity at 50-100 Hz rate (control bandwidth of 5-10 Hz)	3	✓
	Inductive	1 nm / sqrt(Hz) for 1-100 Hz in shear; 100 nm / sqrt(Hz) for 1-10 Hz in gap		3	
	Optical	20 pm / sqrt(Hz) up to 100 Hz		3	
	High-speed Speckle Interferometry	< 5 pm RMS at kHz rates; requires center-of-curvature location and high-speed computing		3	
Laser Metrology	Laser truss with phasemeter electronics	Planar lightwave circuit; 0.1 nm gauge error; LISA-Pathfinder heritage laser	< 100 pm sensitivity at 10 Hz rate (control bandwidth of 1 Hz)	4	✓
Vibration Isolation	Non-contact Isolation System	> 40 dB transmissiability isolation > 1 Hz; Requires electronics development and performance validation	> 40 dB transmissiability isolation > 1 Hz	4	✓

Potential SBIR Contri-butions

UV Instrumentation - Components

Technology Component	Implementation Options	State of the Art	Capability Needed	FY19 TRL	In LUVOIR Baseline?
Far-UV Broadband Coating	Al + eLiF + MgF_2	Meets performance requirements, but requires demonstration on meter-class optics; requires validation of uniformity, repeatability, environmental stability	>50% reflectivity (100-115nm) >80% reflectivity (115-200nm) >88% reflectivity (200-850nm) >96% refelctivity (> 850nm) <1% reflectance nonuniformity (over entire primary mirror) over corongraph bandpass (200 - 2000 nm)	3	✓
	Al + eLiF + AlF_3			3	
	Al + eLiF	Meets performance requirements, but is environmentally unstable		5	
Microshutter Arrays	Next-gen Electrostatic Microshutter Arrays	840 x 420 prototype demonstrated, but requires development survive vibe and acoustic testing	840 x 420 array format, two-side buttable	3	✓
Large-format Microchannel Plates	CsI	Meets requirements for 100-150 nm	200 mm x 200 mm tile size >30% QE between 100 - 200 nm	6	✓
	GaN	Meet requirements for 150-200 nm range; requries development for large tile size and integration with cross-strip readout. GaN has better solar blind performance.		4	✓
	Bi-alkali			4	
	Funnel microchannels	Demonstrated 50% improved quantum efficiency with CsI photocathode		4	
Large-format High-resolution Focal Plane Arrays	8k x 8k CMOS	4k x 4k devices exist, require development for 8k x 8k and readout optimization	8k x 8k format, <7 micron pixels, three-side buttable ~1 e- read noise $\sim1\times10^{-4}$ e-/pix/s dark current at 170 K	4	✓
	4k x 4k CCD	8k x 8k devices exist with 18 micron pixels; lacks programmable high-speed region-of-interest readout for guiding capability		5	

Potential SBIR Contri-butions

Path to TRL 6

Following slides show the technology development plans for each technology system

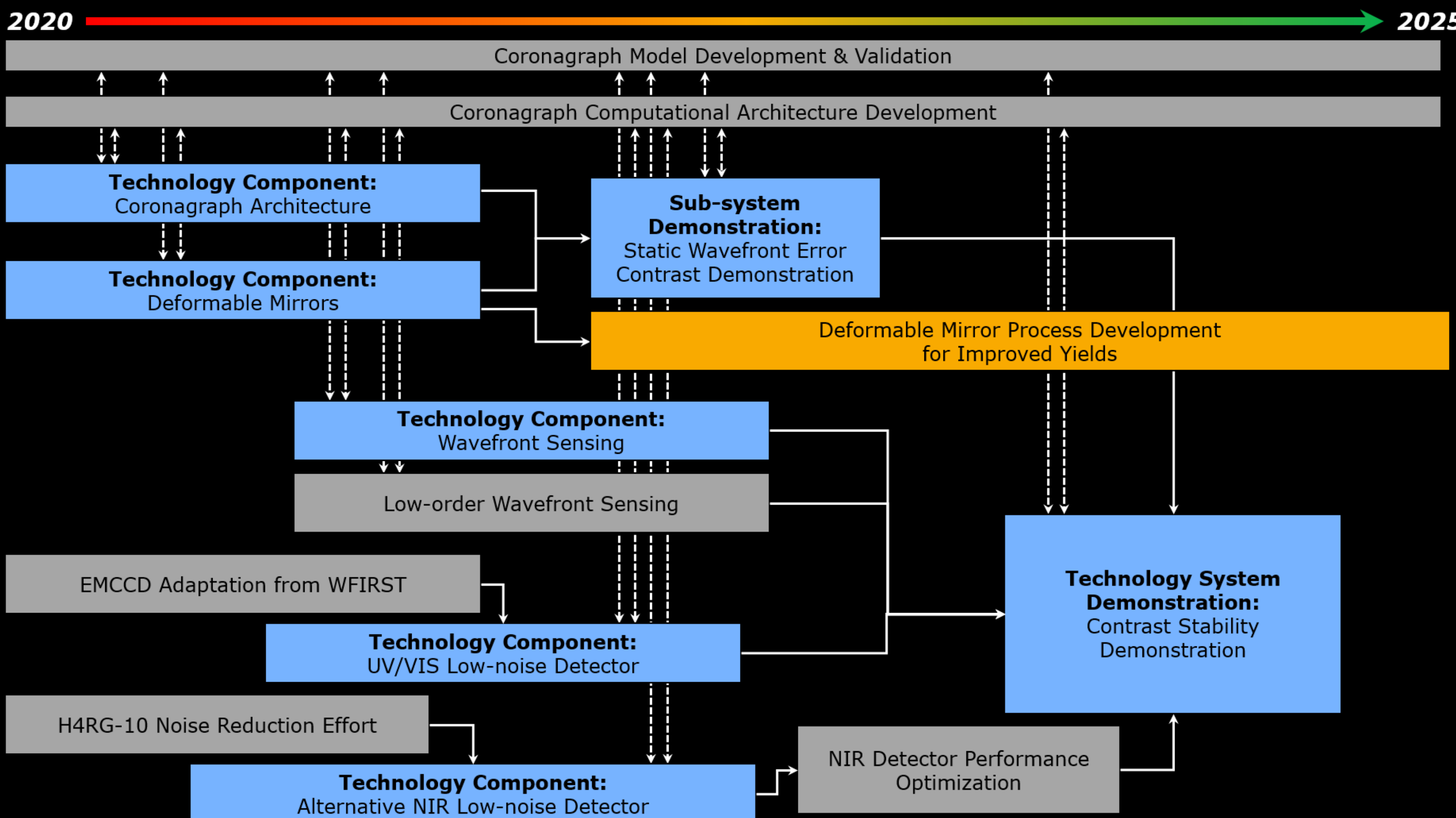
Includes associated manufacturing and engineering developments that will also enable LUVIOR

= Technology Development

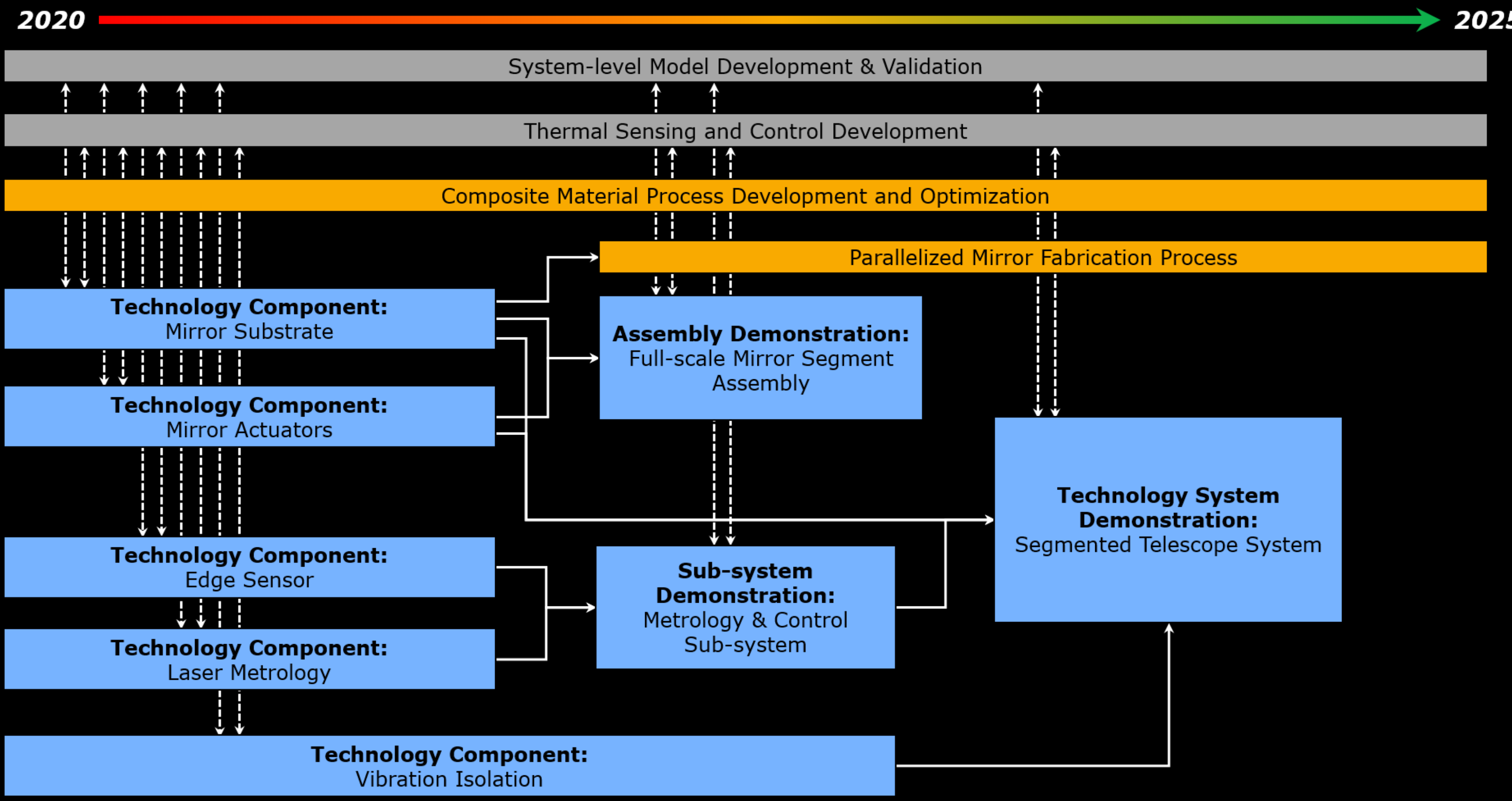
= Engineering Development

= Manufacturing Development

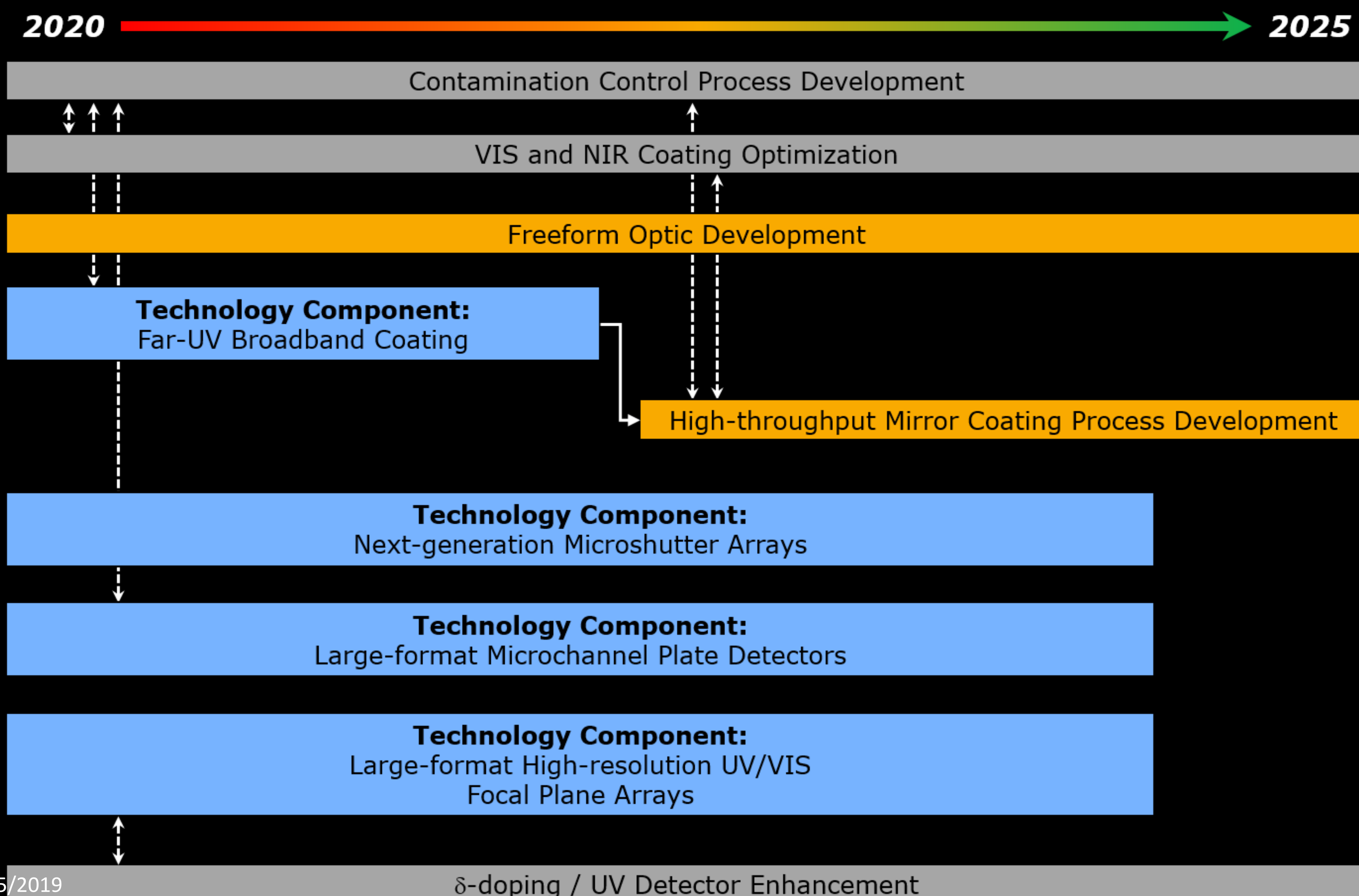
High-Contrast Coronagraphy – Path to TRL 6



Ultra-stable Segmented Telescope – Path to TRL 6



UV Instrumentation – Path to TRL 6



For more detailed information, see our Final Report at www.luvoirtelescope.org

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