SPIE Astronomical Telescopes + Instrumentation

HabEx Lite

A Starshade-only Habitable Exoplanet Observatory Alternative

David Redding, Keith Coste, Otto Polanco, Claudia Pineda, Kevin Hurd, Howard Tseng, Jose Quezada, Stefan Martin, Joel Nissen, Kevin Schulz, Jon Tesch, Eric Cady (JPL), Michael Rodgers (Synopsis), Matthew East, James Mooney (Harris), Chris Stark (STScI)

Jet Propulsion Laboratory
California Institute of Technology

Pre-Decisional Information -- For Planning and Discussion Purposes Only

The Habitable Exoplanet Observatory

HabEx would...

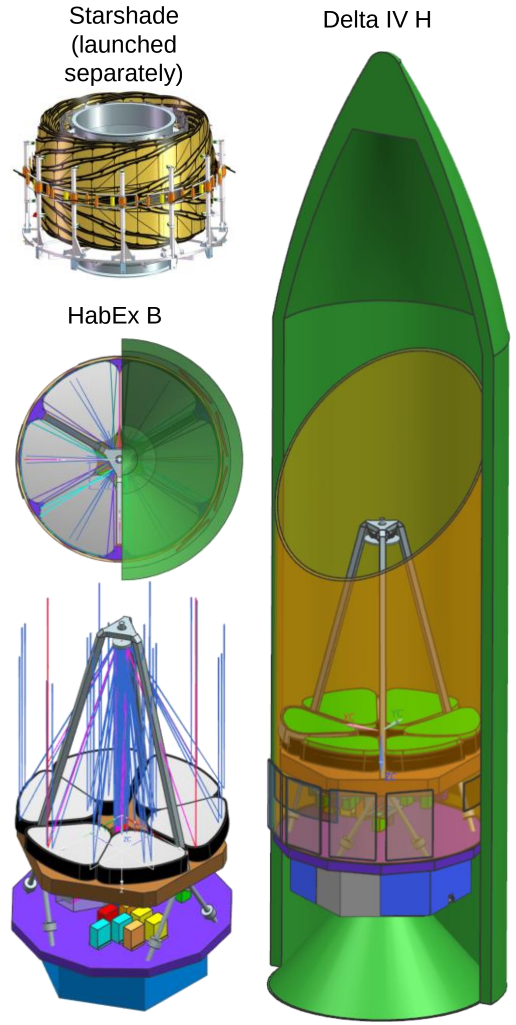
Seek out nearby worlds and explore their habitability.

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

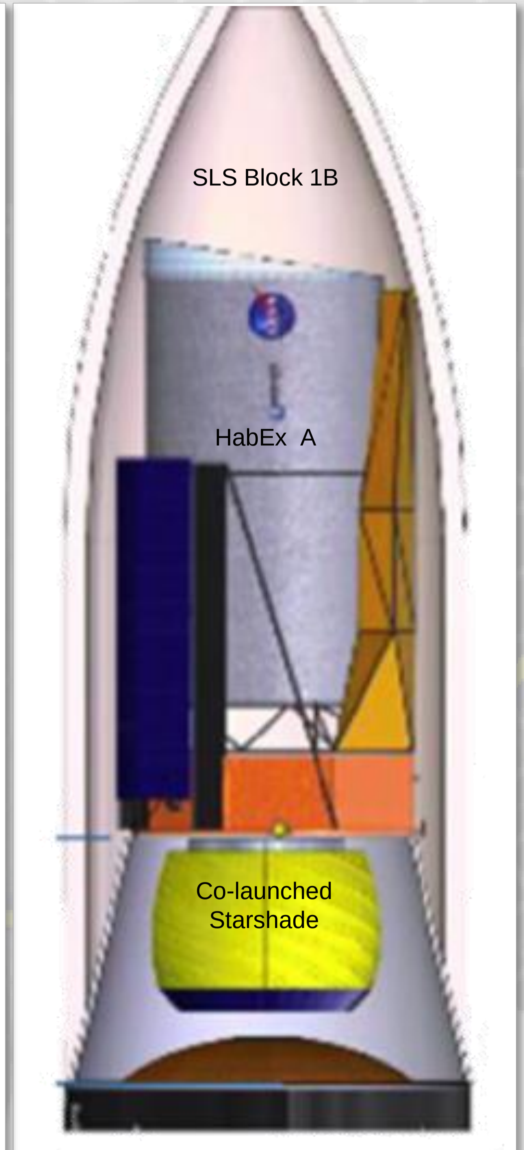
Open up new windows on the universe from the UV through near-IR.

Key Mission Requirements

	Parameter	Value
General	Aperture diameter	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	2.5x2.5 amin
	Spectral resolution	R ≥2 ,000
UV Spectro -graph	Waveband	115-300 nm
	Field of View	2.5x2.5 amin
	Spectral resolution	R ≥ 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



HabEx Architecture B
Starshade-only, Non-deployed Segmented PM, Falcon H or Delta IV H



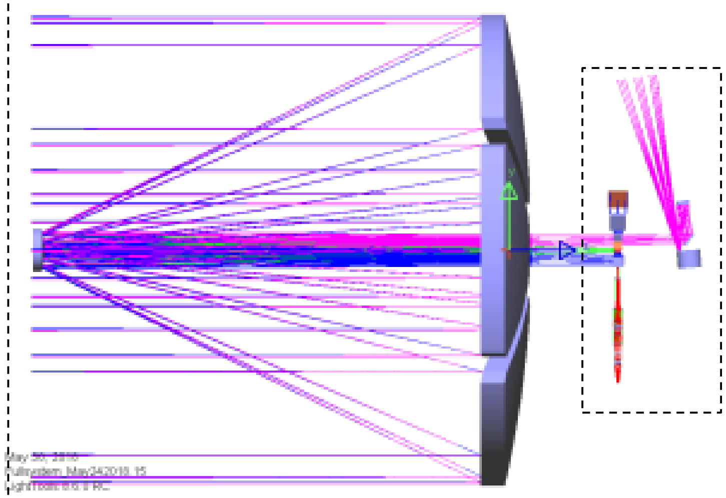
HabEx Architecture A
Coronagraph and Starshade, Monolithic PM, SLS Block 1B

HabEx Lite – aka HabEx Architecture B

- HabEx B implements the HabEx mission concept using only a Starshade for exoplanet imaging – no coronagraph
  - Implements full HabEx General Astrophysics program
  - Separate launch for Observatory and Starshade
- Eliminating the HabEx A coronagraph simplifies the mission to reduce cost:
  - Removes a complex optical instrument
  - Relaxes observatory wavefront stability requirements ~100 times
  - Permits a compact, on-axis telescope design that fits into a lower-cost Super Heavy Launch Vehicle (SHLV, Delta IV Heavy, e.g.)
  - Permits use of a lower mass segmented mirror, whose manufacture is within the current state of practice
  - Lowers overall Observatory mass including margin to 9,420 kg (from 19,350 kg)
- The scientific penalty is that the number of targets that can be visited (and revisited) is reduced, lowering exoEarth yield
  - Yield could be restored, however, if precursor ultrasensitive RV surveys are successful in discovering candidate exoEarths

OTA and Instruments

PM: 8.6 m ROC, F/1.1



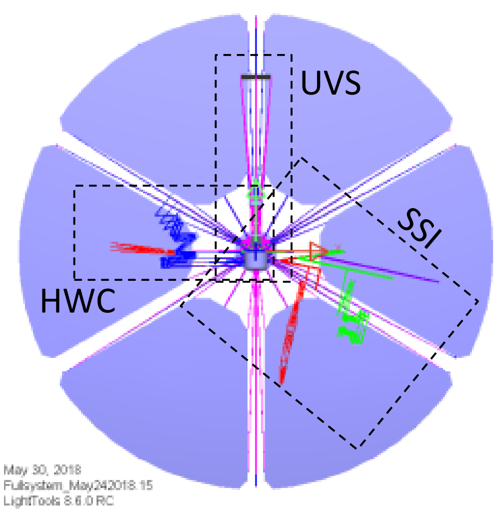
Instrument devices:
- 8 FPAs
- 12 mechanisms

Far-field FOV

UV Spectrograph:
3 x 3 arcmin (0.05°x 0.05°)
Centered 0.075° off axis

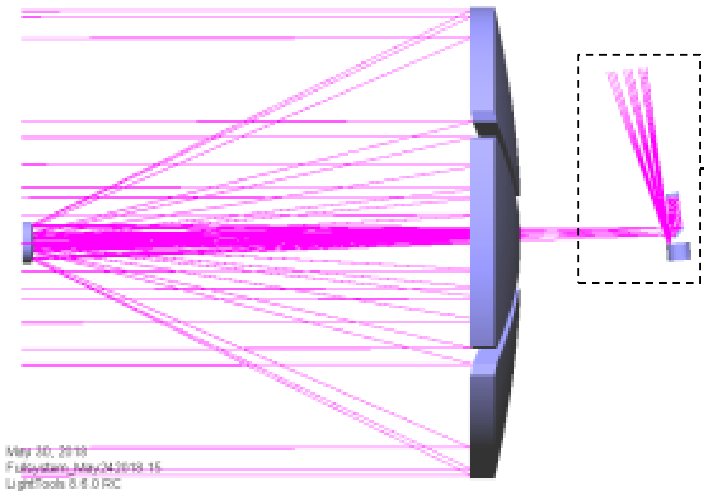
Starshade Camera:
12 arcsec diameter, on axis

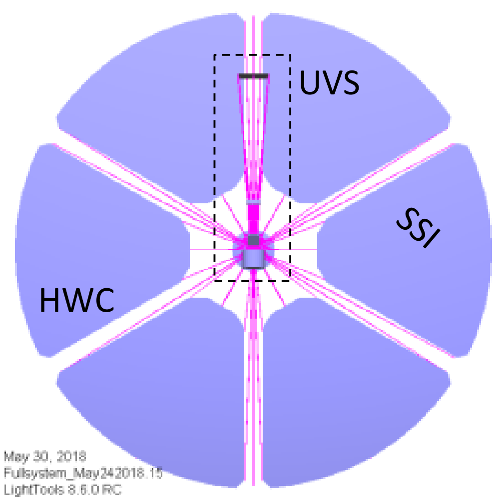
Workhorse Camera:
3 x 3 arcmin (0.05°x 0.05°)
Centered -0.075° off axis

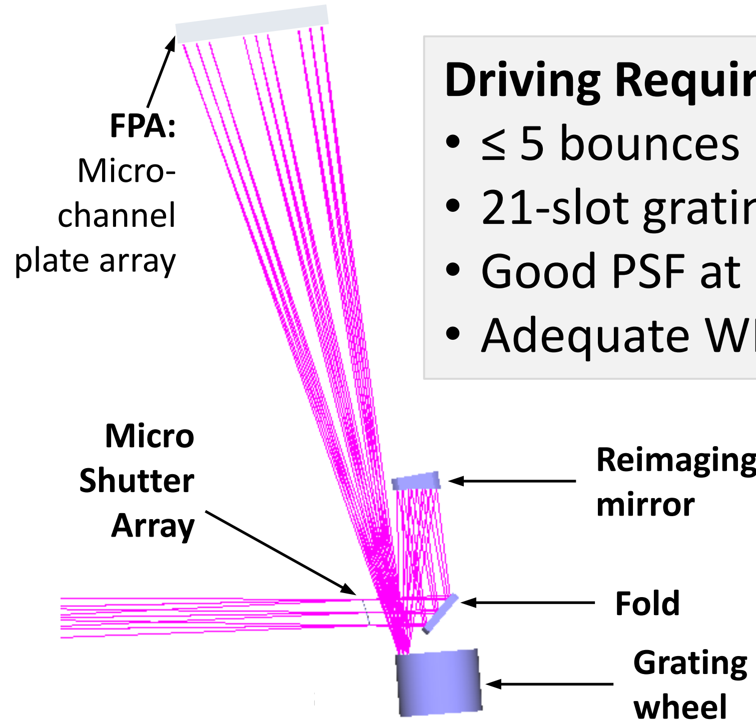


- Cassegrain OTA, F/18
- UV Spectrograph (UVS), up to R = 60,000:
  - 20 grating settings + 1 mirror in wheel
  - Multi-Shutter Array (MSA)
- HabEx Workhorse Camera (HWC),
  - IR and VIS channels, with MSA
  - Imaging and grism spectrometry
- Starshade Instrument (SSI), 8 modes
  - UV, IR, VIS imaging
  - VIS, IR IFS; and UV spectrograph
  - UV, IR pupil imaging for Starshade guiding

UV Spectrograph







Driving Requirements:

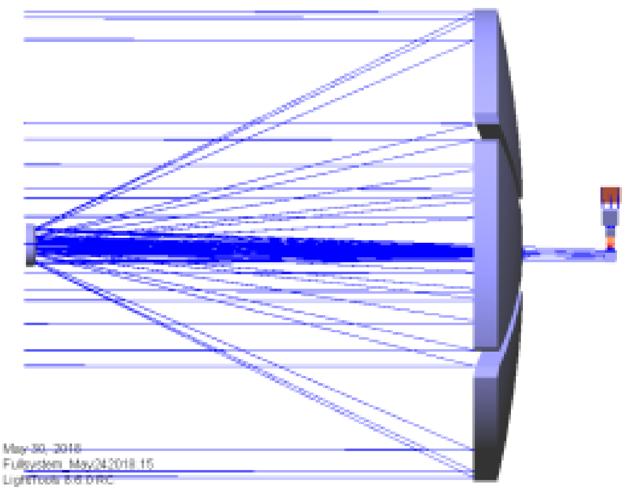
- ≤ 5 bounces
- 21-slot grating wheel
- Good PSF at MSA
- Adequate WFE at EP

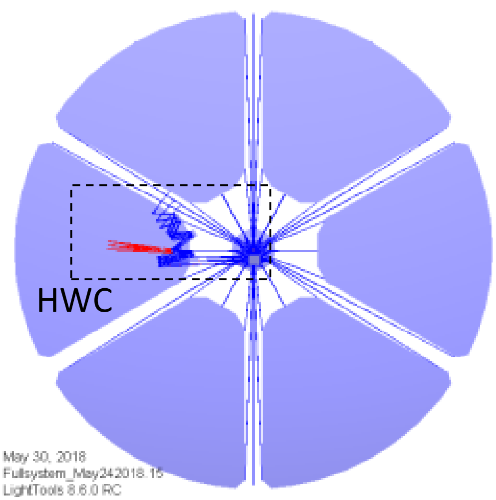
UV Spectrometer instrument	
Spectral band (nm)	115-300
FOV (arc-min)	3x3
F/# at FPA	F/75
Grating	20 grating settings + 1 mirror in a wheel.
Modes	**2:** Spectrograph; imaging.

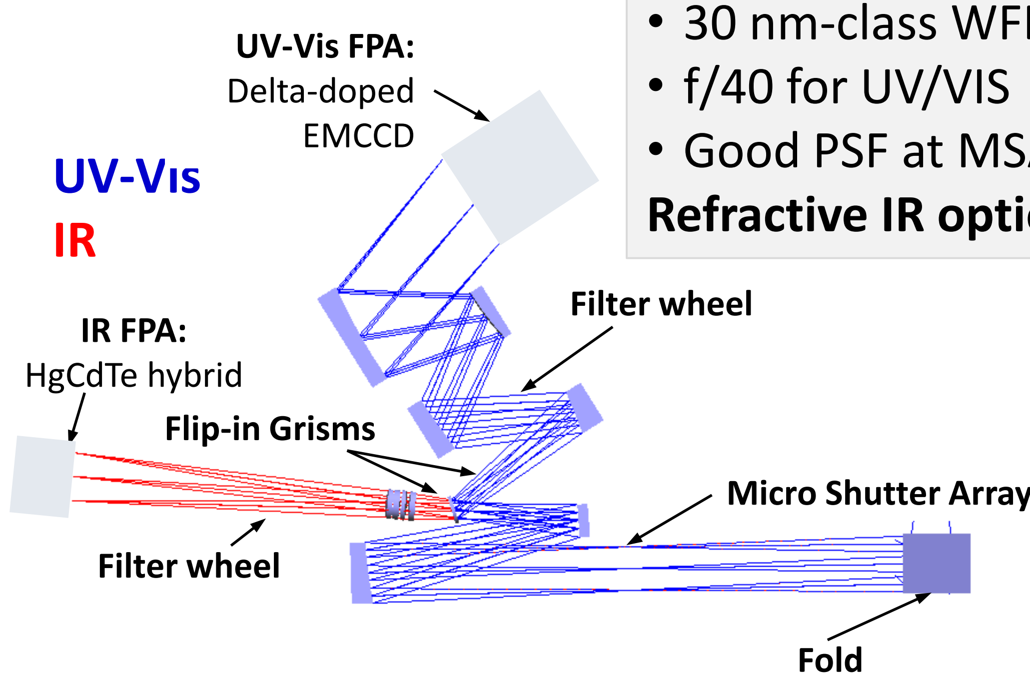
HabEx Workhorse Camera

Driving Requirements:
- 30 nm-class WFE
- f/40 for UV/VIS
- Good PSF at MSA

Refractive IR option



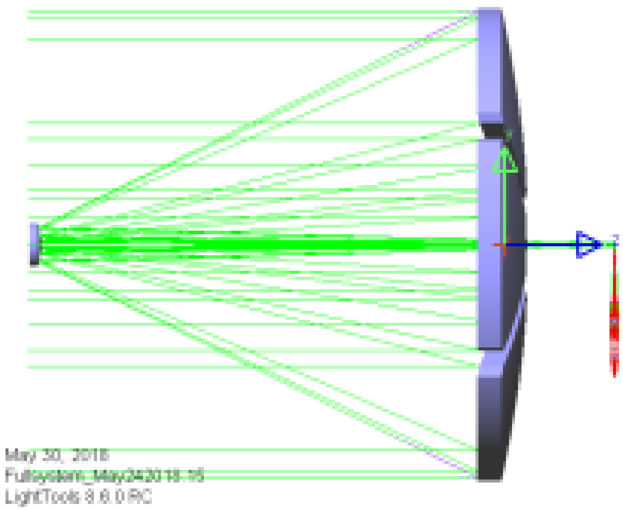


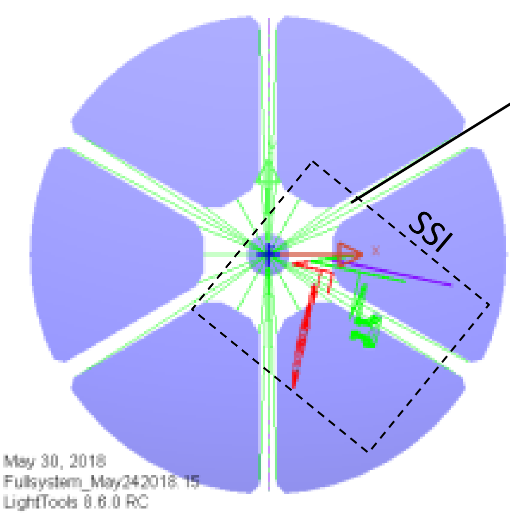


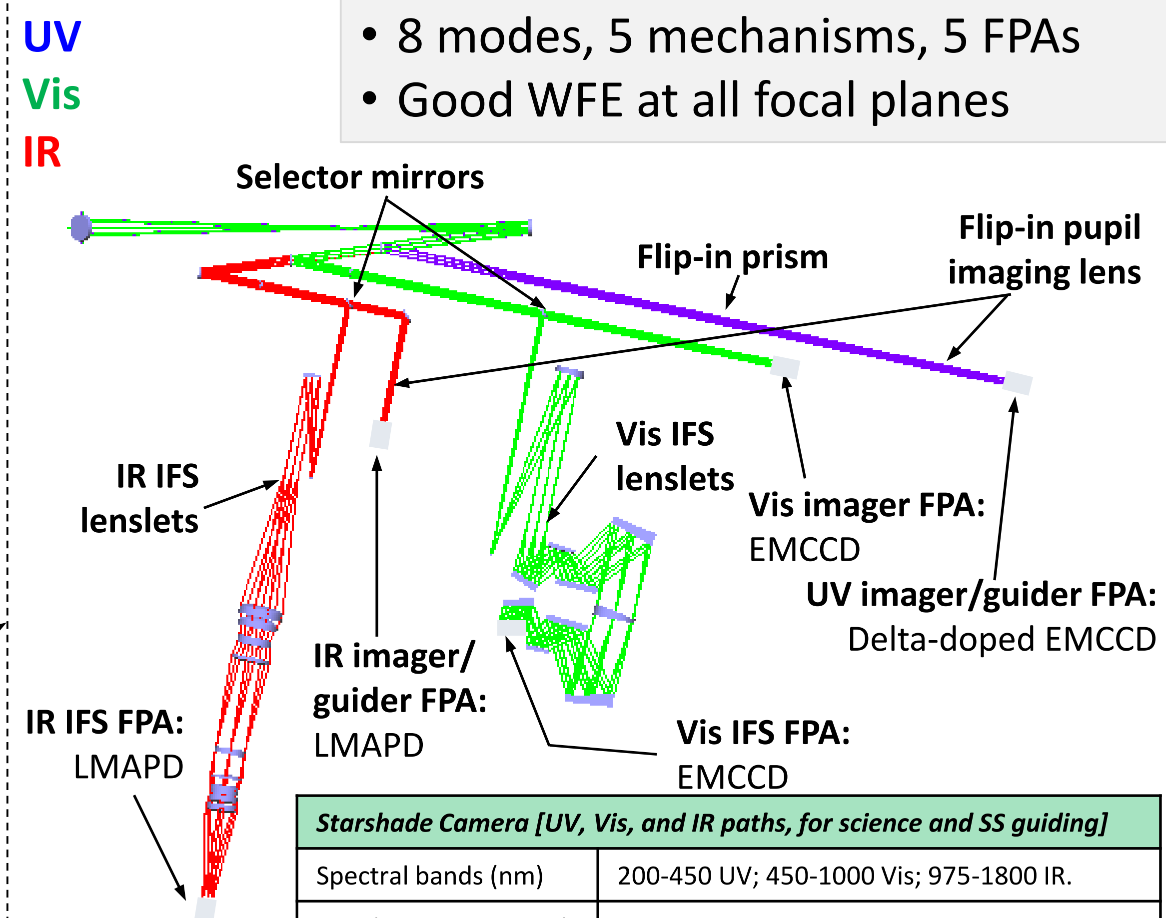
Workhorse Camera [UV-Vis and IR paths]	
Spectral bands (nm)	150-950 UV-Vis; 950-1800 IR
FOV (arc-min)	3x3
F/# at microshutter	About F/18
F/# at FPA	F/40 (UV-Vis), F/21 (IR).
Modes	**4:** 2 imaging, 2 grisms.

Starshade Instrument

Driving Requirements:
- 8 modes, 5 mechanisms, 5 FPAs
- Good WFE at all focal planes



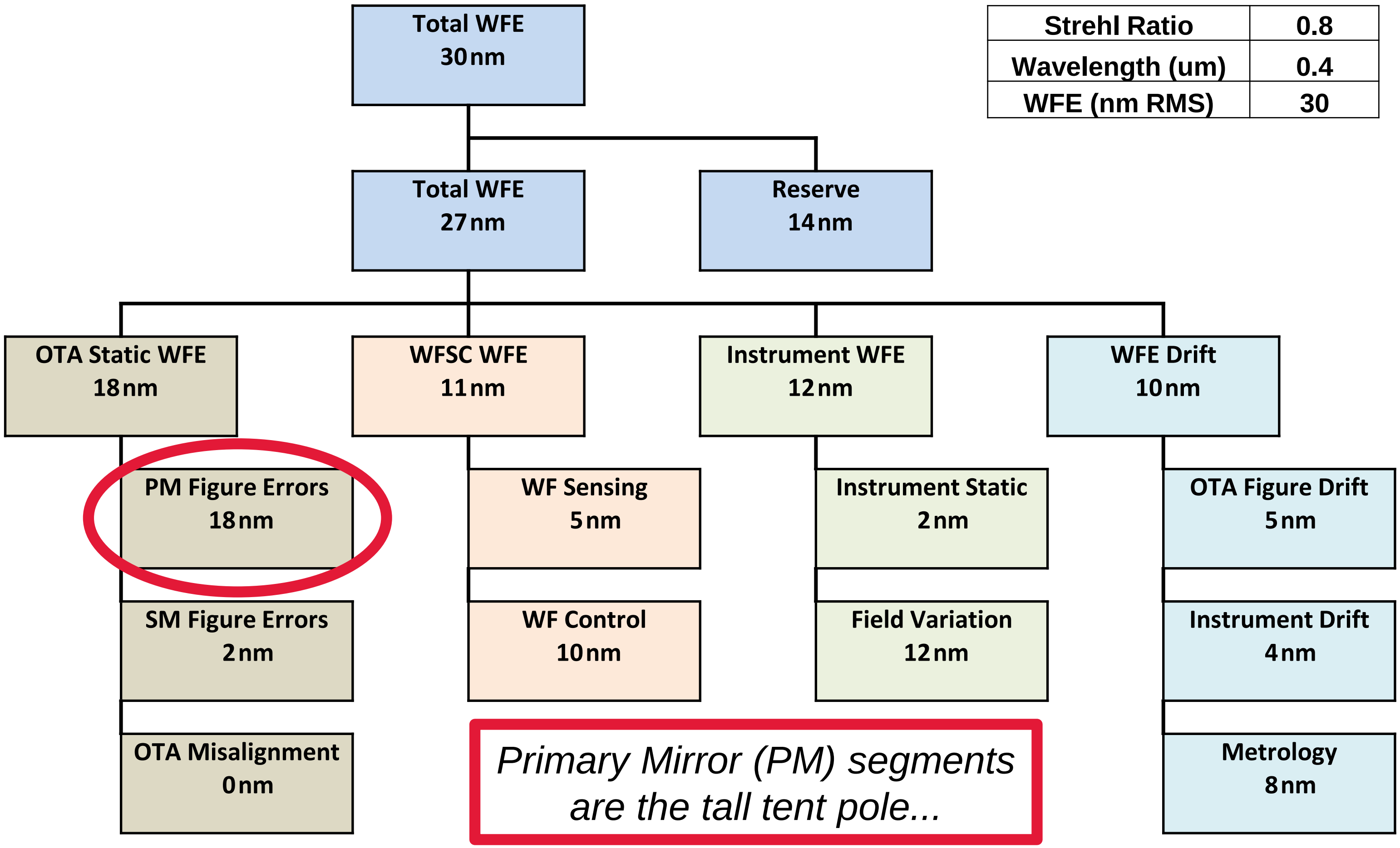




Starshade Camera [UV, Vis, and IR paths, for science and SS guiding]	
Spectral bands (nm)	200-450 UV; 450-1000 Vis; 975-1800 IR.
FOV (arcsec diameter)	12 UV, 12 Vis, 12 IR.
F/# , imaging	80 UV, 71 Vis, 51 IR.
F/#, IFS	6.0 Vis, 3.36 IR.
Modes	**8:** 3 star imaging, 2 pupil imaging (UV and IR), 2 IFS (Vis and IR), 1 spectrograph (UV)

Preliminary HabEx B Wavefront Error Budget

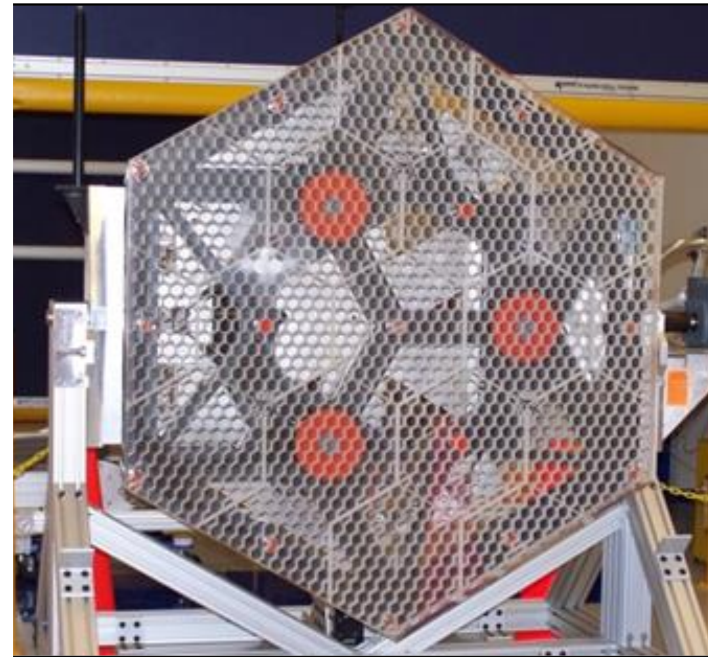
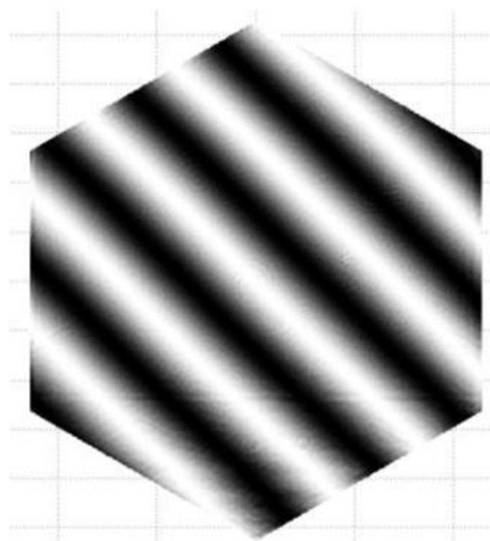
Strehl Ratio	0.8
Wavelength (um)	0.4
WFE (nm RMS)	30



- ***Post-control*** WF error budget
  - WFSC acts to correct initially large alignment and figure errors
  - MET + WFC continuously maintain alignments

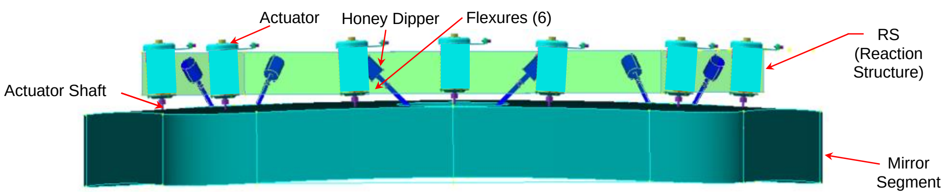
ULE Mirrors: Demonstrated Performance

- 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

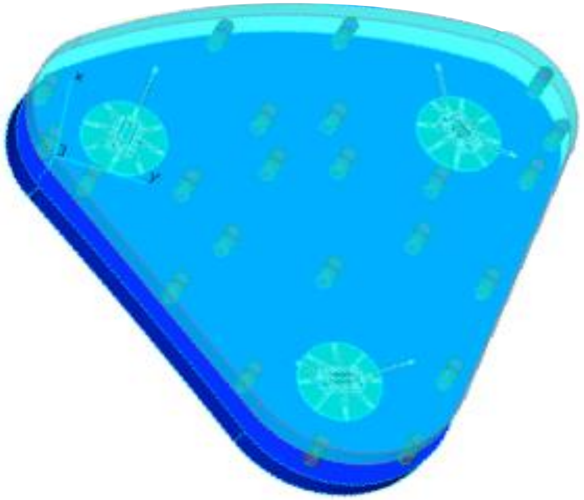





Mirrors for HabEx B: Active or Passive?

- Low-authority active architecture: ~24 **Figure Control Actuators** (FCAs) compensate the most challenging fabrication errors
  - Meet 10 nm RMS figure error over full PM using current processes
  - Enable use of 3DOF rigid-body actuators for smaller gap
- FCAs also provide *on-orbit correctability of system-level errors*
- FCAs use constant-force design for insensitivity to thermal deformation
- When coupled with stiff substrate, FCAs partially compensate gravity sag for improved testing



- **Passive glass segments** meeting 10 nm RMS surface figure error may also be possible with further mfg. process development
  - To reduce ROC-matching errors
  - To improve 0-g figure prediction
  - Will require 6DOF RB actuation

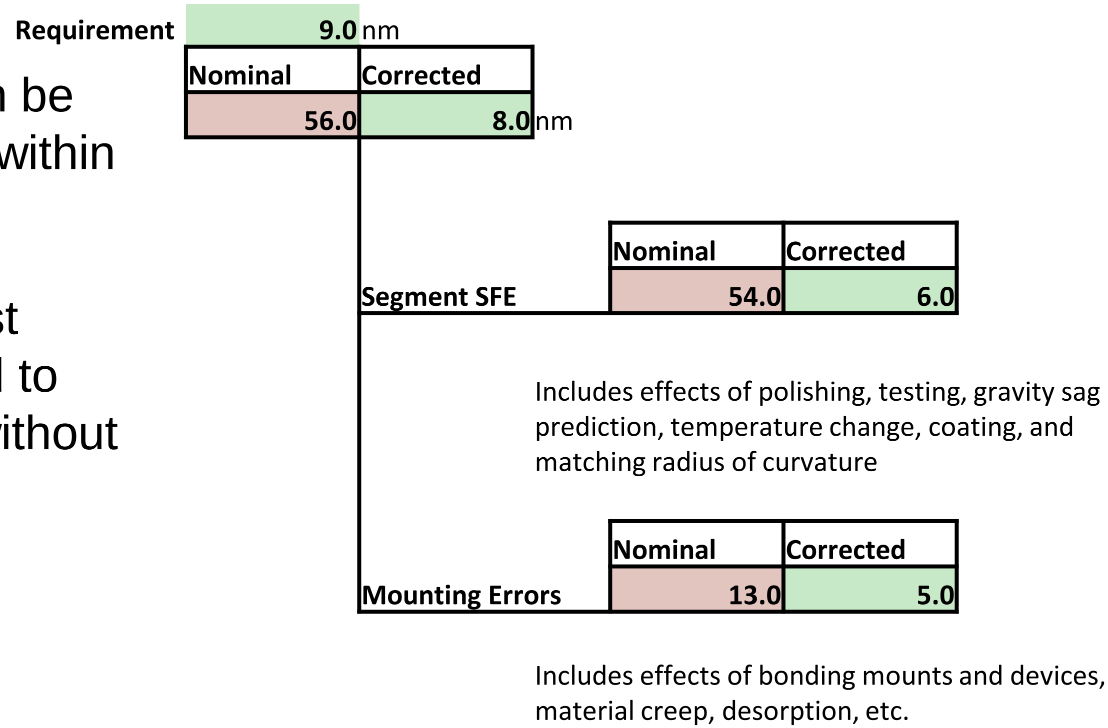


- Mirror total mass = 386 kg (CBE)
  - 34 kg/m^2 areal density (CBE)
  - Includes glass, actuators, mounts, structures, electronics

Preliminary Primary Mirror WF Error Budget

Actuated vs. Passive PM segment figure...

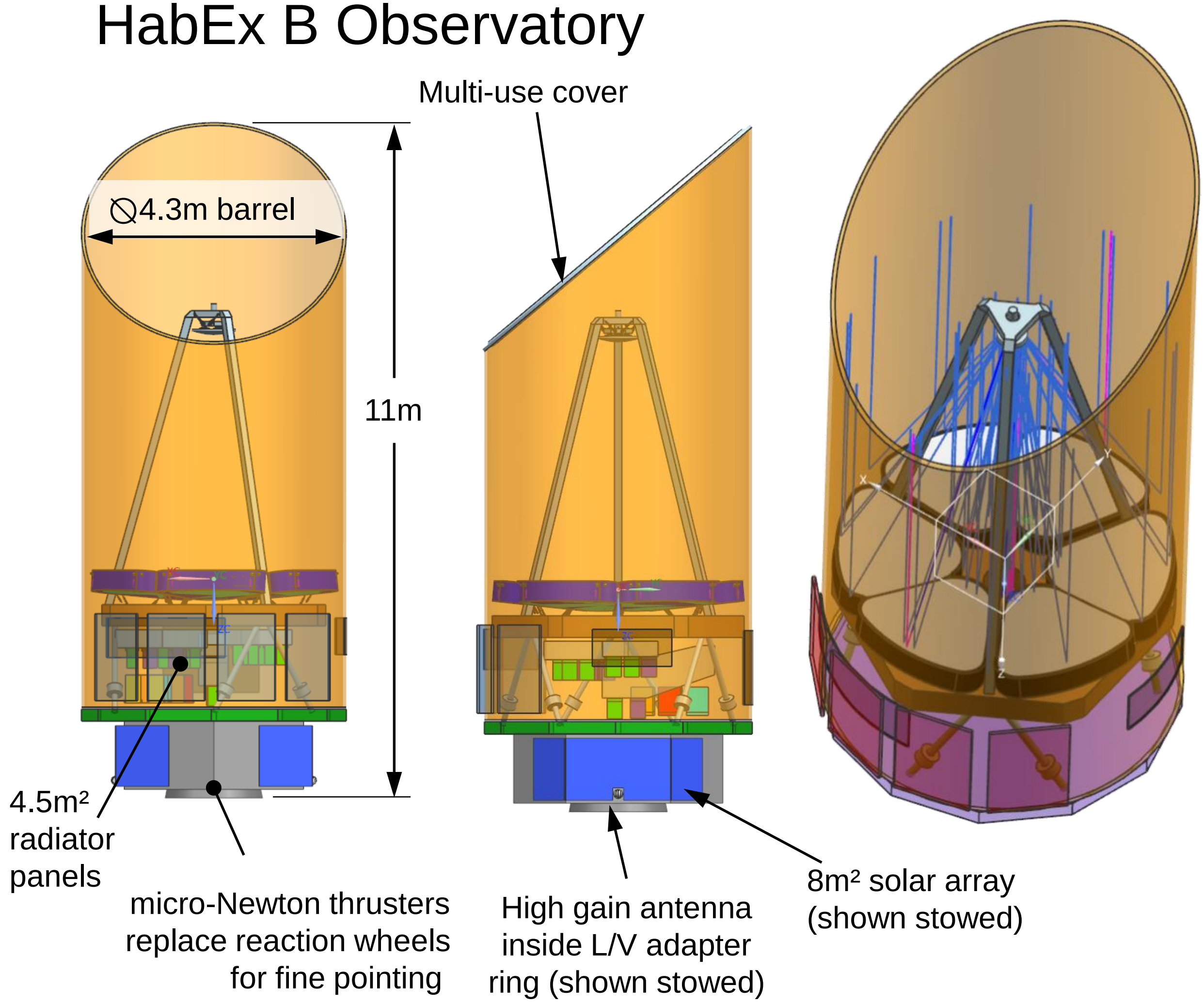
- Low-order PM figure control can be used to reliably meet 9nm SFE within current manufacturing practice
- Segment manufacturing and test improvements would be needed to provide required performance without actuation
  - Improved RoC matching
  - Testing at operational temperature
  - Improved 0-g testing techniques
- However: *the ability to perform on-orbit corrections mitigates risk and uncertainty in final performance*



Manufacturing WFE Budget: Using Figure Control to Meet PM Allocations – and Reduce Risk

Preliminary Configuration

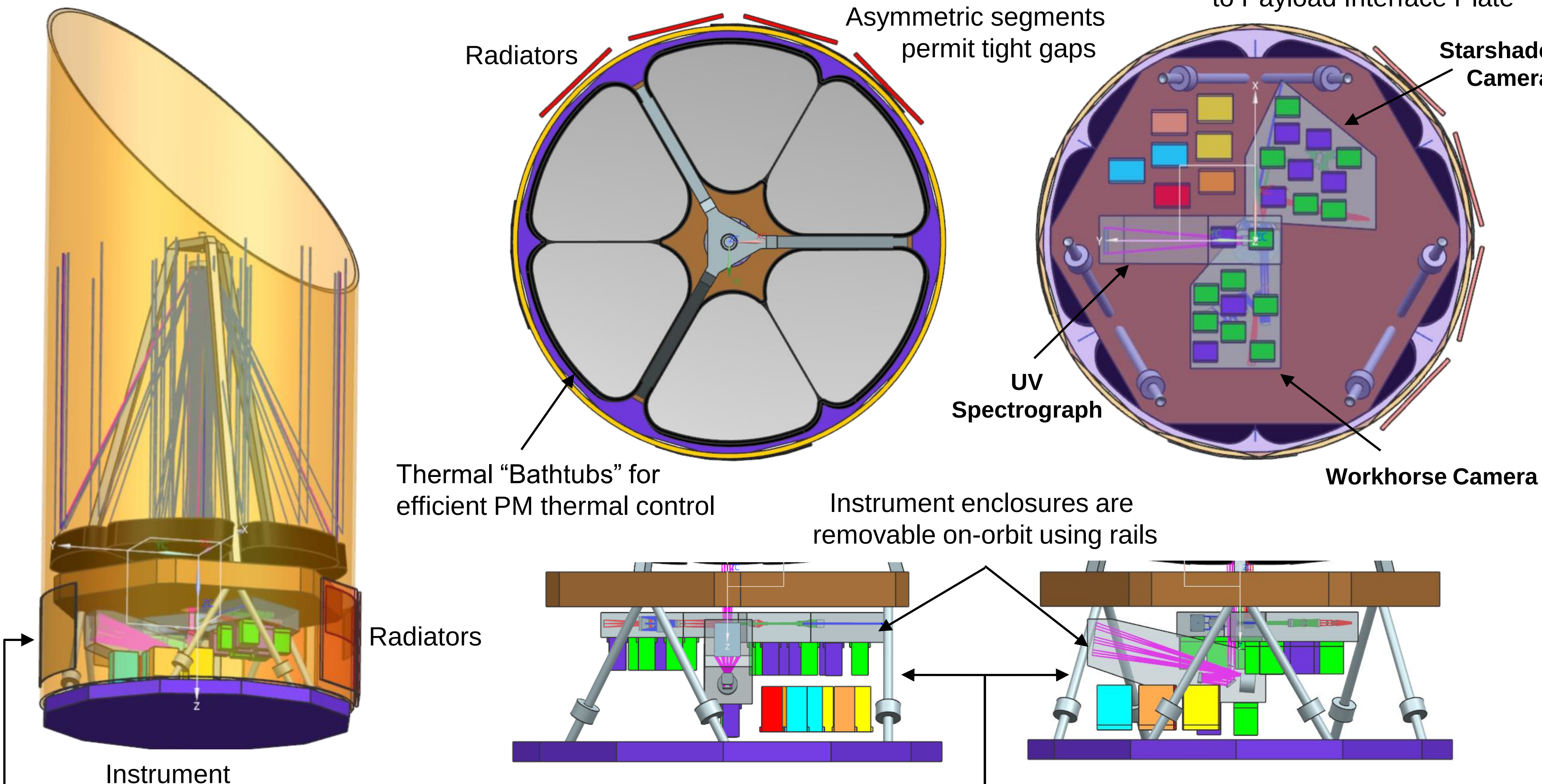
HabEx B Observatory



- **Launch Vehicle Fairing 5m x 16.5 m (Delta IV Heavy)**
- **Barrel Assembly attaches to SC Interface Plate**
- **Barrel has access doors and rails for instrument servicing and replacement**
- **Tripod SM Support Assembly**
- **PM Segments (Pie Shape) are slightly assymmetric to maximize collecting area**
- **Aft Metering Structure (AMS) supports PM, SM struts and all instruments**
- **Isolation Struts between the AMS and SC Bus Interface Plate (not needed if micro-Newton thruster pointing)**
- **SC Bus Interface plate provides a modular interface between the payload and the spacecraft bus**

Preliminary Configuration

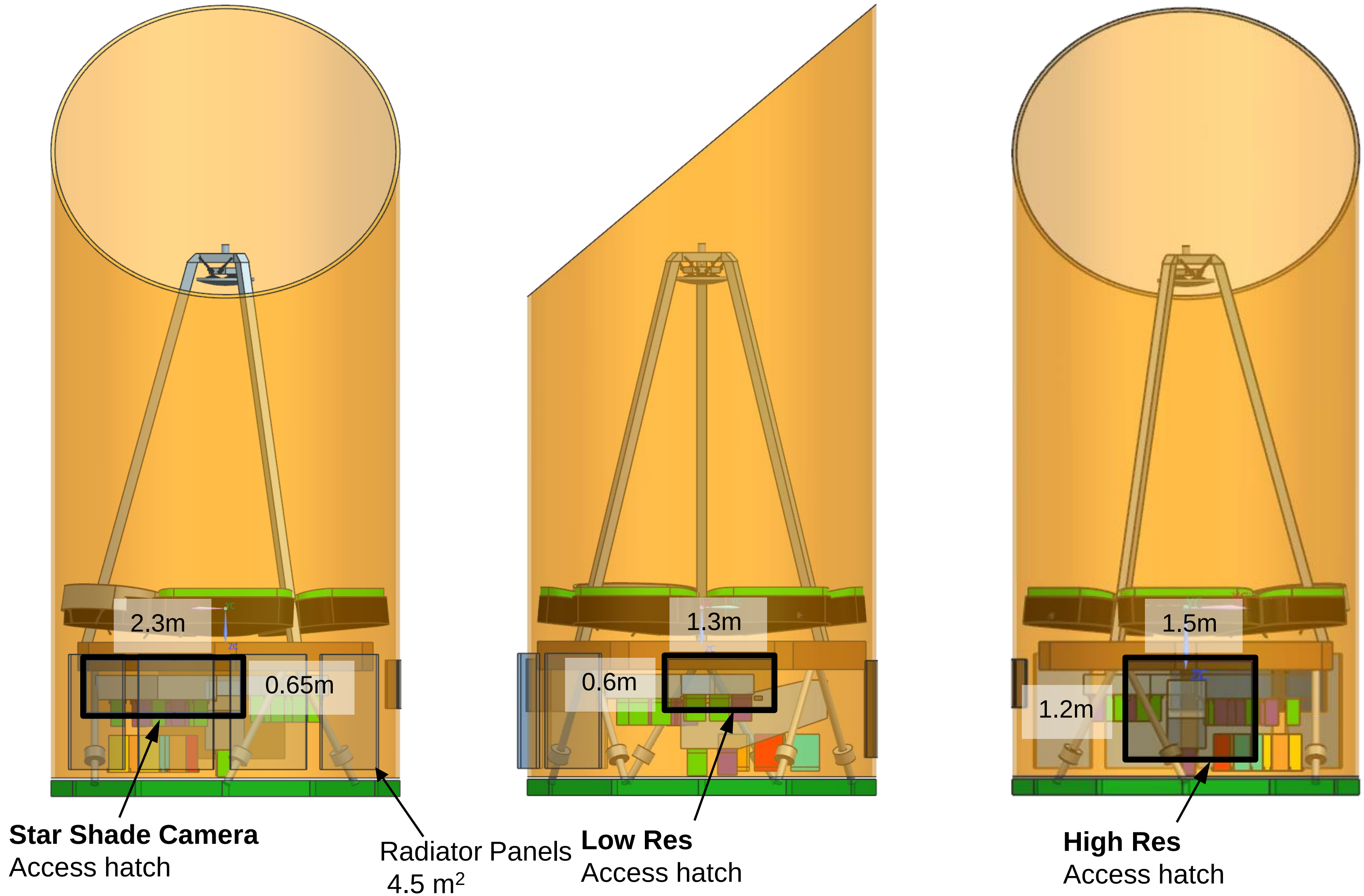
Primary Mirror and Aft Optics



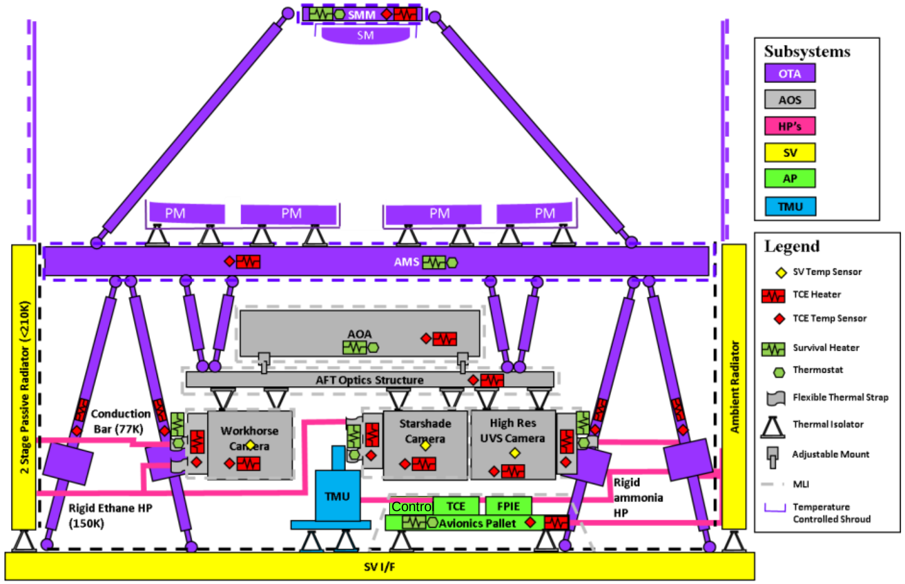
Not shown: cabling; heat pipes; MLI thermal shielding; ...

Preliminary Configuration

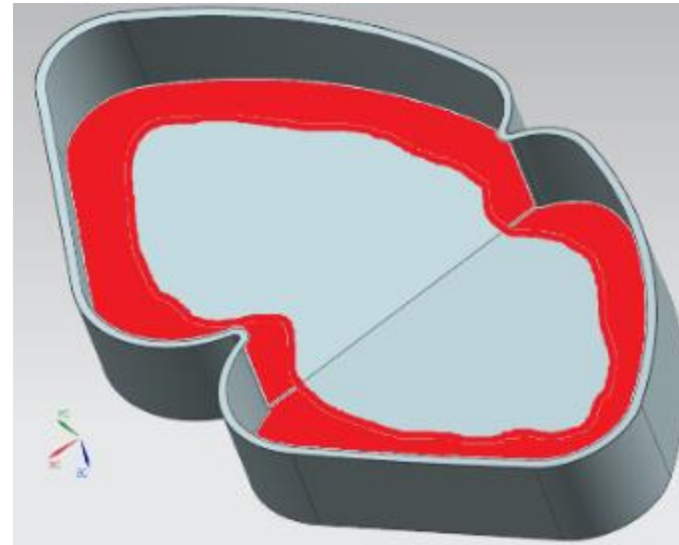
Sunshade Barrel and Instrument Serviceability



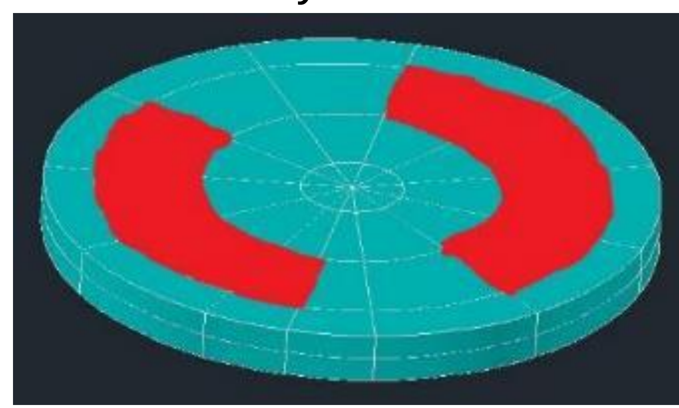
Thermal Architecture and Power Budget



Primary Mirror Heaters



Secondary Mirror Heaters



- Active thermal control keeps the optics at constant temperature, so optical figure is stable
  - Aided by thermal bathtub enclosures
  - Sub-milli Kelvin performance in simulations
- Thermal power consumption CBEs
  - PM and SM: 330 W continuous power
  - AMS and instruments: 276 W continuous power
  - Solar array area for heaters (PM, SM, AMS) = 2.5 m^2
- Cooling will require passive and active systems
  - Radiator area = 4.2 m^2 @ 20C; 2.7 @ -80C
  - Cryocoolers power (estimated) = 330W with electronics

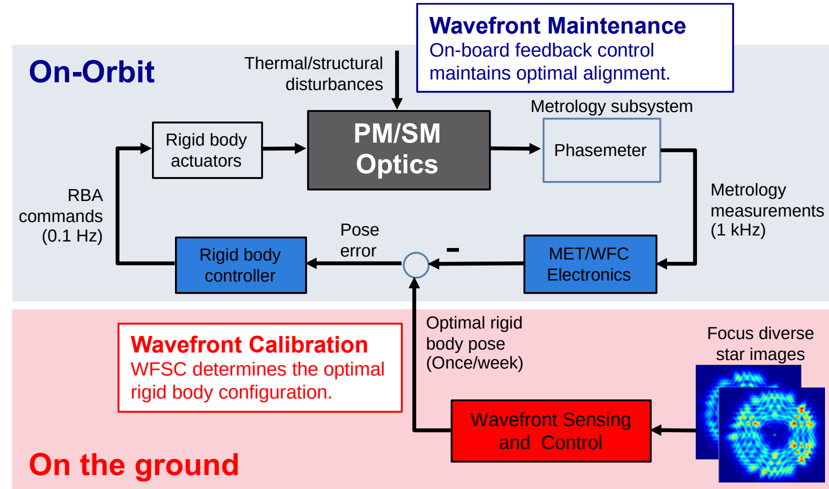
Master Equipment List

Element Name	ASM PARENT	Qty	Material	CBE Mass /Unit (Kg)	CBE MASS (kg)	JPL Uncertainty Factor	CBE Mass+JPL Uncertainty Factor
HABEX SEGMENT TELESCOPE Assembly (4m--6 Segment)	HABEX ASM	1			3471.5	1.43	4987.3
Primary Mirror Assembly	HABEX ASM	1			404	1.43	578.3
Secondary Mirror Assembly	HABEX ASM	1			109	1.43	155.6
UV Spectrograph	HABEX ASM	1			147	1.43	209.5
Workhorse Camera	HABEX ASM	1			203	1.43	290.2
Starshade Camera	HABEX ASM	1			238	1.43	340.0
Electronics Assembly	HABEX ASM	1			164	1.43	234.1
Aft Metering Structure (AMS) Assmebly	HABEX ASM	1			456	1.43	652.1
Secondary Support Assembly	HABEX ASM	1			195	1.43	279.5
Barrel Assembly	HABEX ASM	1			753	1.43	1076.7
Radiator Assembly	HABEX ASM	1			315	1.43	450.5
Telescope to SC Strut Assembly	HABEX ASM	1			142	1.43	202.7
Cabling Assembly	HABEX ASM	12			328	1.5	492.3
Dust Cover Assembly	HABEX ASM	1			18	1.43	25.7
Spacecraft Bus Assembly					2050	1.43	2932
Launch Vehicle Assembly					1050	1.43	1502
Hydrazine	LAUNCH VEHICLE ASM	1		400.000	400	1.43	572
Xenon	LAUNCH VEHICLE ASM	1		200.000	200	1.43	286
Launch Dry Mass (inc. LV Interface)					5972		8562
BOL Mass (post Transfer Orbit)					6122		8777
Launch Wet Mass				6571.535	6572		9420
LV Capability (*Delta IV, M+(5,4)) @ SEL2)*					10000		10000
Total Margin (LV Capability-Launch Wet Mass)							3428.47
Total Margin % of LV Capability							34.28%

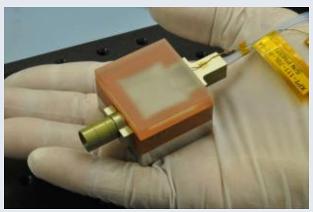
- Estimated mass meets Delta IV Heavy launch capability with 34% margin

Maintaining Alignments

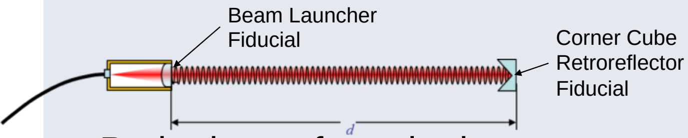
- Laser Metrology (MET) measures SM-PM-Instrument Bench alignments in real time
- Rigid Body Actuators move the SM and PM segments to preserve alignments



Laser Distance Gauge measures distance to <1 nm accuracy

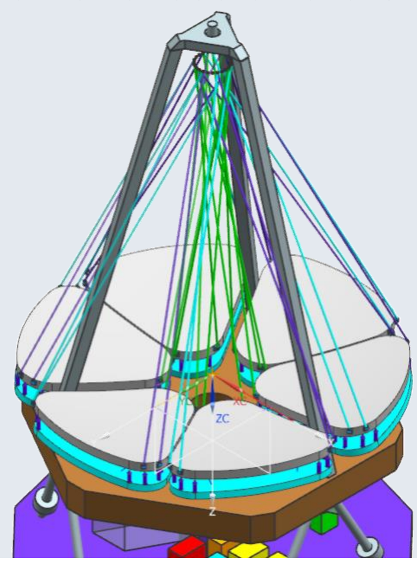


Beam Launcher



- 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

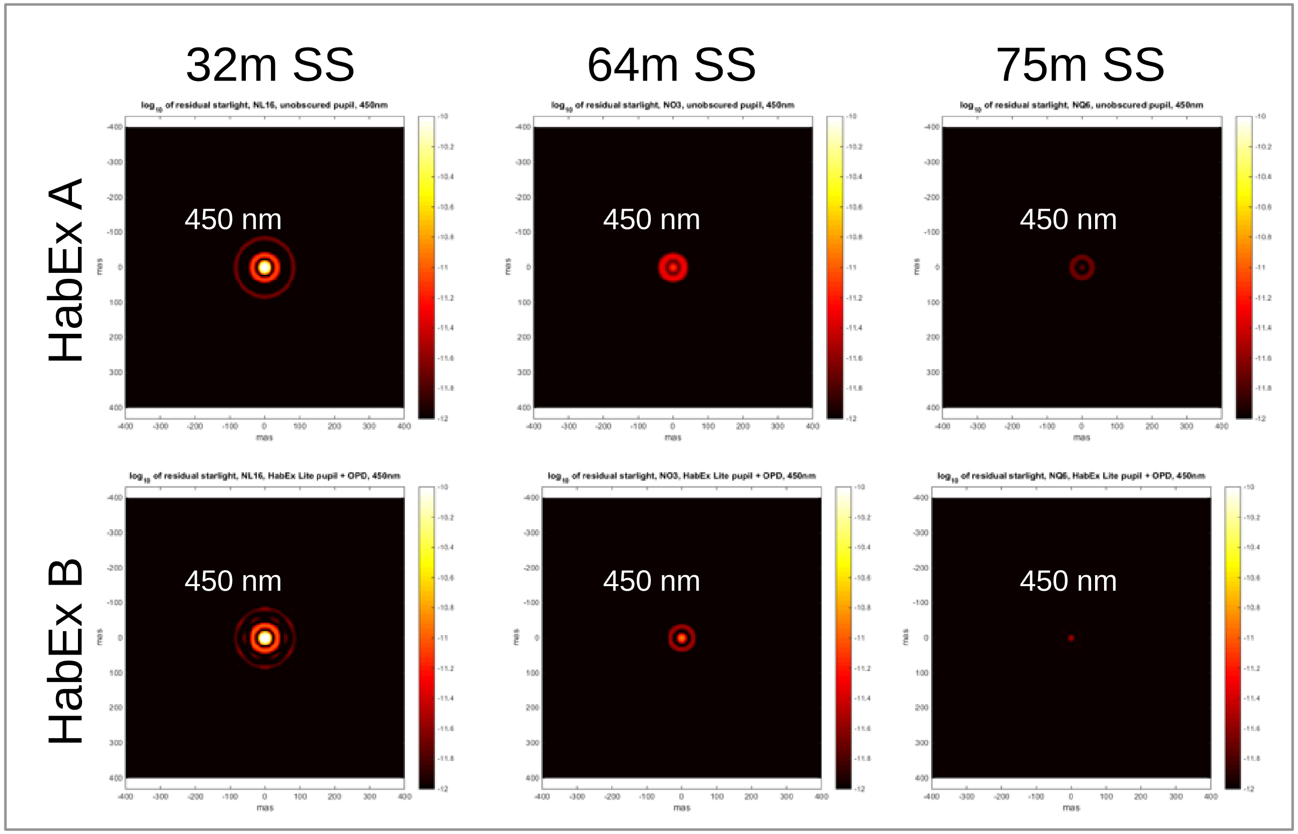
Laser Truss combines gauges to measure 6DOF alignment of all optics wrt corner cubes on the SM



- MET is baselined for HabEx A and B
- Uses technology originally developed for Space Interferometry Mission and LISA
- Requires:
  - Laser frequency stability to <1 MHz
  - Temperature control of all optical elements to <0.2C
  - RBA precision <5 nm

HabEx B Starshade Performance

- Segmented HabEx B Starshade contrast is essentially the same as for the unobscured HabEx A; throughput is reduced by <10%
- Inner Working Angle (IWA), contrast and throughput all meet HabEx goals
- No Outer Working Angle (OWA)
- Full Starshade bandpass is available for all observations



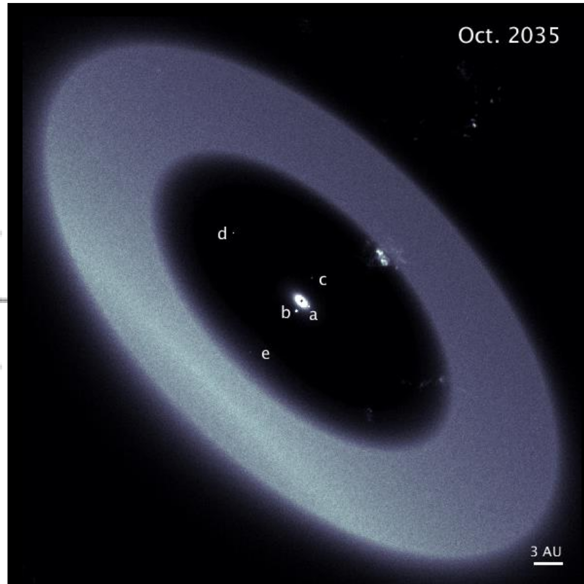
Imaging an exoEarth Candidate

HabEx Starshade

Name	RM12	*preliminary*
Diameter	72m	52m
Petal Length	16m	16m
Minimum F	10	8.8

Bandpass	150-500nm	150-500nm
IWA	30mas	35mas
Distance	251,519 km	153,200 km

Bandpass	300-1000nm	300-1000nm
IWA	60mas	70mas
Distance	125,760 km	76,600 km



- HabEx Interim Report Starshade is 72 m
  - F = 10 design, with 16 m petals
  - Broadband: λ = 300-1000 nm
- Alternate Starshade designs are currently under study
  - IWA = 60 to 70mas
  - Diameter = 52 to 59 m
  - Distance = 76,600 to 101,400 km for **λ** = 300-1,000 nm
- Knowing where to look would improve efficiency
  - Precursor RV surveys may identify target systems in advance, boosting Starshade-only exoEarth yield

- A solar system analog as seen from 5 pc by HabEx + Starshade
  (a) an exoEarth
  (b) a sub-Neptune
  (c) Jupiter, (d) Saturn, (e) Neptune
- Inner dust belt (3x zodiacal dust within 1 AU)
- Outer dust belt (3x Kuiper belt extending 22 to 33 AU)
- FoV = 12x12 arcsec

Credit: S. Hildebrandt

Conclusions

- HabEx B provides a simpler, lighter, lower cost approach to the HabEx mission
- HabEx B addresses all HabEx Observatory Science goals for the UV Spectrograph and Workhorse Camera
- HabEx B retains the full power of Starshade observations – broad-band, high throughput imaging over a full 12-by-12 arcsec field, and high-throughput, full bandwidth spectroscopy – but does not have the search efficiency provided by the HabEx A coronagraph
- HabEx B productivity would benefit from precursor RV observations that are sensitive enough to detect candidate exoEarths
- The HabEx STDT will assess the Starshade-only overall observing strategy and science yield for the HabEx final report

HabEx Presentations & Posters

Title	Presenter	Date • Time
HabEx Ultraviolet spectrograph design and DRM	Paul A. Scowen	10 June 2018 • 10:00 - 10:20 AM
The habitable exoplanet imaging mission (HabEx): science goals and projected capabilities	Scott B. Gaudi	11 June 2018 • 10:30 - 10:55 AM
Solid state detectors for the Habitable Exoplanet imaging mission (HabEx) and the large UV/optical/infrared (LUVOIR) surveyor mission concepts	Shouleh Nikzad	10 June 2018 • 11:10 - 11:30 AM
The habitable exoplanet imaging mission (HabEx)	Bertrand Mennesson	11 June 2018 • 1:20 - 1:40 PM
Overview of the 4m baseline architecture concept of the habitable exoplanet imaging mission (HabEx) study	Gary M. Kuan	11 June 2018 • 1:40 - 2:00 PM
The HabEx workhorse camera	Paul A. Scowen	11 June 2018 • 2:00 - 2:20 PM
Technology maturity for the habitable-zone exoplanet imaging mission (HabEx) concept	Rhonda M. Morgan	11 June 2018 • 2:20 - 2:40 PM
HabEx Space telescope exoplanet instruments	Stefan R. Martin	11 June 2018 • 2:40 - 3:00 PM
HabEx: high precision pointing architecture using micro-thrusters and fine steering mirror	Oscar S. Alvarez-Salazar	11 June 2018 • 3:30 - 3:50 PM
Numerically optimized coronagraph designs for the habitable exoplanet imaging mission (HabEx)	A J Eldorado Riggs	11 June 2018 • 3:50 - 4:10 PM
Overview and performance prediction of the baseline 4-meter telescope concept design for the habitable-zone exoplanet direct imaging mission	H. Philip Stahl	11 June 2018 • 4:10 - 4:30 PM
HabEx Lite: a starshade-only habitable exoplanet imager alternative	David Redding	11 June 2018 • 4:30 - 4:50 PM
Terrestrial exoplanet coronagraph image quality: study of polarization aberrations in Habex and LUVOIR update	James Breckinridge, Russell A. Chipman	13 June 2018 • 10:30 - 10:50 AM

Poster Title	Presenter	Date • Time
HabEx polarization ray trace and aberration analysis	Jeffrey Davis	11 June 2018 • 5:30 - 7:00 PM
HabEx space telescope optical system overview	Stefan R. Martin	11 June 2018 • 5:30 - 7:00 PM
HabEx telescope WFE stability specification derived from coronagraph starlight leakage	Bijan Nemati	11 June 2018 • 5:30 - 7:00 PM
Mirror design study for a segmented HabEx system	James T. Mooney	11 June 2018 • 5:30 - 7:00 PM
Overview and performance prediction fo the alternative 6.5-meter telescope concept design for the habitable-zone exoplanet direct imaging mission	H. Philip Stahl	11 June 2018 • 5:30 - 7:00 PM

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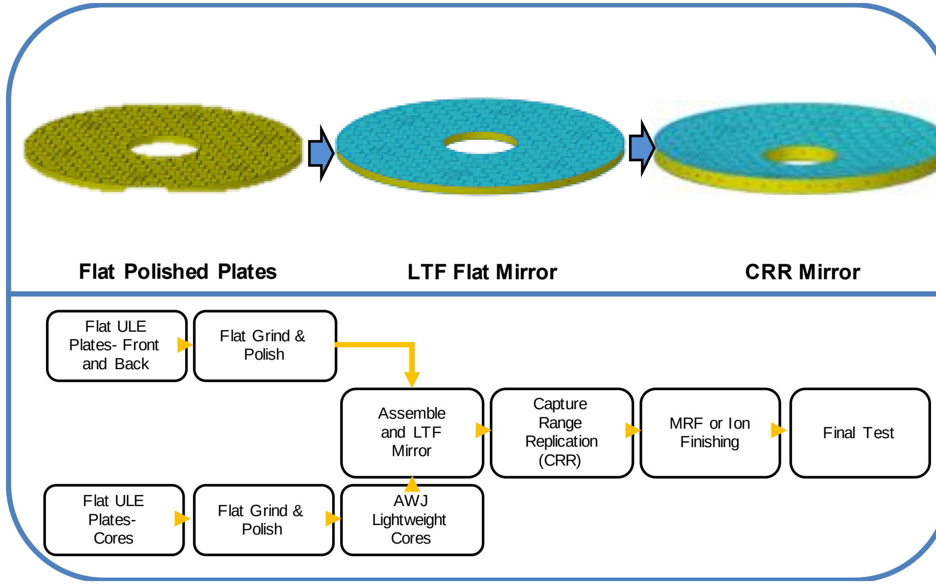
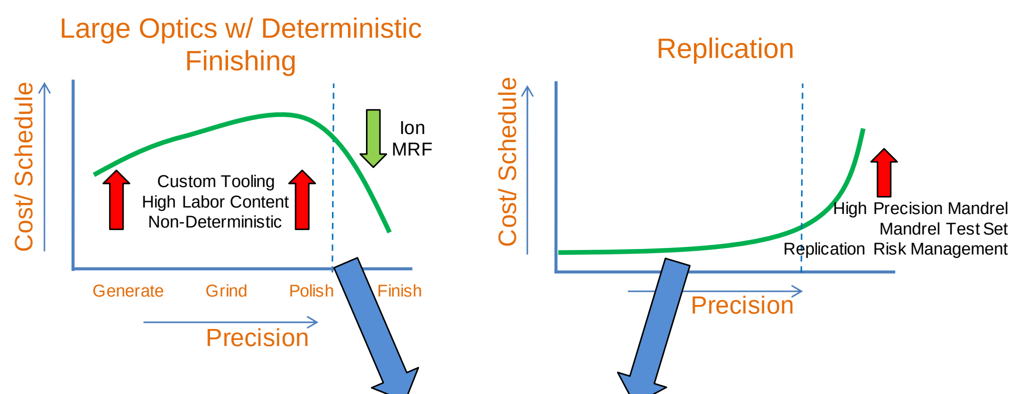
Harris Capture Range Replication

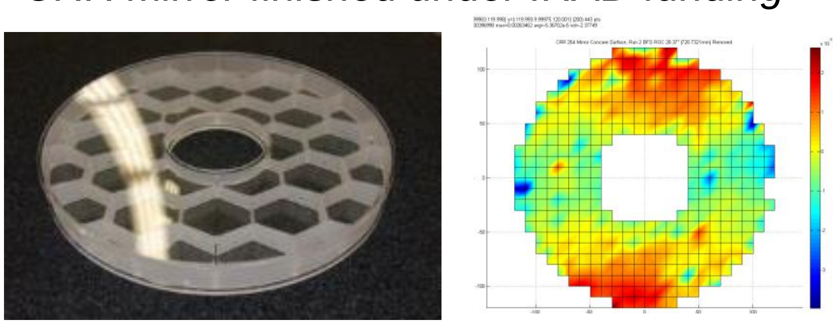
- Capture Range Replication uses precision mandrels and low-temperature slumping to replace traditional generate-grind-polish processes
- CRR finishes a mirror blank to within capture range for final finishing (MRF or Ion Beam)
- Result is a repeatable, efficient process for mirror fabrication, saving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





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

CRR mirror finished under IRAD funding



LC4M Primary Mirror Total Mass

- **The areal density of the mounted mirror assembly is expected to be 34.2 kg/m^2**
  - 44.4 kg/m^2 with 30% mass contingency
  - The mass includes all elements listed in the table
    - Mirrors, mounts and structures
    - Passive & active thermal controls
    - Electronics and cables
- **The least mature term in the mass budget is the reaction structure (backplane), which reflects the total mass of six MCS-like structures**

Mass is consistent with a system mass within existing launch vehicle capabilities

Total LC4M Mass (Six Mounted Petals)

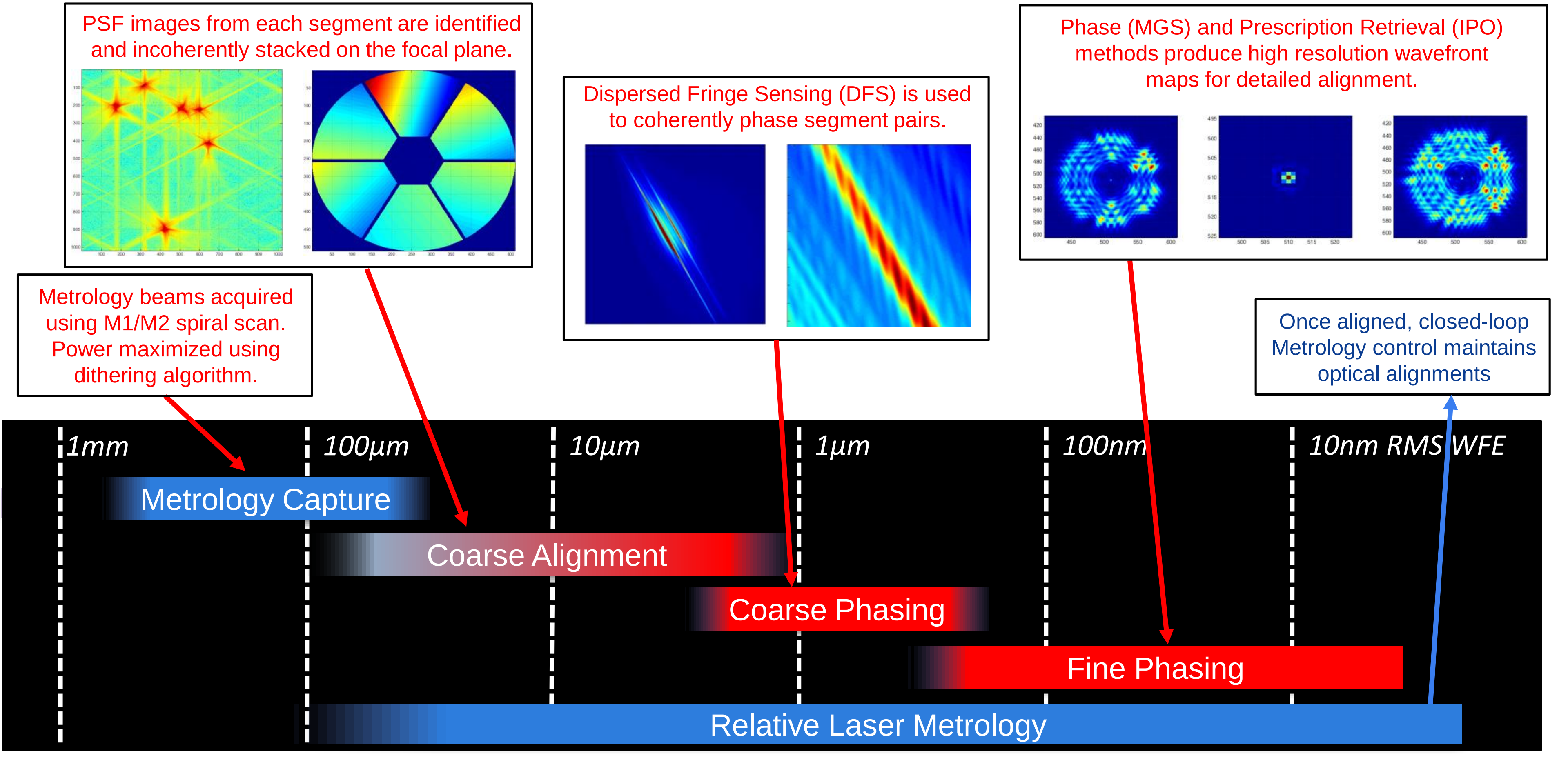
(No Mass Contingency)

Sub-Assembly	Mass (kg)
Glass	186
Mount Pads	43.2
Reaction Structure (Backplane)	49.2
Rigid Body Actuators (6 per mirror)	37.6
Surface Figure Actuators	25.2
Potting Cups	2.9
Beam Launchers	5.4
Electronics	23
Cabling	13
Flexures (6 per mirror)	0.7
Total PMA Mass (6 Petals)	**386.2**

Mounted Mirror Assembly Areal Density (kg/m^2) (No Mass Contingency)	**34.2**

Wavefront Sensing and Control (WFSC)

- Image-based sensing methods are used to align the telescope after launch and achieve initial, diffraction limited performance
- Uses methods developed and demonstrated for JWST and SIM

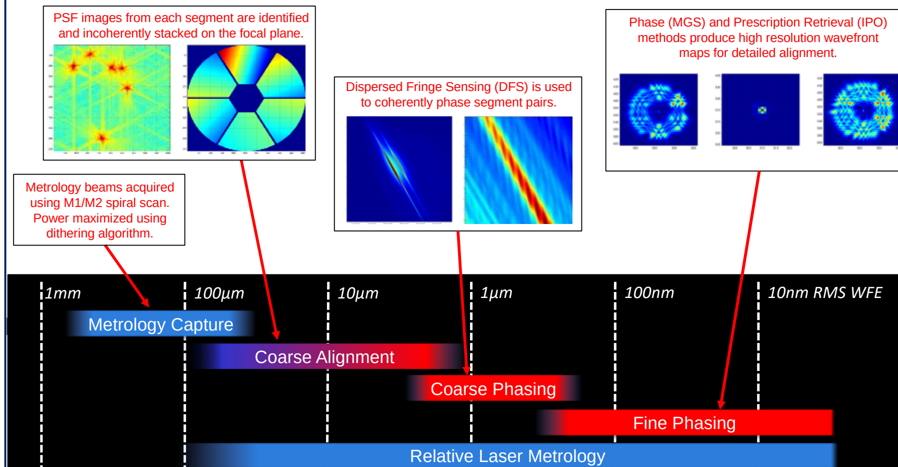


Wavefront Sensing and Control (WFSC)

- Wavefront Sensing and Control (WFSC) establishes exquisite optical quality after launch
- Laser Truss metrology (MET) preserves optical quality during all operations

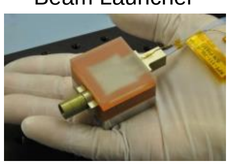
Commissioning and Initial Alignment

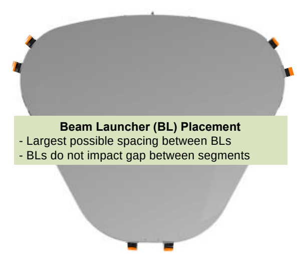
- Image-based sensing methods are used to align the telescope after launch and achieve initial, diffraction limited performance.
- Detailed commissioning timeline in development.

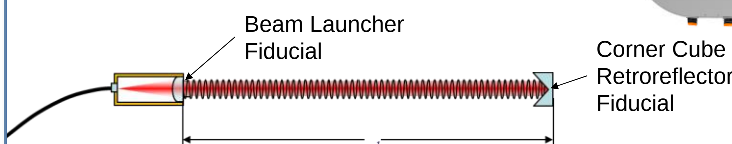


Laser Metrology Overview

Beam Launcher



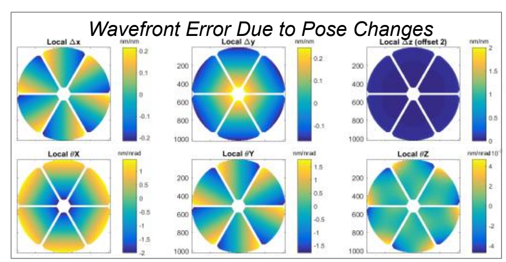


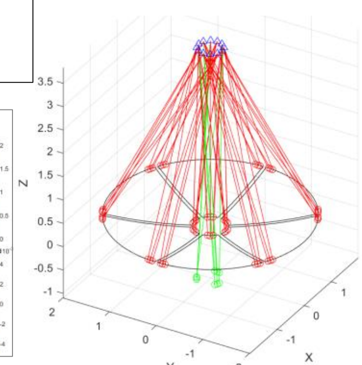


- A collimated beam from the Beam Launcher (BL) propagates through free space and to a corner cube, then back to the BL where it couples back into fiber optics.
- A portion of the beam is also reflected from the BL and coupled back into the optic fiber.
- A heterodyne technique is used to measure changes in the phase between the two paths.

Laser Metrology Truss

- 6 or 9 Laser gauges per optic
- Optic is referenced to the optic bench
- Excellent sensitivity in the optically significant degrees of freedom (θ_X, θ_Y, ΔZ)

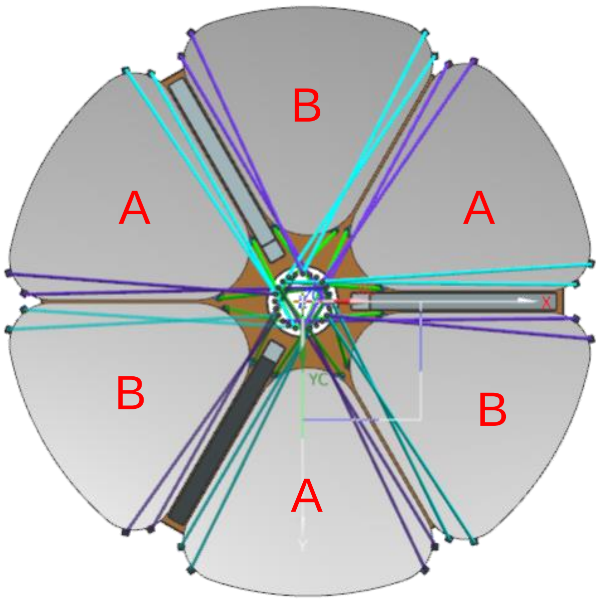


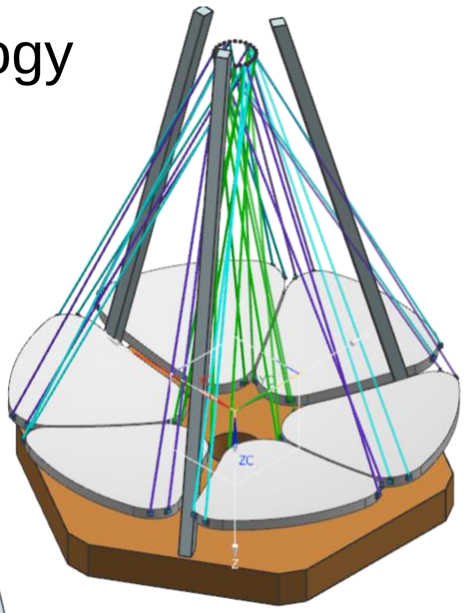


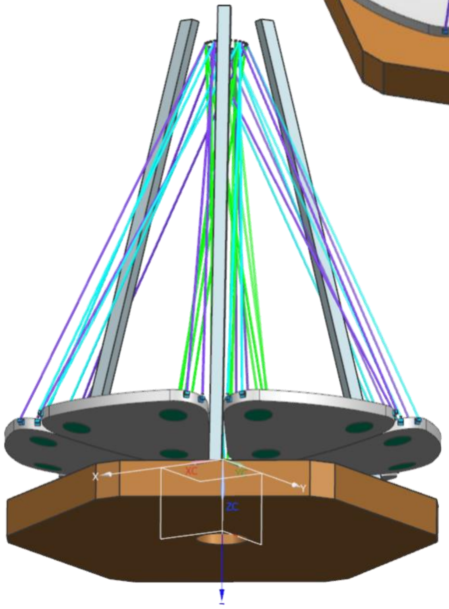
Pose Uncertainty per nm of laser gauge uncertainty (9BL Config)						
	ΔX	ΔY	ΔZ	θ_X	θ_Y	θ_Z
Segment (nm or nrad)	8.2	10.4	0.50	2.6	2.2	8.6
SM (nm or nrad)	8.8	9.1	0.33	2.1	1.8	30.6

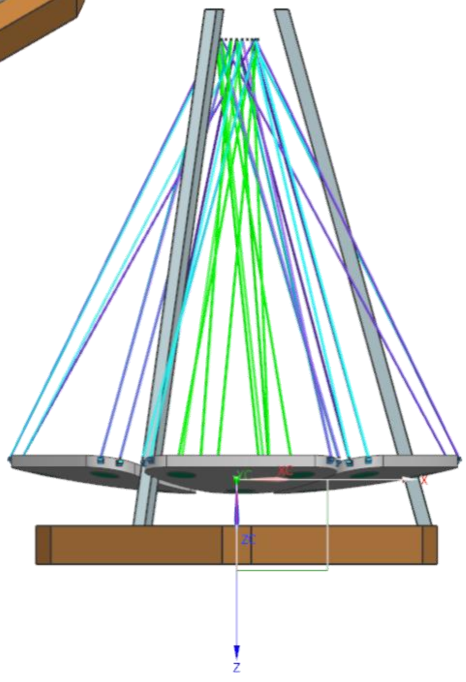
Preliminary Configuration

Secondary Mirror and Laser Metrology









- Metrology trusses for all six segments are symmetrical
- Total of 24 corner cubes
- 1 inch corner cube diameter
- 1 inch diameter of beam path