Technology Maturity for the HabEx Observatory Concept

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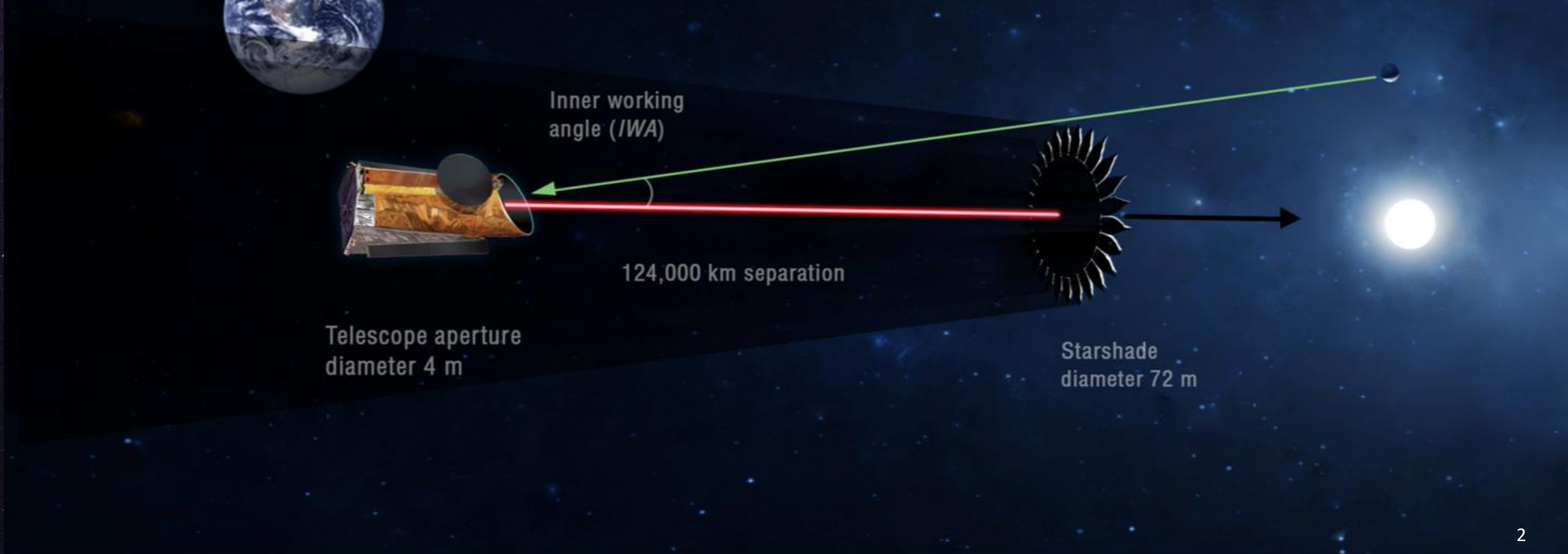
Technology Maturity

	Number of Gaps		
	TRL 3	TRL 4	TRL 5
Expected 2019	1	7	6
Expected 2023	0	3	11

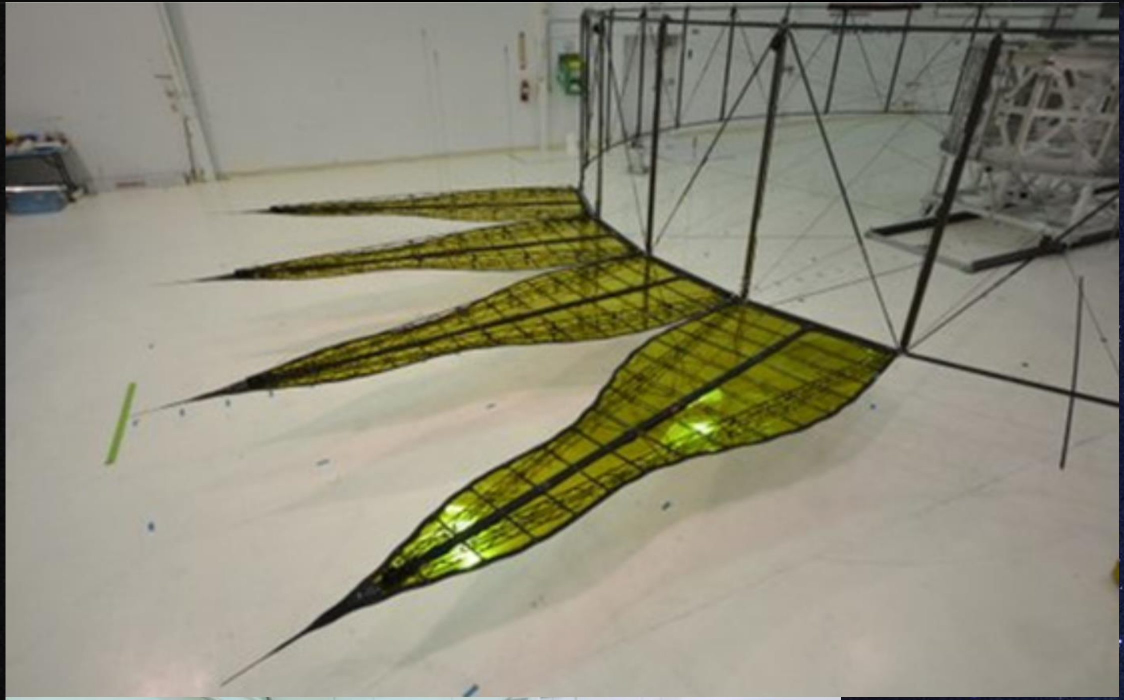


Starshade Deployment

Truss Deployment Test

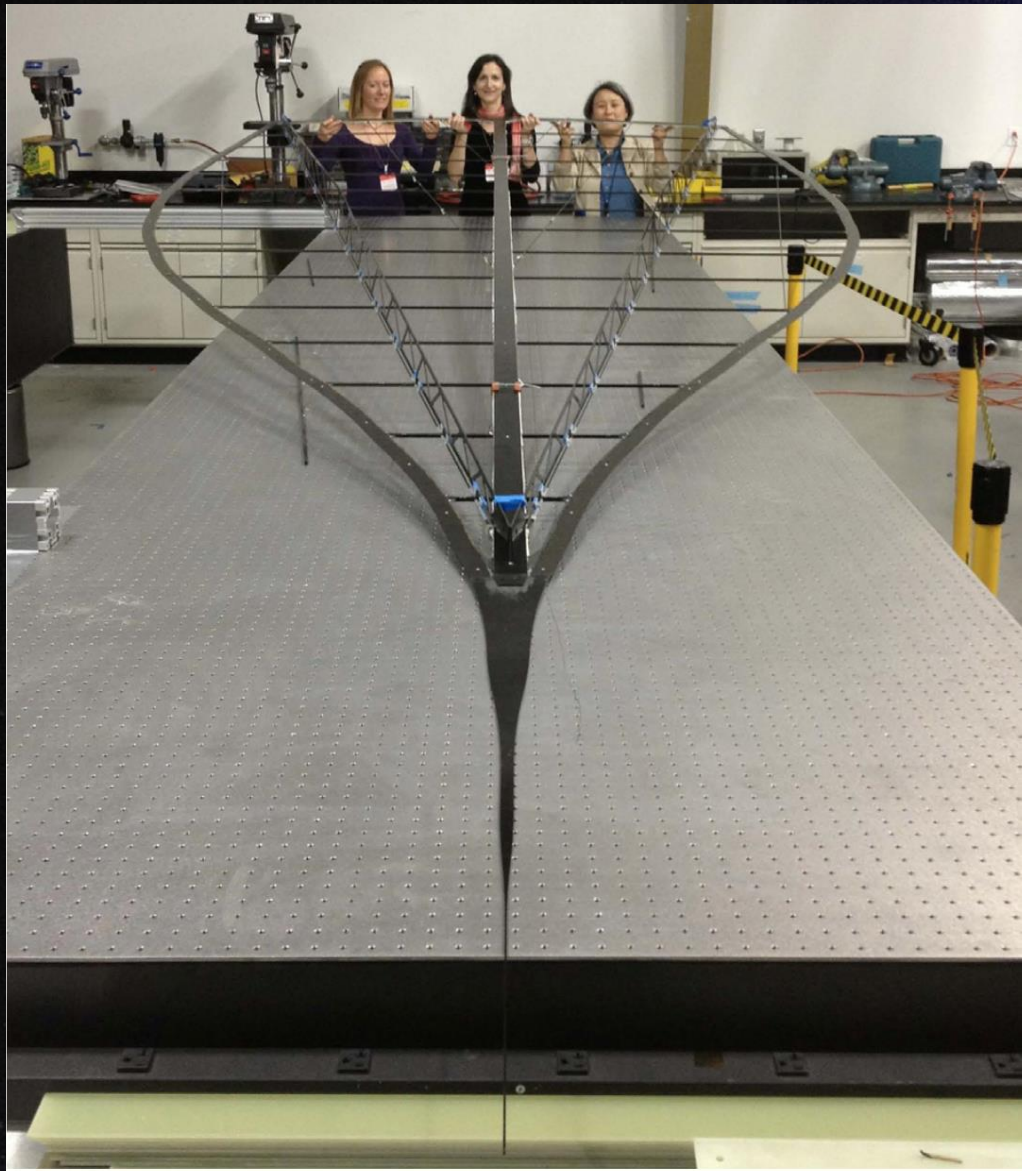
Petal deployment accuracy

- Starshade tolerances scale linearly
- SOA
  - 12 m flight-like truss
  - Petal deployment tolerance <0.15 mm
- Requirement for 20 m truss
  - +- 0.5 mm (3σ) bias
  - +- 1.5 mm (3σ) stability
  - In operational environment
- Path
  - S5 5m truss half-scale demo planned for 10 m truss
  - HabEx 52m starshade requires 10m half-scale demo truss



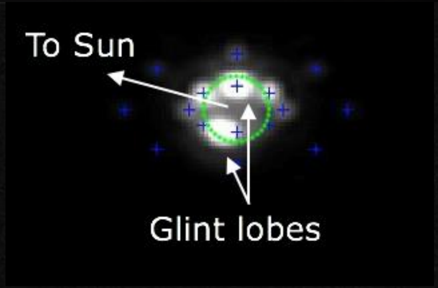
Petal shape and stability.

- SOA
  - 6m prototype petal manufactured to <100 um tolerance
- Requirement for 16m long, 2.6 m wide petal
  - Shape manufacture to +-115 um (3σ)
  - Deployed shape to < +- 230 um (3σ)
  - Stability (thermal)
    - Disk to petal strain < 30 ppm
    - 1-5 cycle petal width <20 ppm
- Path
  - S5 4 m long, 1.5 m demo petal for S5 applies to HabEx (stability driven by width)

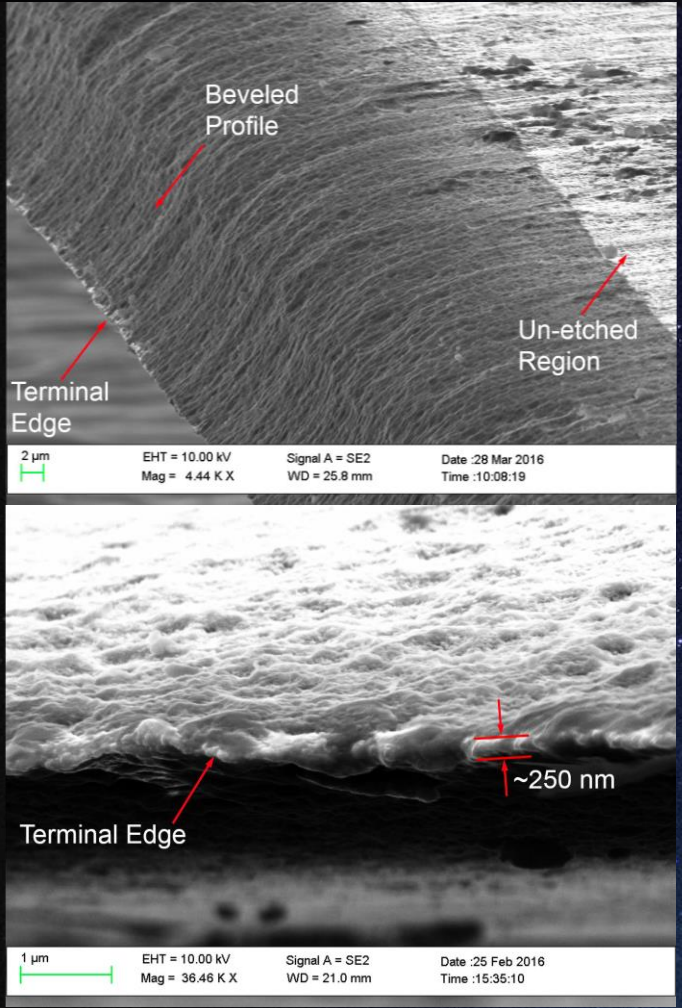


Solar Edge Scatter

- SOA
  - Metal edges (coupons)meet all specs but in-plane shape tolerance
- Requirement
  - Petal-edge in-plane shape tolerance 40 um
  - Solar glint at 25 Vmag in two main lobes
- Path
  - S5 to demonstrate performance at edge segment level
  - Sufficient demonstration for HabEx



Simulated Solar glint due to petal edges



SEM images of the beveled edge and terminal edge

Formation Sensing

- SOA
  - Out-of-band sensing of pupil plane images show structure in the low-contrast starshade shadow
  - Simulations show ample star flux for control loop and < 0.15 cm lateral displacement (0.01 pixel star positions)
- Requirements
  - Demonstrate sensing lateral errors to 0.20 m accuracy, =< 1 mas bearing angle
  - Demonstrate control algorithms to scaled lateral errors =< 1m
- Path
  - S5 testbed demonstration is sufficient for HabEx TRL5 certification expected Feb 2019

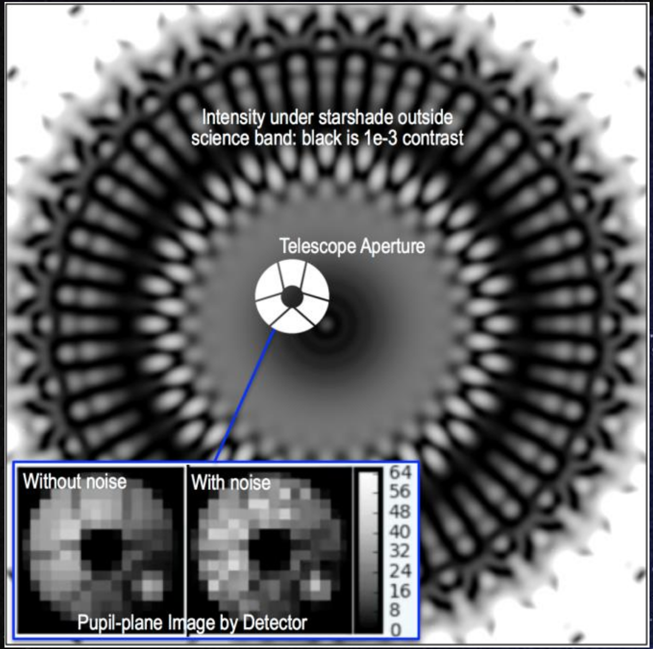
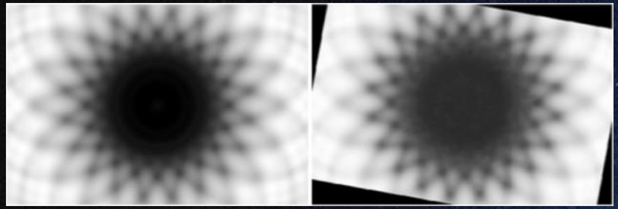


Illustration of lateral sensing using pupil-plane image matching



Preliminary results
Simulation Testbed

HabEx

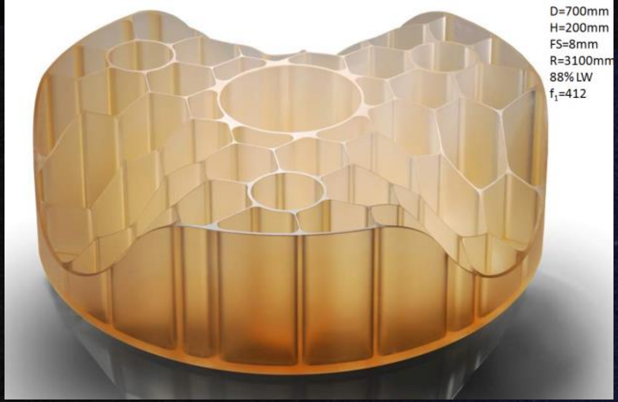
Optical Performance and Model Validation

- SOA
  - 6E-6 suppression in pupil plane at Fresnel No. 15, broadband
  - 6.6e-9 suppression in pupil plane, 4.3e-11 average contrast in focal plane at Fresnel No. 13, monochromatic
- Requirements
  - Experimentally validated models
    - with suppression <1E-8, F1.0 between 5 and 40 (broadband)
    - Traceable to 1E-10 contrast system performance
- Path
  - S5 testbed at Princeton expected TRL 5 2019 is sufficient for HabEx

S5’s starshade model validation testbed at Princeton.

Large Mirror Fabrication

- SLS allows for moderate lightweighting
- Microthrusters allow for low first frequency
- SOA
  - 4.2m DKIST primary mirror by Schott, UA (2nm surface roughness)
  - 4m ELT M2 by Schott
  - Zerodur CTE homogeneity 10 ppb/K
  - Lightweight cell 340 mm deep, 2mm wall
- Requirements
  - Wavefront thermal stability ~1 nm over 100s of seconds
  - First mode > 60 Hz
- Path
  - 4m demonstrator for TRL 5



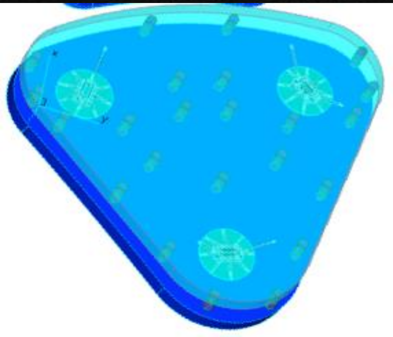
SCHOTT 700 mm diameter and 200 mm high Zerodur® with 2 mm machined walls, and contouring of the back.

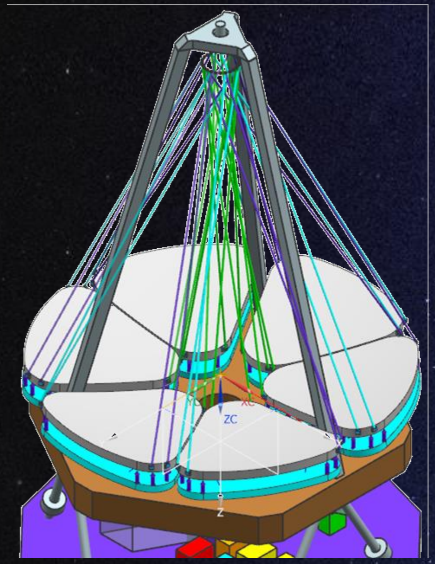
4.2 m Daniel K. Inouye Solar Telescope primary mirror

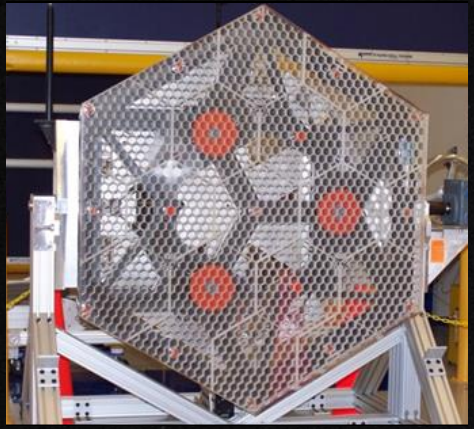
HabEx

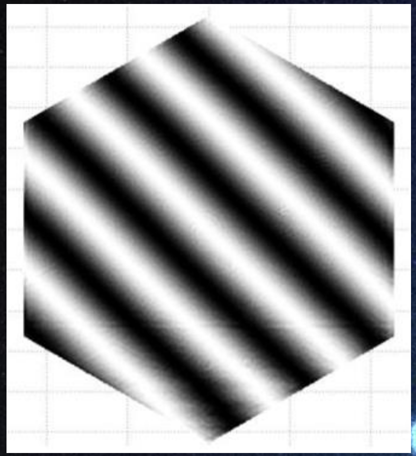
3.2m Starshade Only option

- Starshade only option requires looser WFE
- SOA
  - ULE demonstrator mirror
    - low mass: 10 kg/m2
    - 15 nm RMS WFE stand-alone, with backouts
    - 8 nm WFE RMS post-actuation predicted
- Requirements
  - 34 kg/m2 CBE for Falcon H or Delta IV H
  - 18 nm RMS WFE primary mirror, 10 nm RMS stability
- Enhancing developments:
  - Reduce ROC-matching errors
  - Improve 0-g figure prediction
  - 6DOF RB actuation from 1 nm to 10 cm without launch locks



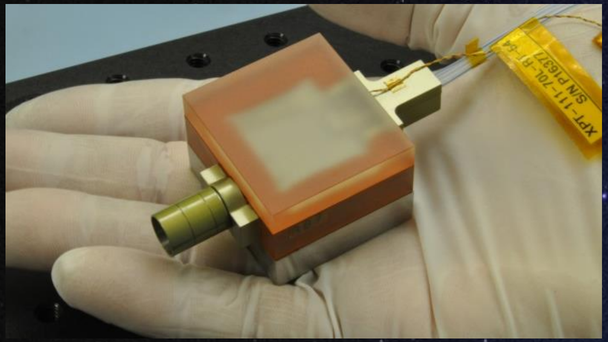






Laser Metrology

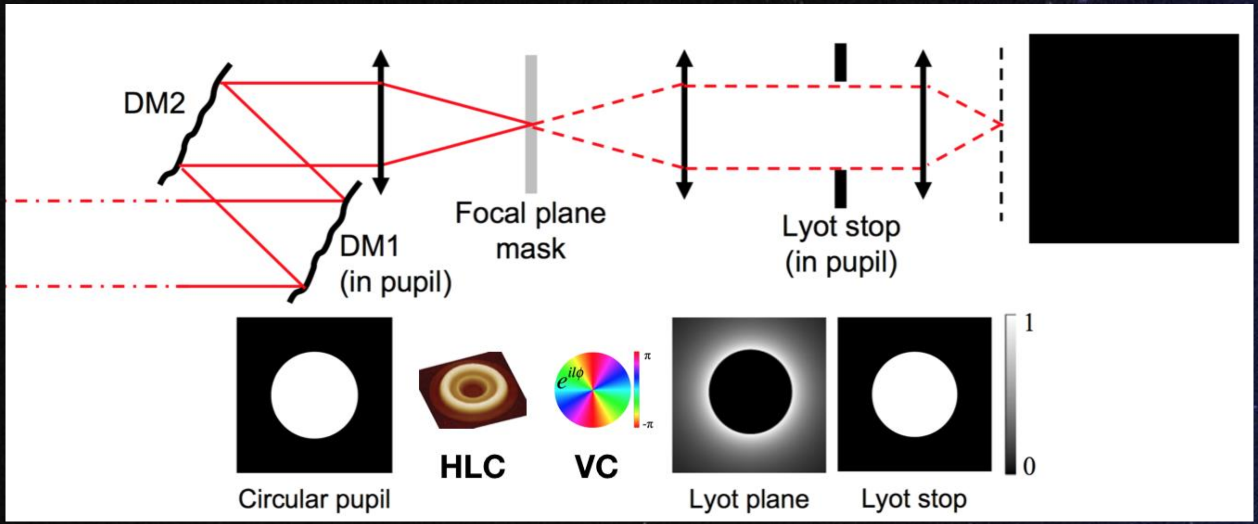
- SOA
  - Laser: Nd:YAG ring laser and modulator on LISA Pathfinder, Grace Follow-On
  - Thermally stabilized Planar Lightwave Circuit fully tested
- Requirements
  - Sense at 1 kHz BW
  - Uncorrelated per gauge error of 0.1nm
- Path
  - At TRL 5 for HabEx



PLC beam launcher

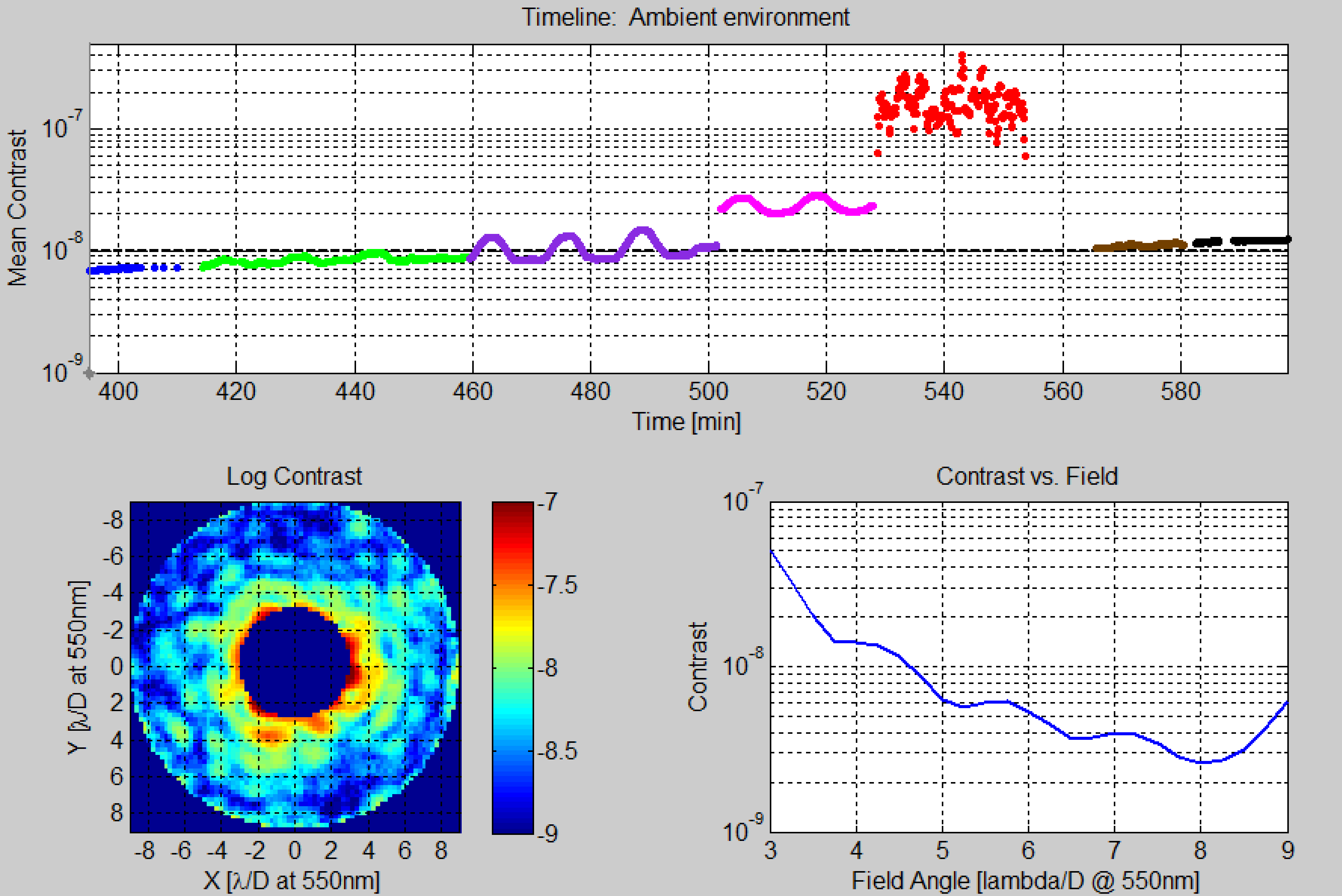
Coronagraph Architecture

- Requires 10^{-10} raw contrast from 2.4 to 32 λ/D for 20% bandwidth
- SOA
  - VVC 5E-10 monochromatic,
    - 3-8 l/D, 2-7 λ/D
    - 1E-8 10% BW
  - HLC linear mask
    - 6E-10, 10% BW, 3-16 λ/D
- Requirement
  - 1E-10 raw contrast, 20% BW,
  - 1E-11 contrast stability
  - IWA = 2.4 λ/D
  - Coronagraph throughput >= 10%
  - Dual polarization operation
- Path
  - ExEP Decadal Studies Testbed seeks to show 1E-10 raw contrast with VVC in static environment by 2019



The ExEP Decadal Studies Testbed (DST) strives to achieve 10^{-10} raw contrast for an unobscured aperture.

LOWFS/C



- Low Order Wavefront Sensing and Control (LOWFS/C) WFIRST testbed
  - Injected
    - 14 mas tip/tilt drift + CBE jitter 600 rpm wheel speed
    - +/- 0.5 nm focus sinusoid
  - Senses:
    - LoS tip/tilt to 0.2 mas
    - low order mode to 12 pm rms
- The HabEx jitter environment is much more benign due to microthrusters.
- **Path**
  - Demonstrate LOWFS/C in full coronagraph testbed with WFIRST CGI like progression

Microthrusters

- SOA
  - Colloidal (CMT): 5-30 uN thrust, 0.1 uN resolution
    - 100 days on ESA/NASA LISA Pathfinder
  - Cold Gas: 1mN max thrust, 0.1 uN resolution
    - 4 years on orbit operations on ESA Gaia
  - *May be on Euclid*
- Requirement
  - Thrust capability of 0.35 mN
  - Operating life of 5 years
- Path:
  - PCOS maturing TRL7 CMT to TRL6 for ESA-led LISA mission
  - Trade Colloidal with cold gas microthrusters
  - Trade: active isolation + RCS with monoprop + microthrusters

A single cluster of four Busek Co. CMTs integrated on the LISA Pathfinder Spacecraft just prior to launch.

HabEx

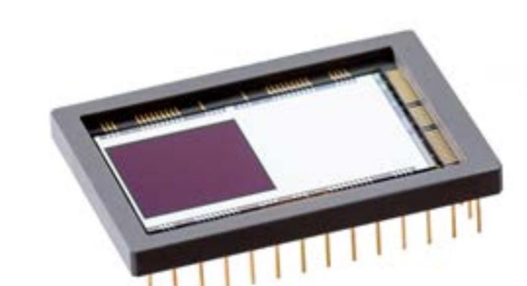
DMs and visible detectors

- Boston Micromachines Corp (BMC) Deformable Mirrors (DMs)
  - 0.4 mm pitch
  - Micro Electrical Mechanical System (MEMS)
  - 64 x 64 actuators (4096 actuators)
- Under test in the DST
- Environmental testing in progress (TDEM)
- Phase 2 SBIR to improve residual WFE

BMC 64x64 DM

Image courtesy BMC

- Visible detectors are EM-CCDs
  - CCD201: 1024 pixels for cameras
  - CCD282: 2048 pixels for coro. IFS
  - CCD282: 4096 pixels for Starshade IFS
- WFIRST-CGI lab results for dark current meet HabEx requirements
- WFIRST-CGI EMCCD requirements meet HabEx needs



E2v CCD201, 1024 pixels wide

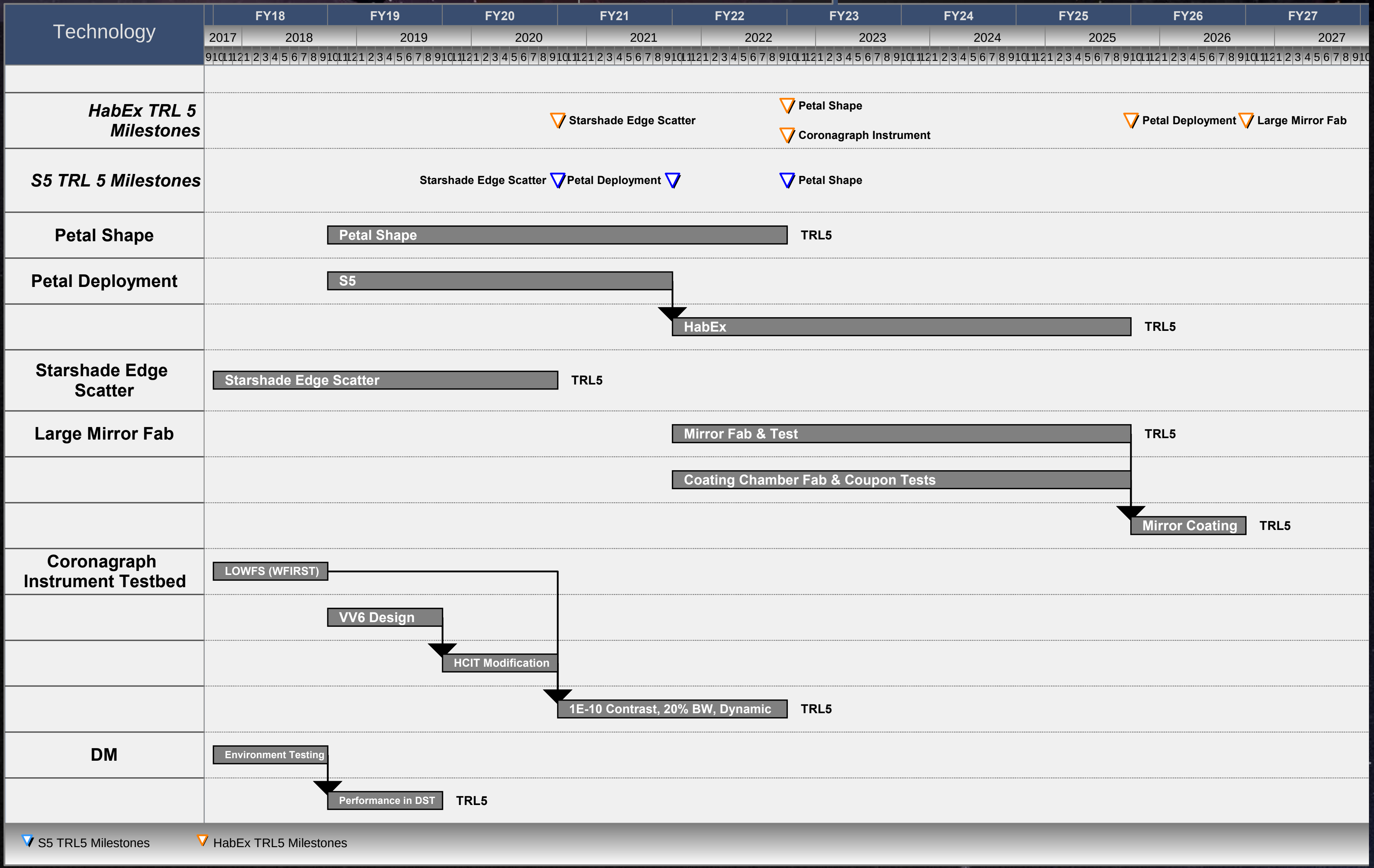
Image courtesy e2v

Enhancing Technologies

- UV Microchannel Plate Detector
- SOA (TRL 4)
  - dark current ≤0.1-1 counts/cm2/s with ALD borosilicate plates
  - QE 44% 115-180 nm with alkalai photocathode
- Requirement
  - Dark current <0.001 e-/pix/s [173.6 counts/cm$_2$/s]
- Path
  - Components integrated into single MCP
  - Adopt if mature in time

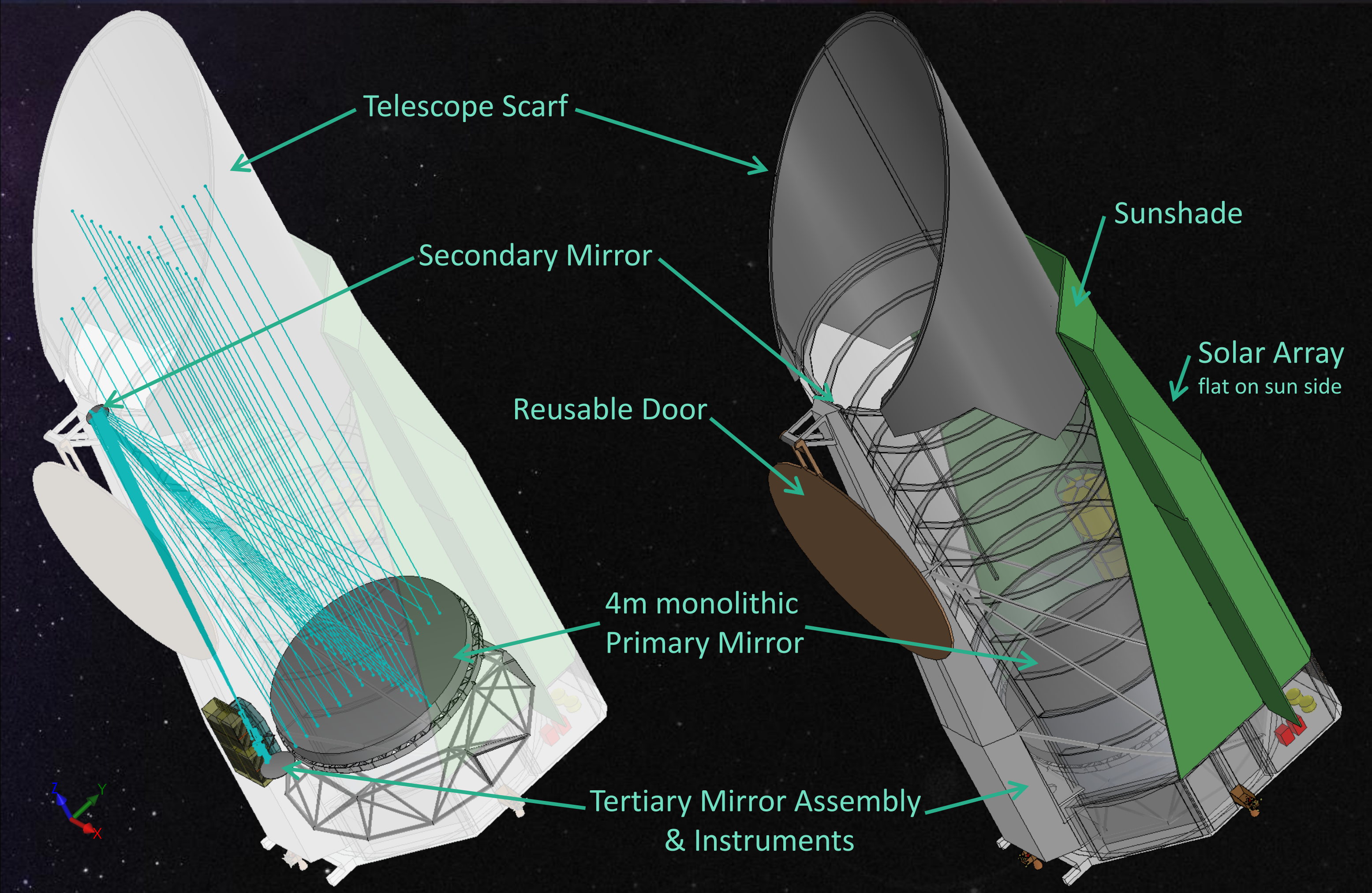
- Far-UV Enhanced coatings for 100 nm cutoff
- SOA (TRL 3)
  - Al+LiF+AlF3 proof of concept show 3 year stability
- Requirement
  - Operational life >10 years
- Path
  - Adopt if mature in time

HabEx Maturation Timeline



BACKUP

Baseline Architecture

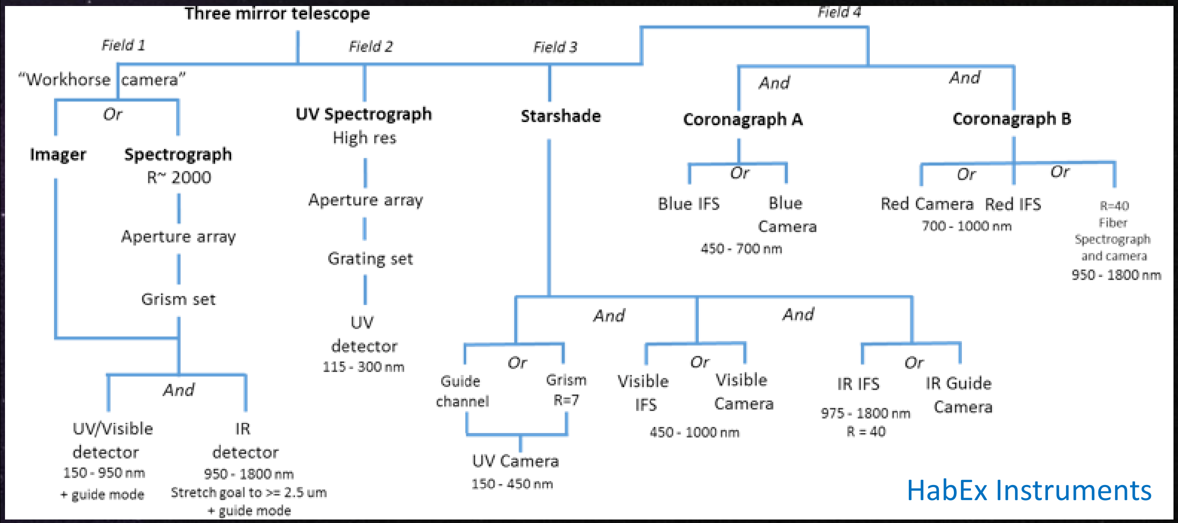


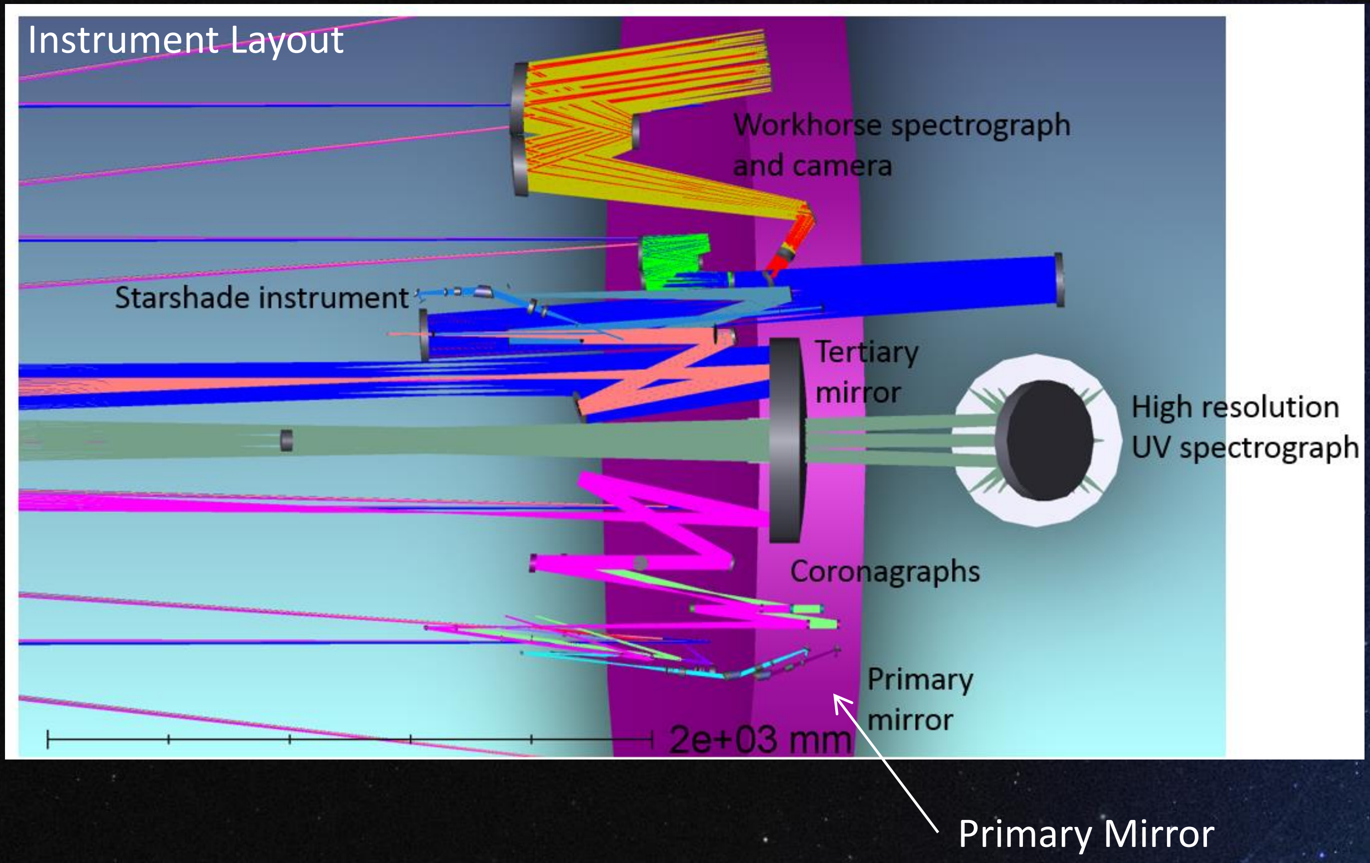
Habitable Exoplanet Imaging Mission	
Mission Duration:	5 years
Orbit:	Earth-Sun L2 Halo orbit
Aperture:	4-meter unobscured
Telescope Architecture:	off-axis, Three Mirror Anastigmat (TMA)
Primary Mirror:	f-number: f/2.5 construction: monolith reflective coating: Al+MgF2
Wavelengths:	115nm – 2500nm (UV, Vis, NIR)
Instruments:	- Coronagraph - Starshade Camera + Starshade Occulter - High-Resolution UV Spectrograph - Multi-purpose, Wide-field Camera & Spectrograph
Starshade	72-meter diameter starshade occulter
Attitude Control System (ACS):	- Fine-Guiding Sensor Instrument - biprop thrusters (slewing) - microthrusters (pointing)
Formation Flying Control System:	- position sensor - local communications
Communications:	phased-array antenna
Serviceability:	- instruments (4) - thrusters - avionics - communications - refueling: telescope + starshade

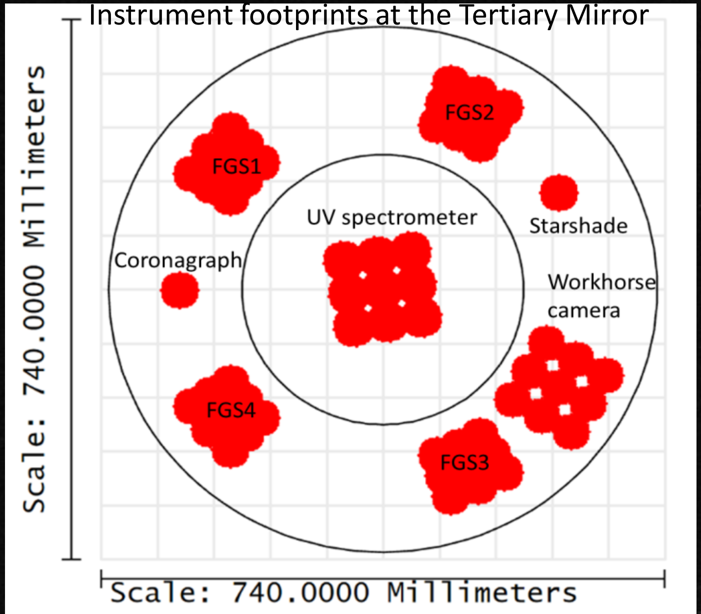
WED 5:30 pm, 246.38. HabEx Optical Telescope Concepts: Design and Performance Analysis *H. P. Stahl*

The 4m monolithic primary TRL of 4 is enabled by microthrusters and the SLS lift capacity

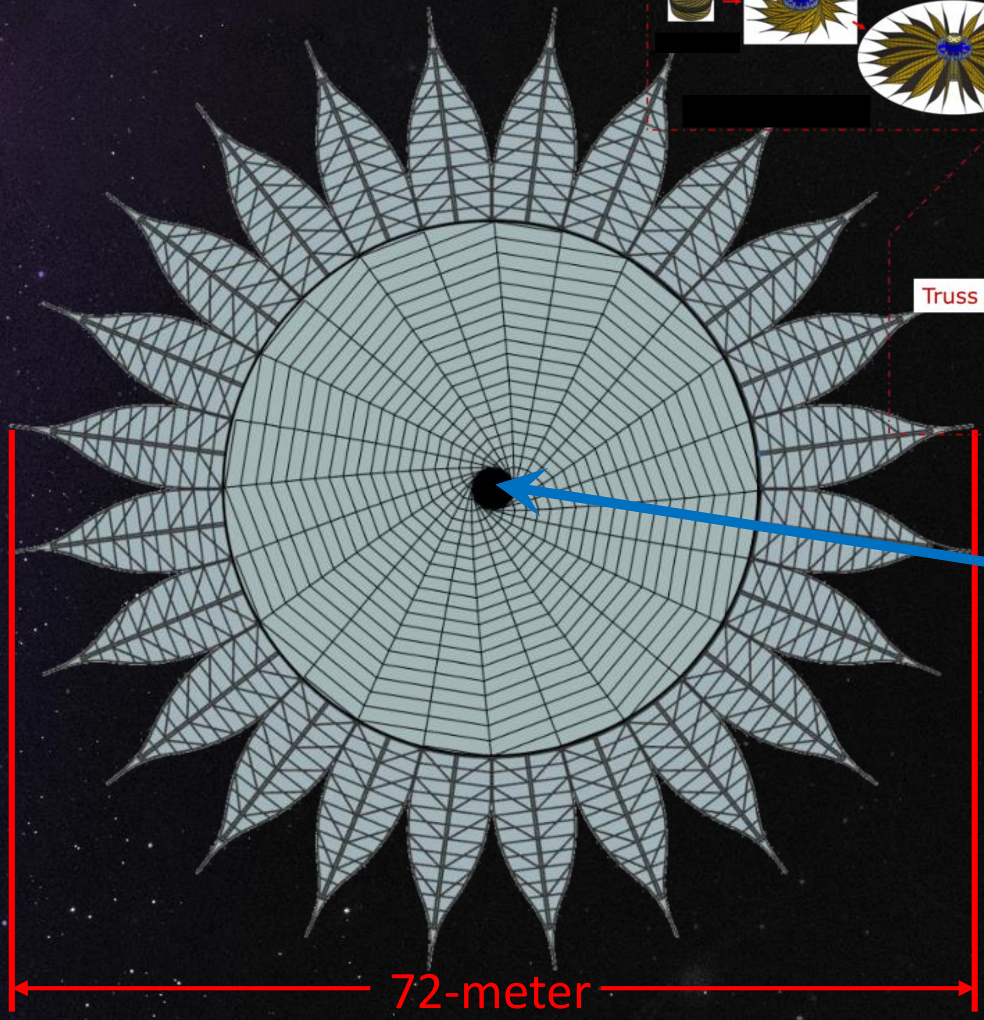
Baseline Instruments

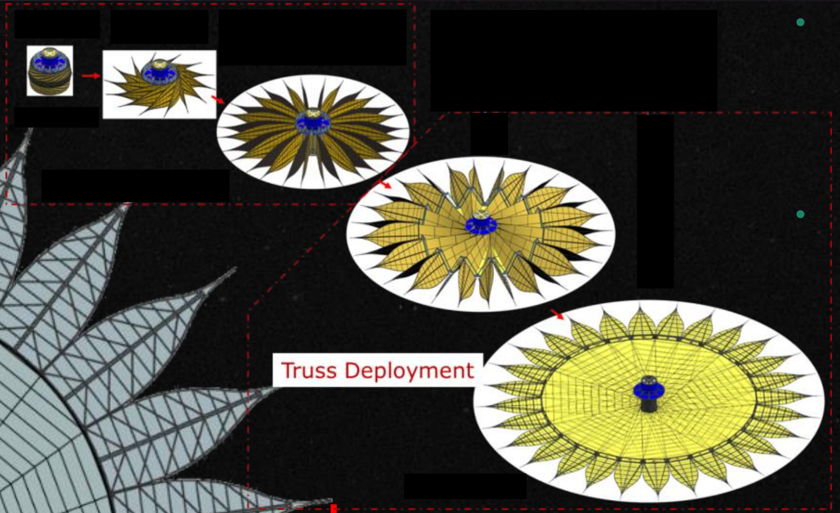




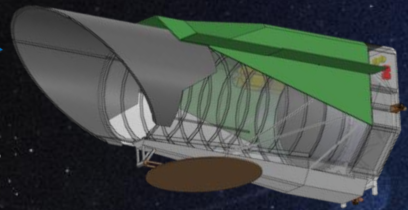


Starshade





124,000km



- **Propulsion (Occulter)**
  - Solar Electric Propulsion (SEP) with Hermes Hall effect thrusters for slewing (repositioning)
  - Biprop thrusters for attitude control
  - >100 targets / 5yrs
- **Observing**
  - ≤10^{-10} Suppression
  - 40 – 83 degree sun-angles
  - 450 – 1000nm wavelengths at **nominal** separation
    - IWA = 62 mas
    - IFS, R = 140
  - 150– 300nm wavelengths at farther distance
    - IWA = 28 mas
    - Grism, R = 7
  - 1000 – 1800nm at closer distance
    - IWA = 111 mas
    - Slit spectrograph, R = 140
  - OWA = 1.9 arcsec

Technology Maturity

- The Starshade to TRL 5 (S-5) project is maturing 5 starshade technology gaps to TRL 5: 3 by the end of 2019 and 2 by 2021
- S-5 demonstration on a 26 m starshade achieves HabEx requirements on HabEx 72 m starshade because requirements scale by angle to starshade.

HabEx

Workhorse camera, UVS

Workhorse Camera Instrument	
Purpose:	Multi-purpose, wide-field imaging camera and spectrograph for general astrophysics
Waveband:	
• UV:	• 150nm – 400nm
• Vis:	• 400nm – 950nm
• NIR:	• 950nm - 1800nm (2500nm goal)
Telescope Diffraction Limit:	400nm
Field-of-view:	3 arcmin x 3 arcmin
Spectral Resolution:	R = 2000
Detector:	
• UV/Vis:	• 3x3 CCD203 12288x12288 pixels
• NIR:	• 2x2 H4RG10 8192x8192 pixels
Multi-Object Spectroscopy (MOS) capable	Micro-shutter array, 2x2 array 200x100 um 171x365 apertures

UV Spectrograph Instrument	
Purpose:	High resolution, UV spectroscopy for general astrophysics
Waveband: • Spectroscopy:	115nm – 360nm (20 bands)
Telescope Diffraction Limit:	400nm
Field-of-view:	3 arcmin x 3 arcmin
Spectral Resolution:	R = 500 – 60,000 (band dependent)
Detector	• 6x6 MCP array, 100mm sq each • 60000x60000 pixels
Multi-Object Spectroscopy (MOS) capable	Micro-shutter array, 2x2 array 200x100 um 171x365 apertures

- UV requirements are met by the state of the art.
- UV Performance can be enhanced by advancements in UV coatings and detectors