Jet Propulsion Laboratory
California Institute of Technology

HabEx Design Status

STDT Meeting #4, Boston, April 19-21, 2017

Gary M Kuan

HabEx Design Team*

JPL, MSFC, NGAS, GSFC

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- Amy Trangsrud
- Luis Marchen
- John Krist
- Mayer “Mike” Rud
- Bijan Nemati (JPL/UAH/MSFC)
- ”Bala” Balasubramanian

*from JPL unless otherwise indicated

Assumed Design Parameters

Based on Architecture #3

- Includes:
  - Off-axis telescope design (unobscured pupil)
  - 4-meter diameter monolithic Primary Mirror, f/2.5
  - Telescope operating temperature: ~270K (to avoid contamination)
  - Coronagraph Instrument(s)
    - 400-1000nm waveband w/Visible ultra-low noise detector
    - 1000-1800nm waveband w/NIR low noise detector
    - Hybrid Lyot Coronagraph (HLC)
    - Vector Vortex Coronagraph (VV6 or VV8)
  - Starshade Instrument
    - 300-1000nm waveband (baseline) w/Visible ultra-low noise detector
    - 200-400nm waveband (goal) w/UV detector
    - 1000-1800nm waveband (goal) w/IR detector
  - General Astrophysics Workhorse Camera + Spectrograph
    - 3x3 arcminute field-of-view
    - 200-2000nm waveband
    - Multi-object spectroscopy
  - General Astrophysics UV Spectrograph
    - 120-1000nm waveband
  - 72-meter diameter class Starshade

Tasks Completed or In Progress to Date

- Selected f# of Primary Mirror (complete)
  - Based on initial optical coating and polarization crossterm analysis for a Coronagraph
- Optical design of instruments and optical layout (initial design complete)
  - Coronagraph
  - Starshade Imager
  - GA workhorse camera (3x3arcmin FOV)
  - GA UV spectrograph (narrow FOV)
- Primary Mirror design (substrate material, 120Hz first-mode design)
- Telescope design & model development (initial design complete; in progress)
- Observatory Design (in progress)
- Starshade error budget (in progress)
- HLC Coronagraph error budget (in progress)
- VV6 & VV8 Coronagraph error budget (in progress)
- Identified necessary specialized components (see next slide)
- Starshade design (JPL & Northrop-Grumman) (initial design complete)
- Starshade structural and thermal models (JPL) (in progress)
- Laser Metrology truss performance analysis (initial analysis in progress)
- Technology Working Groups: (in progress)

HabEx Specialized Components

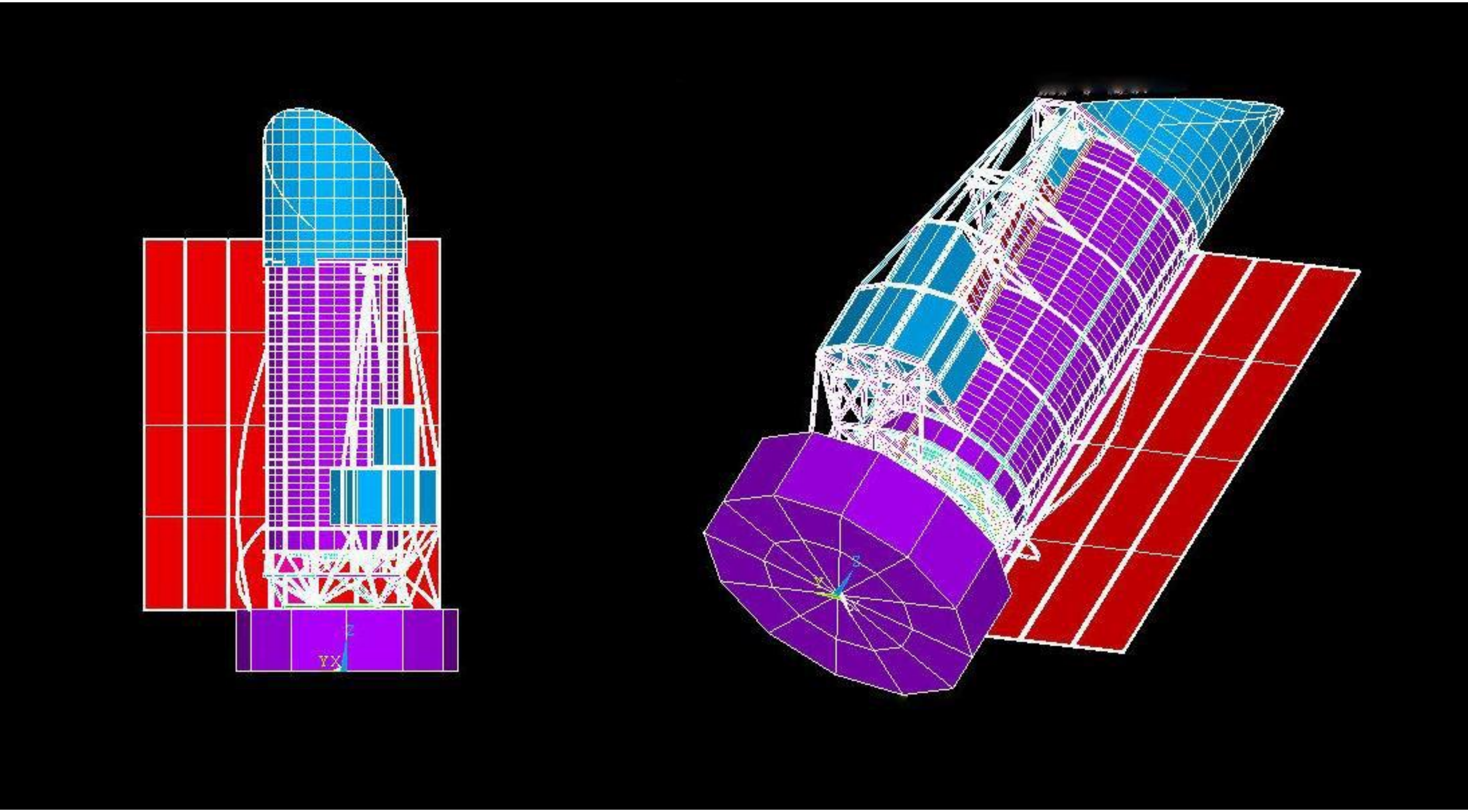
On Observatory (estimated TRL equivalent)*

- Monolithic 4m dia Primary Mirror
  - E-ELT M2, M3, M5, Schott 8m
- Actuated Secondary Mirror
- Laser Metrology Rigid Body Control Truss
  - ~TRL5, JPL AMD/MOST
- Active Spacecraft Isolation (otherwise passive isolation)
  - Harris, has flown
  - Lockheed Martin, ground demonstration
  - NGAS, ?
  - Honeywell D-struts passive isolation
- Micro-thrusters (otherwise reaction wheels)
  - Busek colloid thrusters, TRL7 on ST7 for Lisa Pathfinder
  - Cold gas thrusters, TRL9 on GAIA
  - Greater thrust capability may be required
- Wide field-of-view (FOV) Telescope (to accommodate all instruments)
- Off-axis telescope (to accommodate coronagraph)
- Vector Vortex Charge 8 Coronagraph
  - TRL3, lab demonstration planned for 2017
- Aluminum coating with MgF2 overcoat on Telescope
  - TRL9 on Hubble
- Deformable Mirrors (in coronagraph)
  - ~TRL4 on WFIRST
  - TRL6 by 2021 on WFIRST
- Ultra-low noise visible detectors
  - TRL6 by 2021 on WFIRST
- Fast/Fine Steering Mirror
  - TRL6 by 2021 on WFIRST
- Servicing hardware
  - Similar to WFIRST
- Micro-shutters (for workhorse camera)
  - TRL9 on JWST 2018

*TRL levels are based on the requirements for the particular application, and NOT for HabEx. Unless those requirements envelope the needs of HabEx, TRLs would drop.

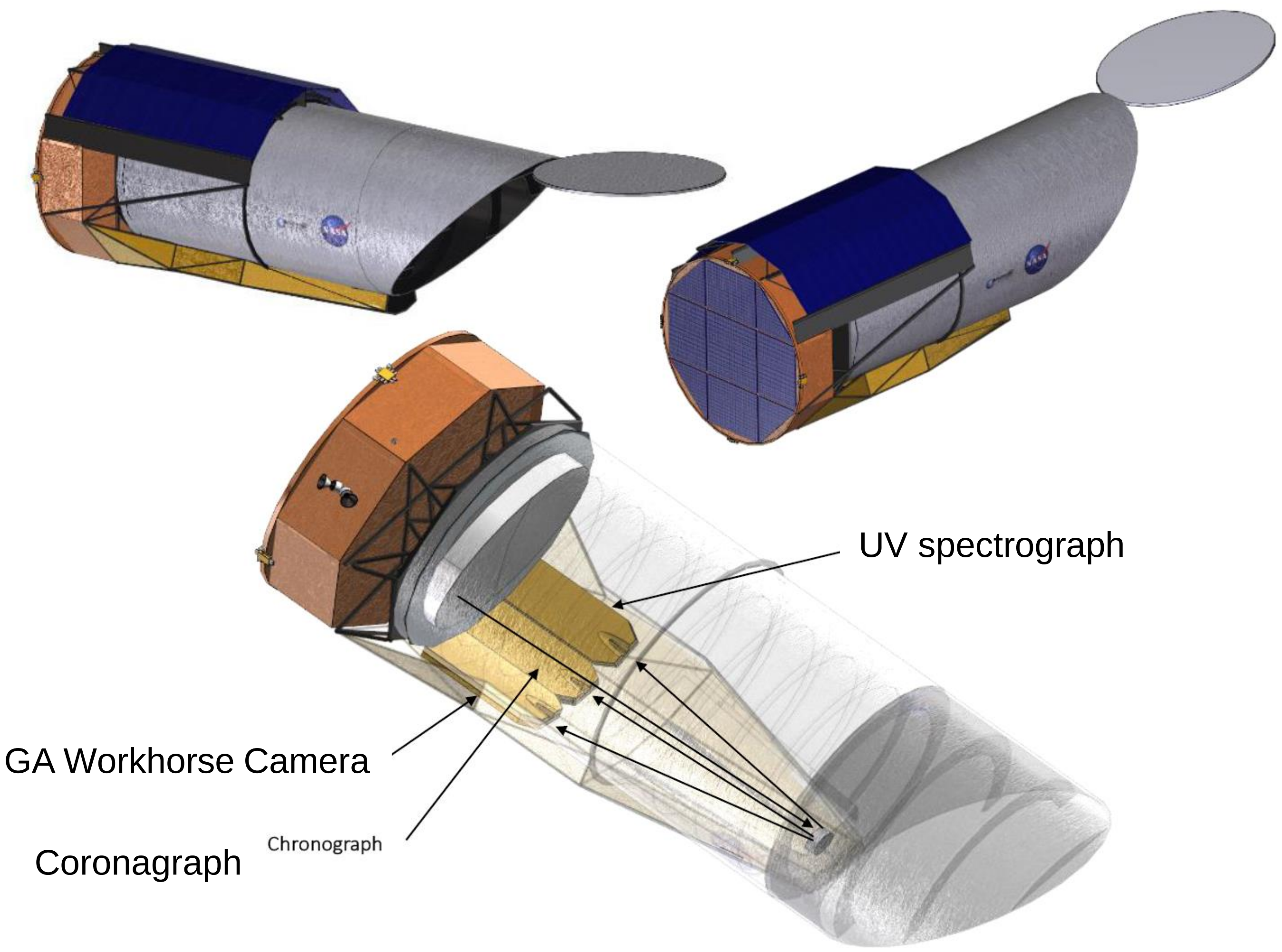
Observatory Configuration

Deployed Configuration (very preliminary)



Observatory Configuration

OTA and Instrument Bays (very preliminary)



Telescope Design and Trades

Phil Stahl, et al. at MSFC

- Primary mirror design trade studies
  - Mirror substrate, design, and stiffness
  - Mirror mounting methods

- Basic CAD layout (preliminary design)
  - Includes: Primary Mirror, Secondary Mirror, SM Support Structure, Primary Mirror Support Structure, Outer Barrel Assembly
- Finite element model (preliminary design)
- Thermal model (preliminary design)
- Primary Mirror Assembly (PMA) modal response analysis
- Secondary Mirror Support Structure (SMSS) response analysis
- Line-of-Sight (LOS) stability analysis
- Thermal stability analysis

- 6.5m diameter design layout (very preliminary)

Starshade Design

JPL and NGAS Designs

- Assumed design parameters:
  - 4m telescope aperture
  - 200nm – 1000nm waveband
  - 60mas Inner Working Angle (IWA)

- Both JPL and NGAS have examined 70+ meter diameter class starshades.
  - JPL has settled on a 72m diameter starshade
    - Tends to be shorter when stowed
  - NGAS has examined an 85m to ~95m diameter starshades (hypergaussian with long tips)
    - Tends to be taller when stowed

JPL Starshade Design

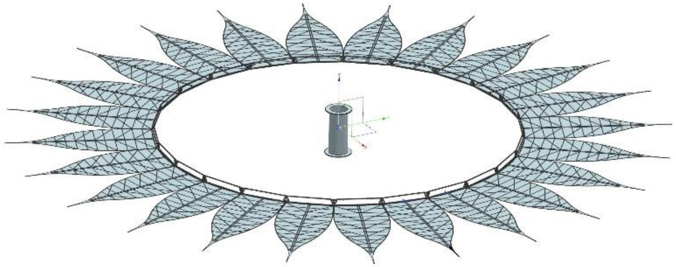
HabEx 72m Starshade Mechanical Configuration Options

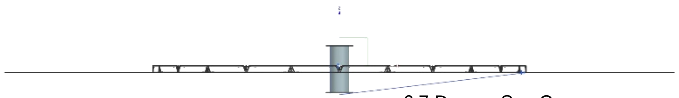
- JPL Mechanical Configuration is driven by many factors
  - Stowed Considerations
    - Launch vehicle fairing fit
      - (truss stow dia, optical shield & petal wrap annuli)
  - On-Orbit Considerations
    - Relative petal length/truss diameter
      - (it is easier to produce a stiff inner disk than petal, however longer petal = better optical performance)
    - Petal length to width ratio (long skinny petals are harder to control in-plane petal shape, however fewer petals = wider truss nodes & more difficult to achieve petal placement precision)
- Key take-aways
  - Every starshade mechanical parameter has a give-take relationship
  - Starshade configuration is a balance of stowed configuration vs on-orbit performance and petal vs disk mechanical performance/configuration

*Slide courtesy of David Webb (JPL)

JPL Starshade Design

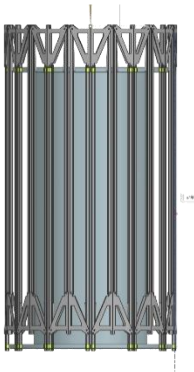
72m-24 Petal Configuration

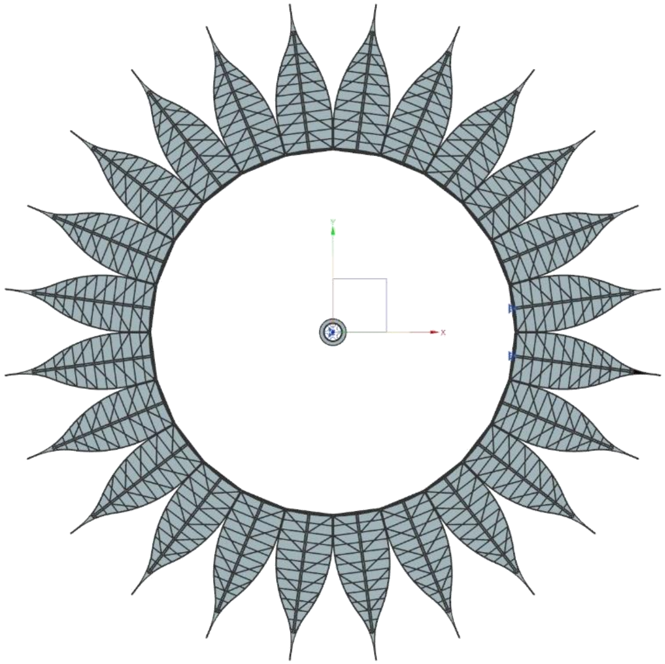


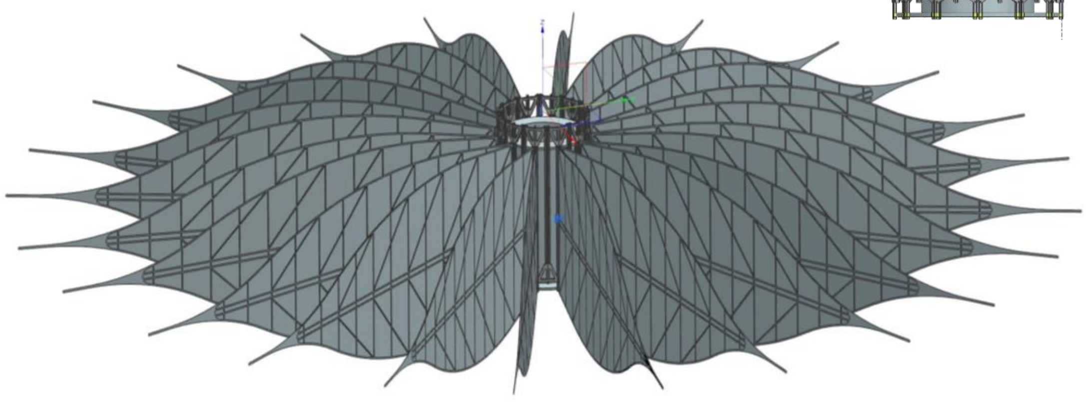


- 72m Starshade, qty 24, 16m Petals
- 38" Batten Spacing, battens at truss longerons only, no battens at shorterons
- Spines are 2" wide, separated by 20"
- FEM analysis needed to validate and optimize

Stowed







Partially deployed

*Slide courtesy of David Webb (JPL)

Error Budget

Initial Budgets In Progress

- Error budget adapted from spreadsheet tool developed by Charley Noecker for the WFIRST Coronagraph Instrument. *(template of only a portion of the tool shown here)*

- Includes detector noise, telescope stability, telescope fabrication and alignment errors, beam walk, low order wavefront sensing and correction, background zodi, target characteristics, etc…

- Includes inputs from:
  – Stability error budget tools developed by Stuart Shaklan and Luis Marchen
  – Brightness dependent error budget developed by Bijan Nemati for WFIRST

WFIRST Coronagraph - Planet Contrast Sensitivity Budget			Sc
	Working angle for instrument contrast values	2 λ/D	Instrument
Target Planet Contrast	*Min. planet contrast detectable*		ppb
SNR			
Required Contrast uncert	*1 σ with reserve*		ppb
Project Reserve	*% of Required Contrast uncert*		
Coronagraph Contrast uncert	*no reserve*		ppb
Brightness Dependent	*SNR, w scatter*		ppb
Detector Noise	*Read, dark, CIC*		ppb
Exoplanet shot	*Sun, Earth, Moon, binaries, etc*		ppb
Local & Exo Zodi	*Shot noise in background*		ppb
Static mean speckle shot	*Incoherent starlight*		ppb
Instrument stray light	*Sun, Earth, Moon, binaries, etc*		ppb
Speckle-Cal Errors	*Zero drift model (RDI)*		ppb
Star 1 speckle cal uncertainty	*Estimation uncert - cal meas't*		ppb
Absolute brightness cal	*Shot noise, read noise*		ppb
Spectral dependence	*Chrom speckles, star color*		ppb
Speckle detection noise	*Calib speckle flux => ppb*		ppb
Mean speckle brightness			ppb
Calibration star mag			
Calibration integ time			sec
Star 2 speckle cal uncertainty	*Estimation uncert - cal meas't*		ppb
Absolute brightness cal	*Shot noise, read noise*		ppb
Spectral dependence	*Chrom speckles, star color*		ppb
Speckle detection noise	*Calib speckle flux => ppb*		ppb
Mean speckle brightness			ppb
Calibration star mag			
Calibration integ time			sec
Temporal weighting uncert	*Linear drift model for speckle cals*		ppb
Speckle stability	*Deviations from zero drift*		ppb
Drifts	*< 2 Hz*		ppb
Observatory pointing	*Rigid ACS beamwalk, WFE*	Pointing Drift RB OTA (FSM Controlled)	ppb
Internal misalignment	*Flex struct beamwalk, WFE*	Optic RB Drift (Flexible OTA, FSM Compensated)	ppb
Occulter pointing drift	*LOWFS pointing drift*	Pointing Drift on the Mask	ppb
Optic bending	*Mirror figure drift*	Optic bending Thermal Zernikes	ppb
DM Drift	*Creep & hysteresis*		ppb
LOWFSC residual	*Control errors, NCPE*		ppb
LOWFSC Suppression	*Loop gains (typical)*		x
Tip-tilt stability at input	*Elec drift, NCPE*		nr
Focus stability at input	*Elec drift, NCPE*		nm
LOWFSC-driven speckle	*Collateral effects of control*		nm
Jitter-induced speckle var'n	*> 2 Hz*		ppb
Tip/tilt Control Error	*LOWFS, knowledge error*		ppb
Coronagraph LOWF Jitter	*Coronagraph portion*		ppb
Telescope LOWF Jitter	*递Uncontr OTA WF ~Z4-Z11*		ppb

JPL

Design Questions

To be answered for Interim Report

- Is a Schott Zerodur PM with 120Hz first mode suitable for HabEx?
  - Or do we need ~200Hz?
- Which Attitude Control System (ACS) and Spacecraft Isolation system are required?
- Can existing EMCCDs be sufficiently shielded from radiation to prevent or reduce radiation induced photon traps?
  - *May be answered by WFIRST CGI*
- Is a laser metrology control system required to stabilize the SM tower?
- How much coating non-uniformity can coronagraphs tolerate?
- How do we test the deployed starshade on the ground?

Design Questions

Primary Mirror substrate material

- **Primary Mirror substrate material**
  - Preliminary selection of Schott Zerodur
    - Schott consistently manufactures 4.2m size boules
    - Standard manufacturing methods for high quality optic with 120Hz+ first mode
    - Demonstrated fabrication of 4m class mirrors
    - High CTE uniformity measured
    - Schott has multiple ~4m size mirrors for ground based telescope on order for the near future
      - E-ELT M2 (3.8m convex)
      - E-ELT M3 (4.2m concave)
  - Alternatives:
    - Corning ULE & Harris Corp using low-temperature fusion (LTF) method to fabricate a 4m optic
      - Current AMTD-2 study commissioned by NASA to develop technology for 4m size optics
    - 4m meniscus optic with shape actuators
    - Segmented, off-axis 4m mirror (six petals around a circular center section)
    - Segmented, on-axis 4m mirror (six petals)
- **To be evaluated:**
  - Does a monolithic Zerodur mirror with a 120Hz first mode and associated supporting system meet static and stability performance requirements? Specifically, how much will spacecraft jitter and temperature fluctuations deform the primary mirror?
  - Otherwise, a stiffer PM will be needed which will require new infrastructure at Schott (they have done this before for an 8m dia substrate) but is a low risk manufacturing task

Design Questions

ACS & Spacecraft Isolation

- **Question**:
  - What form of spacecraft Attitude Control System (ACS) should be used?
- **Concern**:
  - Excessive jitter causes optical wavefront errors and will degrade Coronagraph contrast. Reducing jitter noise (from reaction wheels) will decrease wavefront errors due to optical deformations. Reducing jitter will also stabilize line-of-sight (LOS) jitter which will reduce wavefront errors due to beamwalk on optics.
- **Options**:
  - Attitude Control System (ACS):
    - Microthrusters (in place of wheels)
      - Colloid Thrusters on Lisa Pathfinder (TRL7)
      - Cold Gas Thrusters on GAIA (TRL9)
    - reaction wheels (TRL9)
    - control moment gyroscopes (TRL9)
  - Spacecraft/Payload Isolation:
    - passive isolation:
      - Honeywell D-Struts, (TRL9)
    - active isolation: (likely not required with microthusters)
      - Harris piezo-based active isolation system, (TRL9)
      - LM Disturbance Free Payload (DFP) active isolation, (~TRL4)
      - NG active isolation system?
- **To Be Evaluated:**
  - Model observatory, apply mechanical disturbance due to thrusters, and assess effect on optical performance and coronagraph contrast.

Plan Forward

- Observatory:
  - Full CAD layout of observatory including:
    - Telescope
    - Instruments
    - More detailed coronagraph model
    - Outer Barrel
    - Sun shade, Solar arrays
    - Spacecraft Bus and isolation
    - Microthrusters or reaction wheels
    - Avionics
    - Formation Flying sensors
    - Communications
    - Servicing hardware
  - Finite Element Model (FEM) development
  - Thermal Model (TM) development
  - Structural, Thermal, Optical Performance (STOP) analysis
  - ACS & LOS pointing control analysis
  - Coating uniformity vs coronagraph performance analysis

- Starshade:
  - Full CAD layout of starshade including:
    - Spacecraft bus
    - Reaction wheels
    - Propulsion system
      - SEP
    - Avionics
    - Formation Flying sensors
    - Communications
    - Servicing hardware
  - Finalize Finite Element Model (FEM) development
  - Finalize Thermal Model (TM) development
  - Structural, Thermal, Optical Performance (STOP) analysis

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