# HabEx Optical Telescope Assembly

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## Purpose

- Introduce candidate optical telescope assembly (OTA) architectures
- Illustrate design/analysis process

## Agenda

- Definitions, Specification & Assumptions
- 4-meter Monolithic Mirror Concept
- 6.5-meter Segmented Mirror Concept

# Definitions, Specifications & Assumptions

## Optical Telescope Assembly (OTA)

Optical Telescope Assembly (OTA) is defined to consist of:

- Primary Mirror Assembly
  - Primary Mirror Substrate
  - Primary Mirror Struts
  - Primary Mirror Truss Structure
- Secondary Mirror Assembly
  - Secondary Mirror Substrate
  - Secondary Mirror Struts
  - Secondary Mirror Truss Structure
- OTA Structure

  Connects PMA to SMA and houses Science Instruments (SI).
- OTA Light Tube Baffle

# OTA Specification

Science Requirements
Launch Vehicle Capacity
Programmatic Constraints → Engineering Specifications

| | |
|---|---|
| **Exoplanet** | |
| Habitable Zone Size | Minimum Telescope Diameter |
| Contrast | Mid/High-Spatial Wavefront Error |
| Contrast | WFE Stability |
| Star Size | Line of Sight Stability |
| Architecture | Unobscured (off-axis) |
| **General Astrophysics** | |
| Diffraction Limit | Low/Mid-Spatial Wavefront Error |
| Spatial Resolution | Line of Sight Stability |
| **Launch Vehicle** | |
| Up-Mass Capacity | Mass Budget |
| Fairing Size | Architecture (monolithic/segmented) |
| **Programmatic** | |
| Budget | Maximum Telescope Diameter |

# Design Assumptions

Mission will have an Internal Coronagraph which requires:

- Unobscured Aperture – off-axis
- Stable Wavefront.

General Astrophysics:

- 500 nm diffraction limit requires no development effort

Launch Vehicle

- SLS will exist. Therefore, for 'baseline' design mass and volume constraints are secondary to wavefront stability.
- 'Backup' designs will be considered for EELV.

The Most important Design Constraints are:

- Line of Sight Stability
- Wavefront Stability

## DRAFT OTA Specifications

| | | |
|---|---|---|
| Architecture | Unobscured Off-Axis F/2.5 TMA | |
| Aperture Diameter | 4-meters Monolithic (Minimum)<br>6.5-meters Segmented (Maximum) | |
| Mass Budget | < 10,000 kg (nominal – assumed met) | |
| Line of Sight Stability | < ~5 milli-arc-second | |
| Diffraction Limit | 500 nm (assumed to be achievable) | |
| Wavefront Error | 36 nm rms Total (assumed achievable) | |
| Primary Mirror<br>(cpd = cycles/diameter) | Total SFE | < 8.0 nm rms |
| | Low-Order (< 3 cpd) | < 5.6 nm rms |
| | Mid-Spatial (3 to 60 cpd) | < 5.6 nm rms |
| | High-Spatial (>60 cpd) | < 0.6 nm rms |
| | Roughness | < 0.2 nm rms |
| Wavefront Stability | Architecture and Coronagraph Specific | |

## DRAFT OTA Line of Sight Stability

PSF ($2.44\lambda/D$ full-angle) at 500 nm

| | |
|---|---|
| 4-m | ~300 nano-radian ~ 60 mas |
| 6.5-m | ~200 nano-radian ~ 40 mas |

LOS Jitter < 5 mas (1/8$^{th}$ of 40 mas)

## DRAFT OTA Wavefront Stability

From Garreth Ruane and Dimitri Mawet, RMS wavefront tolerances for vector vortex coronagraphs over 2.5-3.5 λ/D.

| Aberration | Indices | | Allowable RMS error (nm) per mode | | |
|---|---|---|---|---|---|
| | $n$ | $m$ | charge 6 | charge 8 | charge 10 |
| Tip-tilt | 1 | ±1 | 5.5 | 18 | 31 |
| Defocus | 2 | 0 | 4.6 | 15 | 36 |
| Astigmatism | 2 | ±2 | 0.36 | 1.0 | 4.6 |
| Coma | 3 | ±1 | 0.44 | 0.95 | 5.5 |
| Spherical | 4 | 0 | 0.32 | 0.81 | 6.7 |
| Trefoil | 3 | ±3 | 0.0065 | 0.35 | 0.71 |

From Stahl, Stahl and Shaklan, PV wavefront tolerances for a 4$^{th}$ order radial coronagraph over 1.5-2.5 λ/D.

| Aberration | Tolerance | units |
|---|---|---|
| Tip/Tilt | 9.6 | nm |
| Power | 1.1 | nm |
| Astigmatism | 6.8 | nm |
| Seidel Coma | 0.84 | nm |
| Spherical | 0.3 | nm |
| Trefoil | 6.0 | nm |
| Hexafoil | 9.6 | nm |

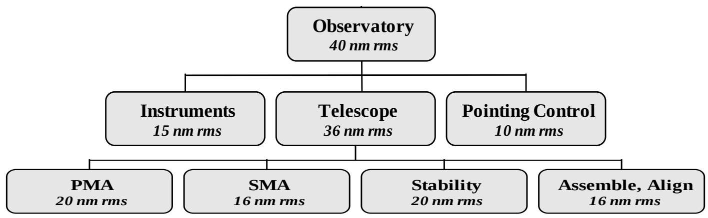
## Design for Stability

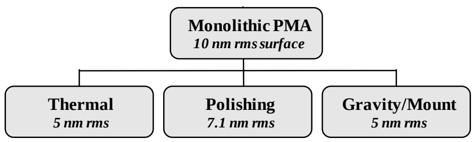
Wavefront and Line of Sight Stability has design consequences.

- Mechanical
  - Secondary Mirror Support Structure Dynamic Response
  - Primary Mirror Dynamic Response
  - Passive/Active Vibration Isolation
  - Passive/Active Dampening/Control
- Thermal
  - PM & SM Mirror CTE
  - Structure CTE
  - Passive Thermal Isolation
  - Active Thermal Control

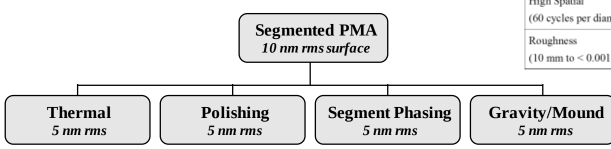
## BACKUP: Diffraction Limit WFE

Diffraction Limit of 500 requires total system WFE ~ 38 nm ms




| Spatial Frequency Band Limited Primary Mirror Surface Specification | | | |
|---|---|---|---|
| PSD Slope | - 2.0 | - 2.25 | - 2.5 |
| Total Surface Error | 8.0 nm rms | 8.0 nm rms | 8.0 nm rms |
| Figure/Low Spatial (1 to 4 cycles per diameter) | 5.2 nm rms | 5.5 nm rms | 5.8 nm rms |
| Mid Spatial (4 to 60 cycles per diameter) | 5.8 nm rms | 5.6 nm rms | 5.4 nm rms |
| High Spatial (60 cycles per diameter to 10 mm) | 1.4 nm rms | 1.0 nm rms | 0.7 nm rms |
| Roughness (10 mm to < 0.001 mm) | 0.6 nm rms | 0.3 nm rms | 0.2 nm rms |




# 4-meter Monolithic Concept

Concept

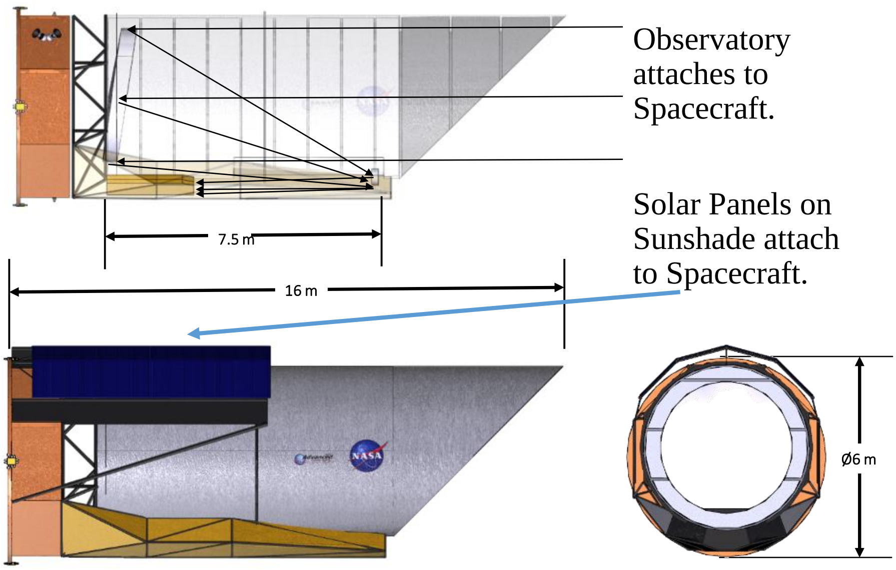
Tolerances

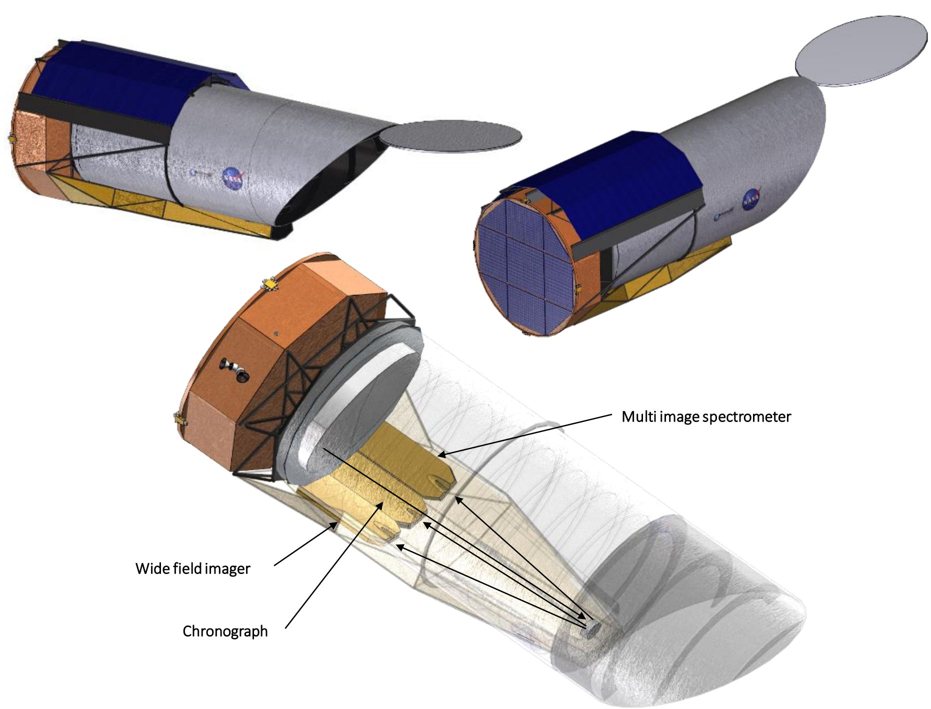
Structural Design

Primary Mirror Design

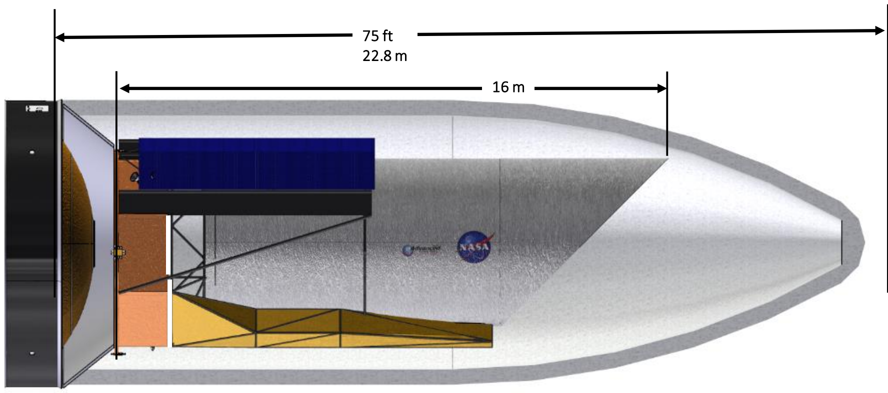
# HabEx 4-m Off-Axis Concept

Observatory = OTA (PM/SM/Tube) & Science Instruments.

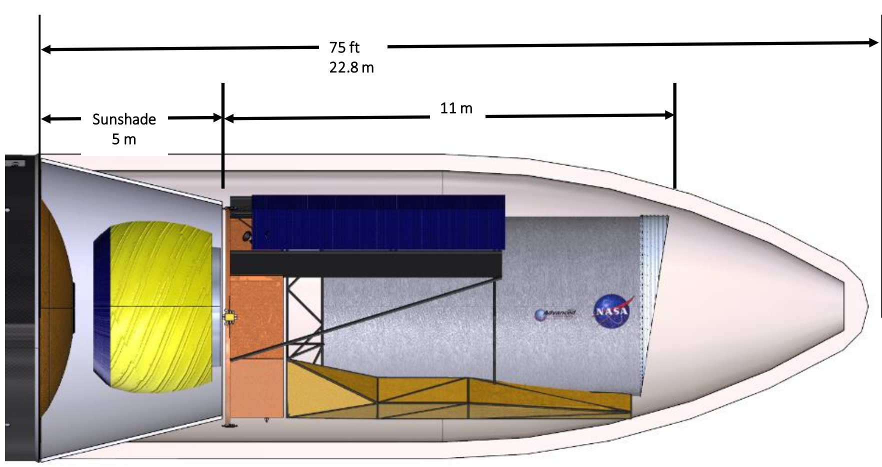


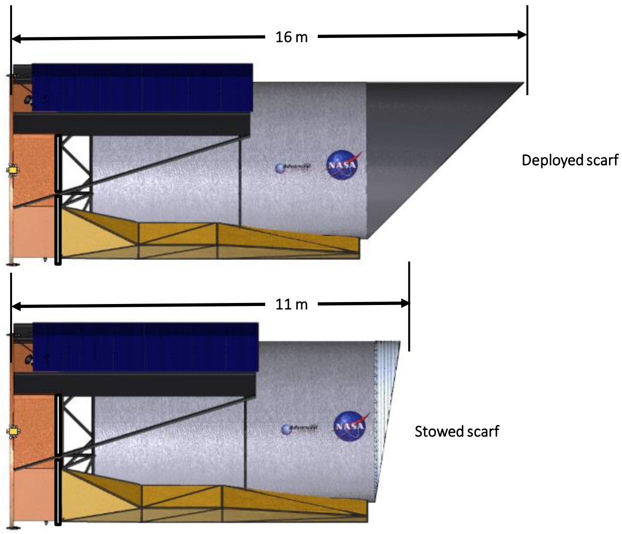
## Launch Configuration – no deployments




## Launch Configuration – Star-Shade below

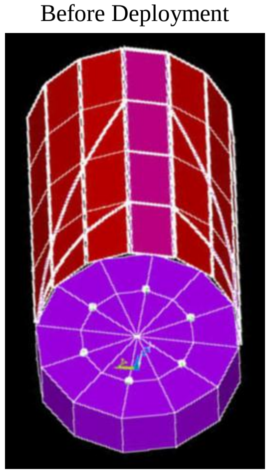


# Deployed Forward Scarf

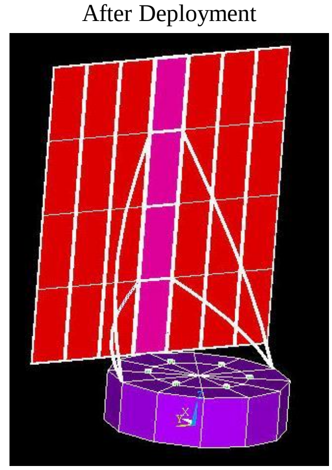


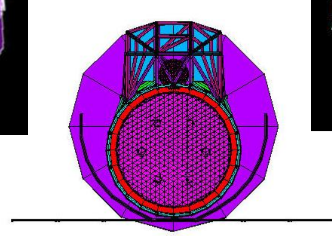

# Spacecraft & Sun Shade / Solar Panels

Before Deployment



After Deployment





# Tolerances

LOS & WFE Stability drive Mechanical Tolerances

## Wavefront Stability

From Garreth Ruane and Dimitri Mawet, RMS wavefront tolerances for vector vortex coronagraphs over 2.5-3.5 λ/D.

| Aberration | Indices | | Allowable RMS error (nm) per mode | | |
|---|---|---|---|---|---|
| | $n$ | $m$ | charge 6 | charge 8 | charge 10 |
| Tip-tilt | 1 | ±1 | 5.5 | 18 | 31 |
| Defocus | 2 | 0 | 4.6 | 15 | 36 |
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| Coma | 3 | ±1 | 0.44 | 0.95 | 5.5 |
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From Stahl, Stahl and Shaklan, PV wavefront tolerances for a 4$^{th}$ order radial coronagraph over 1.5-2.5 λ/D.

| Aberration | Tolerance | units |
|---|---|---|
| Tip/Tilt | 9.6 | nm |
| Power | 1.1 | nm |
| Astigmatism | 6.8 | nm |
| Seidel Coma | 0.84 | nm |
| Spherical | 0.3 | nm |
| Trefoil | 6.0 | nm |
| Hexafoil | 9.6 | nm |

## BACKUP: Wavefront Stability Tolerance

Wavefront Stability is driven by Coronagraph Contrast Leakage.

Wavefront Errors (WFE) are caused by:

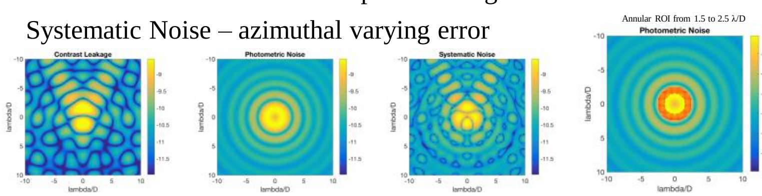
- OTA response to mechanical disturbances
- OTA response to thermal perturbation.

Following the definitions and methodology published by:

Stuart B. Shaklan, Luis Marchen, John Krist and Mayer Rud, "Stability error budget for an aggressive coronagraph on a 3.8m telescope", SPIE Proceedings 8151, 2011.

Contrast leakage decomposed into radial & azimuthal components

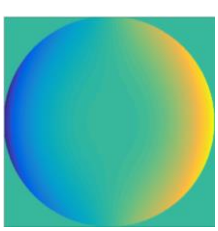
- Photometric Noise – time and spatial averaged radial
- Systematic Noise – azimuthal varying error



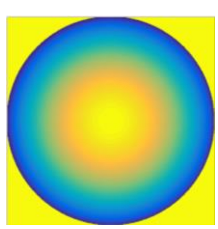
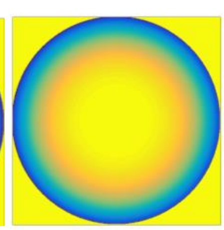

## BACKUP: Wavefront Stability Tolerance

For Monolithic Aperture, the primary WFEs in response to mechanical stimuli are:

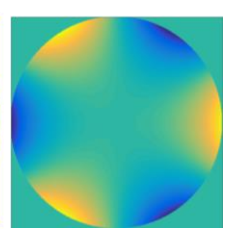
- Alignment Error from motion of PM relative to SM
  - Lateral Displacement produces Seidel Coma (Zernike Coma & Tilt)
  - Longitudinal Displacement produce Power and Spherical
- Bending of PM reacting against its mount - Trefoil



PM to SM Decenter: Coma & Tilt

PM to SM Despace: Power and Spherical

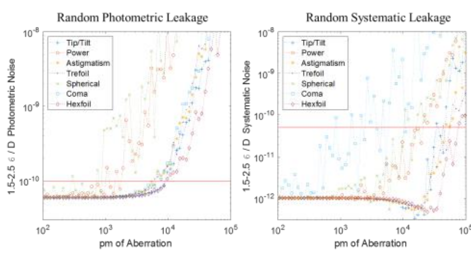


PM Mount: Trefoil

## BACKUP: Coronagraph Contrast Leakage at 1.5-2.5 λ/D

| Tolerance for Monolithic with 4th Order Radial Coronagraph | | | | |
|---|---|---|---|---|
| Aberration | Random | Static | Sinusoidal | units |
| Zernike Tip/Tilt | 9,600 | 9,600 | | pm |
| Seidel Power | 1,100 | 190 | | pm |
| Zernike Astigmatism | 6,800 | 6,800 | | pm |
| Seidel Coma | 840 | 260 | | pm |
| Seidel Spherical | 300 | 73 | | pm |
| Zernike Trefoil | 6,000 | 6,800 | | pm |
| Zernike Hexafoil | 9,600 | 11,000 | | pm |

| 1.5-2.5 λ/D Aberration | WFE (pm) for $1\times10^{-10}$ Photometric Noise | WFE (pm) for $5\times10^{-11}$ Systematic Noise |
|---|---|---|
| Tip / Tilt | 9,600 | 35,000 |
| Power | 1,100 | 22,000 |
| Astigmatism | 6,800 | 49,000 |
| Trefoil | 6,000 | 44,000 |
| Hexafoil | 9,600 | 78,000 |
| Spherical | 300 | 11,000 |
| Seidel Coma | 6,800 | 840 |




## Wavefront Error (WFE) Stability Specification

### Optical Design WFE Alignment Sensitivity

| F/2.5 Design | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Alignment | Tolerance | Units | Z1 | Z2 | Z3 | Z4 | Z5 | Z6 | Z7 | Z8 | Units |
| PM X-Tilt | 1 | micro-degree | 431 | 15 | 15 | 18 | -648 | 214 | 0 | 0 | pm PV |
| PM Y-Tilt | 1 | micro-degree | 0 | 444 | 7 | 668 | 0 | 0 | 221 | 2 | pm PV |
| SM X-Tilt | 1 | micro-degree | 35 | 0 | 0 | 0 | 53 | 18 | 0 | 0 | pm PV |
| SM Y-Tilt | 1 | micro-degree | 0 | 84 | 585 | 91 | 0 | 0 | 42 | 0 | pm PV |
| SM X-Decenter | 10 | nanometer | 25 | 0 | 0 | 37 | 0 | 0 | 12 | 0 | pm PV |
| SM Y-Decenter | 10 | nanometer | 0 | 22 | 37 | 0 | 36 | 11 | 0 | 0 | pm PV |
| SM Z-Despace | 10 | nanometers | 0 | 12 | 146 | 0 | 9 | 6 | 0 | 3 | pm PV |

### Alignment specification to achieve WFE Stability

| Rigid Body Tolerance for F/2.5 Optical Design | | | | | |
|---|---|---|---|---|---|
| | from 1.5 to 2.5 λ/D | from 2.5 to 3.5 λ/D | | | |
| Alignment | 4th Order Radial | VVC6 | VVC8 | VVC10 | Units |
| PM X-Tilt | 10 | 10 | 25 | 180 | nano-radians |
| PM Y-Tilt | 10 | 10 | 25 | 180 | nano-radians |
| SM X-Tilt | 100 | 60 | 250 | 500 | nano-radians |
| SM Y-Tilt | 100 | 60 | 250 | 500 | nano-radians |
| SM X-Decenter | 100 | 100 | 250 | 1000 | nanometers |
| SM Y-Decenter | 100 | 100 | 250 | 1000 | nanometers |
| SM Z-Despace | 25 | 500 | 1000 | 1000 | nanometers |

- 4th order Radial tolerance driven by coma and defocus sensitivity.
- VVC tolerances driven by astigmatism sensitivity

## Line of Sight (LOS) Specification

### Optical Design LOS Alignment Sensitivity

| Alignment | Tolerance | Units | F/2.5 | F/2 | F/1.5 | Units |
|---|---|---|---|---|---|---|
| PM X-Tilt | 1 | micro-degree | 35.2 | 35.4 | 35.6 | nano-radian |
| PM Y-Tilt | 1 | micro-degree | 34.6 | 34.5 | 34.2 | nano-radian |
| SM X-Tilt | 1 | micro-degree | 3.93 | 4.48 | 5.54 | nano-radian |
| SM Y-Tilt | 1 | micro-degree | 2.87 | 2.85 | 2.79 | nano-radian |
| SM X-Decenter | 10 | nanometer | 0.91 | 1.11 | 1.45 | nano-radian |
| SM Y-Decenter | 10 | nanometer | 0.89 | 1.11 | 1.45 | nano-radian |

### Alignment specification to achieve LOS < 5 mas (24 nrad)

Multiple potential distribution of tolerances

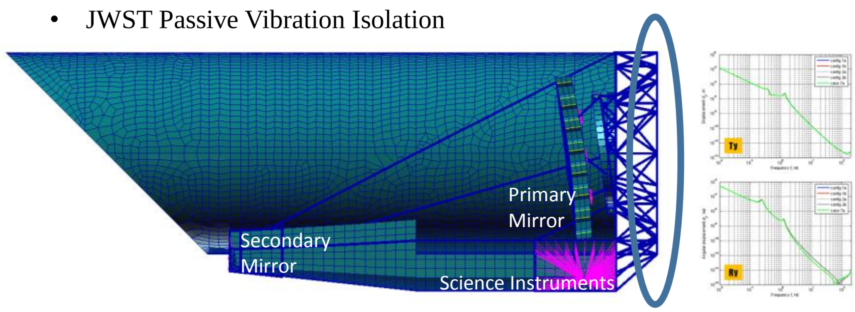
| Distribute LOS Tolerance between all Alignment Errors | | | | | |
|---|---|---|---|---|---|
| Line of Sight Stability | 2 | 4 | 5 | 6 | mas |
| PM X-Tilt | 2.5 | 6 | 8 | 10 | nano-radians |
| PM Y-Tilt | 2.5 | 6 | 8 | 10 | nano-radians |
| SM X-Tilt | 7 | 20 | 16 | 15 | nano-radians |
| SM Y-Tilt | 7 | 20 | 16 | 15 | nano-radians |
| SM X-Decenter | 50 | 50 | 50 | 50 | nanometers |
| SM Y-Decenter | 50 | 50 | 50 | 50 | nanometers |

### 5 mas LOS Stability is more difficult than WFE Stability

## Structure Dynamic Analysis

### To determine PM/SM Rigid Body motions, apply at the OTA/Spacecraft interface:

- JWST Reaction Wheel Vibration Specification
- JWST Passive Vibration Isolation



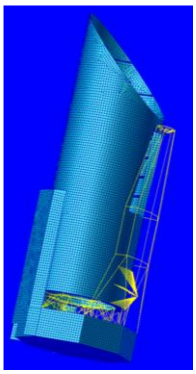
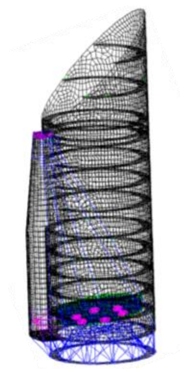

### Key Unknowns that impact analysis

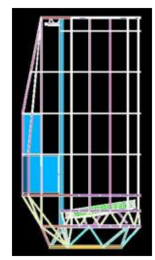
1) Dimensions of Interface between OTA and Spacecraft
2) Amplitude and Location of Science Instrument Mass

## Secondary Mirror Support Structure Stability

### Studied Four Design Concepts

- Free-Standing Tower (~ 10 Hz)
- Tower Attached to Baffle Tube (~20 Hz)
- Tower Attached to Baffle Tube with Struts (~30 Hz)
- HST style Truss Structure

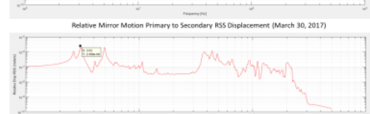





## 30 Hz Secondary Mirror Structure Dynamic Response

Apply JWST Reaction Wheel Assembly Disturbance Specification at 4 locations in the Spacecraft and calculate rigid body motions of the Primary and Secondary Mirrors with 1% dampening

| Rigid Body Alignment Motion | | | |
|---|---|---|---|
| DOF | RWA Disturbance Only | RWA Disturbance & Isolation | Units |
| PM/SM Y-Rotation | 54 | | n-rad |
| PM/SM X-Rotation | 44 | | n-rad |
| PM/SM X-Despace | 910 | | nm |
| PM/SM Y-Despace | 2490 | | nm |
| PM/SM Z-Despace | 1000 | | nm |

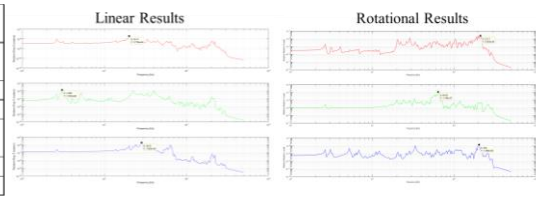




| Passive Isolation Required to meet SM Rigid Body Motion Specification | | | | | | |
|---|---|---|---|---|---|---|
| | | WFE | | | | |
| Alignment | LOS | 4th Radial | VVC6 | VVC8 | VVC10 | Units |
| PM/SM Y-Rotation | 6X | 0.4X | 0.7X | 0.2X | 0.1X | nano-radians |
| PM/SM X-Rotation | 5X | 0.5X | 1X | 0.2X | 0.1X | nano-radians |
| PM/SM X-Despace | 12X | 10X | 10X | 4X | 1X | nanometers |
| PM/SM Y-Despace | 35X | 25X | 25X | 10X | 2.5X | nanometers |
| PM/SM Z-Despace | NA | 40X | 2X | 1X | 1X | nanometers |

# BACKUP: Tower Attached to Baffle Tube (~20 Hz)

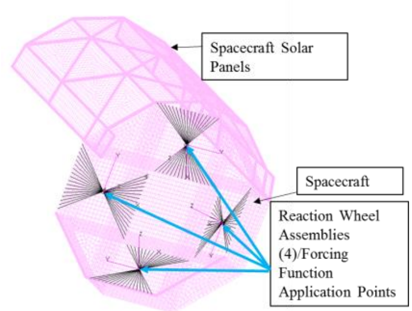
RWA Vibration only, no Passive Isolation, 1% dampening.

| Relative Mirror Motion | Max | Description |
|---|---|---|
| X (meters) | 3.78E-06 | De-Center |
| Y (meters) | 1.37E-06 | Vector Components |
| Z (meters) | 1.92E-06 | De-Space |
| RSS (meters) | 3.78E-06 | Net De-Center |
| RX (Radians) | 2.52E-08 | LOS Delta |
| RY (Radians) | 1.15E-07 | Vector Components |
| RZ (Radians) | 1.50E-08 | N/A |
| RSS (Radians) | 1.15E-07 | Net LOS Delta |




| Passive Isolation Required to meet SM Rigid Body Motion Specification | | | | | | |
|---|---|---|---|---|---|---|
| | | WFE | | | | |
| Alignment | LOS | $4^{th}$ Radial | VVC6 | VVC8 | VVC10 | Units |
| SM X-Tilt | 12X | 0.3X | 0.4X | 0.1X | 0.05X | nano-radians |
| SM Y-Tilt | 3X | 1.2X | 2X | 0.5X | 0.2X | nano-radians |
| SM X-Decenter | 50X | 40X | 40X | 15X | 4X | nanometers |
| SM Y-Decenter | 20X | 15X | 15X | 6X | 1.5X | nanometers |
| SM Z-Despace | NA | 80X | 4X | 2X | 2X | nanometers |

# BACKUP: Reaction Wheel Assemblies




Reaction Wheel Assemblies (RWA) in common pyramid arrangement providing three axis control with redundancy.

RWA disturbance forces and moments applied locally at grids.

RWA radial force and radial moment disturbances are swept through the 360 degree wheel rotation in order to calculate maximum relative displacement between primary and secondary mirror due to a each wheel.

Enveloped disturbances from each RWA are linearly combined to produce the overall maximum relative displacement between the primary and secondary mirror during three axis control.

# BACKUP: Reaction Wheel Assembly Distrubance

**3.3.1.6 Wheel Unbalance**

After exposure to the environments defined in section 3.2.5 of this specification, the unbalance magnitude of the RWA rotating components shall not exceed the following values:

a. Static Unbalance: Less than 1.0 (g-cm) over the operating speed range.

b. Dynamic Unbalance: Less than 14.0 (g.-cm^2) over the operating speed range.

c. The peak radial forces and moments produced by the RWA at any operating speed (including resonant conditions) shall not exceed the values listed in the table below:

**Peak Radial Disturbance Limits Including Resonant Conditions**

| Parameter | Frequency | Max. Limit | Parameter | Frequency | Max. Limit |
|---|---|---|---|---|---|
| Force | 0-70 Hz | 3.5 N | Torque | 0-70 Hz | 0.5 N-m |
| ($F_X$) | 70-210 Hz | 0.7 N | ($M_X$) | 70-195 Hz | 0.3 N-m |
| | 210-270 Hz | 10 N | | 195-225 Hz | 1.5 N-m |
| | 270-500 Hz | 0.7 N | | 225-500 Hz | 0.3 N-m |

**3.3.1.7 Axial Induced Vibration**

The peak force (amplitude) produced by the RWA in the direction parallel to the its spin axis shall not exceed 0.2 N within the frequency range 2-200 Hz, when measured at constant speeds that are within the operational speed range and that are free of major structural resonances. The peak axial force produced by the RWA at any operating speed (including resonant conditions) shall not exceed the following limit values:

| | | | | | |
|---|---|---|---|---|---|
| Frequency Range (in Hz): | 0-150 | 150-195 | 195-225 | 225-300 | 300-500 |
| Axial Force (Fz) Limit: | 0.7 N | 4.5 N | 45 N | 4.5 N | 0.7 N |

RWA Spec Vib Level from Scott Knight, BATC

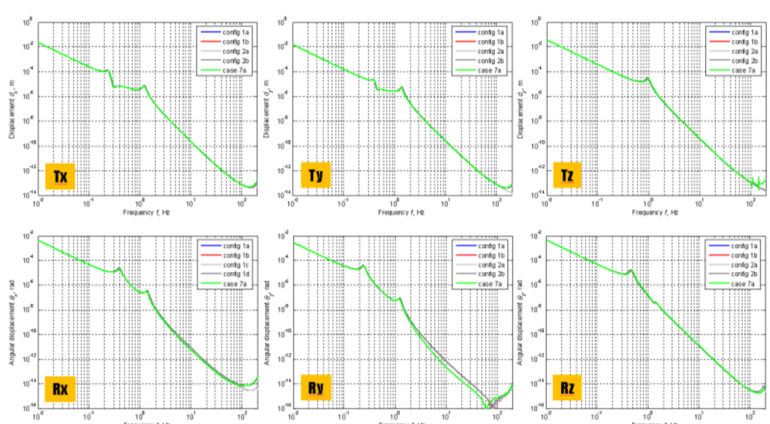
Modal solution is provided by NASTRAN

Boundary conditions to the spacecraft are unconstrained (Free-Free)

Radial force and moment are applied in 10 degree increments around the wheel rotation axis. This results in 144 load cases.

Critical Damping is set at 1%

# BACKUP: JWST Passive Vibration Isolation

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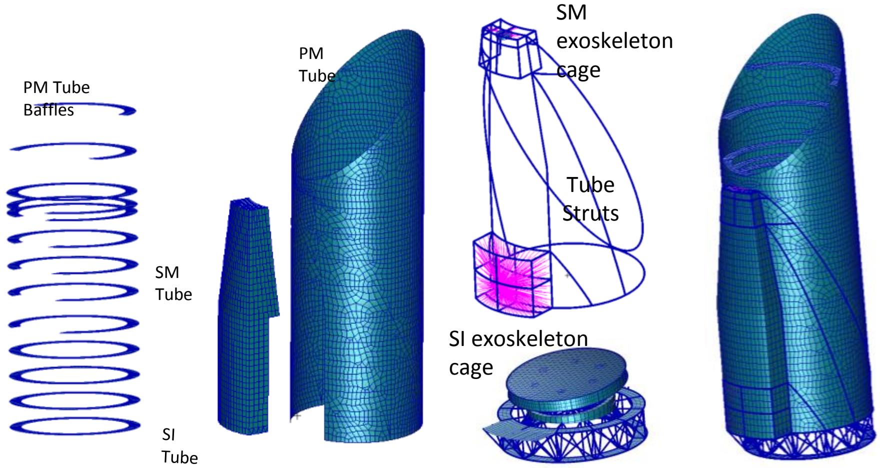
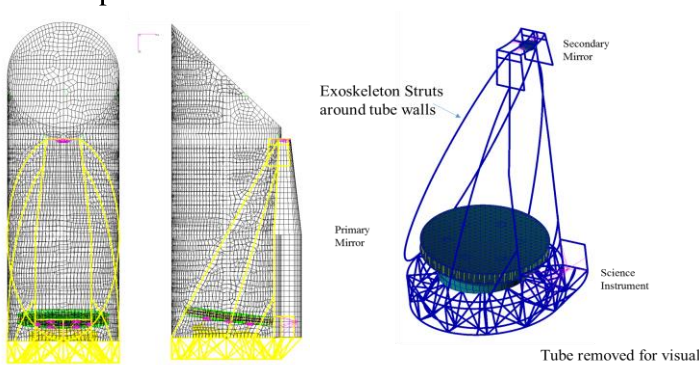
## Tower Attached to Baffle Tube with Struts (~30 Hz)




Structural Material assumed to be M55J.

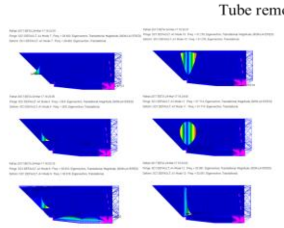
## Secondary Support Tower

Exoskeleton provide stiffness without obscuration.




Tube removed for visual

Mode 7 : Freq. = 29.482
Mode 8 : Freq. = 29.5
Mode 9 : Freq. = 30.016
Mode 10 : Freq. = 31.276
Mode 11 : Freq. = 31.714
Mode 12 : Freq. = 32.091



# Primary Mirror Dynamic Wavefront Error

Dynamic PM WFE arises from two sources:

- Thermal
- Mechanical

Thermal changes produce structural and component motions as a result of material response (bulk CTE and CTE homogeneity)

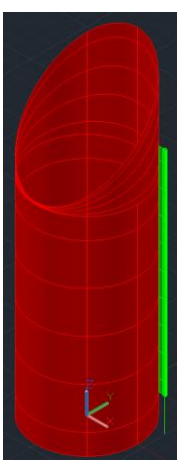
Mechanical Vibrations have a temporal spectrum:

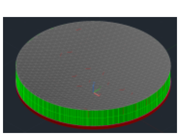
- Specific vibration frequencies induce harmonic modal response.
- All other vibration frequencies cause inertial response.

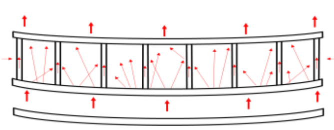
These responses produce structural motions that cause:

- Optical mis-alignment aberrations
- Optical component bending and deformations from mount stress

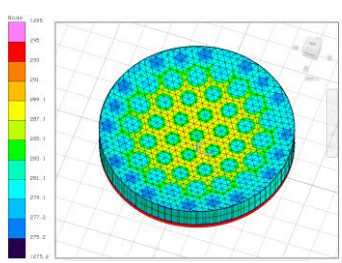
# Static Thermal WFE



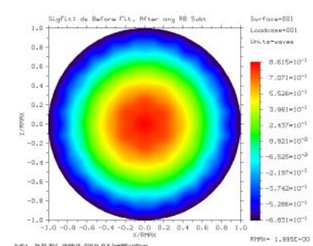




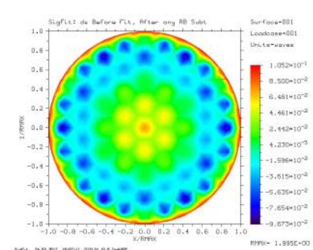
0.5 m thick closed-back ULE mirror
Radial Gradient depends on view factor
and side insulation.



Temperature gradient
Keeping Front Surface > 273K
20C Axial; 10C Radial



SFE from isothermal with defocus
SFE = 977 nm PV; 288 nm RMS



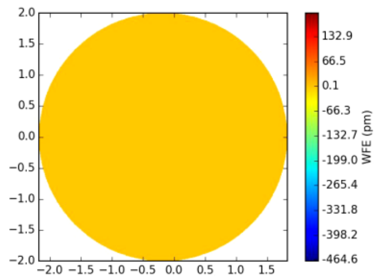
SFE from with defocus removed
SFE = 128 nm PV; 24 nm RMS

## Dynamic Thermal WFE Video

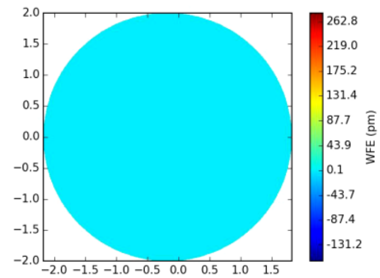
Passive Wavefront Error from 1 hour exposure.

Sun angle changes by 0.0411 degree per hour.

All Errors




Power Removed



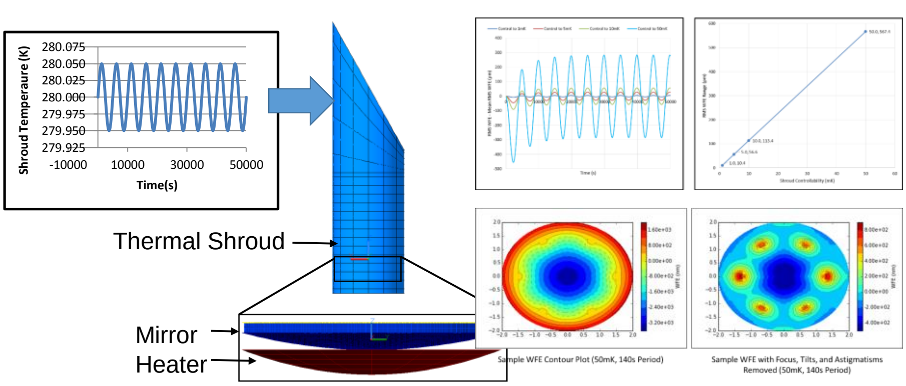

WFE/1-hour = 233 pm PV
WFE/20-min = 28 pm

WFE/1-hour = 101 pm PV
WFE/20-min = 13 pm

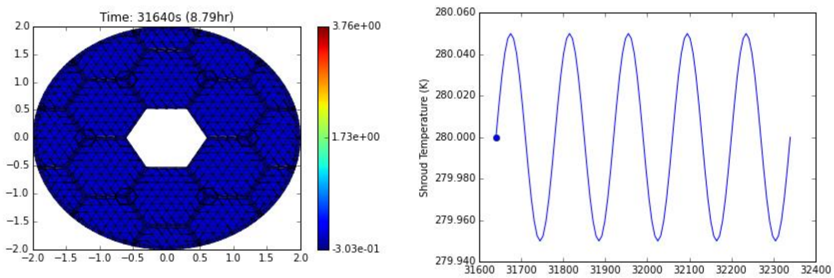
## Dynamic Thermal WFE

Primary mirror responds to dynamic external thermal load

Required stability (10 pm per 10 min) can be achieved by controlling the telescope thermal environment.



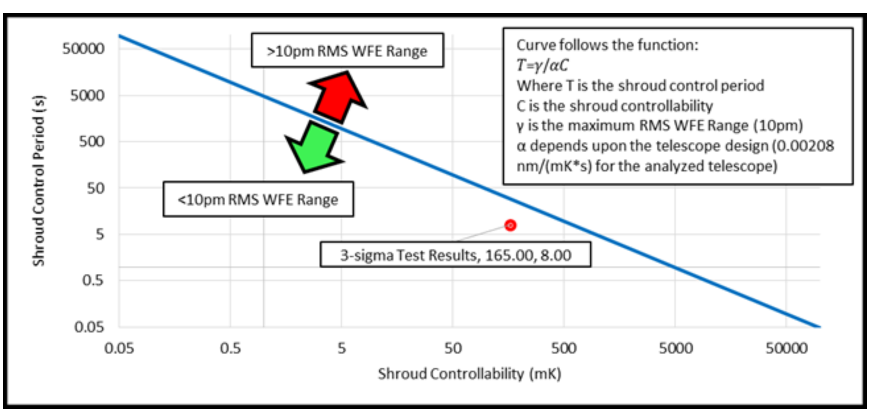
# 4m Aperture Transient WFE Video



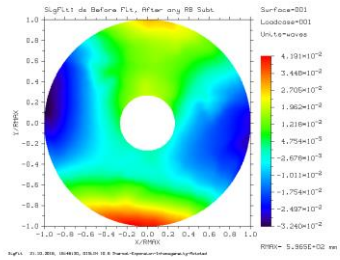

# Thermal Stability

The ability to achieve any required wavefont stability depends on:

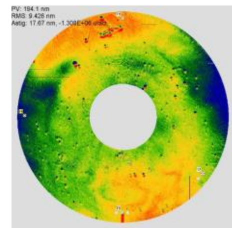
- Mirror Substrate Properties: CTE, Thermal Mass, Conductivity, etc.
- Thermal Environment Controllability
- Control Period.



# 1.2m Zerodur Predicted vs Measured Thermal WFE



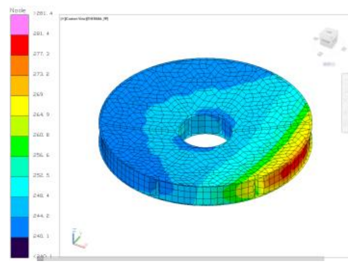
Predicted SFE: 9.55 nm RMS



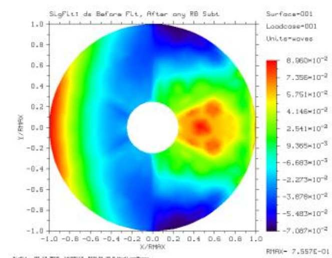
Measured: 9.4 nm RMS

# 1.5m ULE Predicted Lateral Thermal WFE

Lateral Gradient



Predicted Temperature Distribution



Predicted SFE defocus removed

# Primary Mirror Dynamic Wavefront Error

Dynamic PM WFE arises from two sources:

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- All other vibration frequencies cause inertial response.

These responses produce structural motions that cause:

- Optical mis-alignment aberrations
- Optical component bending and deformations from mount stress

## Primary Mirror Dynamic WFE

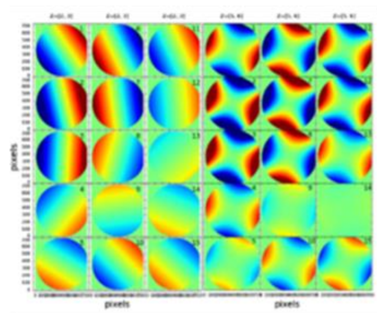
Dynamic WFE depends on the mirror's mounted self-weight deflection (G-sag) and its inertial response function.

G-sag defines the maximum possible WFE for a 1G driving force and a unity response function.

G-sag depends on stiffness of mirror substrate and how it is mounted.

For example, JWST's 220-Hz open-back beryllium primary mirror segments on a 3-point mount have a static horizontal G-sag of approximately 200 nm.

When driven at 87.3 Hz, they have a dynamic Astigmatic WFE of 220 nm per G of driving force.




Saif, et. al., Nanometer level characterization of the James Webb Space Telescope optomechanical systems using high-speed interferometry, Applied Optics, Vol.54, No.13, pg.4295, doi:134285-14, 2015

## Primary Mirror Dynamic WFE

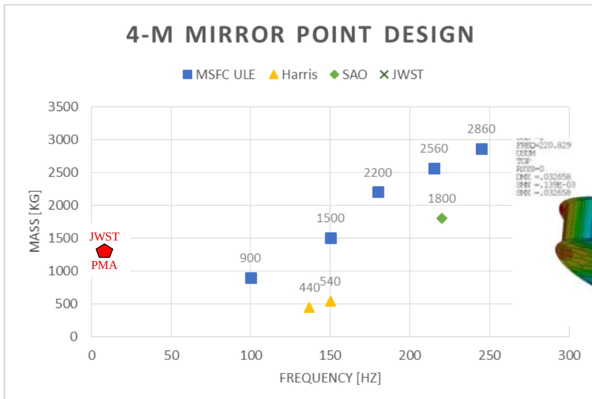
To minimize PM Dynamic WFE:

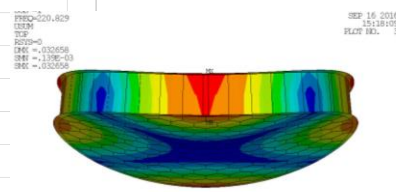
- Design the PM Substrate to be as stiff as possible
- Consider the Mount stiffness and location.

# ULE 4-m Mirror Trade Studies

MSFC explored range of higher mass, more robust designs.

Harris Corporation explored lower limit of mass.



JWST total mass of primary mirror segment assemblies (PMSA) is 700 kg, Total PM Assembly mass is 1250 kg. Individual JWST PM substrates are 220 Hz. Individual PMSA are 40 Hz. Total PMA is 16 Hz.

# ULE PM Trade Study: Substrate Stiffness

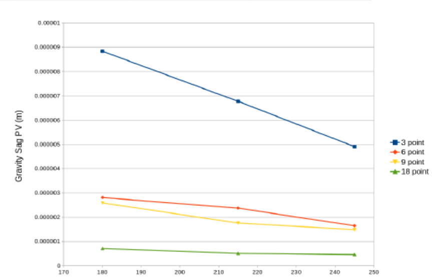
ULE mirrors can be Closed-Back Architectures.

State of Practice Thickness is 35 cm, SOA is 40 cm, 60-cm is developmental.

| | | | |
|---|---|---|---|
| **depth (m)** | 0.45 | 0.6 | 0.75 |
| **mass (kg)** | 1388 | 1707 | 1835 |
| **cell size (m)** | 0.167 | 0.167 | 0.167 |
| **front fs (m)** | 0.0277 | 0.0277 | 0.0277 |
| **back fs (m)** | 0.0231 | 0.0231 | 0.0231 |
| **1st mode (Hz)** | 180 | 215 | 245 |

Gravity Sag:

- Stiffer mirror less G-Sag
- More Mount Points less G-Sag

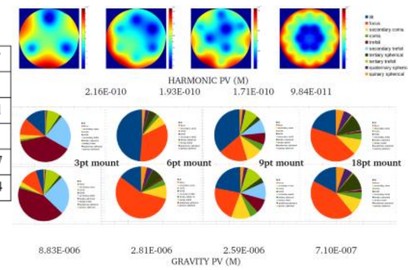


## ULE PM Trade Study: Dynamic WFE

Dynamic WFE for 4-m off-axis 180-Hz 1388-kg Mirror as a function of mount support system when excited at 49.9-Hz.

Dynamic WFE amplitude is similar to gravity sag.

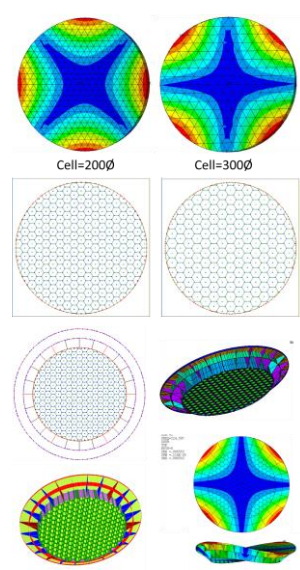
| | 3POINT | 6POINT | 9POINT | 18POINT |
|---|---|---|---|---|
| 1ST MOUNTED MODAL (HZ) | 47.2 | 50.4 | 54.1 | 55.4 |
| HARMONIC PV (M) | 2.16E-010 | 1.93E-010 | 1.71E-010 | 9.84E-011 |
| AT FREQUENCY (HZ) | 49.9 | 49.9 | 49.9 | 49.8 |
| GRAVITY PV (M) | 8.83E-006 | 2.81E-006 | 2.59E-006 | 7.10E-007 |
| SCALE | 2.45E-005 | 6.86E-005 | 6.61E-005 | 1.38E-004 |




Dynamic WFE amplitude goes down with support points.

## ZERODUR PM Trade Study: Substrate Stiffness

ZERODUR mirrors are constrained to Open-Back architectures with a maximum thickness of 42 cm.



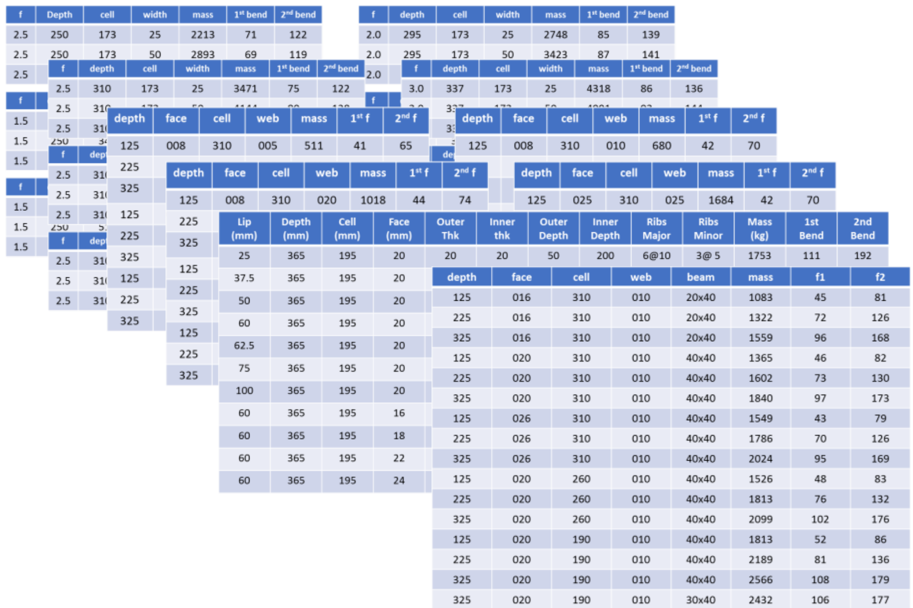

Trade Studies:

#1: Isogrid (triangular) Pockets
- First mode ~ 70 Hz.
- Mass ~ 2600 kg

#2: Hex Pockets with T-back
- First mode ~ 120 Hz.
- Mass ~ 1800 kg

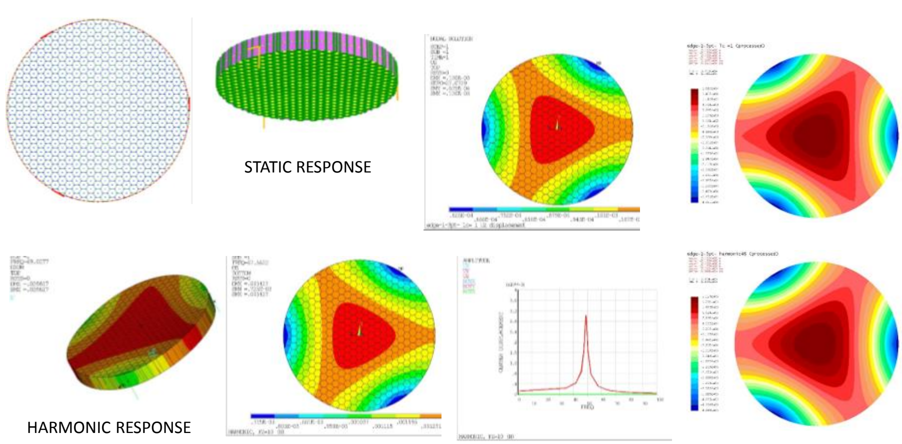
#3: SOFIA Style
- First mode ~ 125 Hz.
- Mass ~ 1350 kg

# ZERODUR PM Trade Study: Multiple Designs

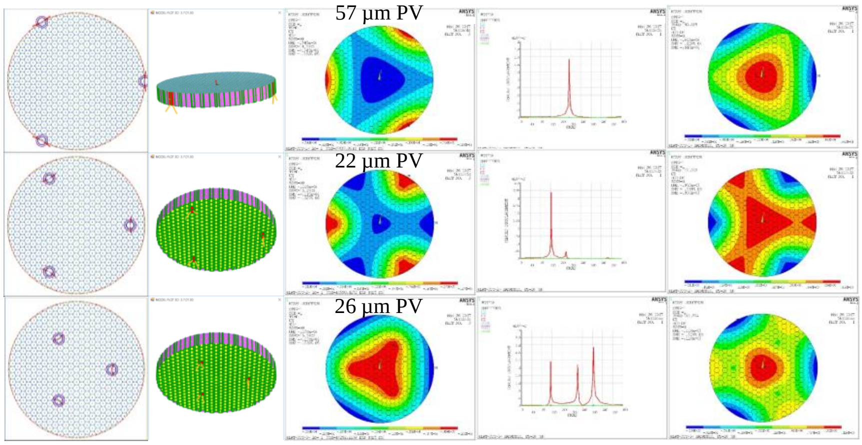


| depth | face | cell | web | beam | mass | f1 | f2 |
|---|---|---|---|---|---|---|---|
| 125 | 016 | 310 | 010 | 20x40 | 1083 | 45 | 81 |
| 225 | 016 | 310 | 010 | 20x40 | 1322 | 72 | 126 |
| 325 | 016 | 310 | 010 | 20x40 | 1559 | 96 | 168 |
| 125 | 020 | 310 | 010 | 40x40 | 1365 | 46 | 82 |
| 225 | 020 | 310 | 010 | 40x40 | 1602 | 73 | 130 |
| 325 | 020 | 310 | 010 | 40x40 | 1840 | 97 | 173 |
| 125 | 026 | 310 | 010 | 40x40 | 1549 | 43 | 79 |
| 225 | 026 | 310 | 010 | 40x40 | 1786 | 70 | 126 |
| 325 | 026 | 310 | 010 | 40x40 | 2024 | 95 | 169 |
| 125 | 020 | 260 | 010 | 40x40 | 1526 | 48 | 83 |
| 225 | 020 | 260 | 010 | 40x40 | 1813 | 76 | 132 |
| 325 | 020 | 260 | 010 | 40x40 | 2099 | 102 | 176 |
| 125 | 020 | 190 | 010 | 40x40 | 1813 | 52 | 86 |
| 225 | 020 | 190 | 010 | 40x40 | 2189 | 81 | 136 |
| 325 | 020 | 190 | 010 | 40x40 | 2566 | 108 | 179 |
| 325 | 020 | 190 | 010 | 30x40 | 2432 | 106 | 177 |

# Support trade studies



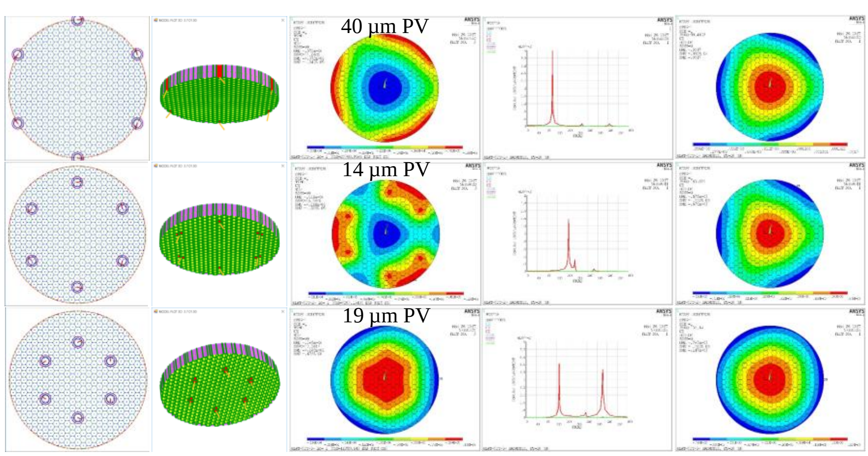
# FLAT 3PT TRADE STUDY




Suspension system consists of beam elements with the desired stiffness and geometry.

Mirror and Mount system assumes 0.5% dampening give a Q (amplification factor) about 100X on transmissibility.

# FLAT 6PT TRADE STUDY



# UTAS 4-m Zerodur Mirror Design

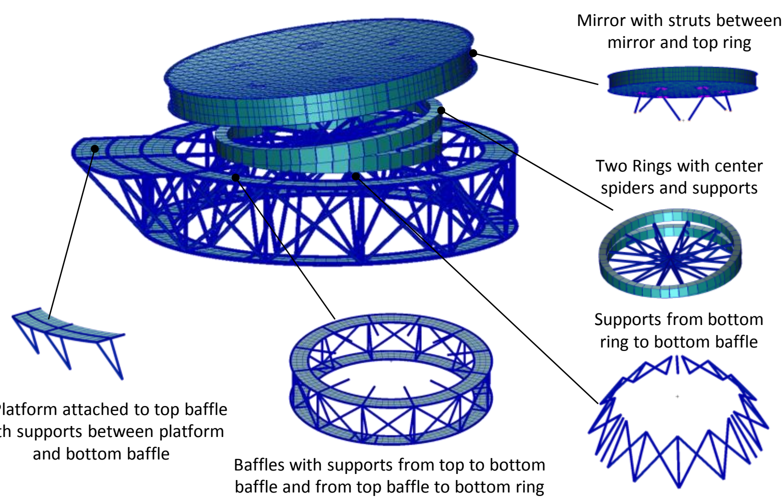
Milled Open-Back Zerodur Mirror

- Diameter 4.2 meters
- Mass 1200 kg
- First Mode 120 Hz Mounted

# Primary Mirror Assembly

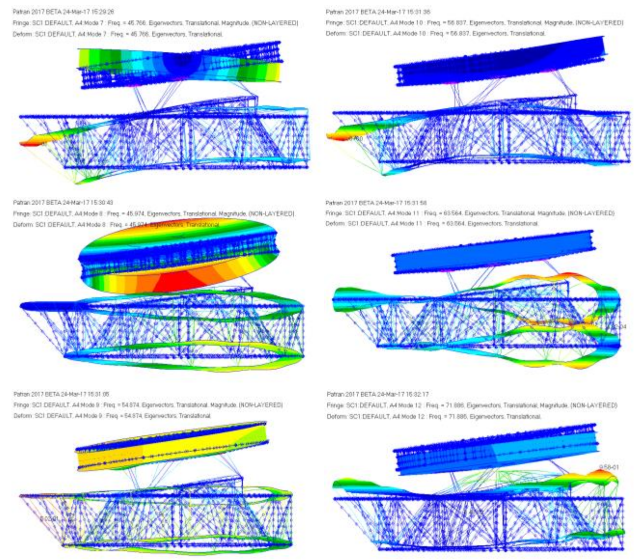
Mirror Substrate is 180 Hz.

Assembly is 45 Hz before attachment to Secondary Tower



# PMA Modal Response

Mode 7 : Freq. = 45.766
Mode 8 : Freq. = 45.974
Mode 9 : Freq. = 54.874
Mode 10 : Freq. = 56.837
Mode 11 : Freq. = 63.564
Mode 12 : Freq. = 71.886



# Primary Mirror Dynamic WFE

Primary Mirror Dynamic Trefoil Specification is defined by Coronagraph Contrast Leakage Sensitivity

| PV Trefoil Tolerance for Primary Mirror | | | | | |
|---|---|---|---|---|---|
| | from 1.5 to 2.5 $\lambda$/D | from 2.5 to 3.5 $\lambda$/D | | | |
| Alignment | 4th Order Radial | VVC6 | VVC8 | VVC10 | Units |
| Trefoil | 6 PV | 0.0065 RMS | 0.35 RMS | 0.71 RMS | nanometers |
| | | 0.0184 PV | 0.99 PV | 2.008 PV | nanometers |

We have not yet analyzed the dynamic WFE for our primary mirror candidates.

# 6.5-meter Segmented Concept

Concept ONLY

No Analysis

Conceptual Deployment Movie

Fairing Packaging

Deployed