# Influence of local reinforcement and hexapod geometry on the performance of ultra lightweight ULE mirror

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# Executive Summary

- Mirror Design is a continuum with infinite possible variations.
- Mass has historically been a primary design metric.
- But stiffness is probably more important – relates to manufacturability and on-orbit performance.
- Gravity sag (related to stiffness) is critical HabEx design metric
- Mount design has critical role on total system stiffness, preferred design is 3-point mount attached at edge of mirror with short stiff hexapod struts.
- Further analysis is needed to determine if HabEx PM will meet its inertial WFE specification based on mass dampening or if additional vibration isolation is needed.
- Arnold Mirror Modeler (AMM) is a invaluable tool in performing mirror design trades.

# INTRODUCTION

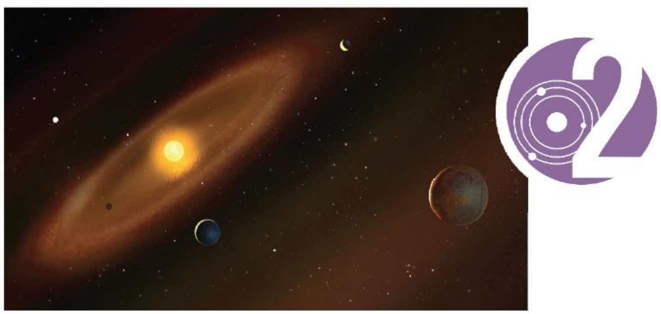
- The Baseline HabEx Primary Mirror is a 4-meter off-axis circular monolith
  - The baseline design is a Zerodur open-back mirror
  - The alternative design is a ULE closed-back mirror
- This trade study is one of a series of primary mirror design studies supporting the HABEX project. Previous papers covered the Zerodur (SCHOTT) option for the primary mirror and limited ULE cases and the overall scope of HABEX.
- This paper expands the ULE (CORNING) option, concentration on suspension system impact. The unique performance requires of the HABEX instruments which drive the mechanical design will be discussed.
- Weight, performance and costs drive any trade study.
- But for HabEx, Gravity Sag (stiffness) is also an important performance parameter both as it relates manufacturing for diffraction limited performance and to inertial wavefront error for ultra-stable coronagraphy performance.
- The ranges of all the parameters used in this study are set by published industrial capabilities. The actual mirror manufacturer may or may not be the raw material supplier. A total of 264 separate models were created and run in period of two weeks using the AMM (Arnold Mirror Modeler) and ANSYS.

# Purpose of HabEx

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

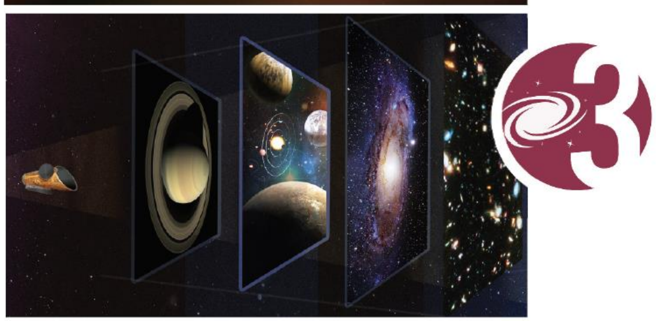
GOAL 1

**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.

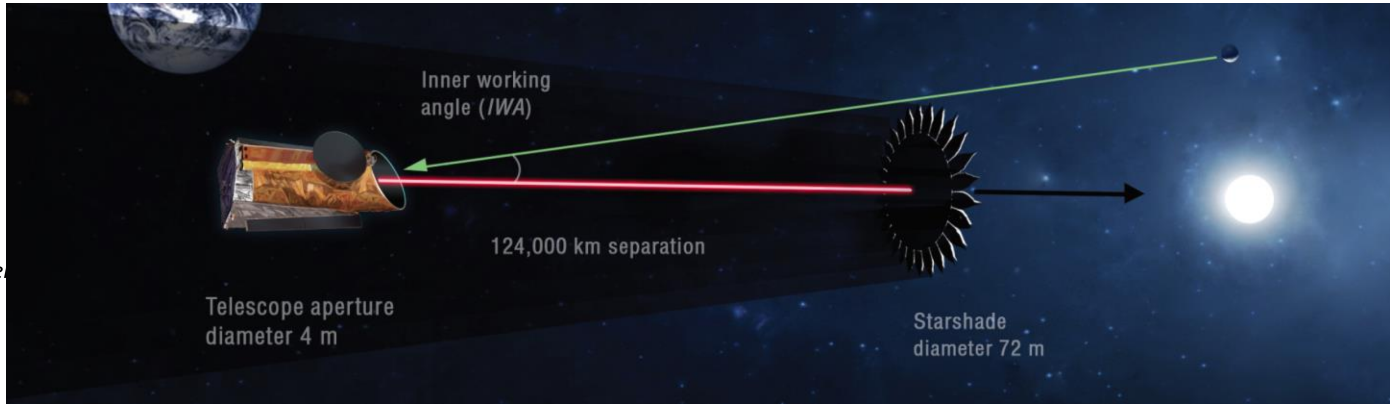
*from HabEx interim report URS273294*

# Architecture A Concept

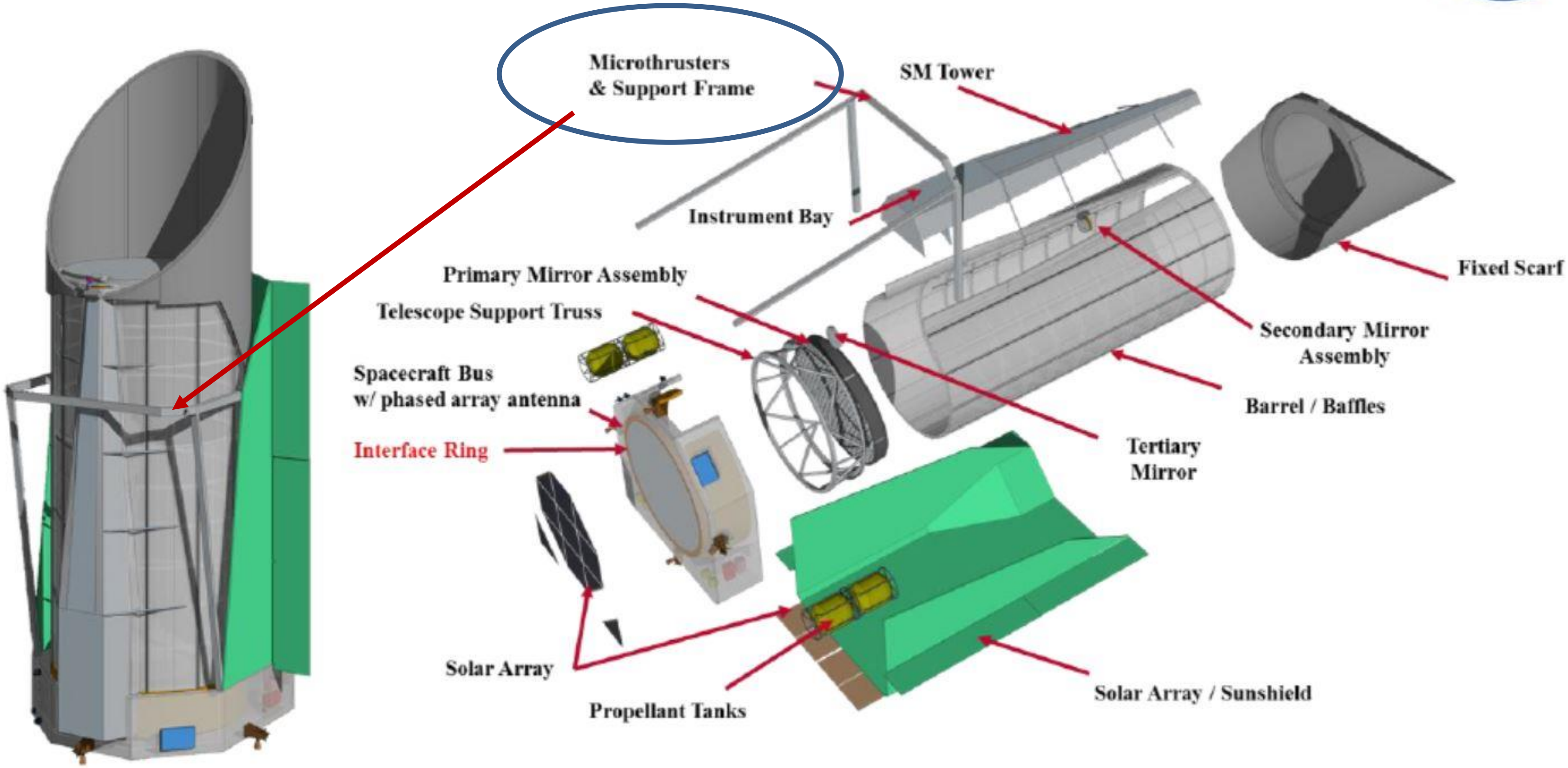
The HabEx STDT chose these parameters for Architecture A:

- Telescope with a 4m aperture
- 72-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 Observatory Science
  - High Resolution UV Spectrograph for General Observatory Science

*Image from HabEx inte*
*report URS273294*



# HabEx Baseline Telescope Design




4 meter Off-axis Telescope with Micro-thrusters for station keeping.
Main instrument for planet finding is an advanced coronagraph.
The design is primarily driven by requirements imposed by this coronagraph.

# HABEX WFE Stability Specification

HabEx Telescope has a Zernike Polynomial based Wavefront Error Budget divided between LOS Jitter, Inertial PM Deformation and Thermal PM Deformation.

| | | | RSS Allocation | 100% | 1% | 60% | 80% | 10% |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | |
| Order | | | | VVC-6 Allowable | LOS | Inertial | Thermal | Reserve |
| K | N | M | Aberration | [pm rms] | [pm rms] | [pm rms] | [pm rms] | [pm rms] |
| | | | TOTAL RMS | 416 | 4 | 250 | 333 | 41 |
| 2 | 1 | 1 | Tilt | | 0 | 0 | 0 | 0 |
| 3 | 2 | 0 | Power (Defocus) | 250 | 2.5 | 150 | 200 | 24.75 |
| 4 | 2 | 2 | Pri Astigmatism | 200 | 2 | 120 | 160 | 19.8 |
| 5 | 3 | 1 | Pri Coma | 175 | 1.75 | 105 | 140 | 17.325 |
| 6 | 4 | 0 | Pri Spherical | 200 | 2 | 120 | 160 | 19.8 |
| 7 | 3 | 3 | Pri Trefoil | 2.6 | 0.026 | 1.56 | 2.08 | 0.2574 |
| 8 | 4 | 2 | Sec Astigmatism | 0.35 | 0.0035 | 0.21 | 0.28 | 0.03465 |
| 9 | 5 | 1 | Sec Coma | 0.35 | 0.0035 | 0.21 | 0.28 | 0.03465 |
| 10 | 6 | 0 | Sec Spherical | 0.35 | 0.0035 | 0.21 | 0.28 | 0.03465 |
| 11 | 4 | 4 | Pri Tetrafoil | 0.35 | 0.0035 | 0.21 | 0.28 | 0.03465 |
| 12 | 5 | 3 | Sec Trefoil | 0.35 | 0.0035 | 0.21 | 0.28 | 0.03465 |
| 13 | 6 | 2 | Ter Astigmatism | 0.1 | 0.001 | 0.06 | 0.08 | 0.0099 |
| 14 | 7 | 1 | Ter Coma | 0.1 | 0.001 | 0.06 | 0.08 | 0.0099 |
| 15 | 8 | 0 | Ter Spherical | 0.1 | 0.001 | 0.06 | 0.08 | 0.0099 |
| 16 | 5 | 5 | Pri Pentafoil | 0.35 | 0.0035 | 0.21 | 0.28 | 0.03465 |
| 17 | 6 | 4 | Sec Tetrafoil | 0.1 | 0.001 | 0.06 | 0.08 | 0.0099 |
| 18 | 7 | 3 | Ter Trefoil | 0.1 | 0.001 | 0.06 | 0.08 | 0.0099 |
| 19 | 8 | 2 | Qua Astigmatism | 0.1 | 0.001 | 0.06 | 0.08 | 0.0099 |
| 20 | 9 | 1 | Qua Coma | 0.1 | 0.001 | 0.06 | 0.08 | 0.0099 |
| 21 | 10 | 0 | Qua Spherical | 0.1 | 0.001 | 0.06 | 0.08 | 0.0099 |
| 22 | 12 | 0 | Qin Spherical | 0.1 | 0.001 | 0.06 | 0.08 | 0.0099 |

# HABEX WFE Stability Specification

Previous analysis shows that LOS Jitter is negligible because HabEx will use microthrusters (specified to have < 0.1 μN noise) instead of reaction wheels (specified to have 1 to 14 N noise).

| | | | RSS Allocation | 100% | 1% | 60% | 80% | 10% |
|---|---|---|---|---|---|---|---|---|
| Order | | | | VVC-6 Allowable | LOS | Inertial | Thermal | Reserve |
| K | N | M | Aberration | [pm rms] | [pm rms] | [pm rms] | [pm rms] | [pm rms] |
| | | | TOTAL RMS | 416 | 4 | 250 | 333 | 41 |
| 2 | 1 | 1 | Tilt | | 0 | 0 | 0 | 0 |
| 3 | 2 | 0 | Power (Defocus) | 250 | 2.5 | 150 | 200 | 24.75 |
| 4 | 2 | 2 | Pri Astigmatism | 200 | 2 | 120 | 160 | 19.8 |
| 5 | 3 | 1 | Pri Coma | 175 | 1.75 | 105 | 140 | 17.325 |
| 6 | 4 | 0 | Pri Spherical | 200 | 2 | 120 | 160 | 19.8 |
| 7 | 3 | 3 | Pri Trefoil | 2.6 | 0.026 | 1.56 | 2.08 | 0.2574 |
| 8 | 4 | 2 | Sec Astigmatism | 0.35 | 0.0035 | 0.21 | 0.28 | 0.03465 |
| 9 | 5 | 1 | Sec Coma | 0.35 | 0.0035 | 0.21 | 0.28 | 0.03465 |
| 10 | 6 | 0 | Sec Spherical | 0.35 | 0.0035 | 0.21 | 0.28 | 0.03465 |
| 11 | 4 | 4 | Pri Tetrafoil | 0.35 | 0.0035 | 0.21 | 0.28 | 0.03465 |
| 12 | 5 | 3 | Sec Trefoil | 0.35 | 0.0035 | 0.21 | 0.28 | 0.03465 |
| 13 | 6 | 2 | Ter Astigmatism | 0.1 | 0.001 | 0.06 | 0.08 | 0.0099 |
| 14 | 7 | 1 | Ter Coma | 0.1 | 0.001 | 0.06 | 0.08 | 0.0099 |
| 15 | 8 | 0 | Ter Spherical | 0.1 | 0.001 | 0.06 | 0.08 | 0.0099 |
| 16 | 5 | 5 | Pri Pentafoil | 0.35 | 0.0035 | 0.21 | 0.28 | 0.03465 |
| 17 | 6 | 4 | Sec Tetrafoil | 0.1 | 0.001 | 0.06 | 0.08 | 0.0099 |
| 18 | 7 | 3 | Ter Trefoil | 0.1 | 0.001 | 0.06 | 0.08 | 0.0099 |
| 19 | 8 | 2 | Qua Astigmatism | 0.1 | 0.001 | 0.06 | 0.08 | 0.0099 |
| 20 | 9 | 1 | Qua Coma | 0.1 | 0.001 | 0.06 | 0.08 | 0.0099 |
| 21 | 10 | 0 | Qua Spherical | 0.1 | 0.001 | 0.06 | 0.08 | 0.0099 |
| 22 | 12 | 0 | Qin Spherical | 0.1 | 0.001 | 0.06 | 0.08 | 0.0099 |

# HABEX WFE Stability Specification

Thermal is beyond the scope of this paper.

| | | | RSS Allocation | 100% | 1% | 60% | 80% | 10% |
|---|---|---|---|---|---|---|---|---|
| Order | | | | VVC-6 Allowable | LOS | Inertial | Thermal | Reserve |
| K | N | M | Aberration | [pm rms] | [pm rms] | [pm rms] | [pm rms] | [pm rms] |
| | | | TOTAL RMS | 416 | 4 | 250 | 333 | 41 |
| 2 | 1 | 1 | Tilt | | 0 | 0 | 0 | 0 |
| 3 | 2 | 0 | Power (Defocus) | 250 | 2.5 | 150 | 200 | 24.75 |
| 4 | 2 | 2 | Pri Astigmatism | 200 | 2 | 120 | 160 | 19.8 |
| 5 | 3 | 1 | Pri Coma | 175 | 1.75 | 105 | 140 | 17.325 |
| 6 | 4 | 0 | Pri Spherical | 200 | 2 | 120 | 160 | 19.8 |
| 7 | 3 | 3 | Pri Trefoil | 2.6 | 0.026 | 1.56 | 2.08 | 0.2574 |
| 8 | 4 | 2 | Sec Astigmatism | 0.35 | 0.0035 | 0.21 | 0.28 | 0.03465 |
| 9 | 5 | 1 | Sec Coma | 0.35 | 0.0035 | 0.21 | 0.28 | 0.03465 |
| 10 | 6 | 0 | Sec Spherical | 0.35 | 0.0035 | 0.21 | 0.28 | 0.03465 |
| 11 | 4 | 4 | Pri Tetrafoil | 0.35 | 0.0035 | 0.21 | 0.28 | 0.03465 |
| 12 | 5 | 3 | Sec Trefoil | 0.35 | 0.0035 | 0.21 | 0.28 | 0.03465 |
| 13 | 6 | 2 | Ter Astigmatism | 0.1 | 0.001 | 0.06 | 0.08 | 0.0099 |
| 14 | 7 | 1 | Ter Coma | 0.1 | 0.001 | 0.06 | 0.08 | 0.0099 |
| 15 | 8 | 0 | Ter Spherical | 0.1 | 0.001 | 0.06 | 0.08 | 0.0099 |
| 16 | 5 | 5 | Pri Pentafoil | 0.35 | 0.0035 | 0.21 | 0.28 | 0.03465 |
| 17 | 6 | 4 | Sec Tetrafoil | 0.1 | 0.001 | 0.06 | 0.08 | 0.0099 |
| 18 | 7 | 3 | Ter Trefoil | 0.1 | 0.001 | 0.06 | 0.08 | 0.0099 |
| 19 | 8 | 2 | Qua Astigmatism | 0.1 | 0.001 | 0.06 | 0.08 | 0.0099 |
| 20 | 9 | 1 | Qua Coma | 0.1 | 0.001 | 0.06 | 0.08 | 0.0099 |
| 21 | 10 | 0 | Qua Spherical | 0.1 | 0.001 | 0.06 | 0.08 | 0.0099 |
| 22 | 12 | 0 | Qin Spherical | 0.1 | 0.001 | 0.06 | 0.08 | 0.0099 |

# HABEX WFE Stability Specification

This paper investigates Inertial WFE stability.

Inertial error occurs when the primary mirror reacts against its mount (i.e. bends) in response to acceleration forces.

| | | | RSS Allocation | 100% | 1% | 60% | 80% | 10% |
|---|---|---|---|---|---|---|---|---|
| Order | | | | VVC-6 Allowable | LOS | Inertial | Thermal | Reserve |
| K | N | M | Aberration | [pm rms] | [pm rms] | [pm rms] | [pm rms] | [pm rms] |
| | | | TOTAL RMS | 416 | 4 | 250 | 333 | 41 |
| 2 | 1 | 1 | Tilt | | 0 | 0 | 0 | 0 |
| 3 | 2 | 0 | Power (Defocus) | 250 | 2.5 | 150 | 200 | 24.75 |
| 4 | 2 | 2 | Pri Astigmatism | 200 | 2 | 120 | 160 | 19.8 |
| 5 | 3 | 1 | Pri Coma | 175 | 1.75 | 105 | 140 | 17.325 |
| 6 | 4 | 0 | Pri Spherical | 200 | 2 | 120 | 160 | 19.8 |
| 7 | 3 | 3 | Pri Trefoil | 2.6 | 0.026 | 1.56 | 2.08 | 0.2574 |
| 8 | 4 | 2 | Sec Astigmatism | 0.35 | 0.0035 | 0.21 | 0.28 | 0.03465 |
| 9 | 5 | 1 | Sec Coma | 0.35 | 0.0035 | 0.21 | 0.28 | 0.03465 |
| 10 | 6 | 0 | Sec Spherical | 0.35 | 0.0035 | 0.21 | 0.28 | 0.03465 |
| 11 | 4 | 4 | Pri Tetrafoil | 0.35 | 0.0035 | 0.21 | 0.28 | 0.03465 |
| 12 | 5 | 3 | Sec Trefoil | 0.35 | 0.0035 | 0.21 | 0.28 | 0.03465 |
| 13 | 6 | 2 | Ter Astigmatism | 0.1 | 0.001 | 0.06 | 0.08 | 0.0099 |
| 14 | 7 | 1 | Ter Coma | 0.1 | 0.001 | 0.06 | 0.08 | 0.0099 |
| 15 | 8 | 0 | Ter Spherical | 0.1 | 0.001 | 0.06 | 0.08 | 0.0099 |
| 16 | 5 | 5 | Pri Pentafoil | 0.35 | 0.0035 | 0.21 | 0.28 | 0.03465 |
| 17 | 6 | 4 | Sec Tetrafoil | 0.1 | 0.001 | 0.06 | 0.08 | 0.0099 |
| 18 | 7 | 3 | Ter Trefoil | 0.1 | 0.001 | 0.06 | 0.08 | 0.0099 |
| 19 | 8 | 2 | Qua Astigmatism | 0.1 | 0.001 | 0.06 | 0.08 | 0.0099 |
| 20 | 9 | 1 | Qua Coma | 0.1 | 0.001 | 0.06 | 0.08 | 0.0099 |
| 21 | 10 | 0 | Qua Spherical | 0.1 | 0.001 | 0.06 | 0.08 | 0.0099 |
| 22 | 12 | 0 | Qin Spherical | 0.1 | 0.001 | 0.06 | 0.08 | 0.0099 |

# Mirror Trade Study

- Purpose of this Trade Study is to maximize stiffness and minimize Gravity Sag
- Investigate influence of:
  - Mirror Geometry – core thickness, core cell size, etc.
  - Mirror Shape – flat back, meniscus, etc.
  - Mount Interface Geometry – 100%, 85%, 70%
  - Hexapod Geometry – strut height, angle, etc.
- Performance Metrics for Study include:
  - Mirror Mass
  - First Mode Frequency
  - RSS μ-Gravity Sag.

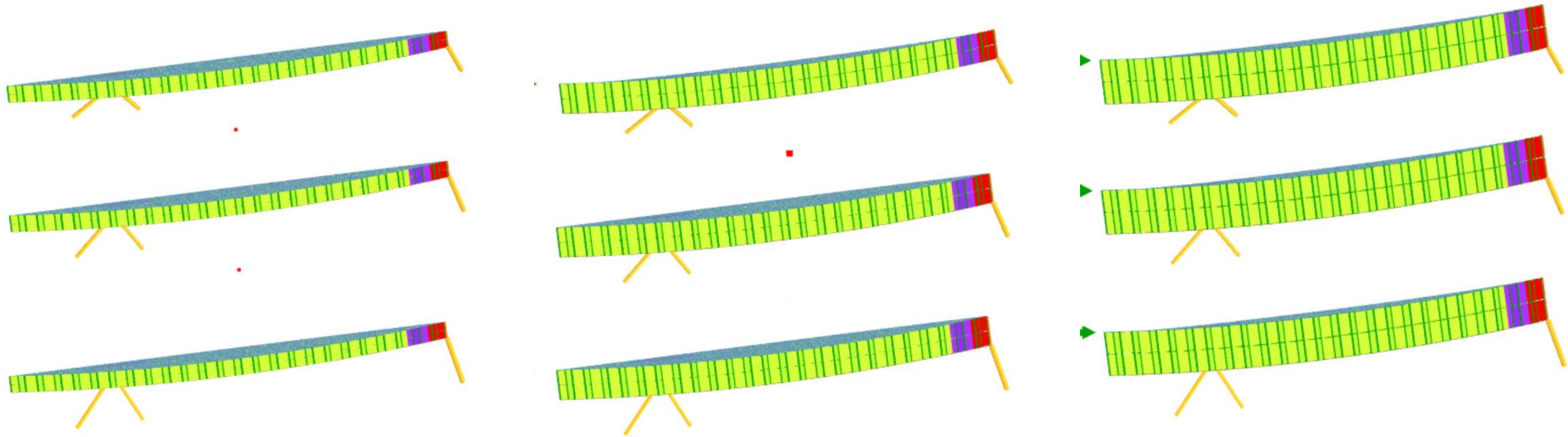
# SCOPE OF TRADE STUDY

- The Arnold Mirror Modeler was used to generate models of each design point. The modeler automates the complete analysis using ANSYS APDL.
- Each model run includes 1g static accelerations in X, Y ad Z directions, plus calculates the first 10 suspended modes and the first 10 free-free modes. These load cases only had to be entered once into the modeler, then the appropriate geometries varied. archives and ANSYS input decks generated.
- The results include deflections, stresses and frequencies: which are store in a summary file and multiple plots. The summary program also contains the surface RMS of the optical surface for each static case. Each run also generates files containing optical surface node locations and displacements for evaluation of Zernike coefficients in a separate program.
- The only manual steps involve transferring the results from the summary files to an EXCEL file for evaluation, manipulation and plotting.

HABEX design goal is balanced response in all three directions!

# CORE DEPTH AND HEXAPOD ANGLES

APPLIES TO BOTH 3 POINTS AND 6 POINTS STUDIES

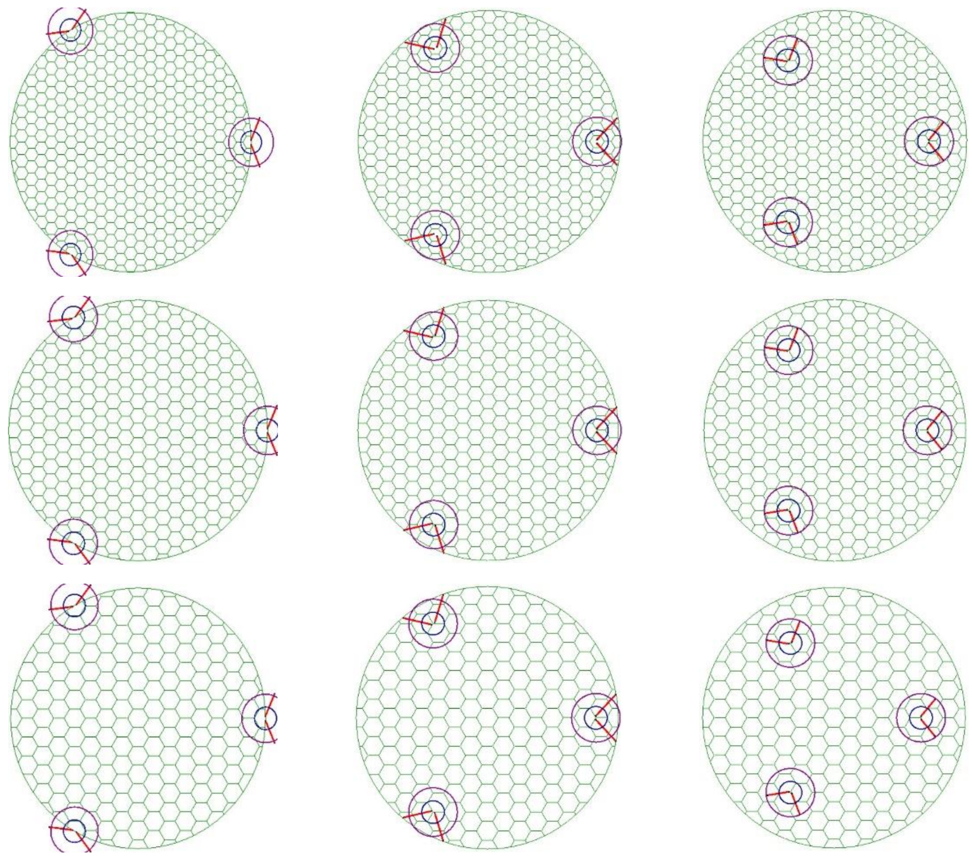


| | | |
|---|---|---|
| **CORE DEPTH 150mm** | **CORE DEPTH 225mm** | **CORE DEPTH 400mm** |
| **CELL WIDTH 192mm**<br>**CELL WIDTH 225mm**<br>**CELL WIDTH 290mm** | **CELL WIDTH 192mm**<br>**CELL WIDTH 225mm**<br>**CELL WIDTH 290mm** | **CELL WIDTH 192mm**<br>**CELL WIDTH 225mm**<br>**CELL WIDTH 290mm** |
| **HEX HEIGHT 250mm**<br>**HEX HEIGHT 350mm**<br>**HEX HEIGHT 450mm** | **HEX HEIGHT 250mm**<br>**HEX HEIGHT 350mm**<br>**HEX HEIGHT 450mm** | **HEX HEIGHT 250mm**<br>**HEX HEIGHT 350mm**<br>**HEX HEIGHT 450mm** |

Hexapod heights cover the range from lowest to highest vertical angle recommended

# 3 POINT HEXAPOD GEOMETRIES

100% Attach Dia. 85% Attach Dia. 70% Attach Dia.

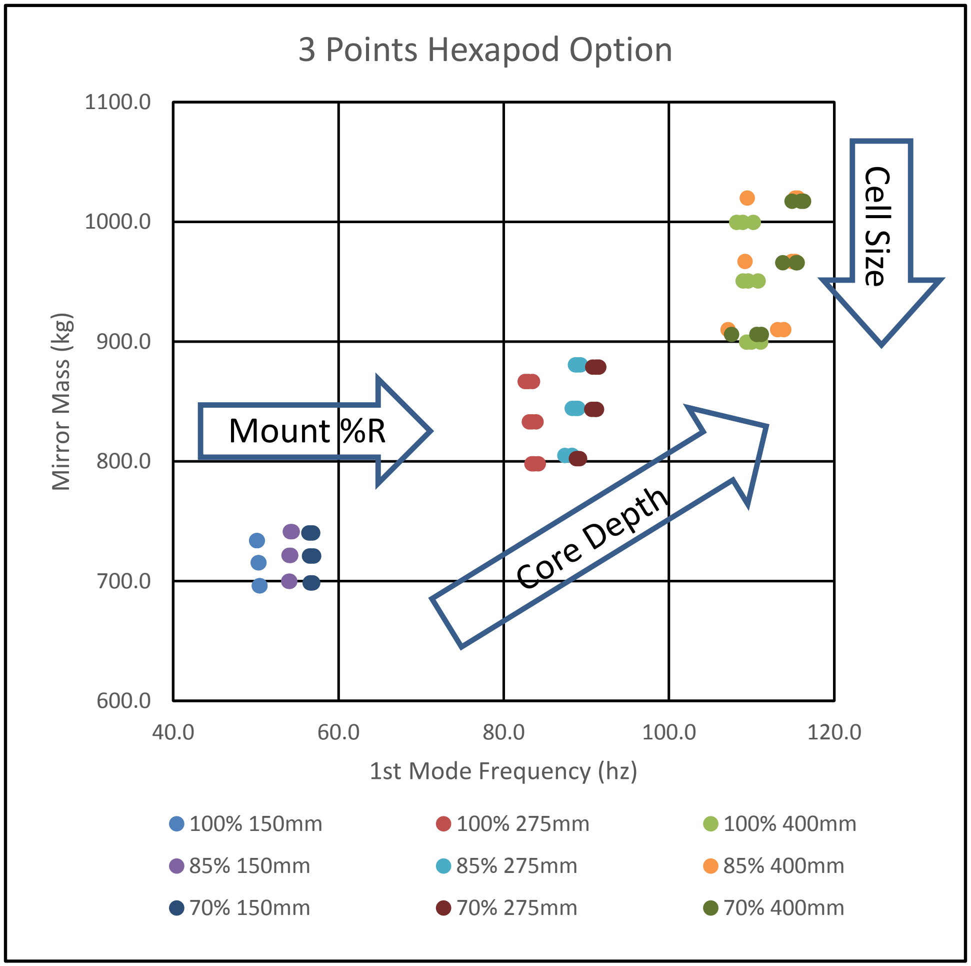


Cell Widths 192mm, 225mm and 290mm were selected to produce reasonable cells around the outer perimeter of the mirror.

The three support attachment diameters were chosen to best match up with cell wall intersections or cell centers. Slight adjustments were made to precisely align the pads.

The horizontal Hexapod angles where kept the same for each diameter to balance the translational and rotational stiffnesses of the system

# 3 POINTS HEXAPOD MASS vs FREQUENCY




- Thicker Cores produce stiffer and more massive mirrors.
- Larger Core Cells reduce mass with negligible frequency change.
- Mount Location increases frequency with negligible mass change.
- Hexapod Height has negligible effect.

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# RESULTS OF 3 POINTS HEXAPODS

## 100% Diameter

| HEX HEIGHT | CORE DEPTH | CELL WIDTH | SUPPORT MASS | SUPPORT 1ST | XYZ RMS |
|---|---|---|---|---|---|
| 0.250 | 0.150 | 0.192 | 733.7 | 50.2 | 3.626E-03 |
| 0.350 | 0.150 | 0.192 | 733.7 | 50.1 | 3.625E-03 |
| 0.450 | 0.150 | 0.192 | 733.7 | 50.1 | 3.639E-03 |
| 0.250 | 0.275 | 0.192 | 866.6 | 83.5 | 1.415E-03 |
| 0.350 | 0.275 | 0.192 | 866.6 | 83.0 | 1.414E-03 |
| 0.450 | 0.275 | 0.192 | 866.6 | 82.6 | 1.403E-03 |
| 0.250 | 0.400 | 0.192 | 999.5 | 110.2 | 8.880E-04 |
| 0.350 | 0.400 | 0.192 | 999.5 | 109.0 | 9.015E-04 |
| 0.450 | 0.400 | 0.192 | 999.5 | 108.2 | 9.009E-04 |
| | | | | | |
| 0.250 | 0.150 | 0.225 | 715.2 | 50.4 | 3.662E-03 |
| 0.350 | 0.150 | 0.225 | 715.2 | 50.3 | 3.660E-03 |
| 0.450 | 0.150 | 0.225 | 715.2 | 50.3 | 3.674E-03 |
| 0.250 | 0.275 | 0.225 | 832.9 | 83.9 | 1.425E-03 |
| 0.350 | 0.275 | 0.225 | 832.9 | 83.4 | 1.423E-03 |
| 0.450 | 0.275 | 0.225 | 832.9 | 83.1 | 1.412E-03 |
| 0.250 | 0.400 | 0.225 | 950.5 | 110.8 | 8.895E-04 |
| 0.350 | 0.400 | 0.225 | 950.5 | 109.6 | 9.009E-04 |
| 0.450 | 0.400 | 0.225 | 950.5 | 109.0 | 8.996E-04 |
| | | | | | |
| 0.250 | 0.150 | 0.290 | 696.0 | 50.5 | 3.686E-03 |
| 0.350 | 0.150 | 0.290 | 696.0 | 50.5 | 3.682E-03 |
| 0.450 | 0.150 | 0.290 | 696.0 | 50.4 | 3.696E-03 |
| 0.250 | 0.275 | 0.290 | 797.8 | 84.2 | 1.445E-03 |
| 0.350 | 0.275 | 0.290 | 797.8 | 83.7 | 1.441E-03 |
| 0.450 | 0.275 | 0.290 | 797.8 | 83.4 | 1.429E-03 |
| 0.250 | 0.400 | 0.290 | 899.6 | 111.1 | 9.020E-04 |
| 0.350 | 0.400 | 0.290 | 899.6 | 110.0 | 9.101E-04 |
| 0.450 | 0.400 | 0.290 | 899.6 | 109.4 | 9.075E-04 |

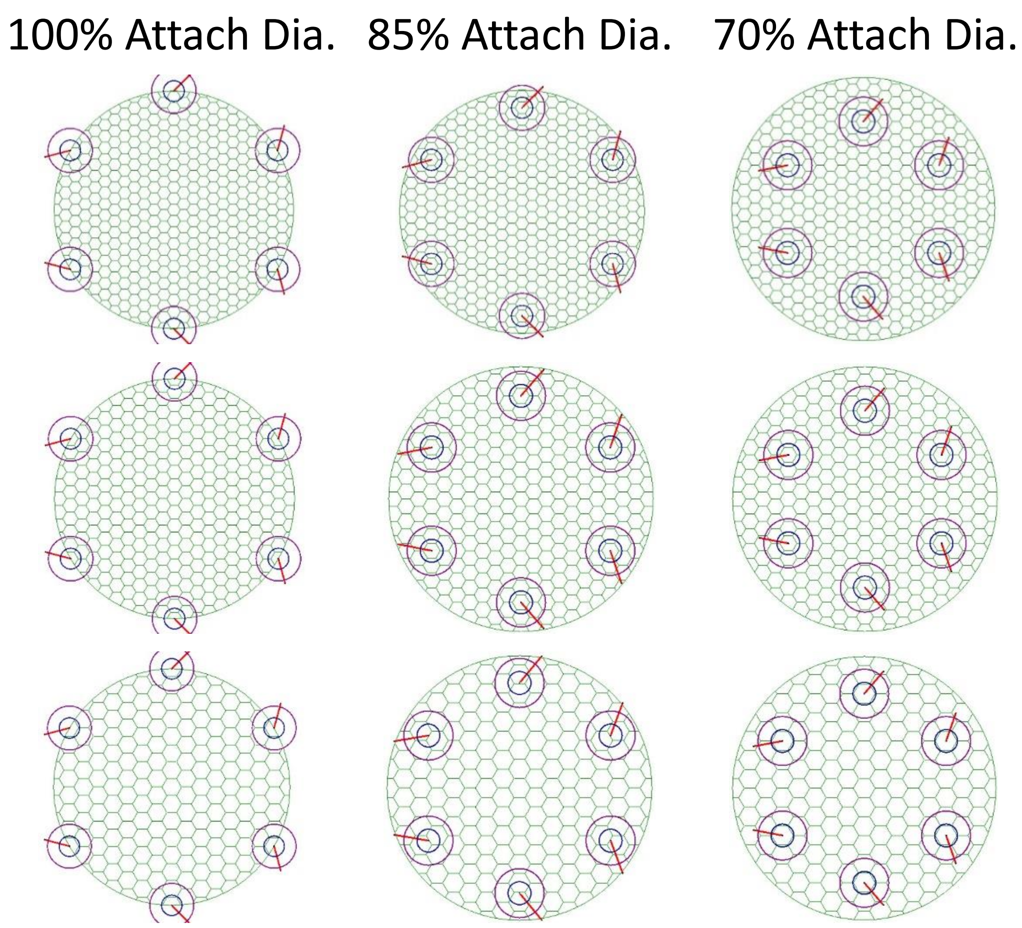
## 85% Diameter

| HEX HEIGHT | CORE DEPTH | CELL WIDTH | SUPPORT MASS | SUPPORT 1ST | XYZ RMS |
|---|---|---|---|---|---|
| 0.250 | 0.150 | 0.192 | 741.2 | 54.4 | 1.895E-03 |
| 0.350 | 0.150 | 0.192 | 741.2 | 54.3 | 1.900E-03 |
| 0.450 | 0.150 | 0.192 | 741.2 | 54.2 | 1.903E-03 |
| 0.250 | 0.275 | 0.192 | 880.4 | 88.7 | 8.171E-04 |
| 0.350 | 0.275 | 0.192 | 880.4 | 89.3 | 8.178E-04 |
| 0.450 | 0.275 | 0.192 | 880.4 | 88.9 | 8.175E-04 |
| 0.250 | 0.400 | 0.192 | 1019.7 | 109.5 | 6.103E-04 |
| 0.350 | 0.400 | 0.192 | 1019.7 | 115.3 | 5.808E-04 |
| 0.450 | 0.400 | 0.192 | 1019.7 | 115.6 | 5.746E-04 |
| | | | | | |
| 0.250 | 0.150 | 0.225 | 721.4 | 54.2 | 2.022E-03 |
| 0.350 | 0.150 | 0.225 | 721.4 | 54.2 | 2.027E-03 |
| 0.450 | 0.150 | 0.225 | 721.4 | 54.0 | 2.032E-03 |
| 0.250 | 0.275 | 0.225 | 844.1 | 88.3 | 8.675E-04 |
| 0.350 | 0.275 | 0.225 | 844.1 | 89.0 | 8.619E-04 |
| 0.450 | 0.275 | 0.225 | 844.1 | 88.7 | 8.542E-04 |
| 0.250 | 0.400 | 0.225 | 966.9 | 109.2 | 6.285E-04 |
| 0.350 | 0.400 | 0.225 | 966.9 | 114.9 | 6.006E-04 |
| 0.450 | 0.400 | 0.225 | 966.9 | 115.3 | 5.940E-04 |
| | | | | | |
| 0.250 | 0.150 | 0.290 | 699.9 | 54.1 | 2.030E-03 |
| 0.350 | 0.150 | 0.290 | 699.9 | 54.1 | 2.028E-03 |
| 0.450 | 0.150 | 0.290 | 699.9 | 54.0 | 2.027E-03 |
| 0.250 | 0.275 | 0.290 | 804.9 | 87.4 | 8.874E-04 |
| 0.350 | 0.275 | 0.290 | 804.9 | 88.3 | 8.764E-04 |
| 0.450 | 0.275 | 0.290 | 804.9 | 88.2 | 8.665E-04 |
| 0.250 | 0.400 | 0.290 | 909.9 | 107.2 | 6.326E-04 |
| 0.350 | 0.400 | 0.290 | 909.9 | 113.2 | 6.108E-04 |
| 0.450 | 0.400 | 0.290 | 909.9 | 113.9 | 6.032E-04 |

## 70% Diameter

| HEX HEIGHT | CORE DEPTH | CELL WIDTH | SUPPORT MASS | SUPPORT 1ST | XYZ RMS |
|---|---|---|---|---|---|
| 0.250 | 0.150 | 0.192 | 740.2 | 56.9 | 1.265E-03 |
| 0.350 | 0.150 | 0.192 | 740.2 | 56.6 | 1.202E-03 |
| 0.450 | 0.150 | 0.192 | 740.2 | 56.4 | 1.144E-03 |
| 0.250 | 0.275 | 0.192 | 878.6 | 91.5 | 6.937E-04 |
| 0.350 | 0.275 | 0.192 | 878.6 | 91.2 | 6.814E-04 |
| 0.450 | 0.275 | 0.192 | 878.6 | 90.8 | 6.585E-04 |
| 0.250 | 0.400 | 0.192 | 1017.1 | 114.9 | 5.284E-04 |
| 0.350 | 0.400 | 0.192 | 1017.1 | 116.3 | 5.287E-04 |
| 0.450 | 0.400 | 0.192 | 1017.1 | 116.0 | 5.275E-04 |
| | | | | | |
| 0.250 | 0.150 | 0.225 | 720.9 | 57.0 | 1.293E-03 |
| 0.350 | 0.150 | 0.225 | 720.9 | 56.7 | 1.234E-03 |
| 0.450 | 0.150 | 0.225 | 720.9 | 56.5 | 1.179E-03 |
| 0.250 | 0.275 | 0.225 | 843.3 | 91.2 | 6.965E-04 |
| 0.350 | 0.275 | 0.225 | 843.3 | 91.0 | 6.849E-04 |
| 0.450 | 0.275 | 0.225 | 843.3 | 90.7 | 6.622E-04 |
| 0.250 | 0.400 | 0.225 | 965.7 | 113.8 | 5.234E-04 |
| 0.350 | 0.400 | 0.225 | 965.7 | 115.5 | 5.257E-04 |
| 0.450 | 0.400 | 0.225 | 965.7 | 115.4 | 5.249E-04 |
| | | | | | |
| 0.250 | 0.150 | 0.290 | 698.4 | 56.9 | 1.347E-03 |
| 0.350 | 0.150 | 0.290 | 698.4 | 56.7 | 1.278E-03 |
| 0.450 | 0.150 | 0.290 | 698.4 | 56.6 | 1.216E-03 |
| 0.250 | 0.275 | 0.290 | 802.1 | 88.8 | 7.314E-04 |
| 0.350 | 0.275 | 0.290 | 802.1 | 89.2 | 7.173E-04 |
| 0.450 | 0.275 | 0.290 | 802.1 | 89.0 | 6.927E-04 |
| 0.250 | 0.400 | 0.290 | 905.8 | 107.6 | 5.478E-04 |
| 0.350 | 0.400 | 0.290 | 905.8 | 110.6 | 5.523E-04 |
| 0.450 | 0.400 | 0.290 | 905.8 | 111.2 | 5.506E-04 |

# 6 POINT HEXAPOD GEOMETRIES

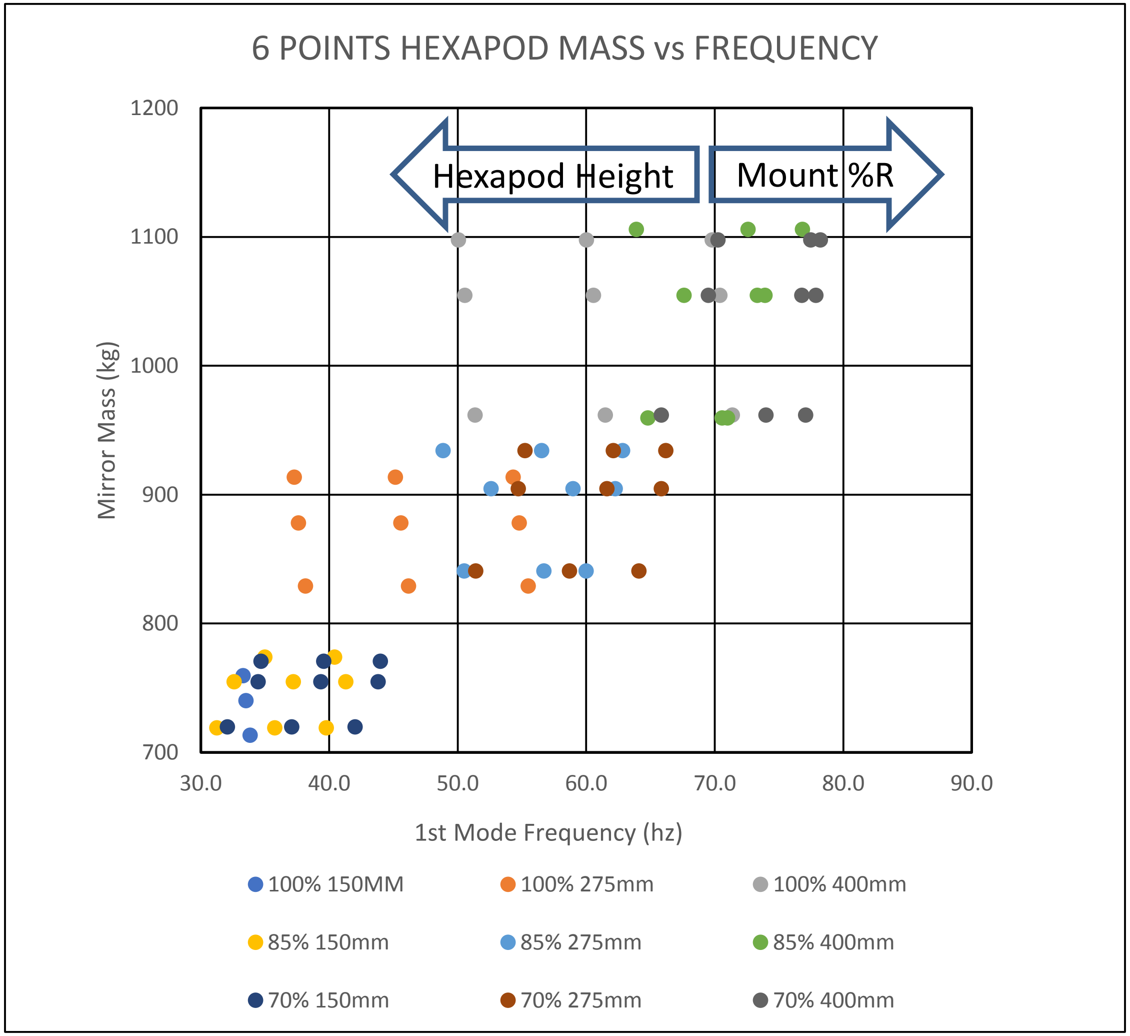



Cell Widths 192mm, 225mm and 290mm were selected to produce reasonable cells around the outer perimeter of the mirror.

The three support attachment diameters were chosen to best match up with cell wall intersections or cell centers. Slight adjustments were made to precisely align the pads.

The horizontal Hexapod angles where kept the same for each diameter to balance the translational and rotational stiffnesses of the system

# 6 POINTS HEXAPOD MASS vs FREQUENCY




- Similar Trend, i.e. thickness increases mass and stiffness & cell size decreases mass.
- But 6-point mount results in greater frequency spread with mount location and hexapod height
- Increasing hexapod height decreases frequency

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# RESULTS OF 6 POINTS HEXAPODS

NASA

## 100% Diameter

| HEX | CORE | CELL | UPPOR | UPPORT | XYZ |
|---|---|---|---|---|---|
| HEIGHT | DEPTH | WIDTH | MASS | 1ST | RMS |
| 0.250 | 0.150 | 0.192 | 759.6 | 33.3 | 1.754E-02 |
| 0.350 | 0.150 | 0.192 | 759.6 | 27.0 | 2.509E-02 |
| 0.450 | 0.150 | 0.192 | 759.6 | 22.2 | 3.276E-02 |
| 0.250 | 0.275 | 0.192 | 913.6 | 54.3 | 6.193E-03 |
| 0.350 | 0.275 | 0.192 | 913.6 | 45.2 | 8.841E-03 |
| 0.450 | 0.275 | 0.192 | 913.6 | 37.3 | 1.160E-02 |
| 0.250 | 0.400 | 0.192 | 1067.6 | 69.8 | 3.474E-03 |
| 0.350 | 0.400 | 0.192 | 1067.6 | 60.0 | 4.895E-03 |
| 0.450 | 0.400 | 0.192 | 1067.6 | 50.1 | 6.411E-03 |
| | | | | | |
| 0.250 | 0.150 | 0.225 | 740.2 | 33.5 | 1.749E-02 |
| 0.350 | 0.150 | 0.225 | 740.2 | 27.2 | 2.501E-02 |
| 0.450 | 0.150 | 0.225 | 740.2 | 22.3 | 3.265E-02 |
| 0.250 | 0.275 | 0.225 | 878.1 | 54.8 | 6.150E-03 |
| 0.350 | 0.275 | 0.225 | 878.1 | 45.6 | 8.767E-03 |
| 0.450 | 0.275 | 0.225 | 878.1 | 37.6 | 1.149E-02 |
| 0.250 | 0.400 | 0.225 | 1016.0 | 70.4 | 3.447E-03 |
| 0.350 | 0.400 | 0.225 | 1016.0 | 60.6 | 4.847E-03 |
| 0.450 | 0.400 | 0.225 | 1016.0 | 50.5 | 6.341E-03 |
| | | | | | |
| 0.250 | 0.150 | 0.290 | 713.4 | 33.9 | 1.756E-02 |
| 0.350 | 0.150 | 0.290 | 713.4 | 27.5 | 2.507E-02 |
| 0.450 | 0.150 | 0.290 | 713.4 | 22.5 | 3.272E-02 |
| 0.250 | 0.275 | 0.290 | 829.2 | 55.5 | 6.129E-03 |
| 0.350 | 0.275 | 0.290 | 829.2 | 46.2 | 8.723E-03 |
| 0.450 | 0.275 | 0.290 | 829.2 | 38.2 | 1.142E-02 |
| 0.250 | 0.400 | 0.290 | 945.0 | 71.4 | 3.423E-03 |
| 0.350 | 0.400 | 0.290 | 945.0 | 61.5 | 4.802E-03 |
| 0.450 | 0.400 | 0.290 | 945.0 | 51.3 | 6.272E-03 |

## 85% Diameter

| HEX | CORE | CELL | UPPOR | UPPORT | XYZ |
|---|---|---|---|---|---|
| HEIGHT | DEPTH | WIDTH | MASS | 1ST | RMS |
| 0.250 | 0.150 | 0.192 | 773.9 | 40.4 | 1.094E-02 |
| 0.350 | 0.150 | 0.192 | 773.9 | 35.0 | 1.584E-02 |
| 0.450 | 0.150 | 0.192 | 773.9 | 29.8 | 2.083E-02 |
| 0.250 | 0.275 | 0.192 | 939.9 | 62.8 | 3.981E-03 |
| 0.350 | 0.275 | 0.192 | 939.9 | 56.5 | 5.755E-03 |
| 0.450 | 0.275 | 0.192 | 939.9 | 48.9 | 7.598E-03 |
| 0.250 | 0.400 | 0.192 | 1105.9 | 76.8 | 2.275E-03 |
| 0.350 | 0.400 | 0.192 | 1105.9 | 72.6 | 3.271E-03 |
| 0.450 | 0.400 | 0.192 | 1105.9 | 63.9 | 4.315E-03 |
| | | | | | |
| 0.250 | 0.150 | 0.225 | 754.7 | 41.3 | 9.516E-03 |
| 0.350 | 0.150 | 0.225 | 754.7 | 37.2 | 1.390E-02 |
| 0.450 | 0.150 | 0.225 | 754.7 | 32.6 | 1.837E-02 |
| 0.250 | 0.275 | 0.225 | 904.7 | 62.3 | 3.536E-03 |
| 0.350 | 0.275 | 0.225 | 904.7 | 59.0 | 5.127E-03 |
| 0.450 | 0.275 | 0.225 | 904.7 | 52.6 | 6.795E-03 |
| 0.250 | 0.400 | 0.225 | 1054.8 | 73.3 | 2.044E-03 |
| 0.350 | 0.400 | 0.225 | 1054.8 | 73.9 | 2.980E-03 |
| 0.450 | 0.400 | 0.225 | 1054.8 | 67.6 | 3.936E-03 |
| | | | | | |
| 0.250 | 0.150 | 0.290 | 718.9 | 39.8 | 1.054E-02 |
| 0.350 | 0.150 | 0.290 | 718.9 | 35.8 | 1.536E-02 |
| 0.450 | 0.150 | 0.290 | 718.9 | 31.3 | 2.028E-02 |
| 0.250 | 0.275 | 0.290 | 839.3 | 60.0 | 3.921E-03 |
| 0.350 | 0.275 | 0.290 | 839.3 | 56.7 | 5.651E-03 |
| 0.450 | 0.275 | 0.290 | 839.3 | 50.5 | 7.466E-03 |
| 0.250 | 0.400 | 0.290 | 959.6 | 70.6 | 2.278E-03 |
| 0.350 | 0.400 | 0.290 | 959.6 | 71.0 | 3.296E-03 |
| 0.450 | 0.400 | 0.290 | 959.6 | 64.8 | 4.334E-03 |

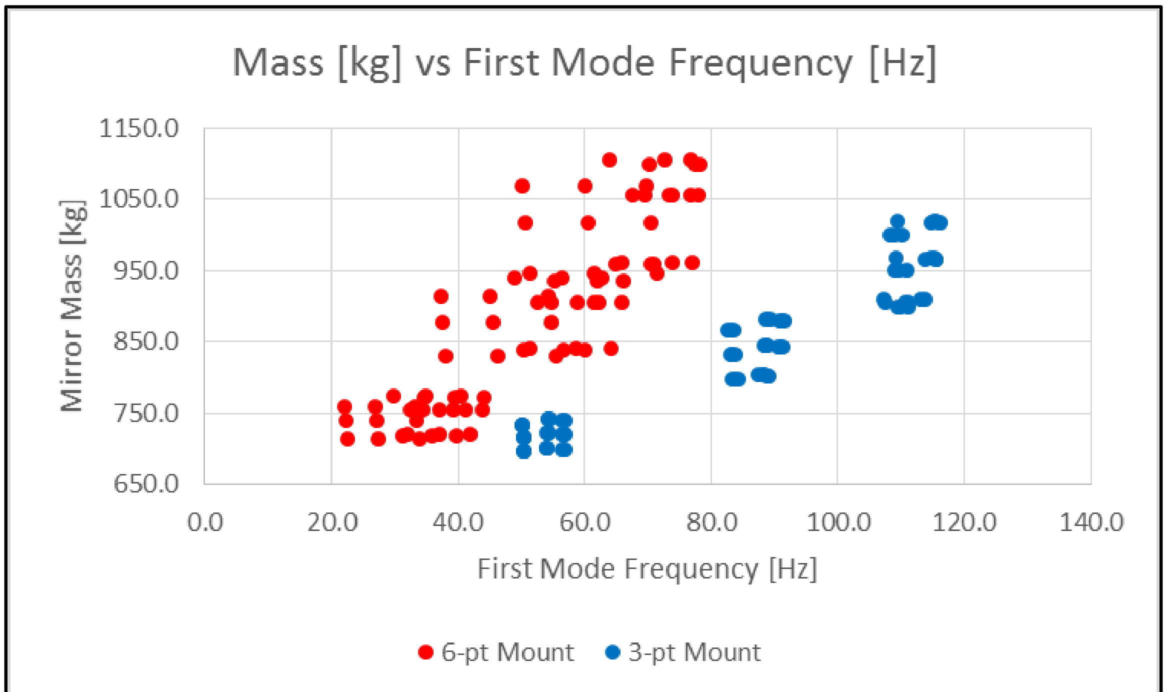
## 70% Diameter

| HEX | CORE | CELL | UPPOR | UPPORT | XYZ |
|---|---|---|---|---|---|
| HEIGHT | DEPTH | WIDTH | MASS | 1ST | RMS |
| 0.250 | 0.150 | 0.192 | 770.8 | 44.0 | 8.112E-03 |
| 0.350 | 0.150 | 0.192 | 770.8 | 39.6 | 1.188E-02 |
| 0.450 | 0.150 | 0.192 | 770.8 | 34.7 | 1.572E-02 |
| 0.250 | 0.275 | 0.192 | 934.2 | 66.2 | 3.066E-03 |
| 0.350 | 0.275 | 0.192 | 934.2 | 62.1 | 4.503E-03 |
| 0.450 | 0.275 | 0.192 | 934.2 | 55.2 | 5.995E-03 |
| 0.250 | 0.400 | 0.192 | 1097.6 | 78.2 | 1.778E-03 |
| 0.350 | 0.400 | 0.192 | 1097.6 | 77.5 | 2.652E-03 |
| 0.450 | 0.400 | 0.192 | 1097.6 | 70.3 | 3.542E-03 |
| | | | | | |
| 0.250 | 0.150 | 0.225 | 754.7 | 43.8 | 8.231E-03 |
| 0.350 | 0.150 | 0.225 | 754.7 | 39.4 | 1.205E-02 |
| 0.450 | 0.150 | 0.225 | 754.7 | 34.5 | 1.593E-02 |
| 0.250 | 0.275 | 0.225 | 904.7 | 65.9 | 3.129E-03 |
| 0.350 | 0.275 | 0.225 | 904.7 | 61.6 | 4.592E-03 |
| 0.450 | 0.275 | 0.225 | 904.7 | 54.7 | 6.107E-03 |
| 0.250 | 0.400 | 0.225 | 1054.8 | 77.9 | 1.821E-03 |
| 0.350 | 0.400 | 0.225 | 1054.8 | 76.8 | 2.716E-03 |
| 0.450 | 0.400 | 0.225 | 1054.8 | 69.5 | 3.626E-03 |
| | | | | | |
| 0.250 | 0.150 | 0.290 | 719.8 | 42.0 | 9.615E-03 |
| 0.350 | 0.150 | 0.290 | 719.8 | 37.1 | 1.403E-02 |
| 0.450 | 0.150 | 0.290 | 719.8 | 32.1 | 1.851E-02 |
| 0.250 | 0.275 | 0.290 | 840.8 | 64.1 | 3.616E-03 |
| 0.350 | 0.275 | 0.290 | 840.8 | 58.7 | 5.280E-03 |
| 0.450 | 0.275 | 0.290 | 840.8 | 51.4 | 6.998E-03 |
| 0.250 | 0.400 | 0.290 | 961.9 | 77.1 | 2.108E-03 |
| 0.350 | 0.400 | 0.290 | 961.9 | 74.0 | 3.100E-03 |
| 0.450 | 0.400 | 0.290 | 961.9 | 65.9 | 4.115E-03 |

# 6 POINTS HEXAPOD MASS vs FREQUENCY

For similar closed back mirror substrate architectures, 3-point mount provides higher assembly stiffness than 6-point mount at a lower total mass.

Spread in Frequency is driven by mount design: Height and %R.



# Gravity Sag Analysis

SPIE 10743-10 SPIE Conference 10743
22 August 2018 in San Diego, Ca United States

# Gravity Sag

Gravity Sag is important to HabEx for two reasons:

- Diffraction Limited Performance
- Wavefront Stability for Coronagraph Performance.

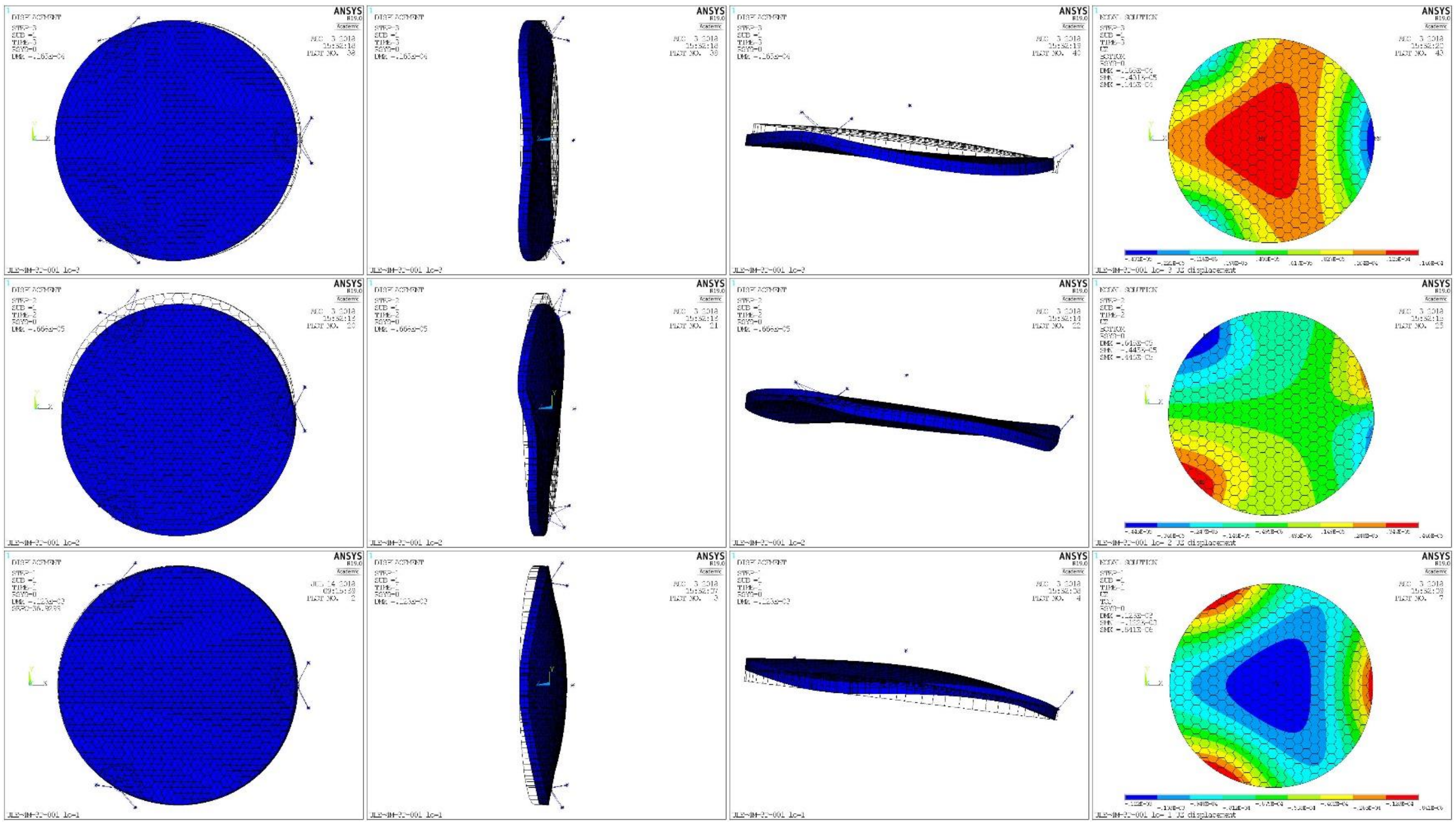
For HabEx to have diffraction limited performance at 400 nm:

- Requires primary mirror on-orbit surface figure < ~ 8 nm rms.
- To achieve this level of precision, G-Release (Gravity Sag back-out uncertainty) needs to be ~ 2 nm rms.
- The smaller the mirrors total Gravity Sag, the easier it is to back it out during manufacture and test.

Exoplanet Science via Coronagraphy:

- requires an ultra-stable wavefront that meets the Zernike polynomial error budget.
- Inertial WFE is a component of that error budget.

# STATIC ACCELERATION DISPLACEMENTS




1G X

1G Y

1G Z

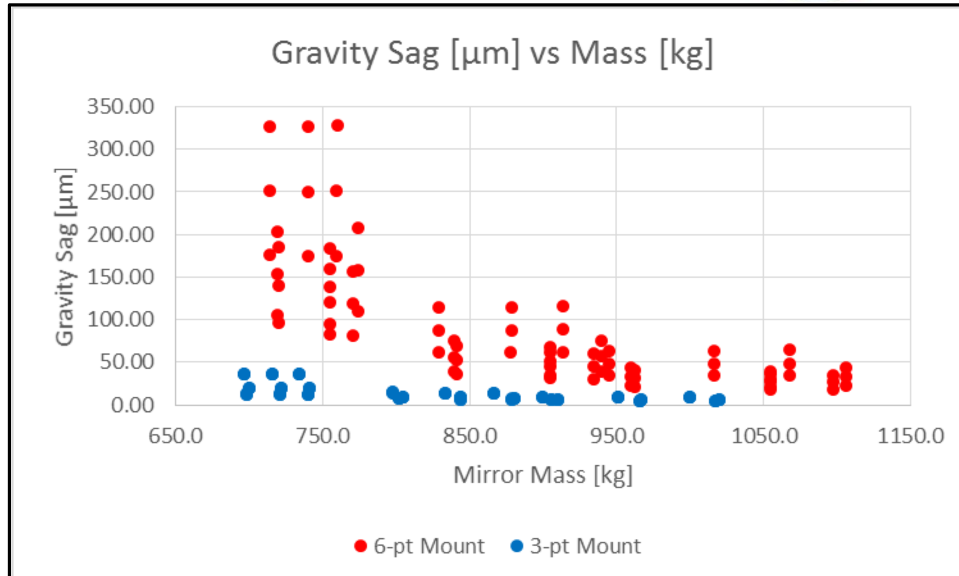
The three directional surface RMS levels are RSS into a "Global RMS" response.

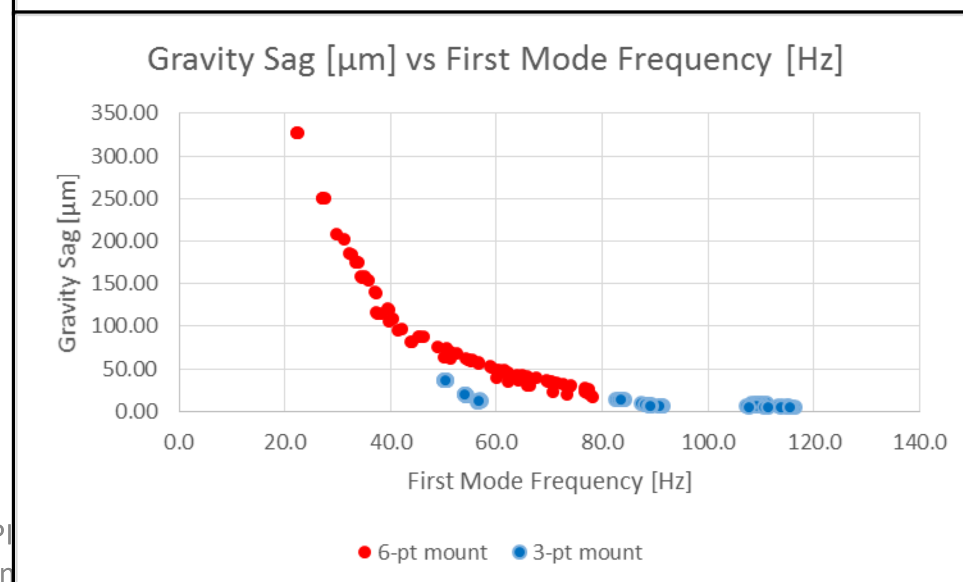
# Gravity Sag

- As expected, thicker mirrors have smaller gravity sag (because they are stiffer).
- 3-point mount has smaller gravity sag than 6-point mount.
- As expected, gravity sag and stiffness are proportional:

  G-sag ~ (1/ Freq)^2

- But for Inertial Stability, the shape of G-sag is important.



# Inertial Error

Inertial error is proportional to Gravity Sag.

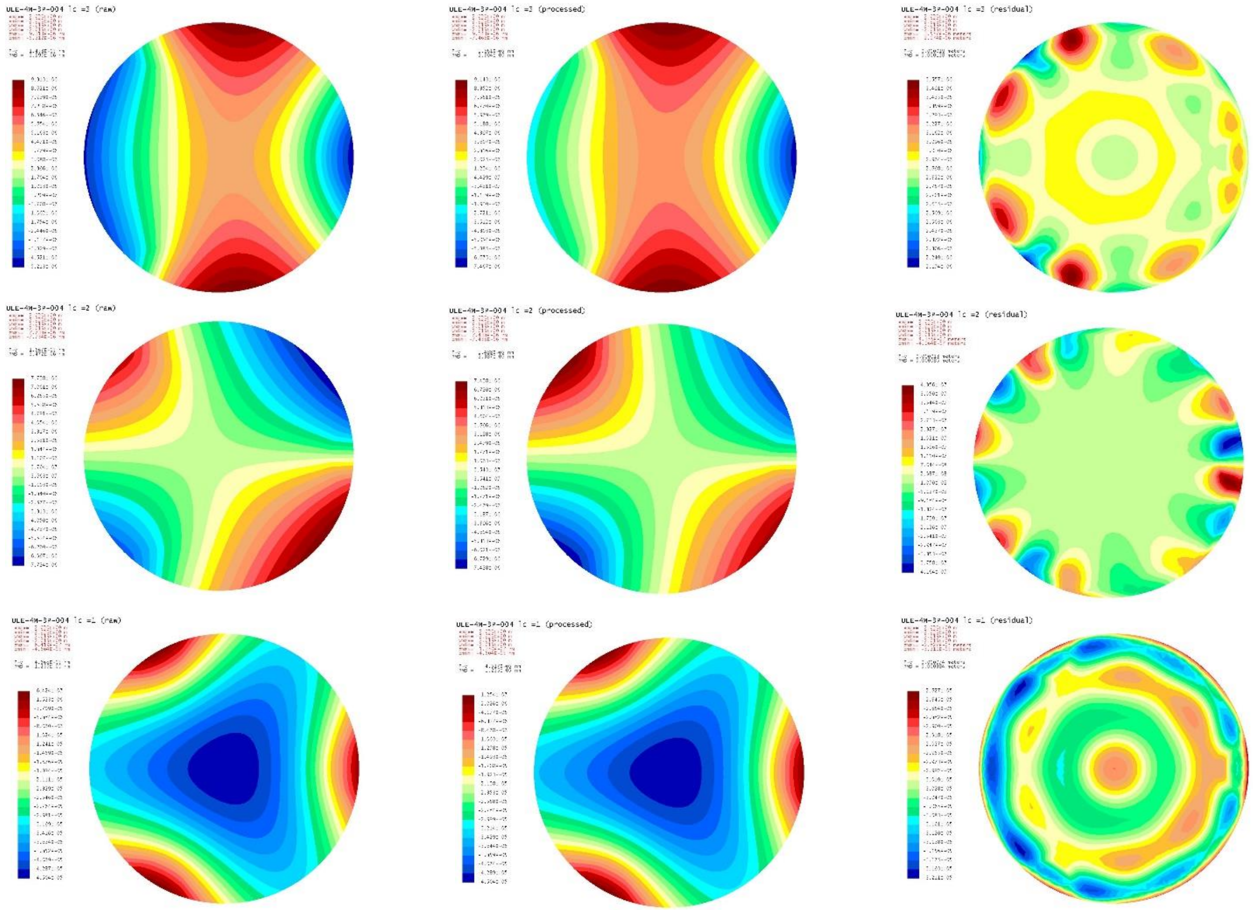
- 1 G acceleration = 1 Gravity Sag
- 1 µG acceleration = 1 µ-Gravity Sag

Methodology for this study is:

- Calculate Gravity Sag for Mirror System in (X,Y,Z)
- Decompose (X,Y,Z) Gravity Sag in to Zernike polynomials.
- Scale from 1G to 0.1 µG
  - Micro-thruster noise specified < 0.07 µN ( < 0.007 µG )
  - HabEx has 16 microthrusters providing a sphere of thrust
  - Vector Noise is < 0.14 µN per axis (< 0.015 µG per axis)
- Multiply each (X,Y,Z) Zernike x 0.15 for 10X margin before dampening.
- RSS (X,Y,Z) Zernike coefficients produces error for 0.15 µG in all 3 axis.

# ZERNIKE CALCULATIONS

Raw Data | Piston & Tilt Removed | Residual All Zij Removed



1g X

1g Y

1g Z

# RAW INPUT TO EXCEL

Sigfit Comparison    Title: ULE-4M-3P-004 lc =1

| Order K | N | M | Aberration | Magnitude (nm) | Phase (Deg) | Residual RMS | Residual P-V |
|---|---|---|---|---|---|---|---|
| | | | Input (wrt) | | | 0.001236 | 0.004568 |
| 1 | 0 | 0 | Bias | 0.002669 | 0.00 | 0.001236 | 0.004568 |
| 2 | 1 | 1 | Tilt | 0.000107 | 0.06 | 0.001235 | 0.004517 |
| 3 | 2 | 0 | Power (Defocus) | 0.001403 | 0.00 | 0.000815 | 0.003402 |
| 4 | 2 | 2 | Pri Astigmatism | 0.000109 | 0.20 | 0.000814 | 0.003316 |
| 5 | 3 | 1 | Pri Coma | 0.000025 | 0.95 | 0.000814 | 0.003266 |
| 6 | 3 | 3 | Pri Trefoil | 0.001797 | 0.00 | 0.000143 | 0.000757 |
| 7 | 4 | 0 | Pri Spherical | 0.000085 | 0.00 | 0.000122 | 0.000643 |
| 8 | 4 | 2 | Sec Astigmatism | 0.000011 | 3.65 | 0.000122 | 0.000649 |
| 9 | 4 | 4 | Pri Tetrafoil | 0.000008 | 3.30 | 0.000121 | 0.000638 |
| 10 | 5 | 1 | Sec Coma | 0.000001 | 39.78 | 0.000121 | 0.000637 |
| 11 | 5 | 3 | Sec Trefoil | 0.000174 | 0.03 | 0.000095 | 0.000519 |
| 12 | 5 | 5 | Pri Pentafoil | 0.000022 | 1.34 | 0.000095 | 0.000505 |
| 13 | 6 | 0 | Sec Spherical | 0.000048 | 0.00 | 0.000090 | 0.000436 |
| 14 | 6 | 2 | Ter Astigmatism | 0.000002 | 8.96 | 0.000090 | 0.000435 |
| 15 | 6 | 4 | Sec Tetrafoil | 0.000001 | 65.56 | 0.000090 | 0.000435 |
| 16 | 6 | 6 | Pri Hexafoil | 0.000214 | 0.04 | 0.000047 | 0.000257 |
| 17 | 7 | 1 | Ter Coma | 0.000003 | 19.05 | 0.000047 | 0.000256 |
| 18 | 7 | 3 | Ter Trefoil | 0.000021 | 0.31 | 0.000045 | 0.000268 |
| 19 | 7 | 5 | Sec Pentafoil | 0.000006 | 11.39 | 0.000045 | 0.000265 |
| 20 | 8 | 0 | Ter Spherical | 0.000147 | 89.70 | 0.000074 | 0.000389 |
| 21 | 8 | 2 | Qua Astigmatism | 0.000002 | 19.29 | 0.000074 | 0.000389 |
| 22 | 8 | 4 | Ter Tetrafoil | 0.000001 | 5.52 | 0.000074 | 0.000388 |
| 23 | 8 | 6 | Sec Hexafoil | 0.000093 | 0.31 | 0.000074 | 0.000384 |

This is sample output from a custom program which uses the SIGFIT data presentation format to match other HABEX activities, the units have been adjusted to RMS nanometers per a micro-g acceleration input.    Note:  SigFit © Sigmadyne Corp.

# Core Depth Trade Study

## 190 mm Core Cell Size & Mount at 100%

- The thicker the core depth, the smaller the Inertial Bending.
- None of the mirrors meet Error Budget Specification.
- Need to do mass damping analysis.

| ZERNIKES | Inertial Bending WFE | 3 Point Mount Error [pm rms] | | | 6 Point Mount Error [pm rms] | | |
|---|---|---|---|---|---|---|---|
| K N M | Tolerance [pm rms] | 150 mm | 275 mm | 400 mm | 150 mm | 275 mm | 400 mm |
| 3 2 0 Power (Defocus) | 150 | 11.364 | 4.239 | 2.335 | 11.057 | 3.822 | 1.939 |
| 4 2 2 Pri Astigmatism | 120 | 1.126 | 3.037 | 3.034 | 60.998 | 19.948 | 9.967 |
| 5 3 1 Pri Coma | 105 | 0.249 | 0.082 | 0.048 | 0.244 | 0.104 | 0.072 |
| 6 3 3 Pri Trefoil | 1.56 | 14.750 | 5.430 | 3.094 | 1.581 | 1.225 | 1.024 |
| 7 4 0 Pri Spherical | 120 | 0.514 | 0.258 | 0.167 | 0.789 | 0.373 | 0.233 |
| 8 4 2 Sec Astigmatism | 0.21 | 0.052 | 0.119 | 0.143 | 2.732 | 1.094 | 0.669 |
| 9 4 4 Pri Tetrafoil | 0.21 | 0.509 | 0.385 | 0.302 | 5.994 | 2.336 | 1.403 |
| 10 5 1 Sec Coma | 0.21 | 0.030 | 0.004 | 0.007 | 0.030 | 0.007 | 0.015 |
| 11 5 3 Sec Trefoil | 0.21 | 1.180 | 0.526 | 0.351 | 0.124 | 0.107 | 0.100 |
| 12 5 5 Pri Pentafoil | 0.21 | 0.372 | 0.377 | 0.344 | 0.689 | 0.529 | 0.442 |
| 13 6 0 Sec Spherical | 0.21 | 0.331 | 0.145 | 0.096 | 0.240 | 0.132 | 0.102 |
| 14 6 2 Ter Astigmatism | 0.06 | 0.042 | 0.016 | 0.013 | 0.153 | 0.150 | 0.124 |
| 15 6 4 Sec Tetrafoil | 0.06 | 0.042 | 0.047 | 0.034 | 0.766 | 0.419 | 0.318 |
| 16 6 6 Pri Hexafoil | | 1.451 | 0.647 | 0.421 | 1.995 | 0.855 | 0.544 |
| 17 7 1 Ter Coma | 0.06 | 0.030 | 0.010 | 0.010 | 0.030 | 0.011 | 0.010 |
| 18 7 3 Ter Trefoil | 0.06 | 0.030 | 0.064 | 0.064 | 0.030 | 0.010 | 0.003 |
| 19 7 5 Sec Pentafoil | | 0.052 | 0.066 | 0.065 | 0.112 | 0.102 | 0.095 |
| 20 8 0 Ter Spherical | 0.06 | 1.215 | 0.453 | 0.266 | 0.681 | 0.296 | 0.208 |
| 21 8 2 Qua Astigmatism | 0.06 | 0.000 | 0.006 | 0.005 | 0.042 | 0.022 | 0.017 |
| 22 8 4 Ter Tetrafoil | | 0.000 | 0.004 | 0.004 | 0.112 | 0.075 | 0.062 |
| 23 8 6 Sec Hexafoil | | 0.543 | 0.281 | 0.208 | 0.351 | 0.249 | 0.198 |

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# Core Depth Trade Study

## 190 mm Core Cell Size & Mount at 100%

- The thicker the core depth, the smaller the Inertial Bending.
- None of the mirrors meet Error Budget Specification.
- Need to do mass damping analysis.

| ZERNIKES | WFE Tol | 3 Point Mount Error [pm rms] | | | 6 Point Mount Error [pm rms] | | |
|---|---|---|---|---|---|---|---|
| K N M | [pm rms] | 150 mm | 275 mm | 400 mm | 150 mm | 275 mm | 400 mm |
| 3 2 0 Power (Defocus) | 150.00 | 11.376 | 4.238 | 2.335 | 11.067 | 3.822 | 1.939 |
| 4 2 2 Pri Astigmatism | 120.00 | 1.128 | 3.037 | 3.033 | 60.995 | 19.948 | 9.967 |
| 5 3 1 Pri Coma | 105.00 | 0.252 | 0.083 | 0.047 | 0.253 | 0.104 | 0.071 |
| 6 4 0 Pri Spherical | 120.00 | 0.520 | 0.258 | 0.166 | 0.797 | 0.373 | 0.233 |
| 7 3 3 Pri Trefoil | 1.56 | 14.761 | 5.431 | 3.094 | 1.597 | 1.225 | 1.025 |
| 8 4 2 Sec Astigmatism | 0.21 | 0.051 | 0.120 | 0.144 | 2.718 | 1.094 | 0.669 |
| 9 5 1 Sec Coma | 0.21 | 0.022 | 0.004 | 0.009 | 0.017 | 0.007 | 0.016 |
| 10 6 0 Sec Spherical | 0.21 | 0.334 | 0.146 | 0.097 | 0.252 | 0.132 | 0.102 |
| 11 4 4 Pri Tetrafoil | 0.21 | 0.491 | 0.384 | 0.302 | 5.996 | 2.336 | 1.404 |
| 12 5 3 Sec Trefoil | 0.21 | 1.171 | 0.527 | 0.352 | 0.120 | 0.108 | 0.100 |
| 13 6 2 Ter Astigmatism | 0.06 | 0.029 | 0.016 | 0.014 | 0.224 | 0.151 | 0.124 |
| 14 7 1 Ter Coma | 0.06 | 0.026 | 0.011 | 0.011 | 0.019 | 0.010 | 0.012 |
| 15 8 0 Ter Spherical | 0.06 | 1.213 | 0.454 | 0.266 | 0.671 | 0.295 | 0.208 |
| 16 5 5 Pri Pentafoil | 0.21 | 0.365 | 0.377 | 0.342 | 0.693 | 0.528 | 0.443 |
| 17 6 4 Sec Tetrafoil | 0.06 | 0.055 | 0.047 | 0.035 | 0.749 | 0.418 | 0.318 |
| 18 7 3 Ter Trefoil | 0.06 | 0.044 | 0.065 | 0.064 | 0.016 | 0.008 | 0.003 |
| 19 8 2 Qua Astigmatism | 0.06 | 0.012 | 0.005 | 0.007 | 0.033 | 0.022 | 0.017 |
| 20 9 1 Qua Coma | 0.06 | 0.097 | 0.088 | 0.078 | 0.182 | 0.084 | 0.053 |
| 21 10 2 Qua Astigmatism | 0.06 | 0.003 | 0.003 | 0.005 | 0.003 | 0.002 | 0.003 |
| 22 12 0 Qin Spherical | 0.06 | 2.613 | 0.943 | 0.536 | 1.350 | 0.540 | 0.373 |

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# Mount Location Trade Study

## 400 mm Core Depth & 290 mm Core Cell Size

- No definitive answer as to best location to mount mirror.
- Some Zernike terms are lower for edge mount & others higher
- 3-point mount in general has less higher frequency error.

| ZERNIKES | Inertial Bending WFE | 3 Point Mount Error [pm rms] | | | 6 Point Mount Error [pm rms] | | |
|---|---|---|---|---|---|---|---|
| K N M | Tolerance [pm rms] | 100% | 85% | 70% | 100% | 85% | 70% |
| 3 2 0 Power (Defocus) | 150 | 2.600 | 0.631 | 0.834 | 2.225 | 0.082 | 0.632 |
| 4 2 2 Pri Astigmatism | 120 | 2.876 | 2.814 | 2.633 | 9.527 | 4.728 | 5.050 |
| 5 3 1 Pri Coma | 105 | 0.051 | 0.230 | 0.492 | 0.071 | 0.357 | 0.479 |
| 6 3 3 Pri Trefoil | 1.56 | 3.128 | 2.397 | 1.608 | 0.969 | 0.787 | 0.590 |
| 7 4 0 Pri Spherical | 120 | 0.030 | 0.364 | 0.243 | 0.136 | 0.450 | 0.325 |
| 8 4 2 Sec Astigmatism | 0.21 | 0.134 | 0.360 | 0.637 | 0.683 | 1.371 | 1.806 |
| 9 4 4 Pri Tetrafoil | 0.21 | 0.290 | 0.085 | 0.022 | 1.457 | 0.954 | 0.894 |
| 10 5 1 Sec Coma | 0.21 | 0.012 | 0.047 | 0.046 | 0.021 | 0.039 | 0.024 |
| 11 5 3 Sec Trefoil | 0.21 | 0.396 | 1.170 | 1.242 | 0.094 | 0.184 | 0.190 |
| 12 5 5 Pri Pentafoil | 0.21 | 0.345 | 0.245 | 0.150 | 0.437 | 0.319 | 0.284 |
| 13 6 0 Sec Spherical | 0.21 | 0.060 | 0.006 | 0.257 | 0.067 | 0.023 | 0.223 |
| 14 6 2 Ter Astigmatism | 0.06 | 0.017 | 0.012 | 0.167 | 0.150 | 0.064 | 0.360 |
| 15 6 4 Sec Tetrafoil | 0.06 | 0.028 | 0.051 | 0.047 | 0.353 | 0.810 | 0.971 |
| 16 6 6 Pri Hexafoil | | 0.430 | 0.339 | 0.179 | 0.607 | 0.310 | 0.329 |
| 17 7 1 Ter Coma | 0.06 | 0.016 | 0.021 | 0.064 | 0.016 | 0.040 | 0.066 |
| 18 7 3 Ter Trefoil | 0.06 | 0.085 | 0.121 | 0.508 | 0.000 | 0.030 | 0.051 |
| 19 7 5 Sec Pentafoil | | 0.070 | 0.142 | 0.163 | 0.096 | 0.247 | 0.277 |
| 20 8 0 Ter Spherical | 0.06 | 0.380 | 0.208 | 0.174 | 0.278 | 0.160 | 0.084 |
| 21 8 2 Qua Astigmatism | 0.06 | 0.009 | 0.038 | 0.019 | 0.015 | 0.169 | 0.126 |
| 22 8 4 Ter Tetrafoil | | 0.005 | 0.020 | 0.028 | 0.070 | 0.263 | 0.474 |
| 23 8 6 Sec Hexafoil | | 0.323 | 0.498 | 0.305 | 0.175 | 0.387 | 0.227 |

# Mount Location Trade Study

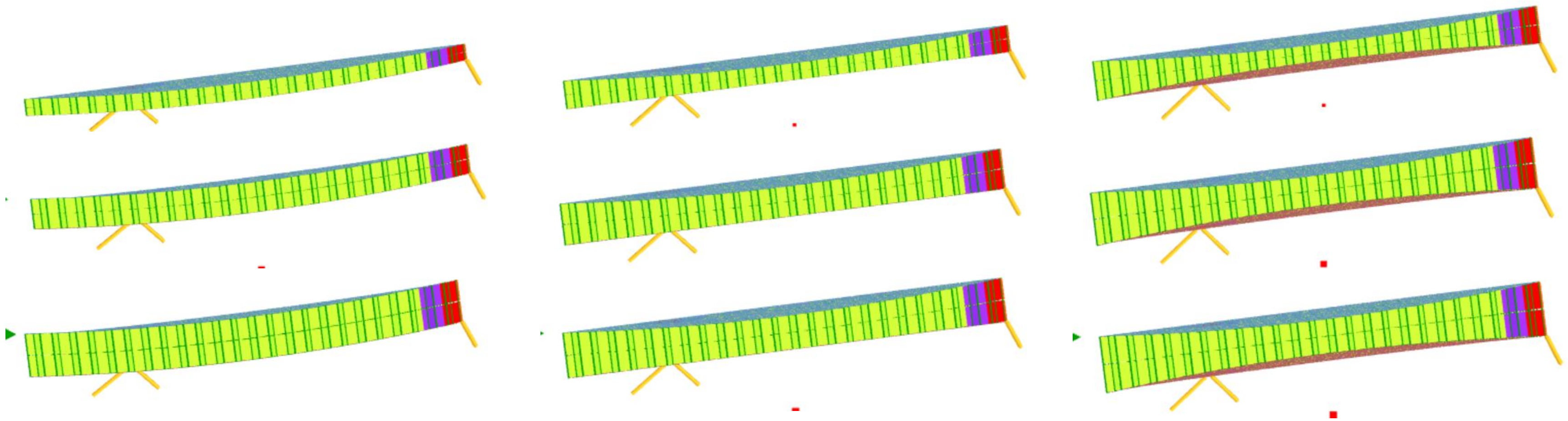
## 400 mm Core Depth & 290 mm Core Cell Size

- No definitive answer as to best location to mount mirror.
- Some Zernike terms are lower for edge mount & others higher
- 3-point mount in general has less higher frequency error.

| ZERNIKES | WFE Tol | 3 Point Mount Error [pm rms] | | | 6 Point Mount Error [pm rms] | | |
|---|---|---|---|---|---|---|---|
| K N M | [pm rms] | 100% | 85% | 70% | 100% | 85% | 70% |
| 3 2 0 Power (Defocus) | 150.00 | 2.599 | 0.632 | 0.834 | 2.226 | 0.083 | 0.633 |
| 4 2 2 Pri Astigmatism | 120.00 | 2.876 | 2.813 | 2.633 | 9.527 | 4.727 | 5.050 |
| 5 3 1 Pri Coma | 105.00 | 0.050 | 0.231 | 0.491 | 0.069 | 0.357 | 0.478 |
| 6 4 0 Pri Spherical | 120.00 | 0.031 | 0.365 | 0.244 | 0.136 | 0.451 | 0.325 |
| 7 3 3 Pri Trefoil | 1.56 | 3.129 | 2.397 | 1.608 | 0.969 | 0.788 | 0.589 |
| 8 4 2 Sec Astigmatism | 0.21 | 0.135 | 0.361 | 0.639 | 0.684 | 1.371 | 1.807 |
| 9 5 1 Sec Coma | 0.21 | 0.013 | 0.048 | 0.047 | 0.021 | 0.039 | 0.023 |
| 10 6 0 Sec Spherical | 0.21 | 0.060 | 0.006 | 0.258 | 0.067 | 0.023 | 0.222 |
| 11 4 4 Pri Tetrafoil | 0.21 | 0.289 | 0.085 | 0.022 | 1.457 | 0.953 | 0.895 |
| 12 5 3 Sec Trefoil | 0.21 | 0.397 | 1.169 | 1.243 | 0.093 | 0.182 | 0.188 |
| 13 6 2 Ter Astigmatism | 0.06 | 0.019 | 0.012 | 0.166 | 0.150 | 0.064 | 0.361 |
| 14 7 1 Ter Coma | 0.06 | 0.013 | 0.023 | 0.064 | 0.017 | 0.041 | 0.066 |
| 15 8 0 Ter Spherical | 0.06 | 0.382 | 0.208 | 0.174 | 0.278 | 0.160 | 0.083 |
| 16 5 5 Pri Pentafoil | 0.21 | 0.345 | 0.247 | 0.151 | 0.437 | 0.319 | 0.284 |
| 17 6 4 Sec Tetrafoil | 0.06 | 0.029 | 0.050 | 0.046 | 0.354 | 0.810 | 0.971 |
| 18 7 3 Ter Trefoil | 0.06 | 0.083 | 0.122 | 0.509 | 0.002 | 0.030 | 0.051 |
| 19 8 2 Qua Astigmatism | 0.06 | 0.009 | 0.038 | 0.020 | 0.015 | 0.169 | 0.127 |
| 20 9 1 Qua Coma | 0.06 | 0.077 | 0.039 | 0.027 | 0.068 | 0.013 | 0.018 |
| 21 10 2 Qua Astigmatism | 0.06 | 0.009 | 0.005 | 0.022 | 0.005 | 0.002 | 0.014 |
| 22 12 0 Qin Spherical | 0.06 | 0.857 | 0.629 | 0.491 | 0.639 | 0.484 | 0.414 |

# SUBSTUDY ON BACK PROFILES

ALL CASES: 3 PTS HEXAPOD, 250mm HEIGHT

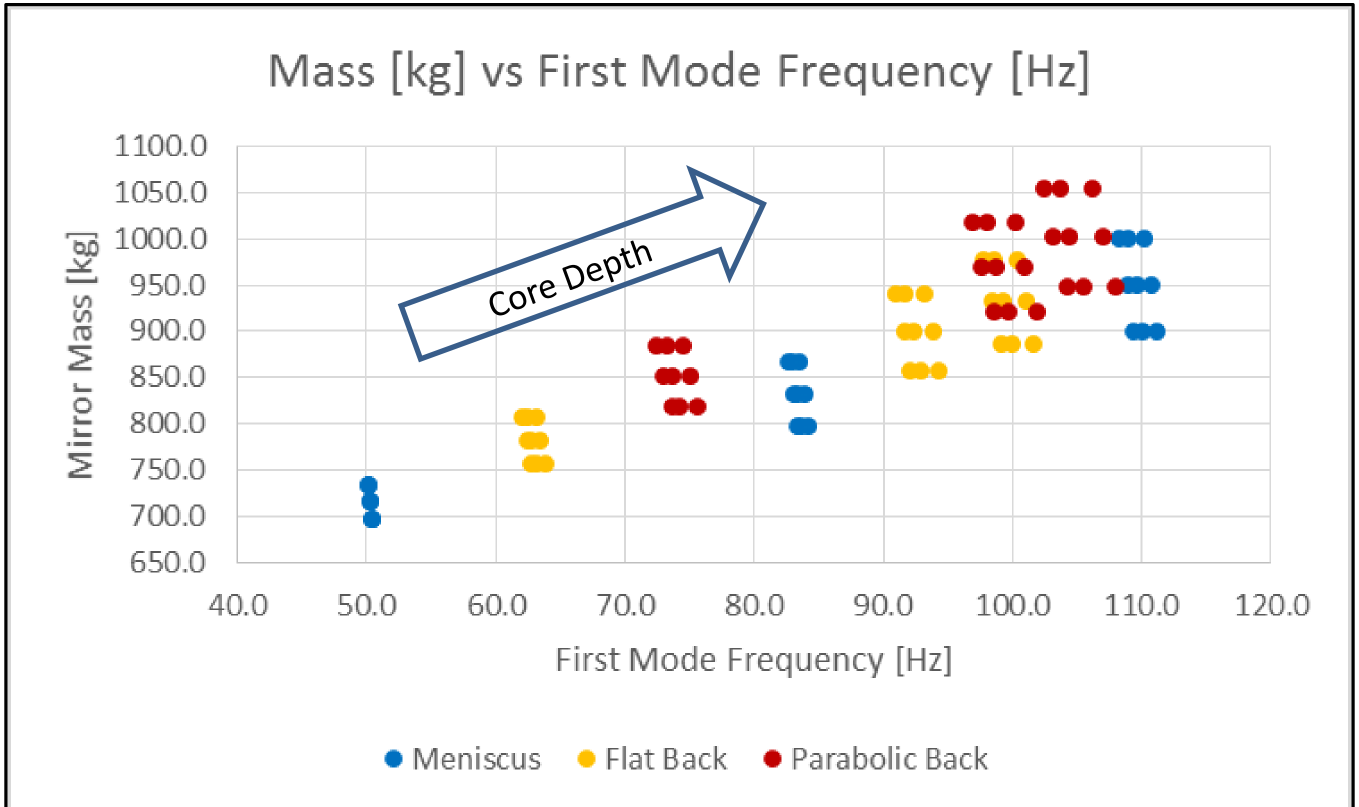


| MENISCUS BACK | FLAT BACK | PARABOLIC BACK |
|---|---|---|
| CORE DEPTH 150mm | CORE DEPTH 150mm | CORE DEPTH 150mm |
| CORE DEPTH 275mm | CORE DEPTH 275mm | CORE DEPTH 275mm |
| CORE DEPTH 400mm | CORE DEPTH 310mm | CORE DEPTH 310mm |
| CELL WIDTH 192mm | CELL WIDTH 192mm | CELL WIDTH 192mm |
| CELL WIDTH 225mm | CELL WIDTH 225mm | CELL WIDTH 225mm |
| CELL WIDTH 290mm | CELL WIDTH 290mm | CELL WIDTH 290mm |

These three options are all practical with Frit bonded ULE mirrors.

# Gravity Sag

- Meniscus produces highest stiffness for lowest mass
- Flat back has same thickness at edge but is thinner in center.
- Parabolic has no significant advantage.



# RESULTS OF BACK SURFACE PROFILE

## MENISCUS

| HEX HEIGHT | CORE DEPTH | CELL WIDTH | SUPPORT MASS | SUPPORT 1ST | XYZ RMS |
|---|---|---|---|---|---|
| 0.250 | 0.150 | 0.192 | 733.7 | 50.2 | 3.626E-03 |
| 0.350 | 0.150 | 0.192 | 733.7 | 50.1 | 3.625E-03 |
| 0.450 | 0.150 | 0.192 | 733.7 | 50.1 | 3.639E-03 |
| 0.250 | 0.275 | 0.192 | 866.6 | 83.5 | 1.415E-03 |
| 0.350 | 0.275 | 0.192 | 866.6 | 83.0 | 1.414E-03 |
| 0.450 | 0.275 | 0.192 | 866.6 | 82.6 | 1.403E-03 |
| 0.250 | 0.400 | 0.192 | 999.5 | 110.2 | 8.880E-04 |
| 0.350 | 0.400 | 0.192 | 999.5 | 109.0 | 9.015E-04 |
| 0.450 | 0.400 | 0.192 | 999.5 | 108.2 | 9.009E-04 |
| | | | | | |
| 0.250 | 0.150 | 0.225 | 715.2 | 50.4 | 3.662E-03 |
| 0.350 | 0.150 | 0.225 | 715.2 | 50.3 | 3.660E-03 |
| 0.450 | 0.150 | 0.225 | 715.2 | 50.3 | 3.674E-03 |
| 0.250 | 0.275 | 0.225 | 832.9 | 83.9 | 1.425E-03 |
| 0.350 | 0.275 | 0.225 | 832.9 | 83.4 | 1.423E-03 |
| 0.450 | 0.275 | 0.225 | 832.9 | 83.1 | 1.412E-03 |
| 0.250 | 0.400 | 0.225 | 950.5 | 110.8 | 8.895E-04 |
| 0.350 | 0.400 | 0.225 | 950.5 | 109.6 | 9.009E-04 |
| 0.450 | 0.400 | 0.225 | 950.5 | 109.0 | 8.996E-04 |
| | | | | | |
| 0.250 | 0.150 | 0.290 | 696.0 | 50.5 | 3.686E-03 |
| 0.350 | 0.150 | 0.290 | 696.0 | 50.5 | 3.682E-03 |
| 0.450 | 0.150 | 0.290 | 696.0 | 50.4 | 3.696E-03 |
| 0.250 | 0.275 | 0.290 | 797.8 | 84.2 | 1.445E-03 |
| 0.350 | 0.275 | 0.290 | 797.8 | 83.7 | 1.441E-03 |
| 0.450 | 0.275 | 0.290 | 797.8 | 83.4 | 1.429E-03 |
| 0.250 | 0.400 | 0.290 | 899.6 | 111.1 | 9.020E-04 |
| 0.350 | 0.400 | 0.290 | 899.6 | 110.0 | 9.101E-04 |
| 0.450 | 0.400 | 0.290 | 899.6 | 109.4 | 9.075E-04 |

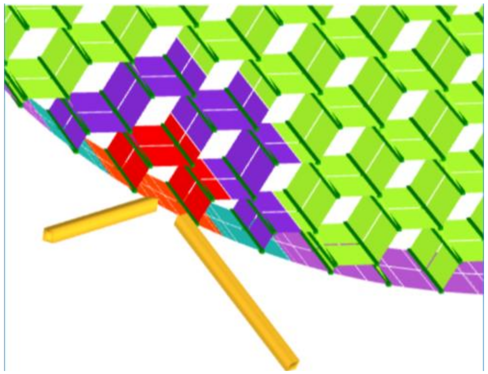
## FLAT BACK

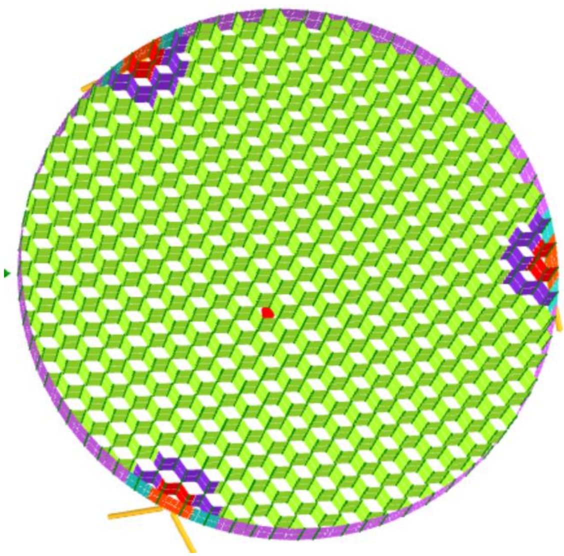
| HEX HEIGHT | CORE DEPTH | CELL WIDTH | SUPPORT MASS | SUPPORT 1ST | XYZ RMS |
|---|---|---|---|---|---|
| 0.250 | 0.150 | 0.192 | 807.8 | 63.2 | 4.168E-03 |
| 0.350 | 0.150 | 0.192 | 807.8 | 62.5 | 4.300E-03 |
| 0.450 | 0.150 | 0.192 | 807.8 | 62.1 | 4.382E-03 |
| 0.250 | 0.275 | 0.192 | 940.7 | 93.2 | 1.911E-03 |
| 0.350 | 0.275 | 0.192 | 940.7 | 91.7 | 1.978E-03 |
| 0.450 | 0.275 | 0.192 | 940.7 | 90.9 | 2.026E-03 |
| 0.250 | 0.310 | 0.192 | 977.9 | 100.4 | 1.647E-03 |
| 0.350 | 0.310 | 0.192 | 977.9 | 98.6 | 1.703E-03 |
| 0.450 | 0.310 | 0.192 | 977.9 | 97.7 | 1.745E-03 |
| | | | | | |
| 0.250 | 0.150 | 0.225 | 782.0 | 63.5 | 4.103E-03 |
| 0.350 | 0.150 | 0.225 | 782.0 | 62.8 | 4.228E-03 |
| 0.450 | 0.150 | 0.225 | 782.0 | 62.5 | 4.306E-03 |
| 0.250 | 0.275 | 0.225 | 899.7 | 93.9 | 1.884E-03 |
| 0.350 | 0.275 | 0.225 | 899.7 | 92.3 | 1.946E-03 |
| 0.450 | 0.275 | 0.225 | 899.7 | 91.6 | 1.991E-03 |
| 0.250 | 0.310 | 0.225 | 932.6 | 101.1 | 1.625E-03 |
| 0.350 | 0.310 | 0.225 | 932.6 | 99.3 | 1.676E-03 |
| 0.450 | 0.310 | 0.225 | 932.6 | 98.5 | 1.714E-03 |
| | | | | | |
| 0.250 | 0.150 | 0.290 | 756.3 | 63.8 | 3.937E-03 |
| 0.350 | 0.150 | 0.290 | 756.3 | 63.1 | 4.052E-03 |
| 0.450 | 0.150 | 0.290 | 756.3 | 62.8 | 4.125E-03 |
| 0.250 | 0.275 | 0.290 | 858.1 | 94.3 | 1.818E-03 |
| 0.350 | 0.275 | 0.290 | 858.1 | 92.9 | 1.872E-03 |
| 0.450 | 0.275 | 0.290 | 858.1 | 92.1 | 1.912E-03 |
| 0.250 | 0.310 | 0.290 | 886.6 | 101.6 | 1.569E-03 |
| 0.350 | 0.310 | 0.290 | 886.6 | 99.9 | 1.613E-03 |
| 0.450 | 0.310 | 0.290 | 886.6 | 99.1 | 1.647E-03 |

## PARABOLIC BACK

| HEX HEIGHT | CORE DEPTH | CELL WIDTH | SUPPORT MASS | SUPPORT 1ST | XYZ RMS |
|---|---|---|---|---|---|
| 0.250 | 0.150 | 0.192 | 883.9 | 74.5 | 2.647E-03 |
| 0.350 | 0.150 | 0.192 | 883.9 | 73.2 | 2.805E-03 |
| 0.450 | 0.150 | 0.192 | 883.9 | 72.5 | 2.906E-03 |
| 0.250 | 0.275 | 0.192 | 1016.9 | 100.3 | 1.438E-03 |
| 0.350 | 0.275 | 0.192 | 1016.9 | 98.0 | 1.520E-03 |
| 0.450 | 0.275 | 0.192 | 1016.9 | 96.9 | 1.578E-03 |
| 0.250 | 0.310 | 0.192 | 1054.1 | 106.2 | 1.278E-03 |
| 0.350 | 0.310 | 0.192 | 1054.1 | 103.7 | 1.346E-03 |
| 0.450 | 0.310 | 0.192 | 1054.1 | 102.4 | 1.397E-03 |
| | | | | | |
| 0.250 | 0.150 | 0.225 | 850.8 | 75.0 | 2.611E-03 |
| 0.350 | 0.150 | 0.225 | 850.8 | 73.7 | 2.761E-03 |
| 0.450 | 0.150 | 0.225 | 850.8 | 73.0 | 2.858E-03 |
| 0.250 | 0.275 | 0.225 | 968.5 | 101.0 | 1.423E-03 |
| 0.350 | 0.275 | 0.225 | 968.5 | 98.7 | 1.498E-03 |
| 0.450 | 0.275 | 0.225 | 968.5 | 97.6 | 1.552E-03 |
| 0.250 | 0.310 | 0.225 | 1001.4 | 107.0 | 1.265E-03 |
| 0.350 | 0.310 | 0.225 | 1001.4 | 104.4 | 1.327E-03 |
| 0.450 | 0.310 | 0.225 | 1001.4 | 103.2 | 1.374E-03 |
| | | | | | |
| 0.250 | 0.150 | 0.290 | 818.6 | 75.7 | 2.502E-03 |
| 0.350 | 0.150 | 0.290 | 818.6 | 74.3 | 2.645E-03 |
| 0.450 | 0.150 | 0.290 | 818.6 | 73.7 | 2.738E-03 |
| 0.250 | 0.275 | 0.290 | 920.3 | 101.9 | 1.368E-03 |
| 0.350 | 0.275 | 0.290 | 920.3 | 99.7 | 1.439E-03 |
| 0.450 | 0.275 | 0.290 | 920.3 | 98.6 | 1.490E-03 |
| 0.250 | 0.310 | 0.290 | 948.8 | 108.0 | 1.217E-03 |
| 0.350 | 0.310 | 0.290 | 948.8 | 105.5 | 1.275E-03 |
| 0.450 | 0.310 | 0.290 | 948.8 | 104.3 | 1.319E-03 |

# LOCAL REINFORCEMENT





- Local Reinforcement usually refers to increase web thickness in core. Front and back facesheets are usually uniform thickness.
- Classic core construction method (waterjet cutting) can easily vary cell wall thickness.
- There is a weight penalty associated with this additional wall thickness.
- Trade study examined three cases:
  1. One pad diameter and one perimeter zone size.
  2. Same mesh, but no thickness increase.
  3. Smaller pad diameter.

# RESULTS OF LOCAL REINFORCEMENT

Local Reinforcement increases stiffness and reduces gravity sag, but may not be worth the mass increase.

| RUN ID | UPPER DIA | HEX HEIGHT | CORE DEPTH | CELL WIDTH | PAD DIA | PERIM DIA | SUPPORT MASS | SUPPORT 1ST | XYZ RMS |
|---|---|---|---|---|---|---|---|---|---|
| ULE-4M-3P-019 | 4.040 | 0.250 | 0.150 | 0.290 | 0.350 | 0.750 | 696.0 | 50.5 | 3.686E-03 |
| ULE-4M-3P-019N | 4.040 | 0.250 | 0.150 | 0.290 | 0.350 | 0.750 | 677.0 | 49.7 | 3.826E-03 |
| ULE-4M-3P-019SP | 4.040 | 0.250 | 0.150 | 0.290 | 0.175 | 0.350 | 677.0 | 48.5 | 4.092E-03 |
| | | | | | | | | | |
| ULE-4M-3P-046 | 3.430 | 0.250 | 0.150 | 0.290 | 0.350 | 0.750 | 699.9 | 54.1 | 2.030E-03 |
| ULE-4M-3P-046N | 3.430 | 0.250 | 0.150 | 0.290 | 0.350 | 0.750 | 677.0 | 52.5 | 2.172E-03 |
| ULE-4M-3P-046SP | 3.430 | 0.250 | 0.150 | 0.290 | 0.175 | 0.350 | 677.0 | 50.2 | 2.411E-03 |
| | | | | | | | | | |
| ULE-4M-3P-073 | 2.820 | 0.250 | 0.150 | 0.290 | 0.350 | 0.750 | 698.4 | 56.9 | 1.347E-03 |
| ULE-4M-3P-073N | 2.820 | 0.250 | 0.150 | 0.290 | 0.350 | 0.750 | 677.0 | 54.7 | 1.350E-03 |
| ULE-4M-3P-073SP | 2.820 | 0.250 | 0.150 | 0.290 | 0.175 | 0.350 | 677.0 | 51.4 | 1.506E-03 |

The run id with no letter is the reinforced core case.
The run id with letter N is the same mesh, but no additional web thickness.
The run id with the letters SP has smaller pad diameters and no additional web thickness.

# RESULTS OF HEXAPOD LEG STIFFNESS

- Stiffer legs increase assembly stiffness and reduce gravity sag.
- But only until threshold leg stiffness is reached

| RUN ID | UPPER DIA | HEX HEIGHT | LEG STIFF | CORE DEPTH | CELL WIDTH | SUPPORT MASS | SUPPORT 1ST | XYZ RMS |
|---|---|---|---|---|---|---|---|---|
| ULE-4M-3P-001 | 4.040 | 0.250 | 8.E+11 | 0.150 | 0.192 | 733.7 | 50.2 | 3.626E-03 |
| ULE-4M-3P-001A | 4.040 | 0.250 | 8.E+09 | 0.150 | 0.192 | 733.7 | 50.1 | 3.628E-03 |
| ULE-4M-3P-001B | 4.040 | 0.250 | 8.E+07 | 0.150 | 0.192 | 733.7 | 41.69 | 4.469E-03 |
| | | | | | | | | |
| ULE-4M-3P-028 | 3.430 | 0.250 | 8.E+11 | 0.150 | 0.192 | 741.2 | 54.4 | 1.895E-03 |
| ULE-4M-3P-028A | 3.430 | 0.250 | 8.E+09 | 0.150 | 0.192 | 741.2 | 54.2 | 1.906E-03 |
| ULE-4M-3P-028B | 3.430 | 0.250 | 8.E+07 | 0.150 | 0.192 | 741.2 | 35.1 | 8.828E-03 |
| | | | | | | | | |
| ULE-4M-3P-055 | 2.820 | 0.250 | 8.E+11 | 0.150 | 0.192 | 740.2 | 56.9 | 1.265E-03 |
| ULE-4M-3P-055A | 2.820 | 0.250 | 8.E+09 | 0.150 | 0.192 | 740.2 | 56.7 | 1.256E-03 |
| ULE-4M-3P-055B | 2.820 | 0.250 | 8.E+07 | 0.150 | 0.192 | 740.2 | 39.4 | 6.701E-03 |
| | | | | | | | | |
| ULE-4M-6P-001 | 4.040 | 0.250 | 8.E+11 | 0.150 | 0.192 | 759.6 | 33.3 | 1.754E-02 |
| ULE-4M-6P-001A | 4.040 | 0.250 | 8.E+09 | 0.150 | 0.192 | 759.6 | 33.2 | 1.762E-02 |
| ULE-4M-6P-001B | 4.040 | 0.250 | 8.E+07 | 0.150 | 0.192 | 759.6 | 26.8 | 2.563E-02 |
| | | | | | | | | |
| ULE-4M-6P-028 | 3.430 | 0.250 | 8.E+11 | 0.150 | 0.192 | 773.9 | 40.4 | 1.094E-02 |
| ULE-4M-6P-028A | 3.430 | 0.250 | 8.E+09 | 0.150 | 0.192 | 773.9 | 40.3 | 1.103E-02 |
| ULE-4M-6P-028B | 3.430 | 0.250 | 8.E+07 | 0.150 | 0.192 | 773.9 | 28.2 | 2.047E-02 |
| | | | | | | | | |
| ULE-4M-6P-055 | 2.820 | 0.250 | 8.E+11 | 0.150 | 0.192 | 770.8 | 44.0 | 8.112E-03 |
| ULE-4M-6P-055A | 2.820 | 0.250 | 8.E+09 | 0.150 | 0.192 | 770.8 | 43.7 | 8.234E-03 |
| ULE-4M-6P-055B | 2.820 | 0.250 | 8.E+07 | 0.150 | 0.192 | 770.8 | 25.8 | 2.052E-02 |

# Conclusions

- Mirror Design is a continuum with infinite possible variations.
- Mass has historically been a primary design metric.
- But stiffness is probably more important – relates to manufacturability and on-orbit performance.
- Gravity sag (related to stiffness) is critical HabEx design metric
- Mount design has critical role on total system stiffness, preferred design is 3-point mount attached at edge of mirror with short stiff hexapod struts.
- Further analysis is needed to determine if HabEx PM will meet its inertial WFE specification based on mass dampening or if additional vibration isolation is needed.
- Arnold Mirror Modeler (AMM) is a invaluable tool in performing mirror design trades.

# REFERENCES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3. Arnold, W. R., "AMTD DESIGN PROCESS", NASA/SPIE Mirror Technology Days 2014, Albuquerque, NM (2014)
4. Arnold, W. R., Etal., "Next-generation lightweight mirror modeling software", SPIE Opto-mechanical Engineering 2013, San Diego, CA SPIE 8836-15 (2013)
5. Arnold, W. R., Etal., "Integration of mirror design with suspension system using NASA's new mirror modeling software", SPIE Opto-mechanical Engineering 2013, San Diego, CA SPIE 8836-17 (2013)
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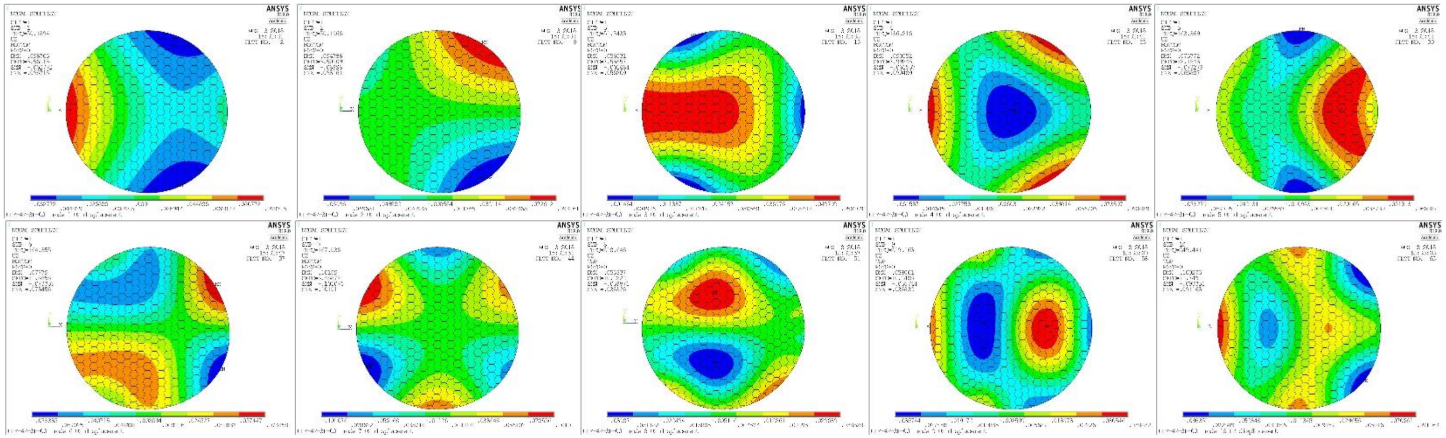
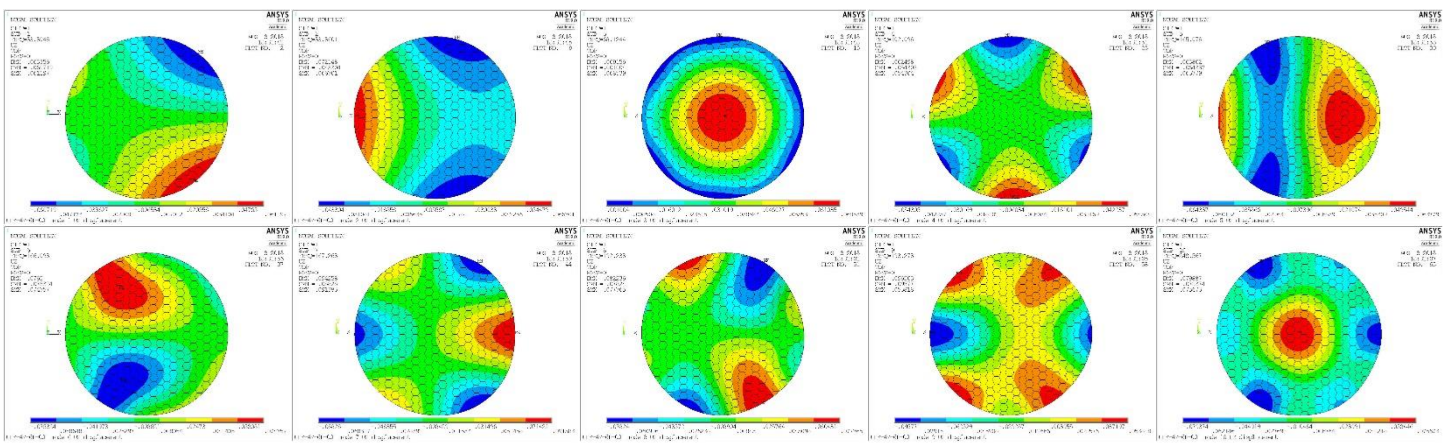
# BACKUP

# MOUNTING AFFECTS MODE SHAPES

FIRST 10 MODES of THREE POINTS HEXAPOD



FIRST 10 MODES of SIX POINTS HEXAPOD



# UNITS USED IN STUDY

All dimensions are in meters.
All mass or weights are in kilograms.
All frequencies are in hertz.

The ANSYS results for global displacements and directional surface RMS values are in meters in response to a 1g acceleration.