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

H. Philip Stahl, PhD
h.philip.stahl@nasa.gov
NASA MSFC

William R. Arnold, Sr.
william.arnold@nasa.gov
NASA MSFC

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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

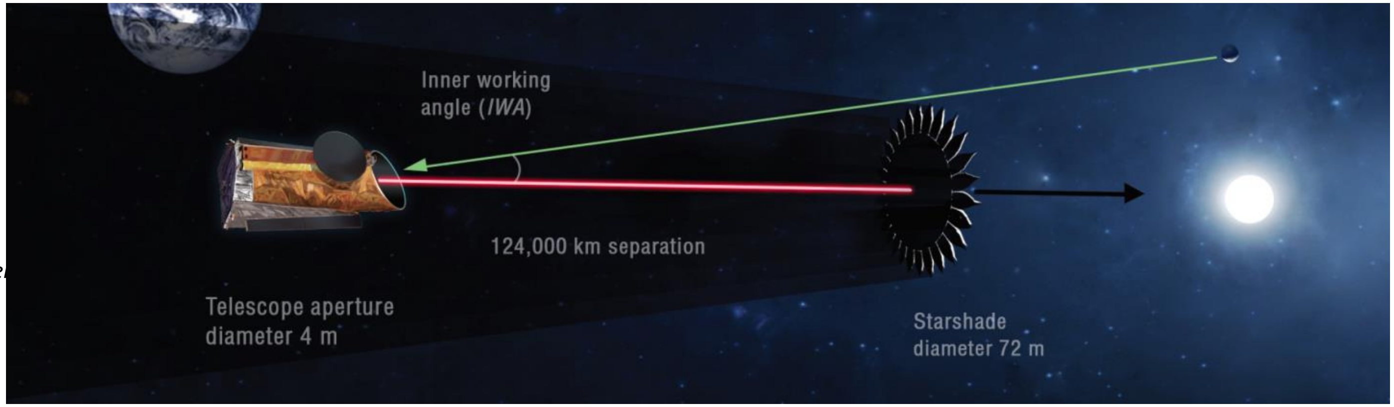
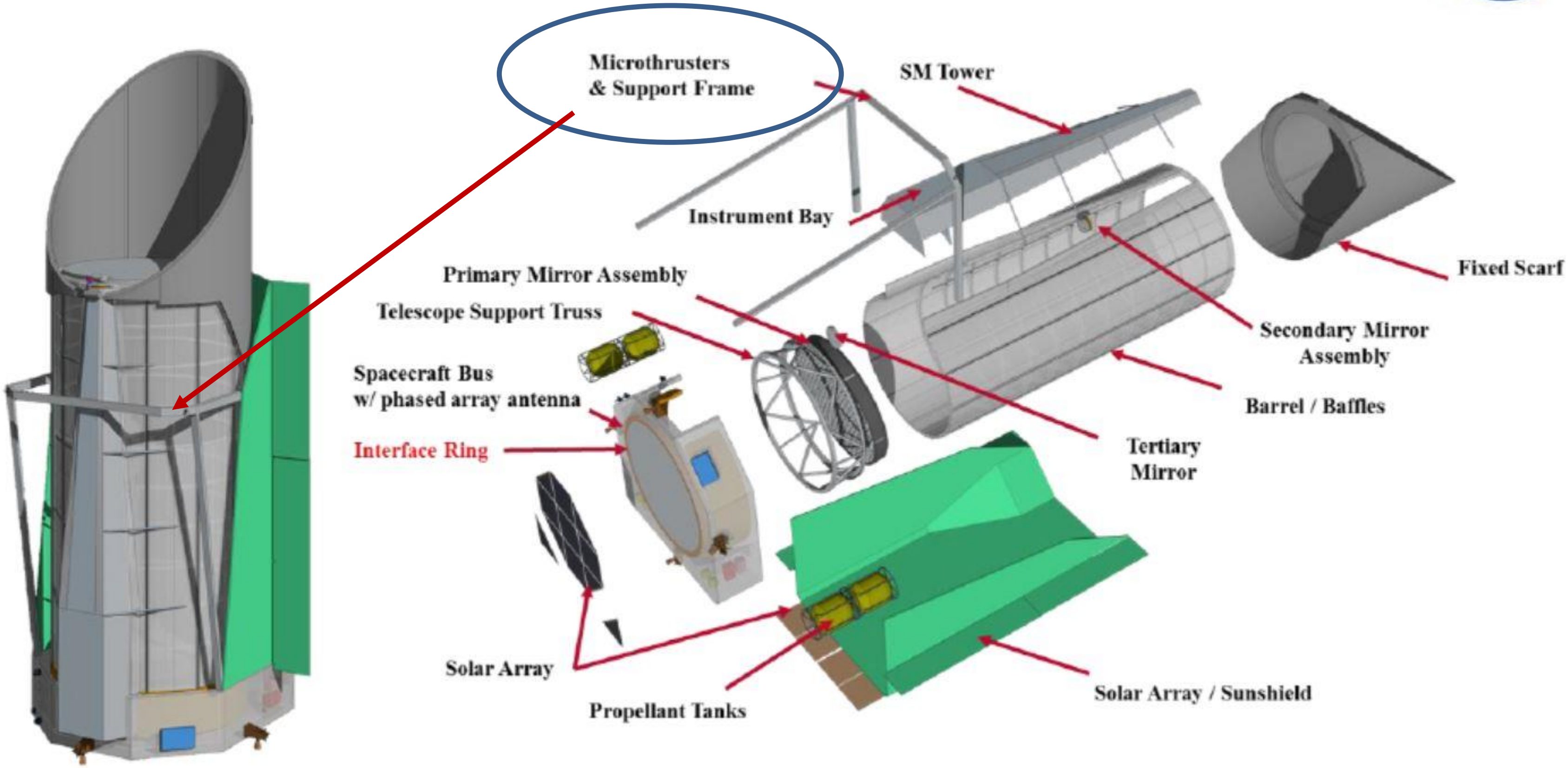


Image from HabEx inte
report URS273294

Pre-Decisional - For Planning Purposes Only

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).

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TELEDYNE BROWN ENGINEERING

a.i. solutions

HABEX WFE Stability Specification

NASA

Thermal is beyond the scope of this paper.

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19	8	2	Qua Astigmatism	0.1	0.001	0.06	0.08	0.0099
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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.

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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
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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
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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.

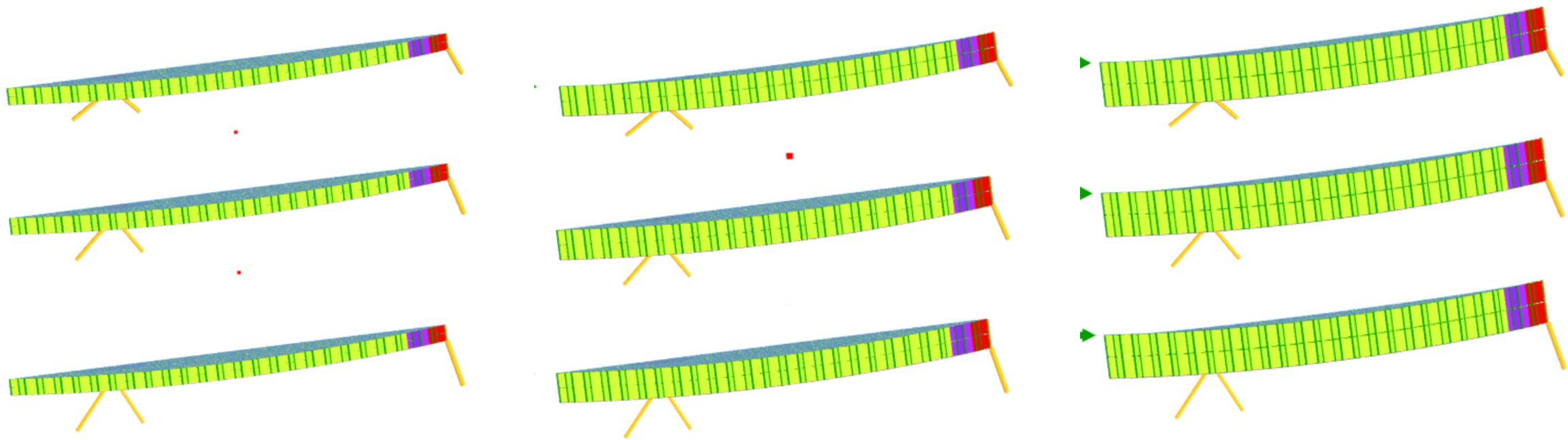
SCOPE OF TRADE STUDY

- 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

CELL WIDTH 192mm
CELL WIDTH 225mm
CELL WIDTH 290mm

HEX HEIGHT 250mm
HEX HEIGHT 350mm
HEX HEIGHT 450mm

CORE DEPTH 225mm

CELL WIDTH 192mm
CELL WIDTH 225mm
CELL WIDTH 290mm

HEX HEIGHT 250mm
HEX HEIGHT 350mm
HEX HEIGHT 450mm

CORE DEPTH 400mm

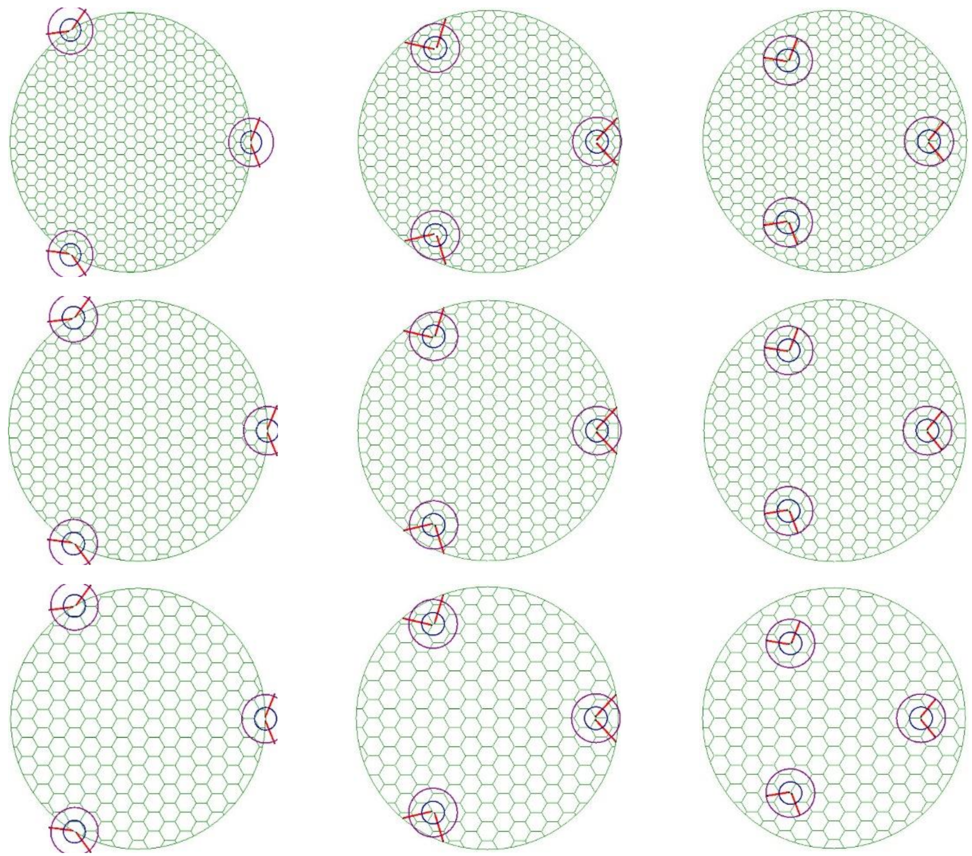
CELL WIDTH 192mm
CELL WIDTH 225mm
CELL WIDTH 290mm

HEX HEIGHT 250mm
HEX HEIGHT 350mm
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.



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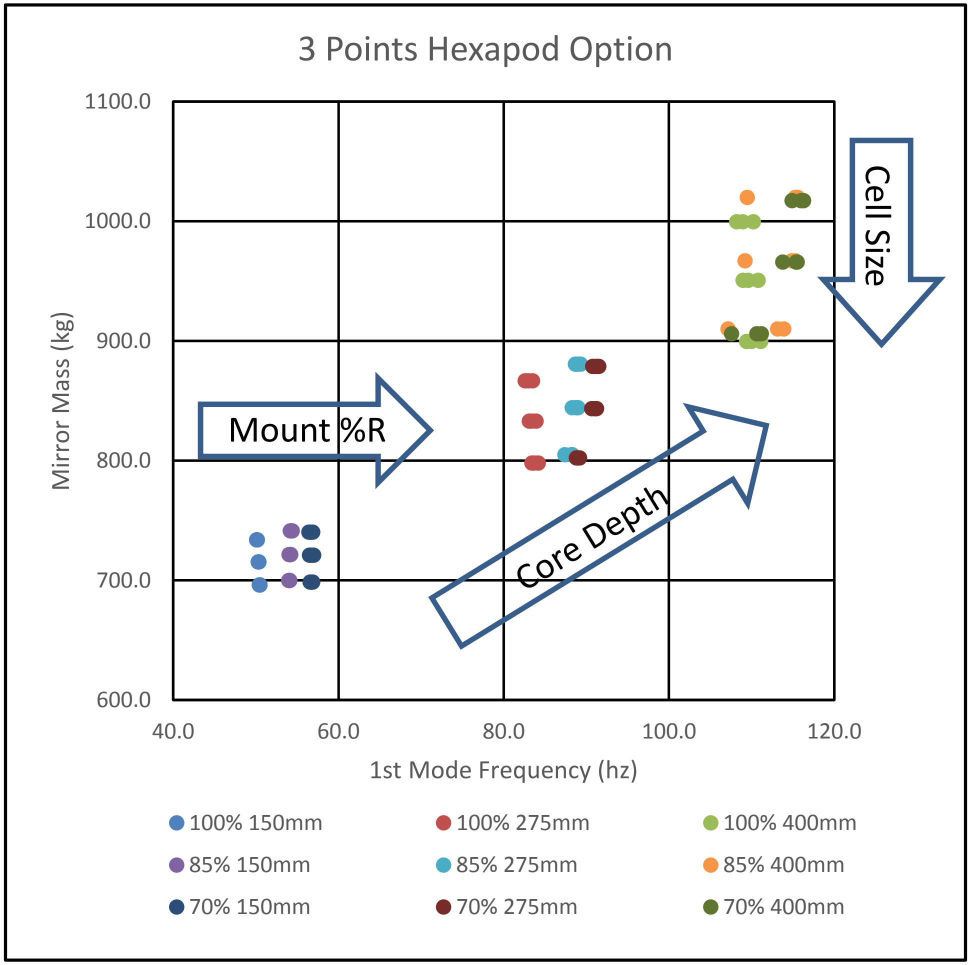
The three support attachment diameters were chosen to best match up with cell wall intersections or cell centers. Slight adjustments were made to precisely align the pads.

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.

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

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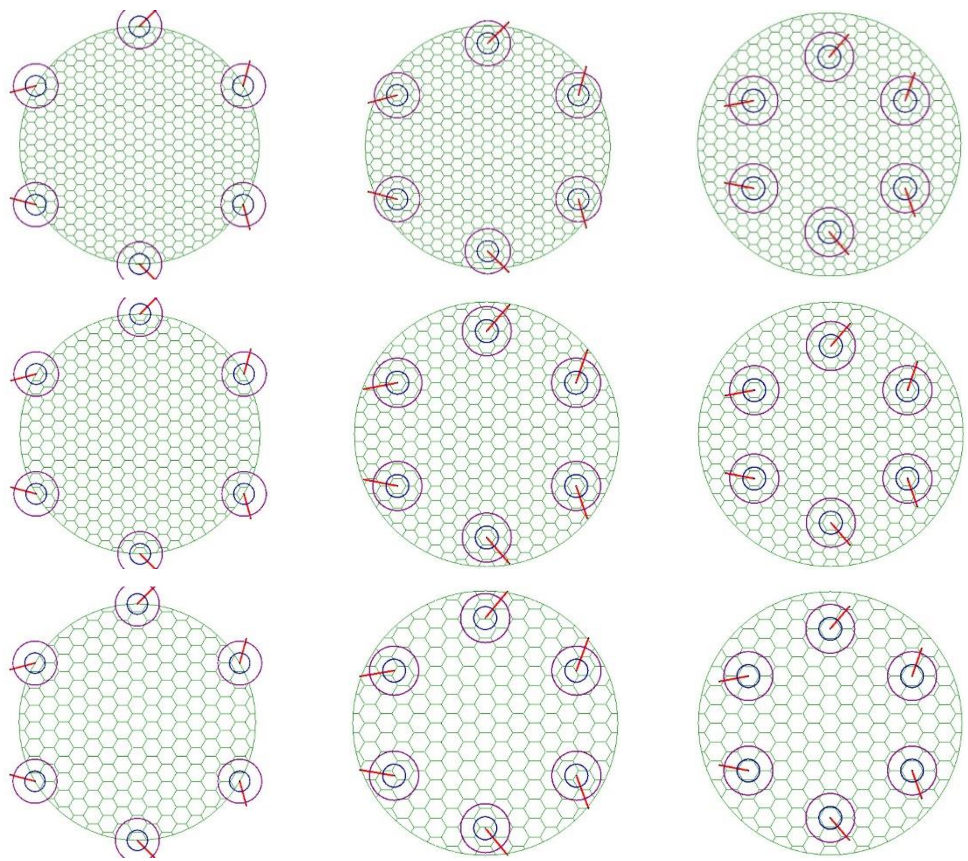

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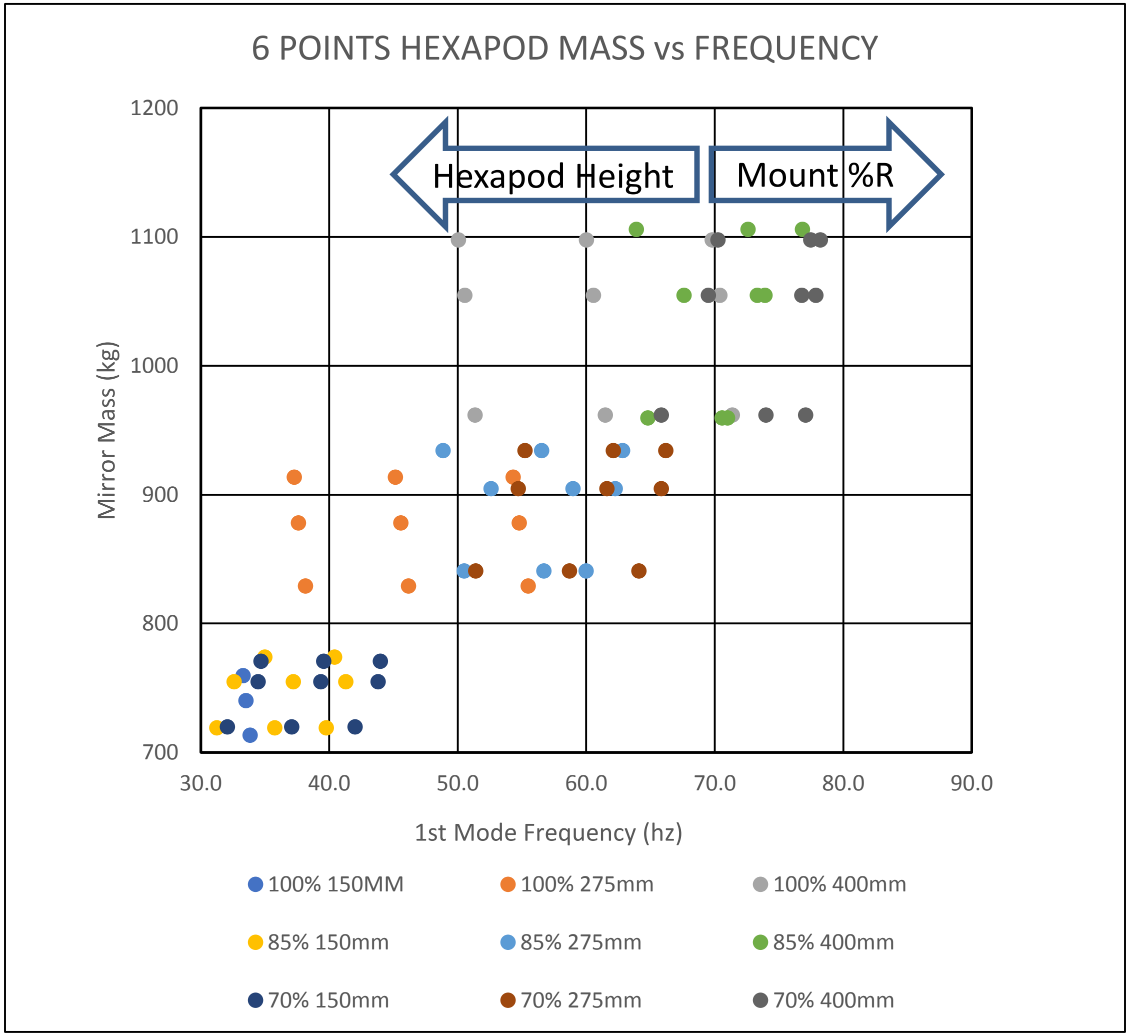
The horizontal Hexapod angles where kept the same for each diameter to balance the translational and rotational stiffnesses of the system

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

RESULTS OF 6 POINTS HEXAPODS

100% Diameter

HEX HEIGHT	CORE DEPTH	CELL WIDTH	SUPPORT MASS	SUPPORT 1ST	XYZ 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 HEIGHT	CORE DEPTH	CELL WIDTH	SUPPORT MASS	SUPPORT 1ST	XYZ 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

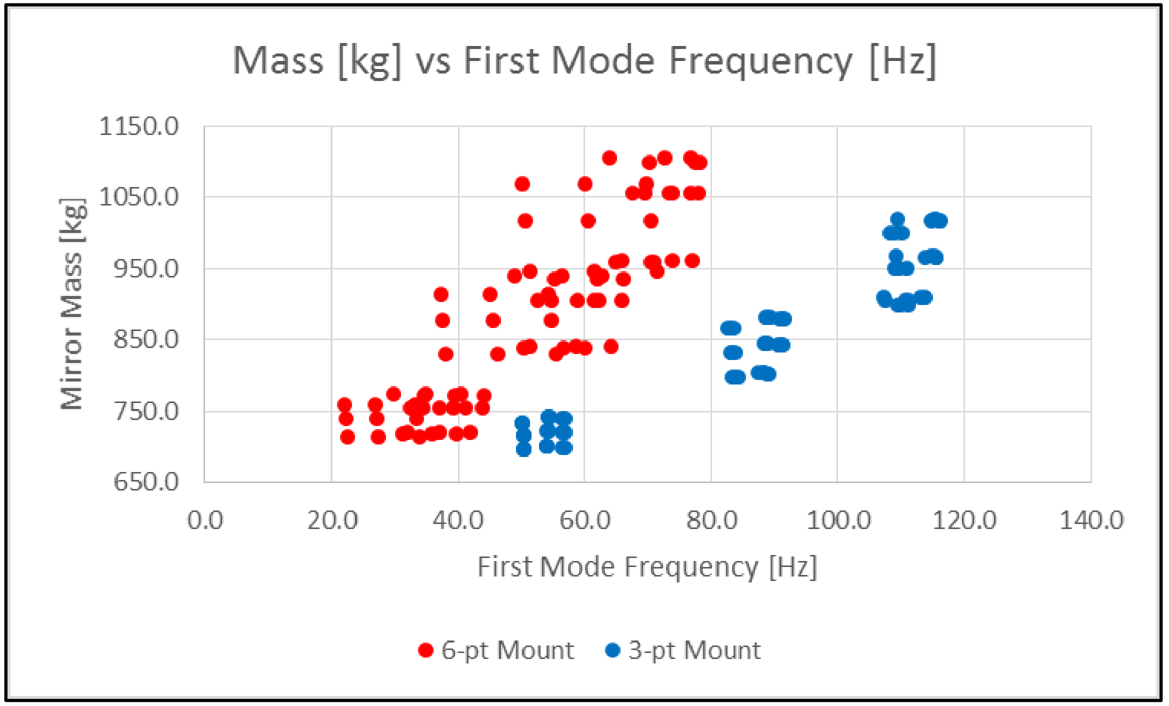
70% Diameter

HEX HEIGHT	CORE DEPTH	CELL WIDTH	SUPPORT MASS	SUPPORT 1ST	XYZ 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.

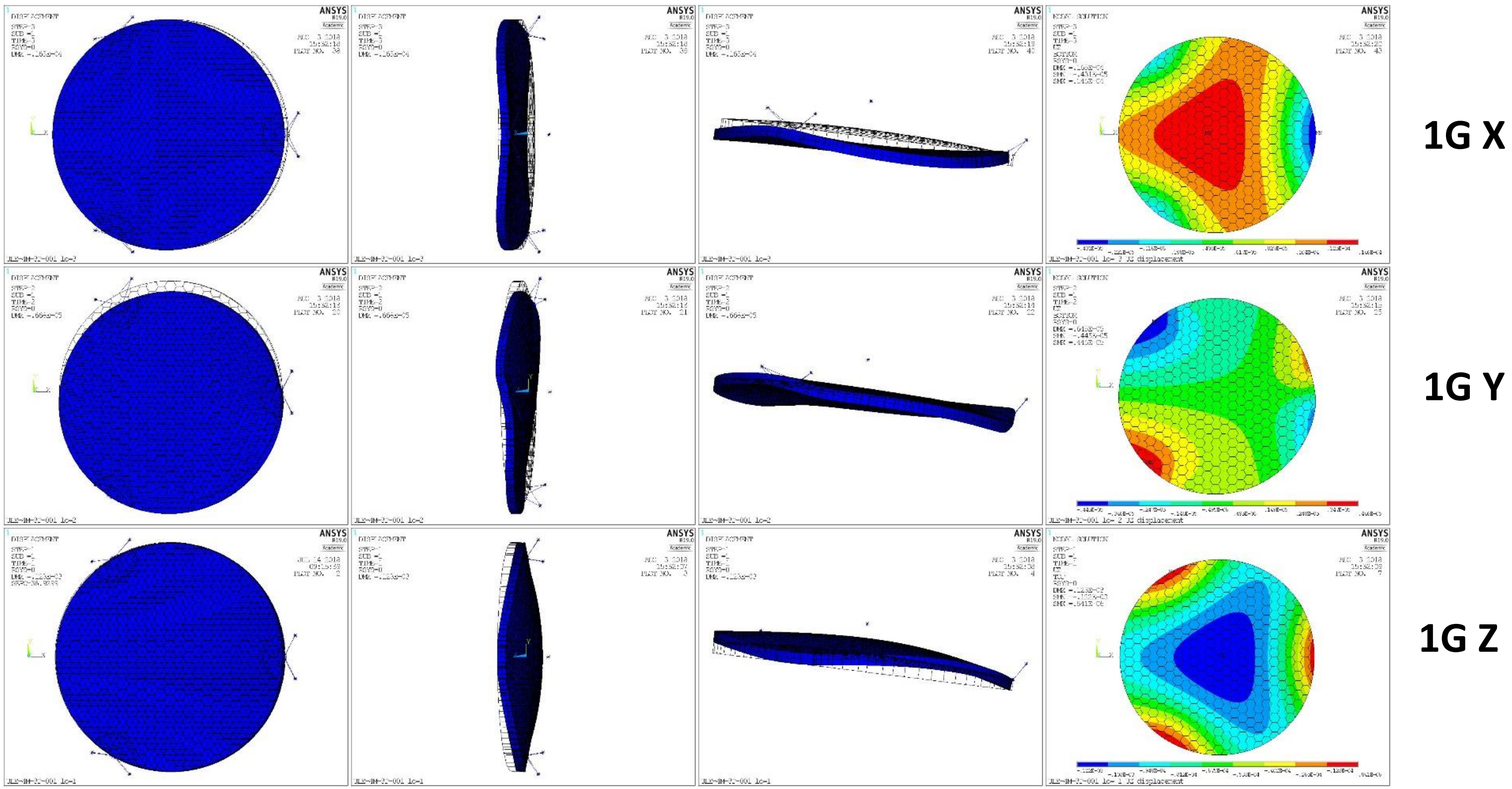
For HabEx to have diffraction limited performance at 400 nm:

- 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



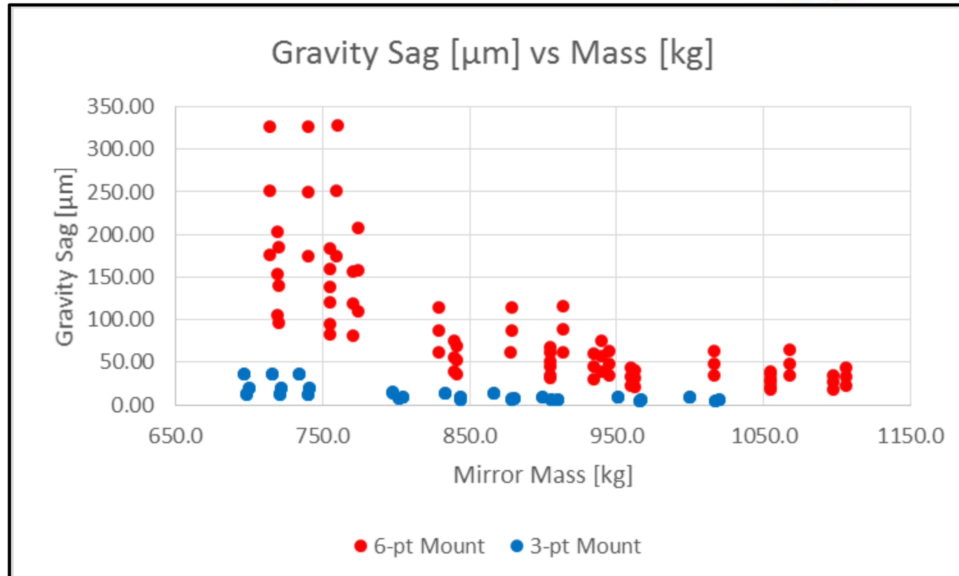
The three directional surface RMS levels are RSS into a "Global RMS" response.

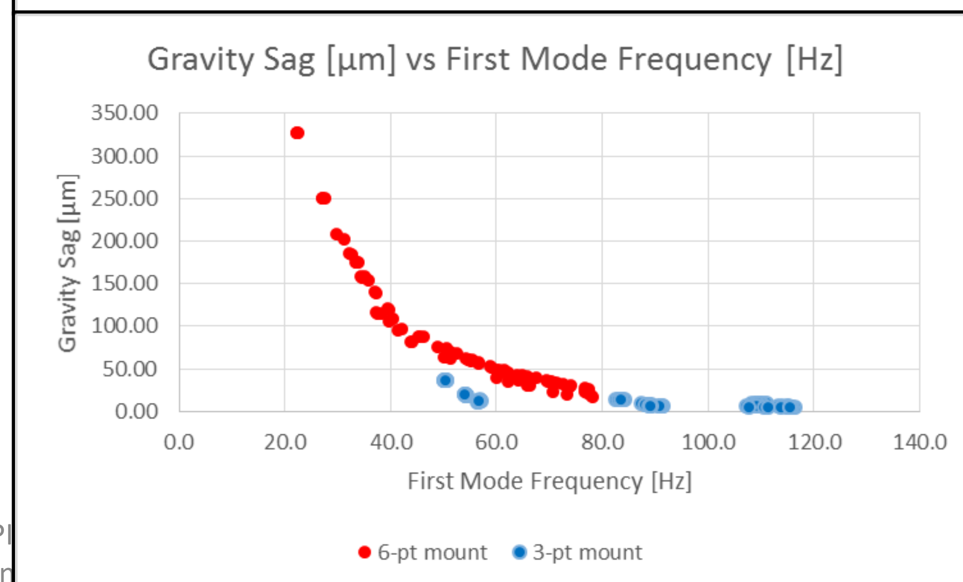
Gravity Sag

- 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.

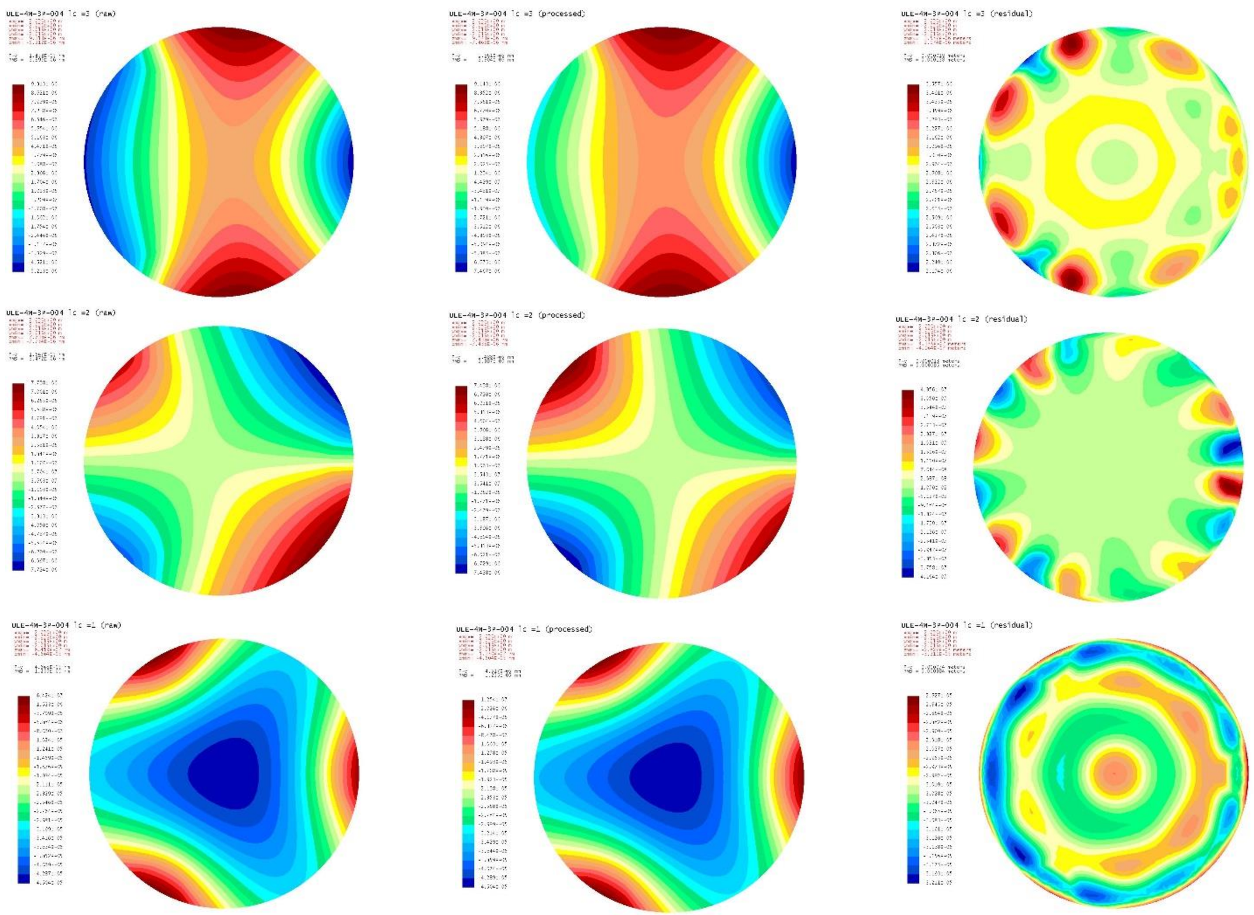
- 1 G acceleration = 1 Gravity Sag
- 1 μG acceleration = 1 μ-Gravity Sag

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.

TELEDYNE BROWN ENGINEERING

a.i. solutions

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

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

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

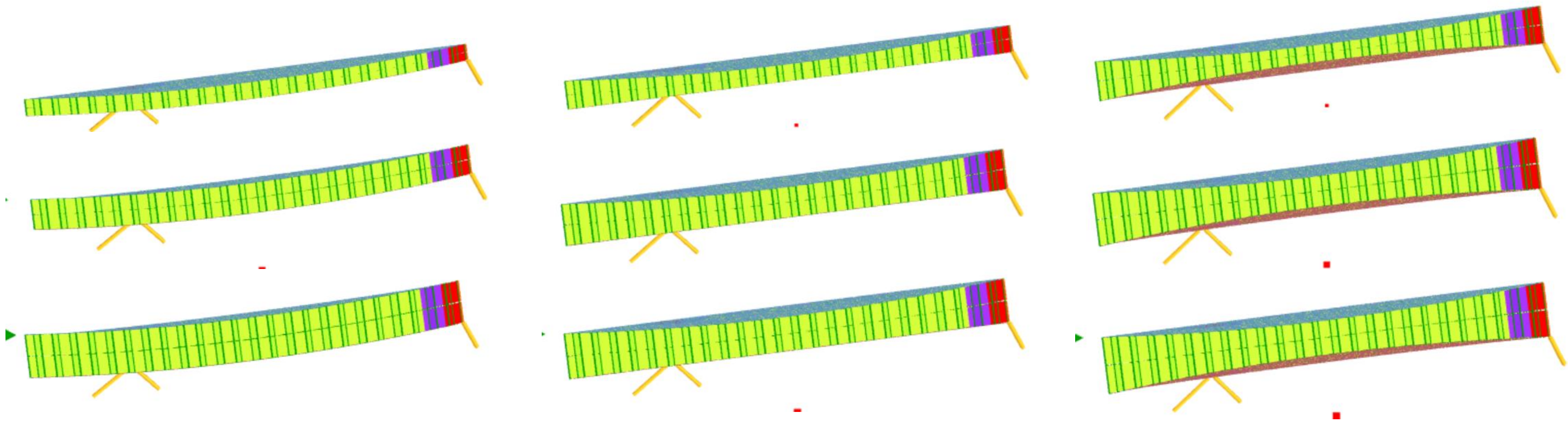
400 mm Core Depth & 290 mm Core Cell Size

- 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

CORE DEPTH 150mm
CORE DEPTH 275mm
CORE DEPTH 400mm

CELL WIDTH 192mm
CELL WIDTH 225mm
CELL WIDTH 290mm

FLAT BACK

CORE DEPTH 150mm
CORE DEPTH 275mm
CORE DEPTH 310mm

CELL WIDTH 192mm
CELL WIDTH 225mm
CELL WIDTH 290mm

PARABOLIC BACK

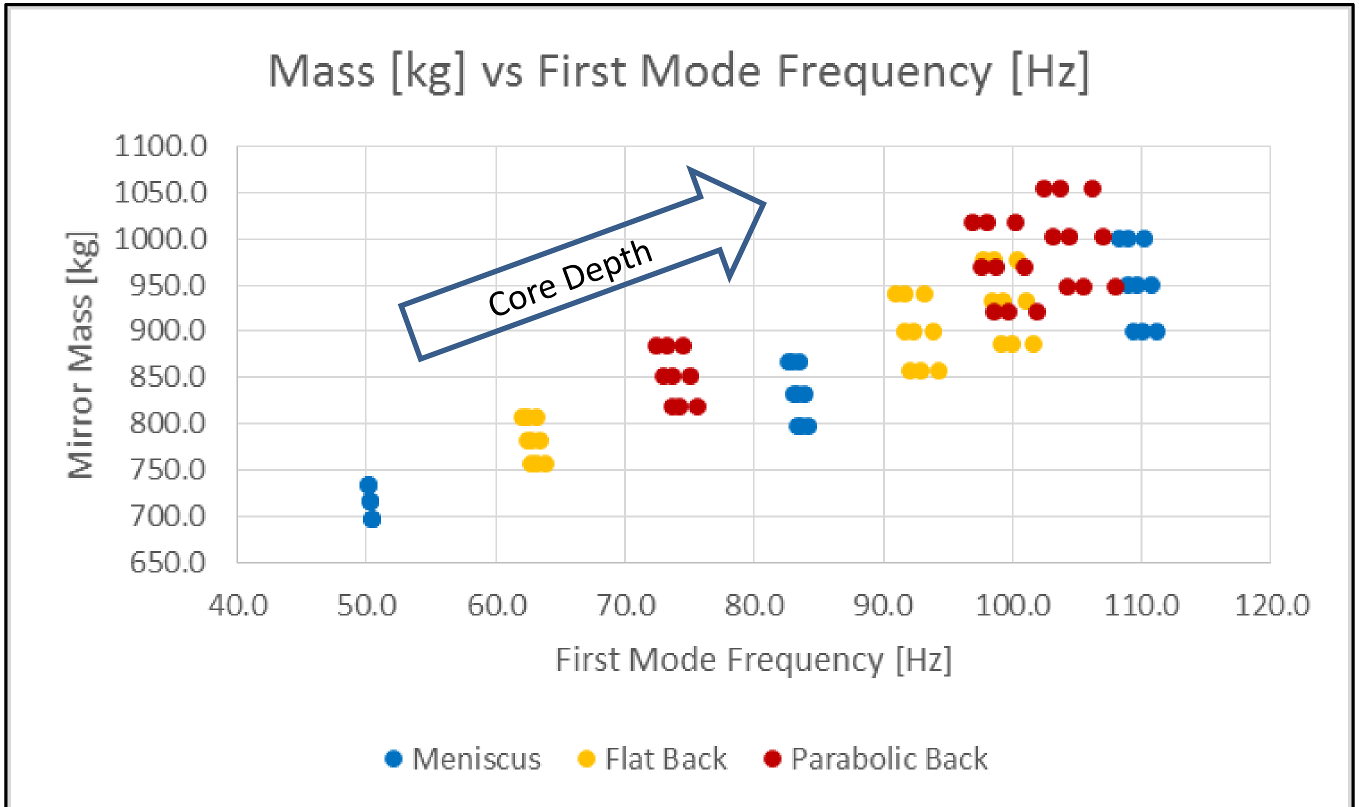
CORE DEPTH 150mm
CORE DEPTH 275mm
CORE DEPTH 310mm

CELL WIDTH 192mm
CELL WIDTH 225mm
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

TELEDYNE BROWN ENGINEERING

a.i. solutions

NASA

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

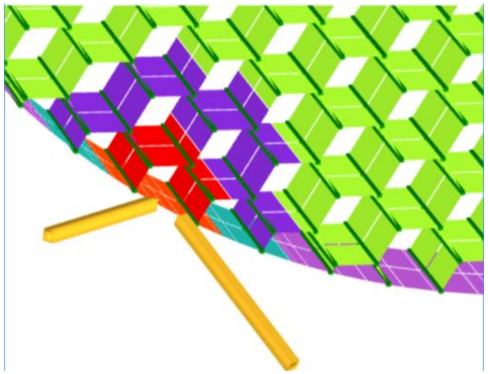
FLAT BACK

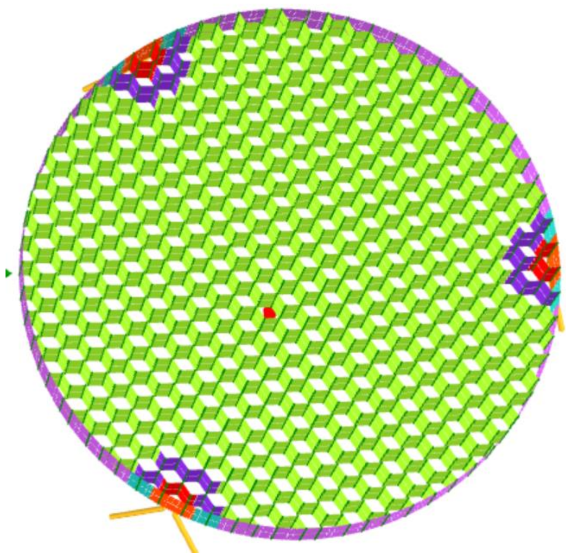
HEX HEIGHT	CORE DEPTH	CELL WIDTH	SUPPORT MASS	SUPPORT 1ST	XYZ RMS
0.250	0.150	0.192	807.8	63.2	4.168E-03
0.350	0.150	0.192	807.8	62.5	4.300E-03
0.450	0.150	0.192	807.8	62.1	4.382E-03
0.250	0.275	0.192	940.7	93.2	1.911E-03
0.350	0.275	0.192	940.7	91.7	1.978E-03
0.450	0.275	0.192	940.7	90.9	2.026E-03
0.250	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.

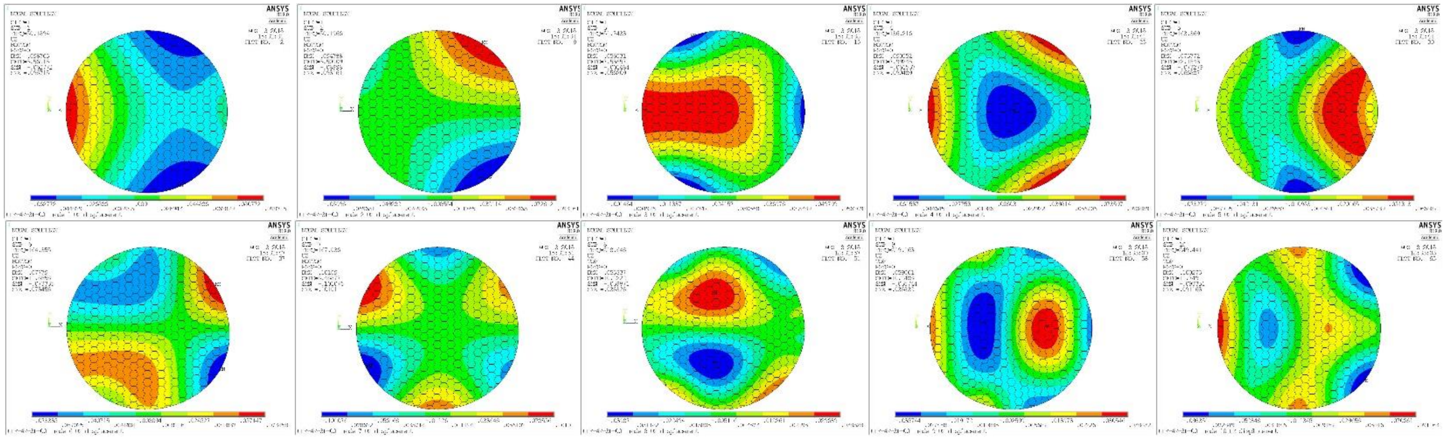
REFERENCES

1. Stahl, H. Philip, "Overview and performance prediction of the baseline 4-meter telescope concept design for the habitable-zone exoplanet observatory",
2. Arnold, W. R., and Stahl, H. Philip, "Structural design of a 4-meter off-axis space telescope for the Habitable-zone Exoplanet Direct Imaging Mission ", SPIE 10398-7 (2017)
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)
6. Arnold, W. R., Etal. "Next-generation lightweight mirror modeling software", NASA Mirror Tech Days 2013, Redondo Beach, CA (2013)

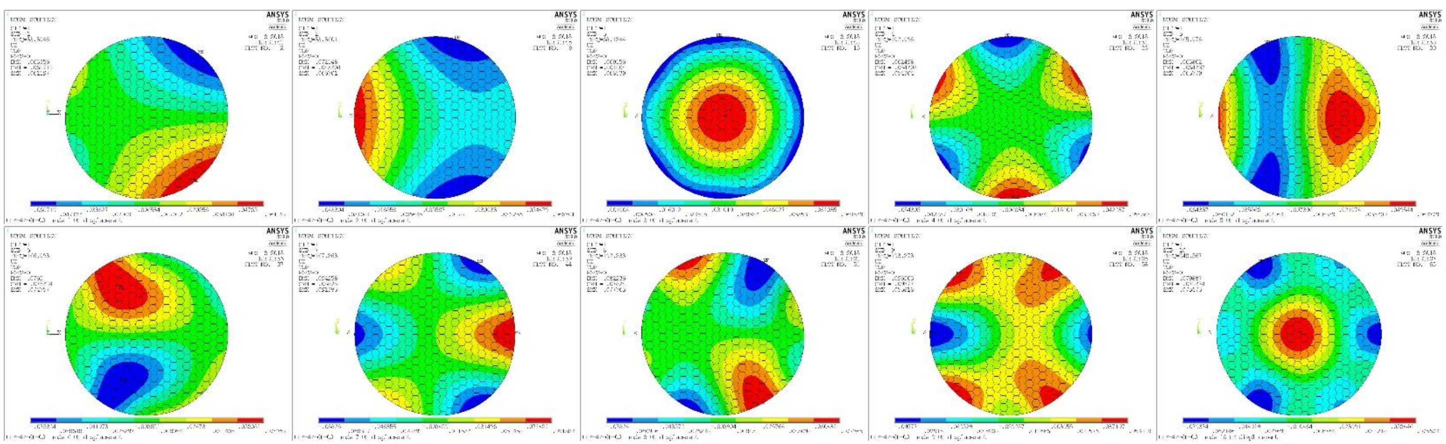
BACKUP

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.