Multiple Methods of Determining the Gravity-Sag of Light-Weighted Optics

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MSFC, AL 35812

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Introduction

What is Gravity Sag?

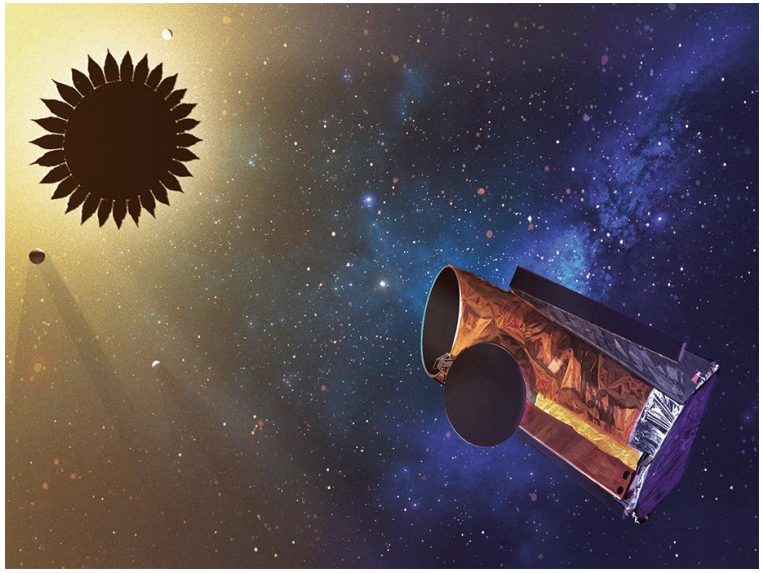
- Bending of the mirror substrate as it is accelerated by gravity

Why should we care about Gravity Sag?

- Because we want to fly HWO

How is gravity sag determined?

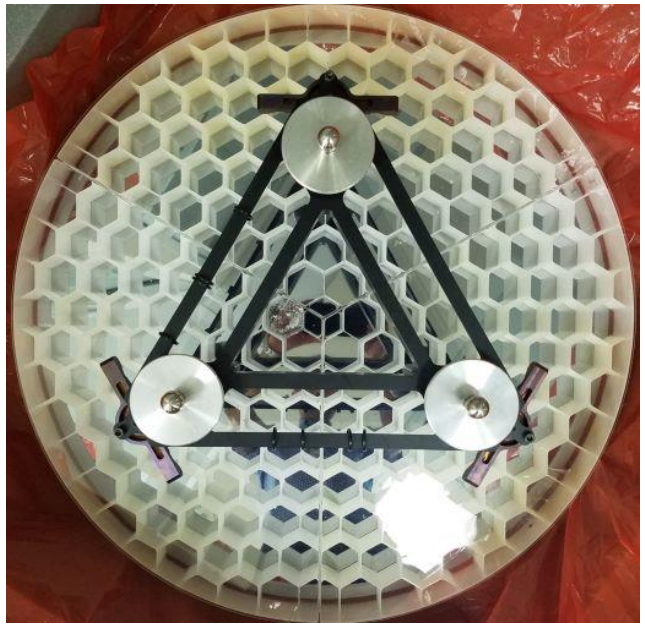
- That’s what we are talking about today

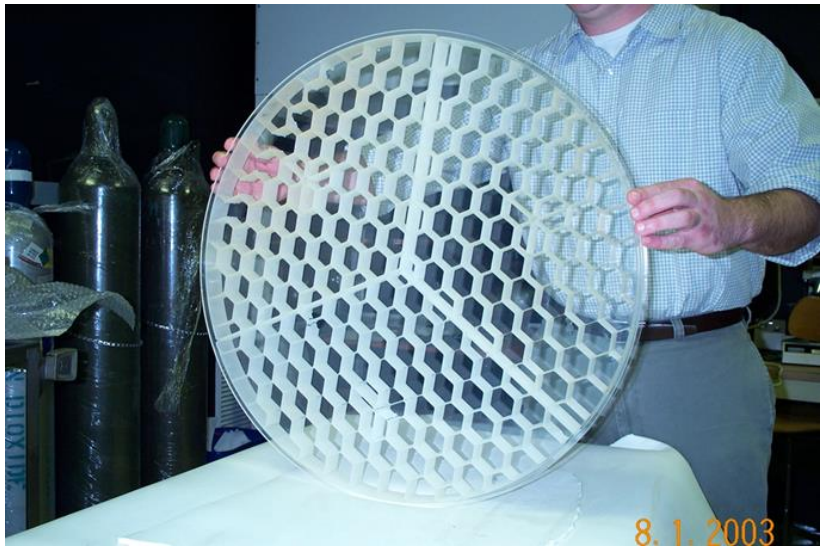


Deployable Optical Telescope (DOT) Mirror

The DOT mirror was used because it was light-weighted, large and best of all free!

- Diameter: 0.6 m
- ROC: 5.0 m
- Mass: 5.9kg
- Edge thickness: 44.5mm
- Material: Corning ULE® glass front and back plates low temperature fused between abrasive waterjet ULE® core.
- Facesheet 1.9mm/ backsheet 1.65mm
- Areal density 14.7kg/m^2 (91% light-weighted)



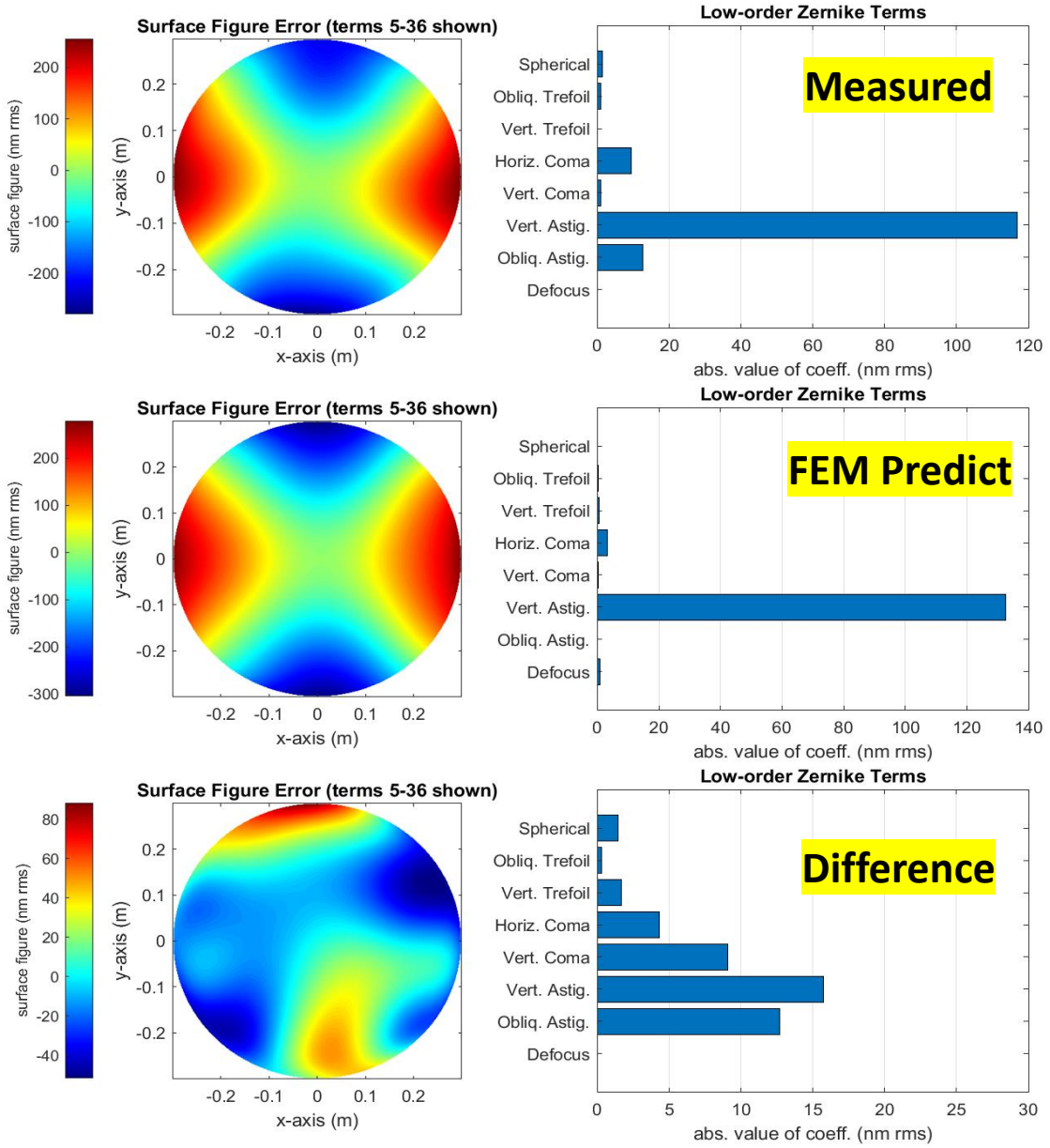


FEM Modeling

FEM modeling enables approximation of 0G shape

An enabling technology for designing and manufacturing large space mirrors are validated modeling tools for predicting gravity sag.

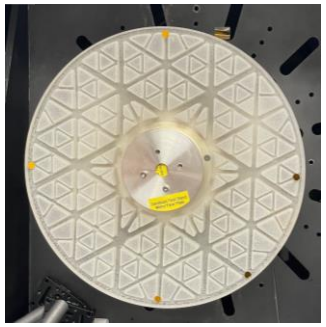
Modeling is essential for determining G-sag for large floppy mirrors that can have microns to mm of deformation



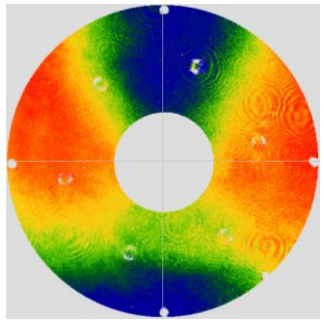
Process Flow for Calculating Zernike Coefficients

Measurement

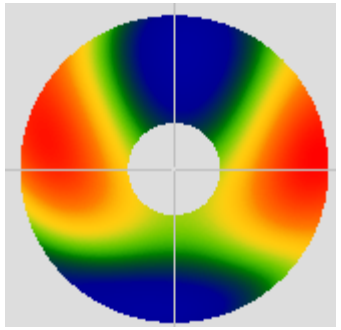
Mirror



Raw Data



Zernike fit



Zernike Coefficients

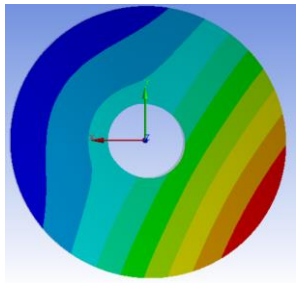
	Coef (nm)	Remove	Aberration	
0	0.0114	✔	Piston or Bias	1
1	0.1206	✔	Tilt X	R cos[A]
2	0.1537	✔	Tilt Y	R sin[A]
3	-0.4323	✔	Power	2R^2 - 1
4	47.4300	✔	Astig X	R^2 cos[2A]
5	-8.9210	✔	Astig Y	R^2 sin[2A]

4D Technology Interferometer Measurement Data → 4D Technology | 4Sight Advanced Wavefront Analysis Software (Calculate Zernike Coefficients)

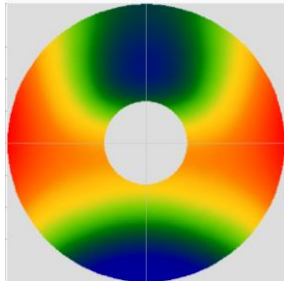
Modeling Prediction

FEM

Deformation



Zernike fit



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Finite Element Model (Ansys) → Convert the data to 4Sight compatible file (Matlab) → 4D Technology | 4Sight Advanced Wavefront Analysis Software (Calculate Zernike Coefficients)

Horizontal Rotation Testing

Horizontal Rotation Test

Because horizontal gravity sag is asymmetric, rotation tests can absolutely quantify gravity sag –thus allowing its removal from a surface measurement.

$$S(x,y,\theta_i)_{Horizontal} = \left[S(x,y)_{G(0,0,0)_{symmetric}} + S(x,y,\theta_i)_{G(0,0,0)_{asymmetric}}\right] + S(x,y,\theta=0)_{G(0,-1,0)}$$

Rotating a mirror in angles around its surface normal that are symmetric with its flight mount, only rotates the mirror's asymmetric component. The gravity sag does not rotate, nor does its rotationally symmetric component.

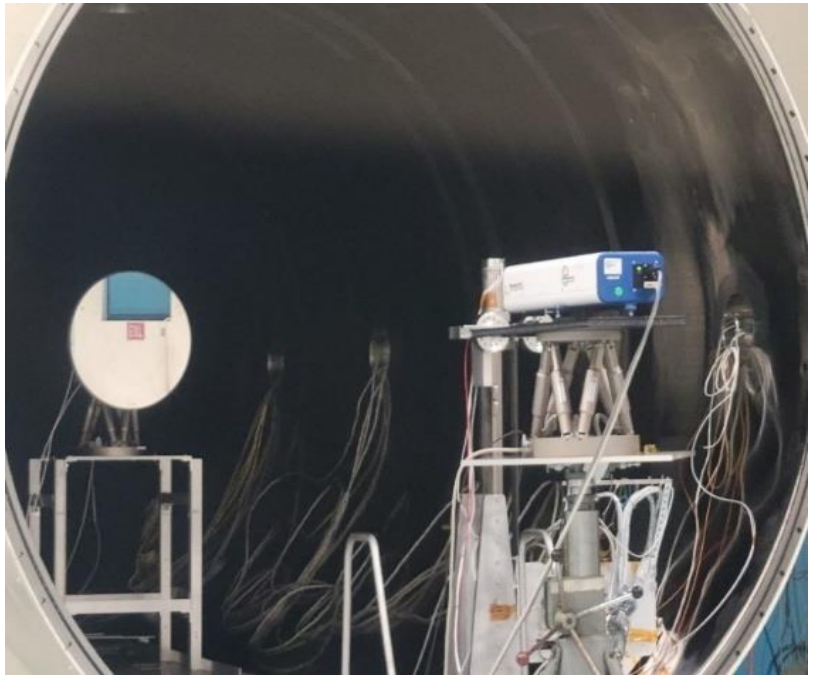
Averaging these N-rotation measurements results in a measurement consisting of only the mirror's symmetric surface shape and its gravity-sag.

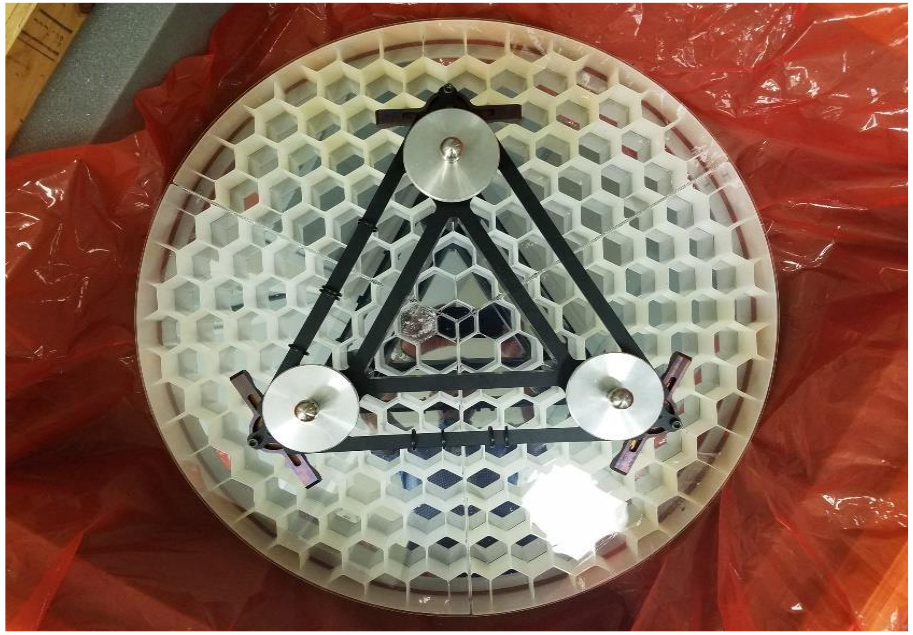
Back rotating each data set to theta = 0 before averaging, removes the gravity sag term, leaving only the mirror's symmetric and asymmetric terms.

$$\frac{1}{N}\sum_{i=0}^{N-1} S(x,y,(\theta_i=0)_{Horizontal} = \left[S(x,y)_{G(0,0,0)_{symmetric}} + S(x,y,\theta_i)_{G(0,0,0)_{asymmetric}}\right]$$

Test Setup

- 3-point mount in 120° offsets i.e. (0°, 120°, 240°)
- Mirror is attached to rotary stage
- Mirror and 4D are attached to hexapods for fine alignment





The horizontal rotation test makes use of the ‘N-rotation’ algorithm where the interferometer measures a surface at N-rotation angles, i.e. N=3 (0°, 120°, 240°) or N=6 (0°, 60°, 120°, 180°, 240°, 300°).

Gravity Sag Measurements

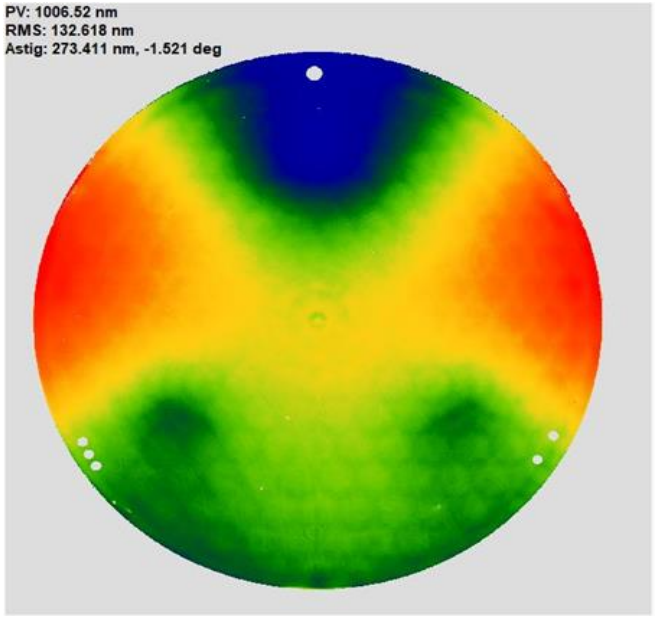
DOT mirror was tested with N-6, N-12 and N-24 rotations

Averaging multiple measurements allows for thermal and vibration to be damped out of the data

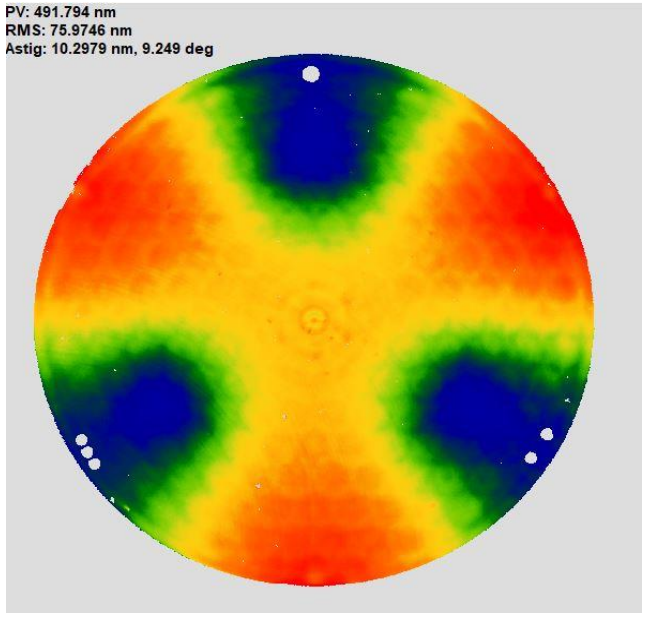
G-sag ranged from ~108nm to ~122nm RMS

0G figure reproducibility was to ~5 +/- 3 nm RMS

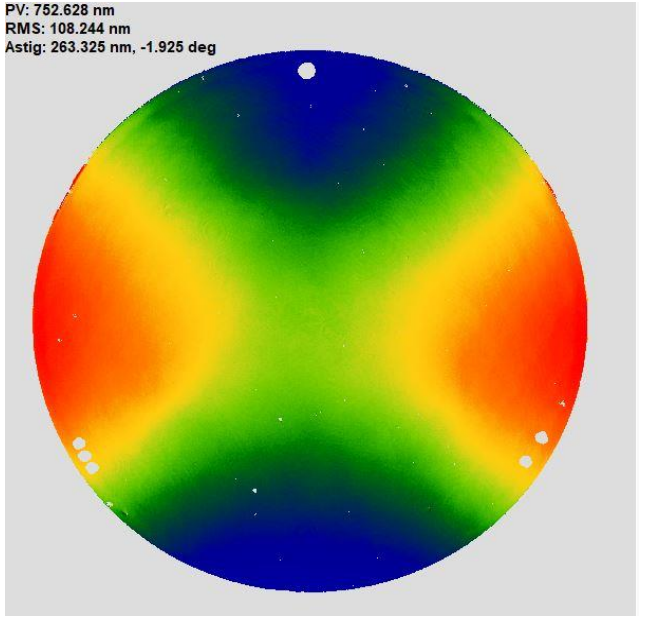
Raw phase map



0G Figure



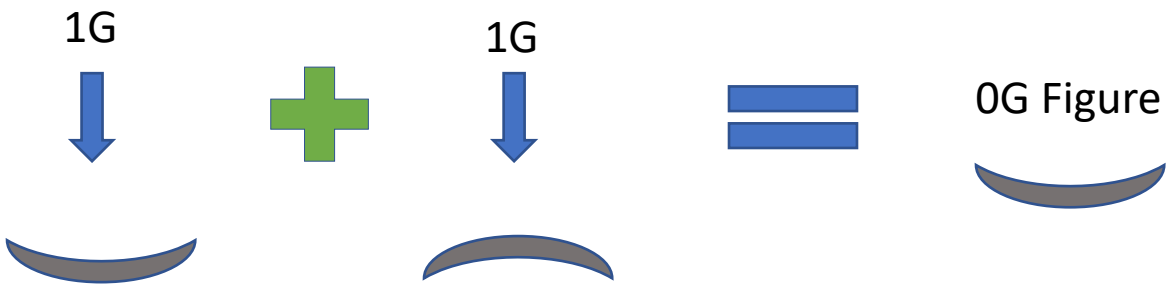
Gravity sag



Vertical Testing

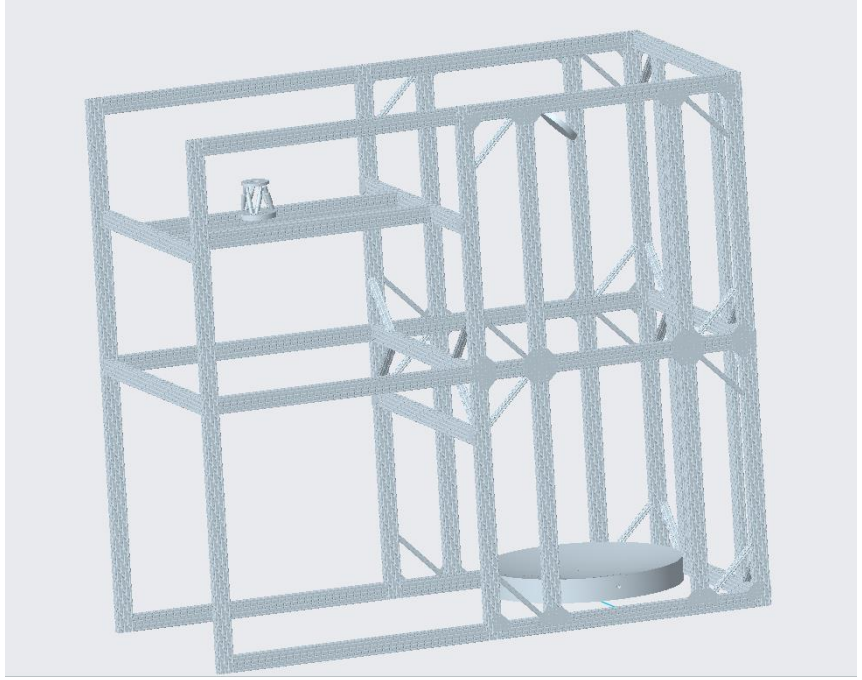
- Mirror is tested in both the Face-up/ Face-Down orientations
- Mirror is tested on its flight mount.
- G-Sag should be identical in the two orientations except for its polarity.

$$S(x,y)_{face-up} = S(x,y)_{G(0,0,0)} - S(x,y)_{G(0,0,-1)}$$
$$S(x,y)_{face-down} = S(x,y)_{G(0,0,0)} + S(x,y)_{G(0,0,1)}$$
$$0G\ Shape = S(x,y)_{G(0,0,0)} = [S(x,y)_{face-up} + S(x,y)_{face-down}]/2$$
$$1G\ Sag = S(x,y)_{G(0,0,-1)} = [S(x,y)_{face-up} - S(x,y)_{face-down}]/2$$

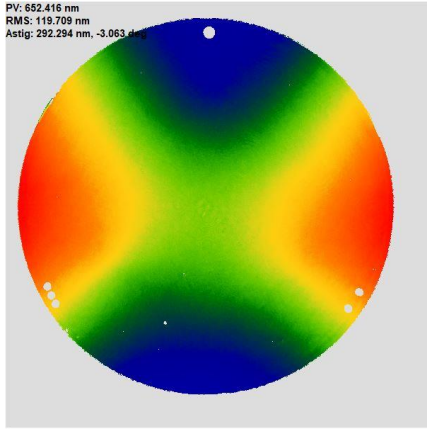


Vertical Testing

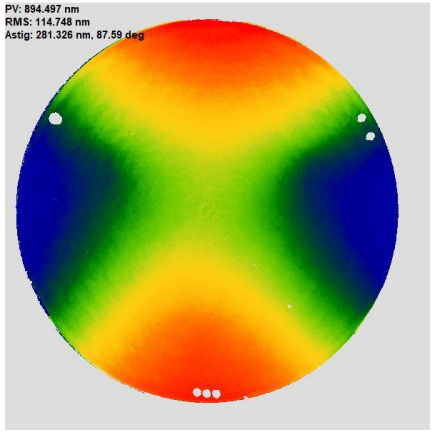
- Test mirrors up to 2 m in diameter in face up/face down orientation
  - Further develop understanding of gravity sag
  - Verify horizontal rotation test vs. face up/face down test
- Test mirrors at different elevation angles
  - Test change in WFE as function of elevation angle
  - Verify null polishing for G-sag compensation



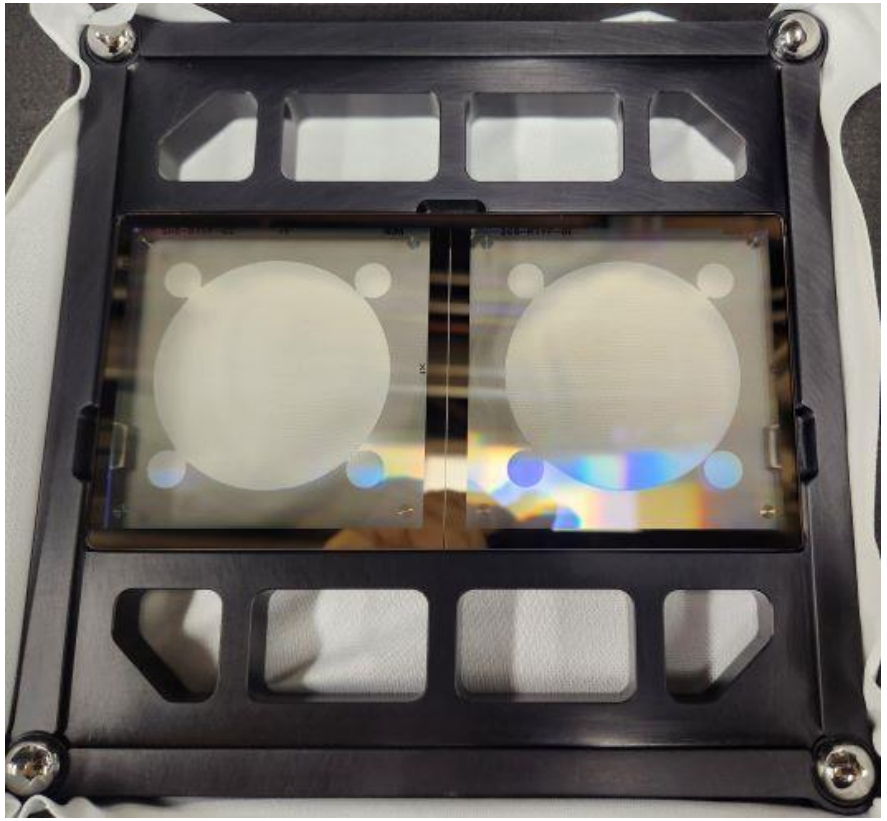
CGH Testing



0 deg. rotation



60 deg. rotation

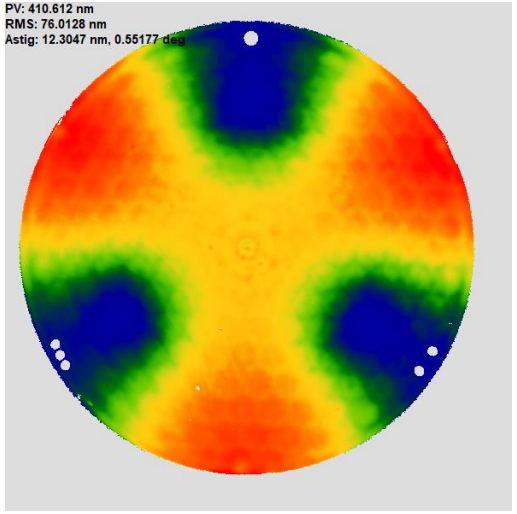


CGH for 0 deg and 60 deg rotations

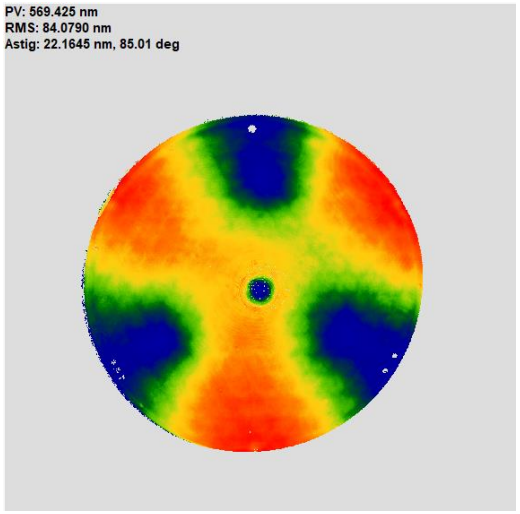
CGH Testing

- CGH testing was done with the same setup as the horizontal rotation test
- The CGH was used to remove the G-sag from 0, 60, 120 and 240 orientations
- ~26nm difference between 0G figure from the horizontal test and the CGH test

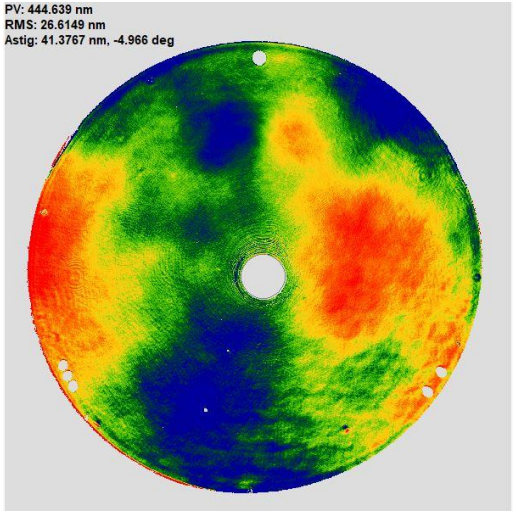
0G Horizontal Rotation Test



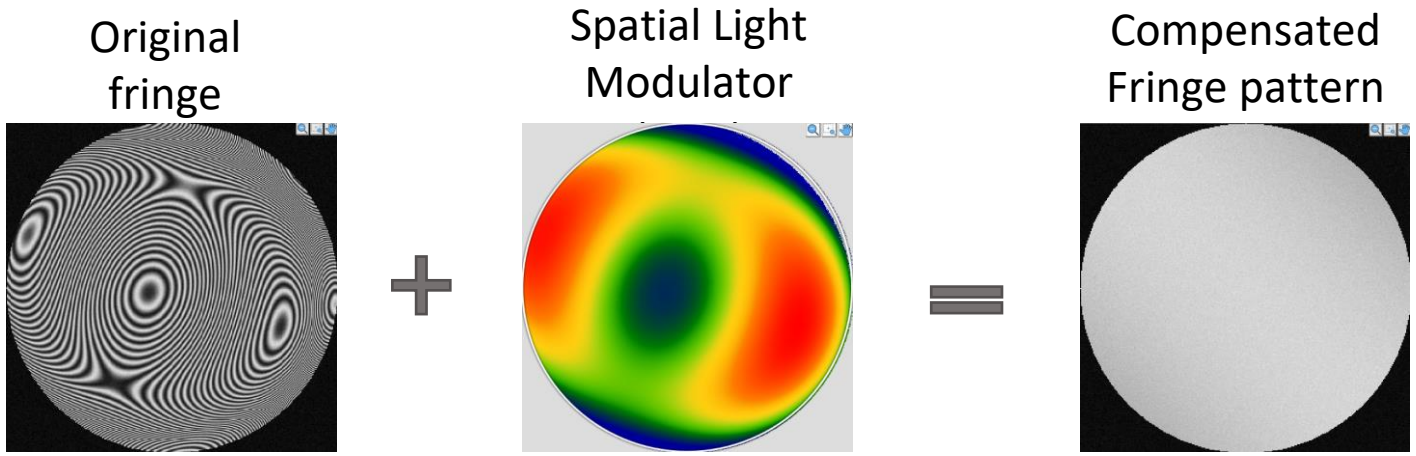
0G CGH test

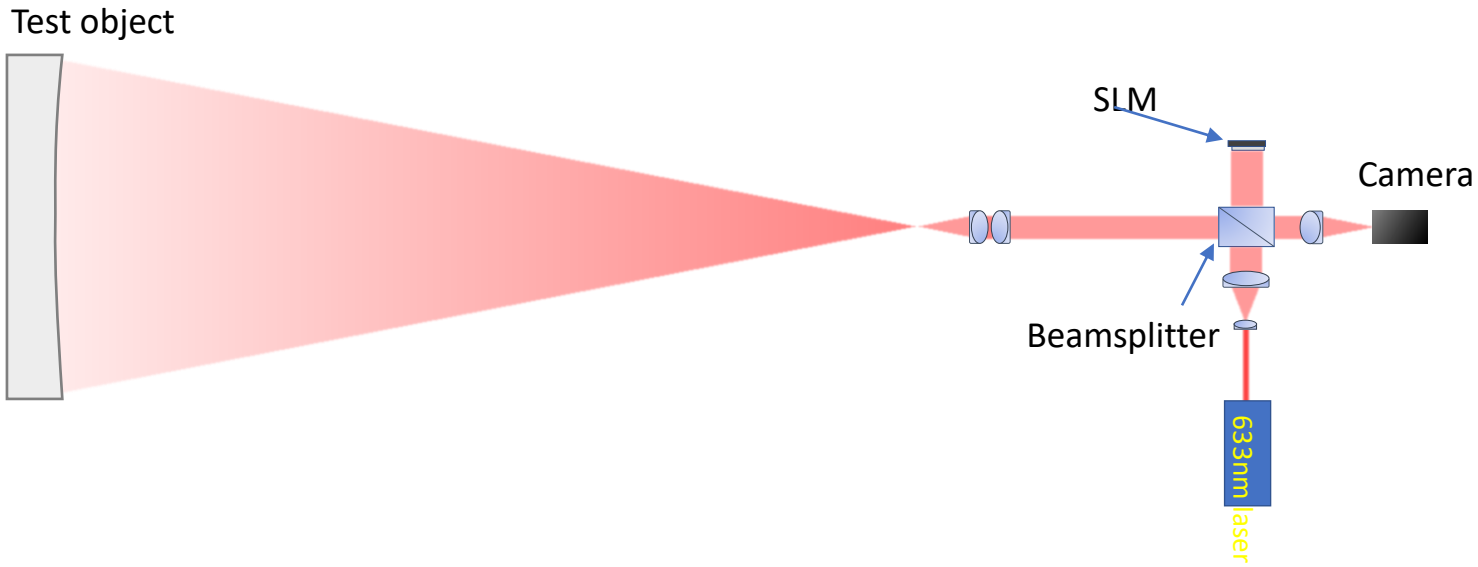


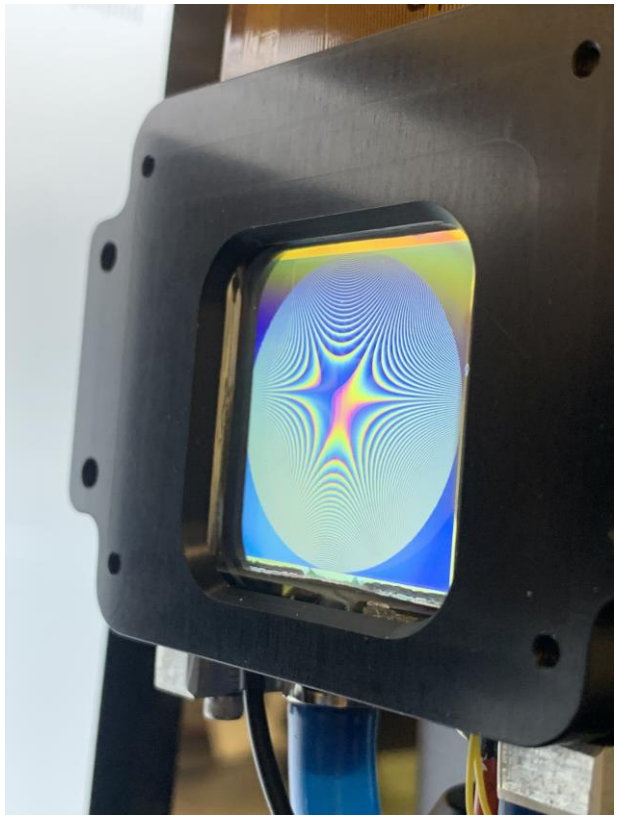
Difference



eCGH Testing







Conclusions/Future Work

G-release is a critical component of the error budget for light-weighted mirror

Multiple methods for estimating a mirror's zero-gravity surface figure have been demonstrated

Modeling has shown that we can predict the gravity sag to within ~20nm of the test value

Removing G-sag with a CGH provided comparable results to the model and horizontal testing

Modeling provides the ability to create CGH's for light-weighted mirrors with gravity sag.

Face-up/face-down testing will be done to compare the results from the from the analytical methods

Testing of mirrors that have a gravity sag in the micron plus range.

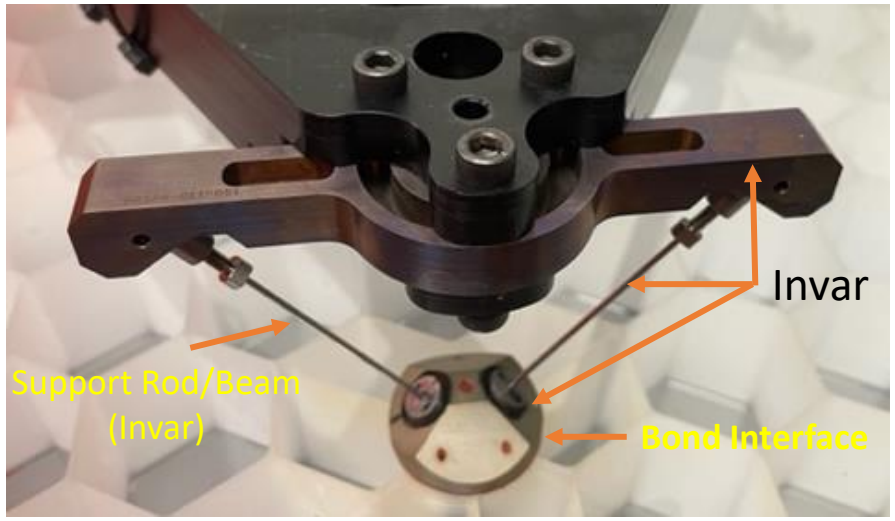
Testing and verification of eCGH with all the other methods of determining gravity sag.

eCGH Testing

- Precision
  - **Goal:** lambda/100 waves
- Repeatability
- Flatness
- Range
  - **Theory:** 768 waves
  - **Goal:** > 250 waves

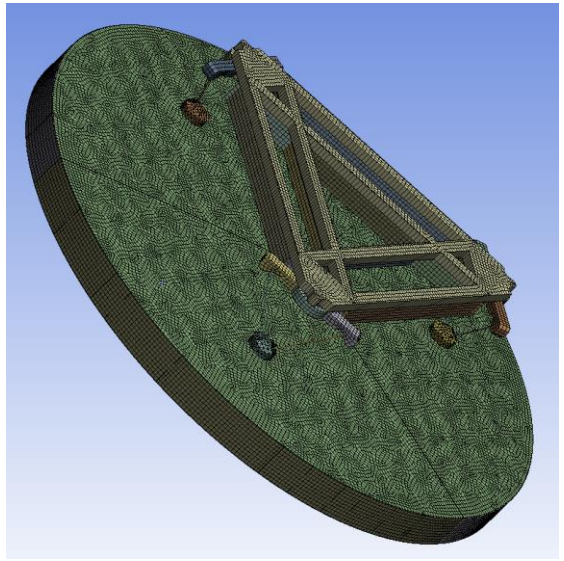
- Nulling with diverging lens
- Nulling with CGH
- Off-axis parabola testing

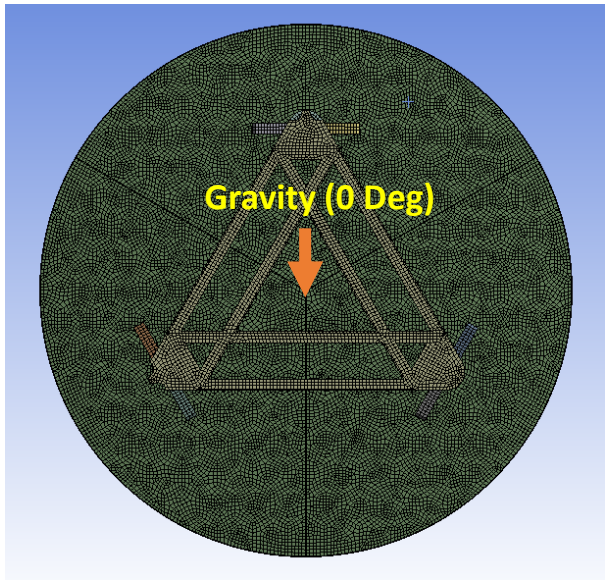
DOT Mirror Finite Element Model Assumptions

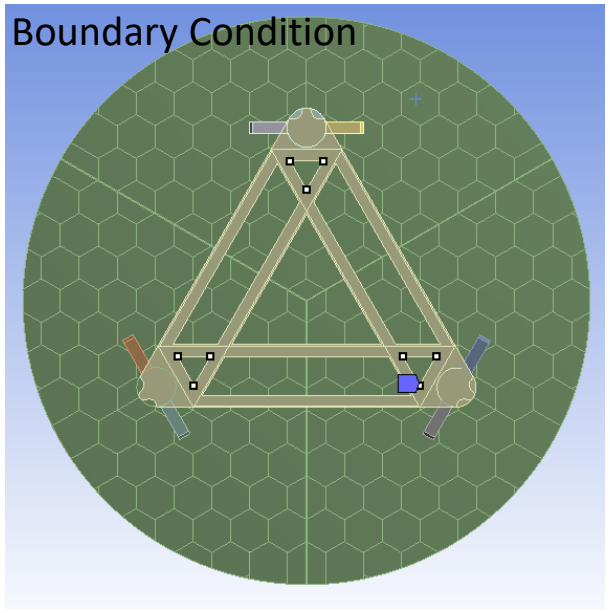


Nominal Design

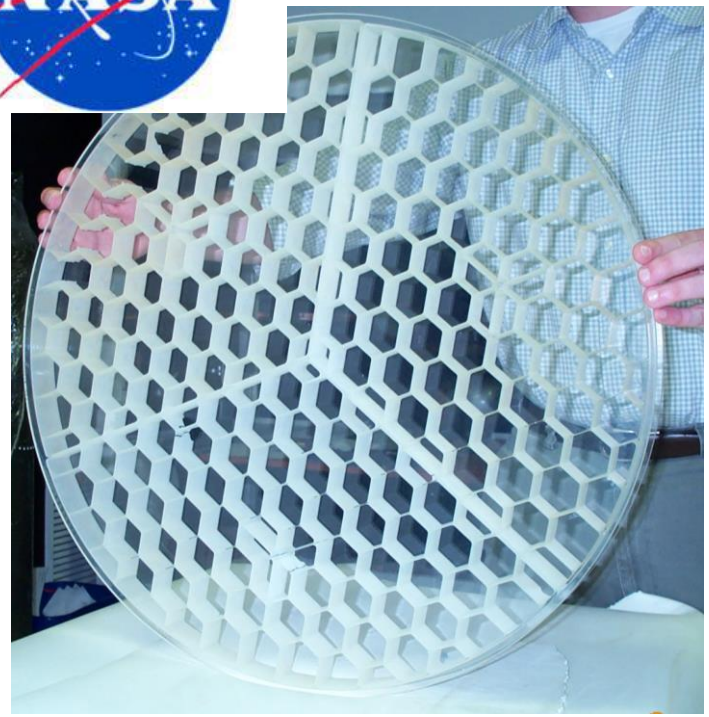
Material Property			
	Elastic Modulus, GPa	Possion's Ratio	Density, Kg/m^3
ULE	67.60	0.17	2200.0
Aluminum	69.26	0.33	2712.6
Invar	140.00	0.29	8150.0
Critical Parameters and Dimensions			
Facesheet Thickness	1.9 mm		
Backsheet Thickness	1.65 mm		
Core Rib Thickness	0.76 mm		
Support Beam Radius	0.75mm		

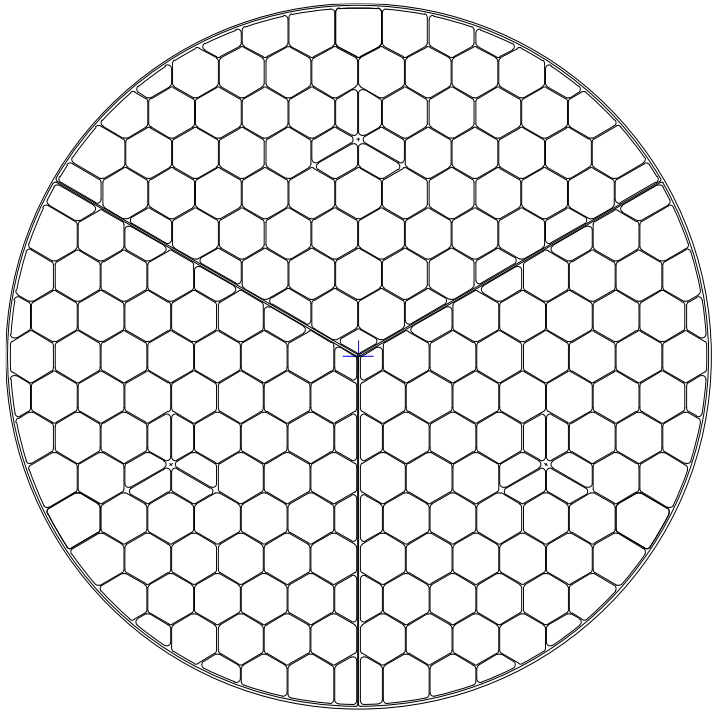


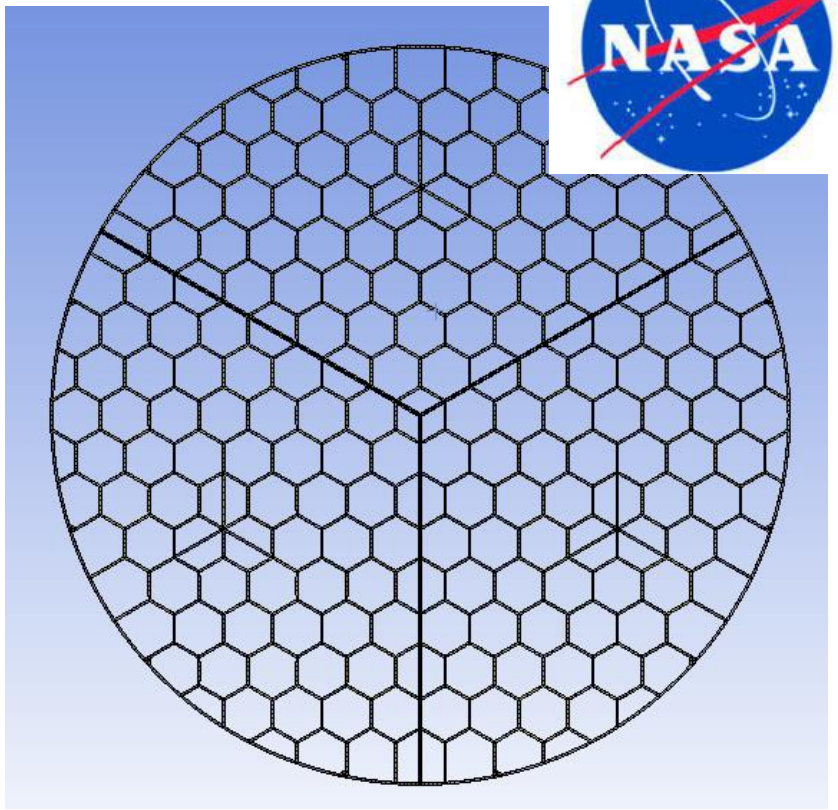




DOT Mirror Design Comparison





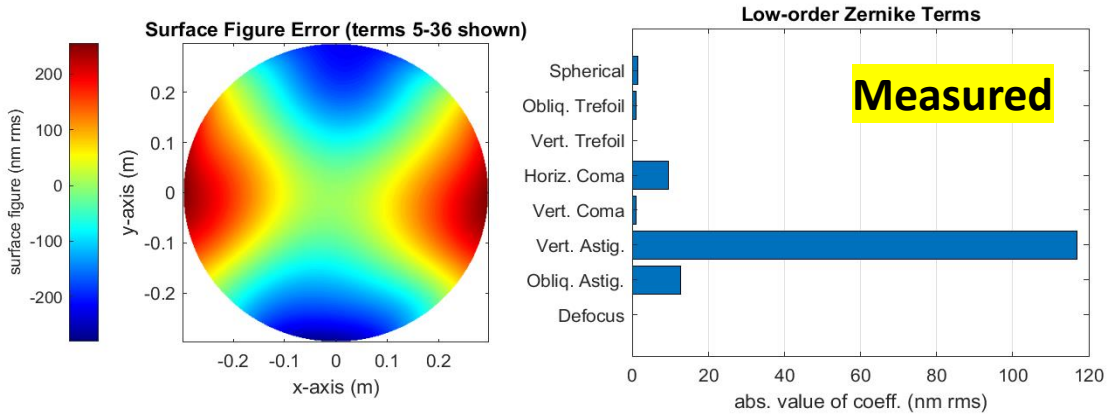


Source: AFRL-DOT Radius Matched Mirror Presentation (August 17,2004)

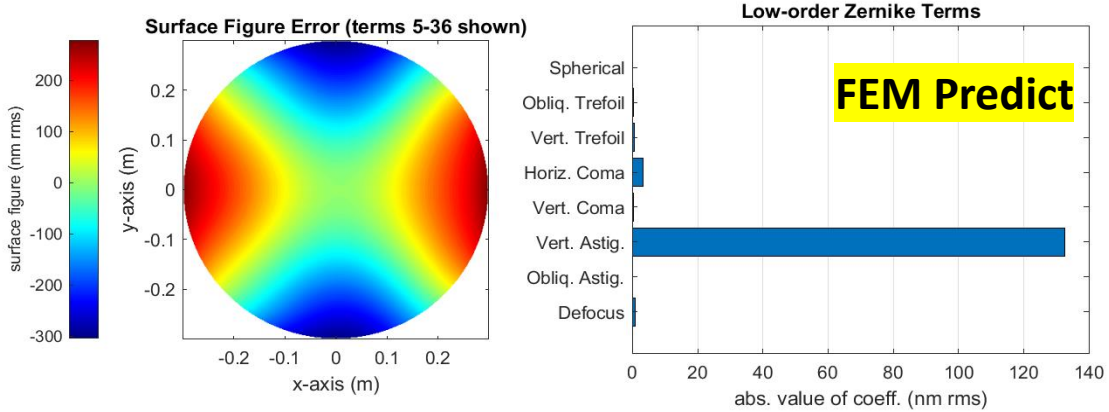
FEM Model

Parameter	Value (mm)
Diameter	600
FP Thickness	1.9
BP Thickness	1.65
Core Depth	38
Core Rib Thickness	0.76

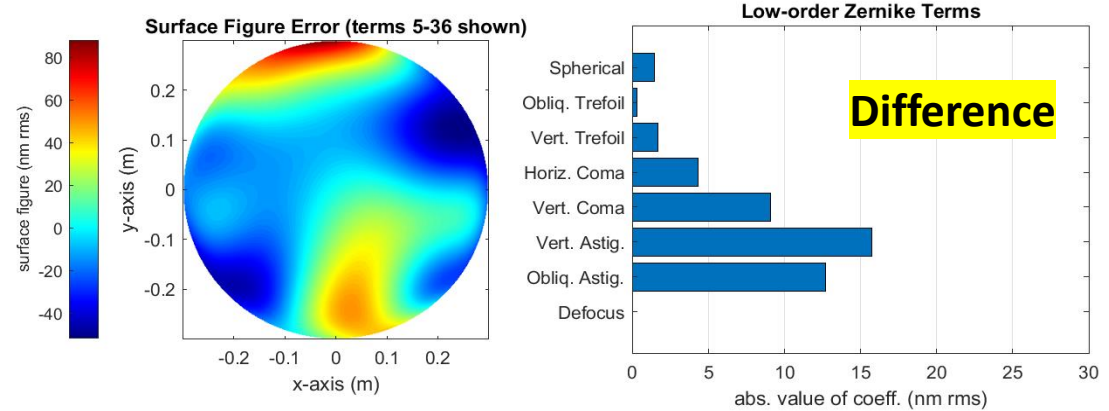
Modeling


Surface Figure Error (terms 5-36 shown)
surface figure (nm rms)
200
100
0
-100
-200
y-axis (m)
0.2
0.1
0
-0.1
-0.2
-0.2 -0.1 0 0.1 0.2
x-axis (m)

Low-order Zernike Terms
Spherical
Obliq. Trefoil
Vert. Trefoil
Horiz. Coma
Vert. Coma
Vert. Astig.
Obliq. Astig.
Defocus
0 20 40 60 80 100 120
abs. value of coeff. (nm rms)
Measured

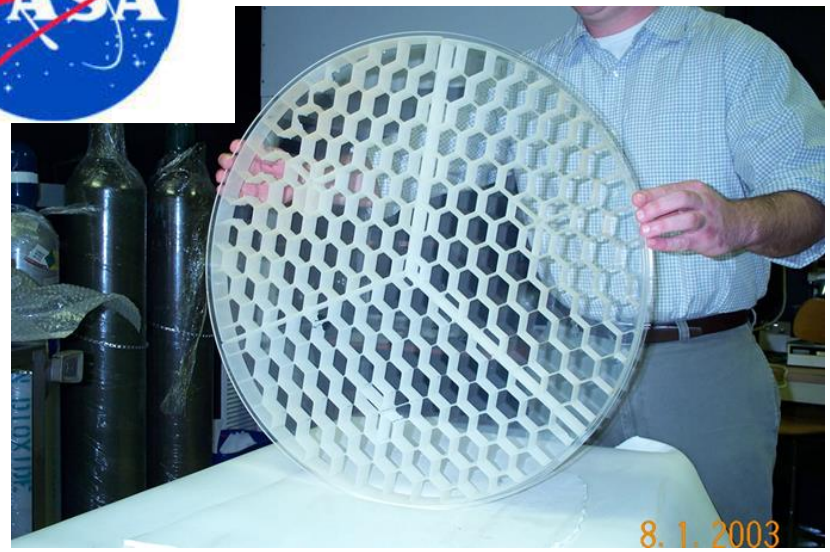

Surface Figure Error (terms 5-36 shown)
surface figure (nm rms)
200
100
0
-100
-200
-300
y-axis (m)
0.2
0.1
0
-0.1
-0.2
-0.2 -0.1 0 0.1 0.2
x-axis (m)

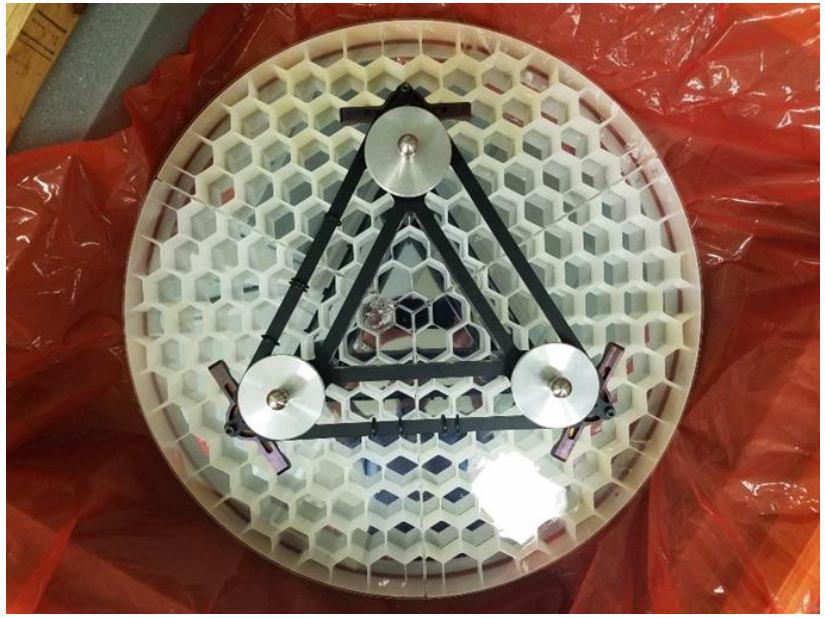
Low-order Zernike Terms
Spherical
Obliq. Trefoil
Vert. Trefoil
Horiz. Coma
Vert. Coma
Vert. Astig.
Obliq. Astig.
Defocus
0 20 40 60 80 100 120 140
abs. value of coeff. (nm rms)
FEM Predict


Surface Figure Error (terms 5-36 shown)
surface figure (nm rms)
80
60
40
20
0
-20
-40
y-axis (m)
0.2
0.1
0
-0.1
-0.2
-0.2 -0.1 0 0.1 0.2
x-axis (m)

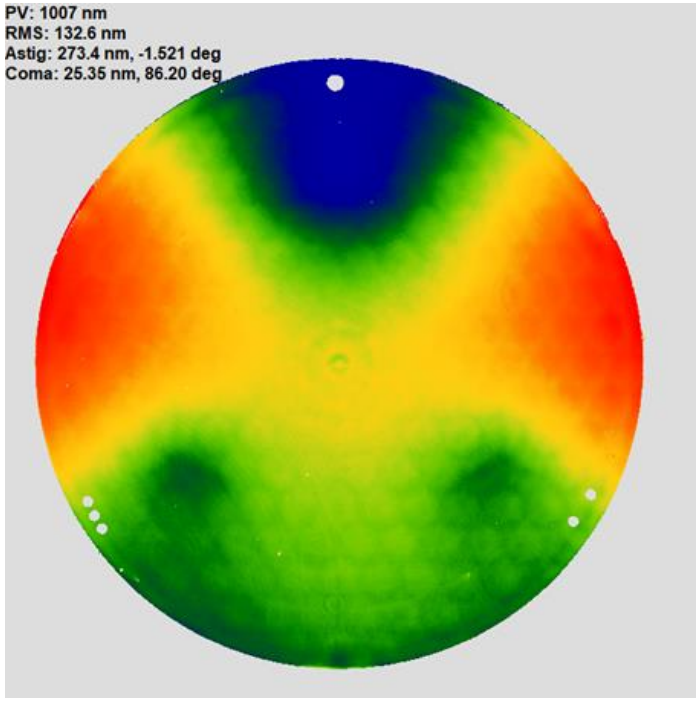
Low-order Zernike Terms
Spherical
Obliq. Trefoil
Vert. Trefoil
Horiz. Coma
Vert. Coma
Vert. Astig.
Obliq. Astig.
Defocus
0 5 10 15 20 25 30
abs. value of coeff. (nm rms)
Difference

Mirrors available for gravity sag characterization





Deployable Optical Telescope (DOT) mirror
Diameter: 0.6 m
Edge thickness: 44.5mm
Radius of curvature (ROC): 5 m
R/#: 8.33 (ROC/dia.)
Mass: 5 kg
$F_n \geq 80$ Hz
Material: Corning ULE® glass front and back plates low temperature fused between abrasive waterjet ULE® core.



Self-Weight Deflection

Self-weight deflection consists of two components: mount and face-sheet deflection.

Mount Deflection (or Gravity Sag) is low-order bending of the mirror substrate as it is accelerated by gravity against its opto-mechanical support mount.

Face-sheet Deflection (or Quilting) occurs when mirrors are light-weighted –leaving parts of the face-sheet without support. These parts deflect slightly due to the acceleration of gravity against the vertical core ribs and deflect more due to fabrication tool forces.

G-Release Error

G-release error is defined as the knowledge uncertainty of a mirror's gravity-sag or the residual error between the mirror's predicted and actual on-orbit shape.

- G-release occurs because space mirrors are manufactured in a 1-G environment.
- In 1-G, mirrors have self-weight deflection.
- But in 0-G, there is no gravity and thus no self-weight deflection.
- The change in the mirror's shape from 1-G to 0-G is called G-release.
- G-release is most important for the primary because it is the largest, lowest stiffness mirror in the telescope.

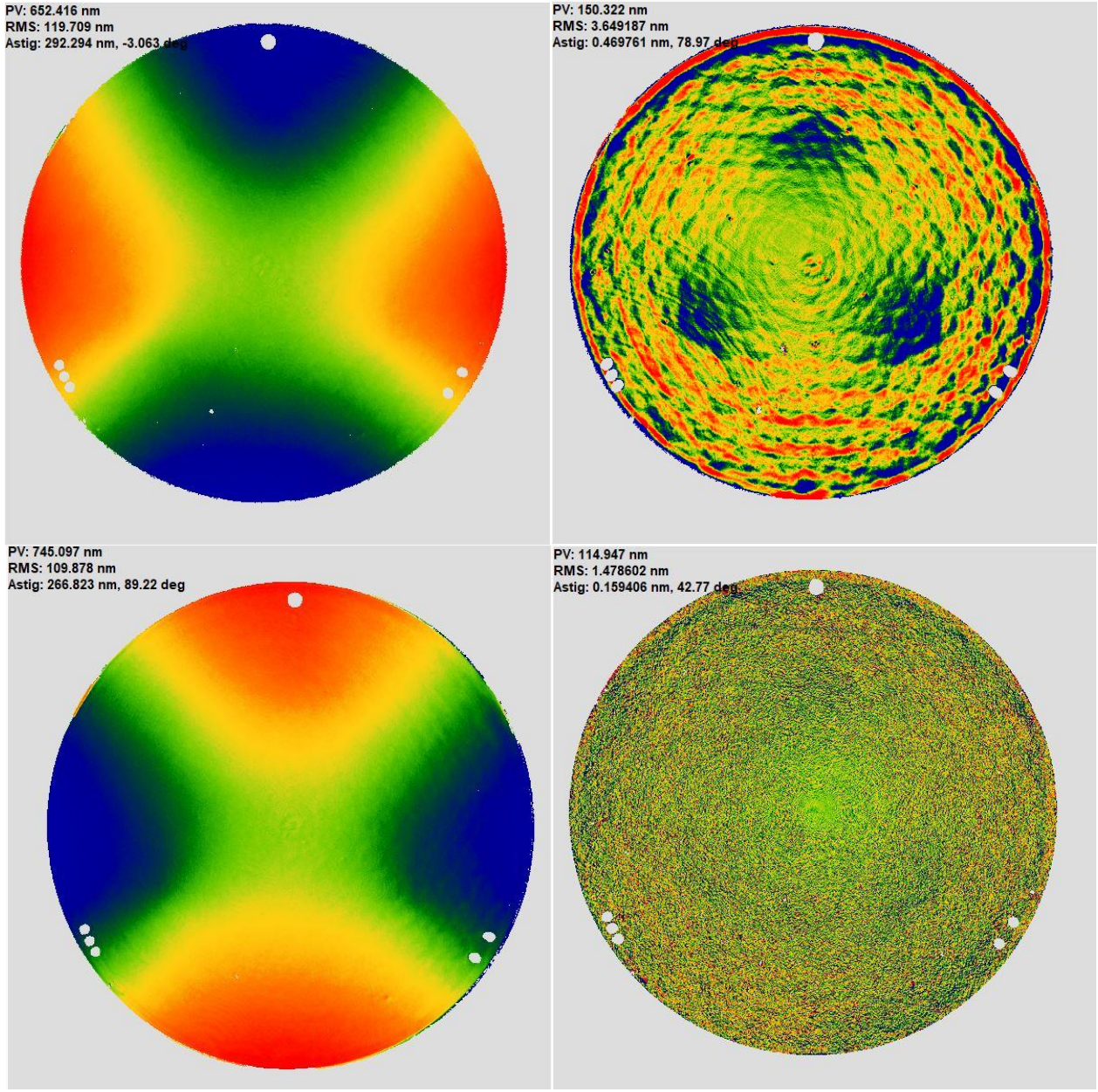
Gravity Sag Uncertainty

To determine the uncertainty in the gravity sag estimate the gravity sag measurements are back-rotated to the theta=0 positions.

Uncertainty for a G-sag estimate has an RMS value of ~3.6 nm.

Possible sources for the uncertainty can come from multiple sources such as: mis-registration shear error of pocket quilting, variation in pocket quilting, mount pad deflection as a function of rotation, etc.

Error seen is from limitations of registration from the 4D and shear effects from bending of the substrate and mount.



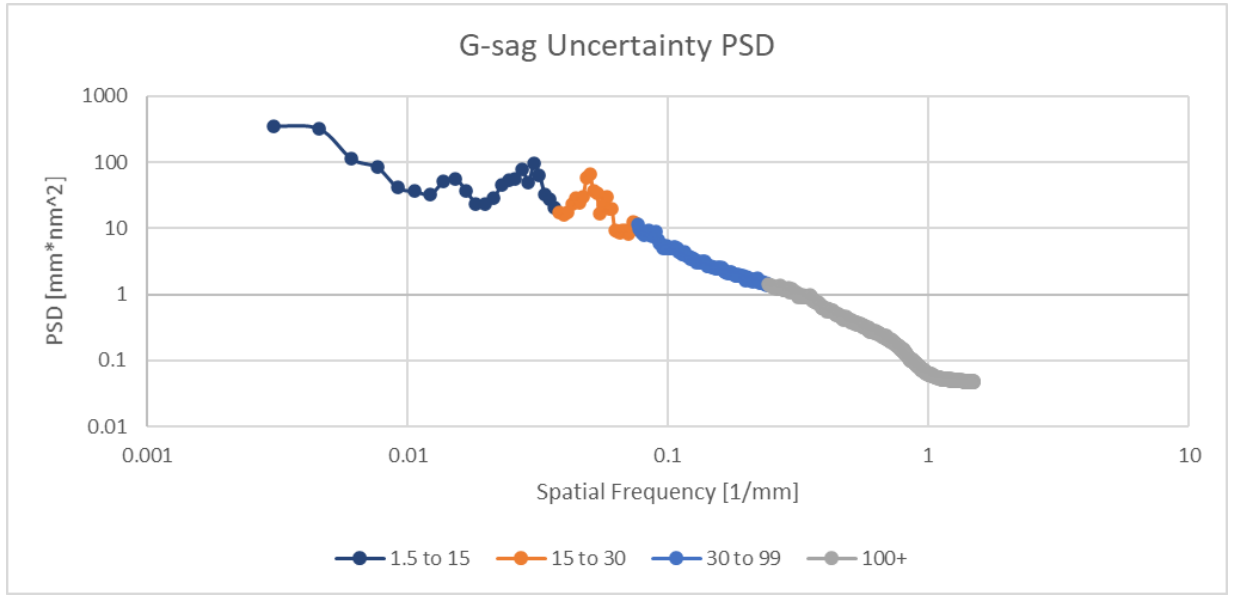
Gravity Sag Uncertainty

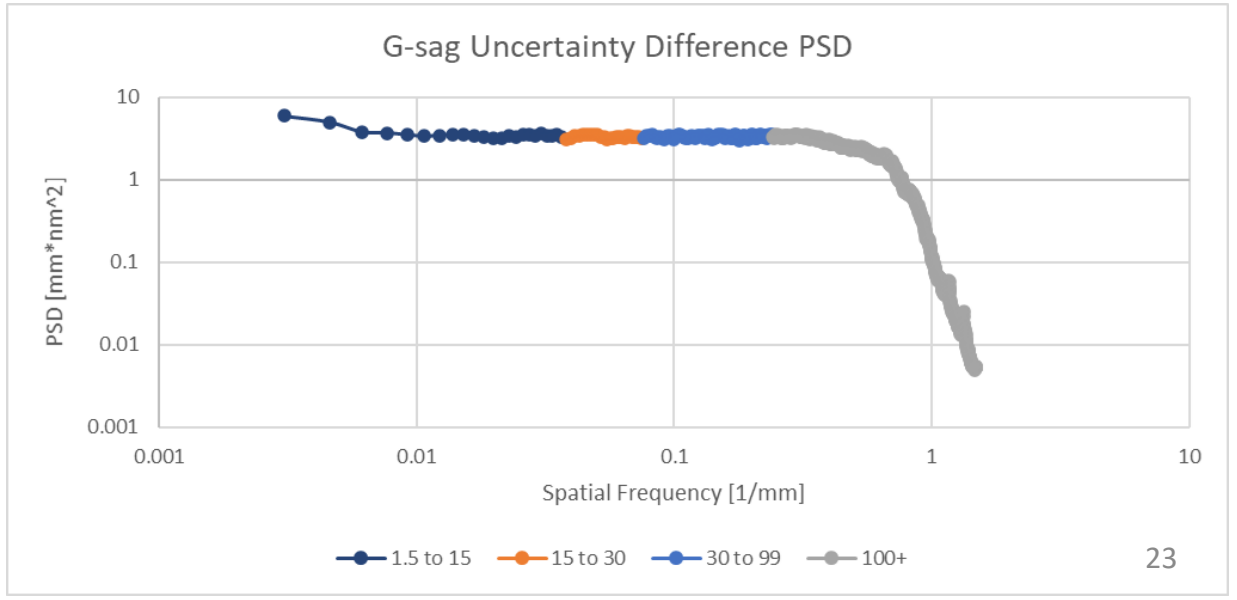
PSD of the uncertainty of the G-sag has noticeable mid-spatial frequency structure.

Bottom graph is the PSD for the difference between the uncertainty of two data sets.

Mid-spatial “bumps” seen are repeatable and present in the mirror itself so when the gravity sag phase map is calculated by removing the 0-G phase map some asymmetric components are left in the gravity sag phase maps.

note that the uncertainty in the estimate of the low-order gravity sag terms, including astigmatism, is very good – less than 1 nm rms.





N-Rotation Test

The horizontal rotation test makes use of the ‘N-rotation’ algorithm where the interferometer measures a surface at N-rotation angles, i.e. N=3 (0°, 120°, 240°) or N=6 (0°, 60°, 120°, 180°, 240°, 300°).

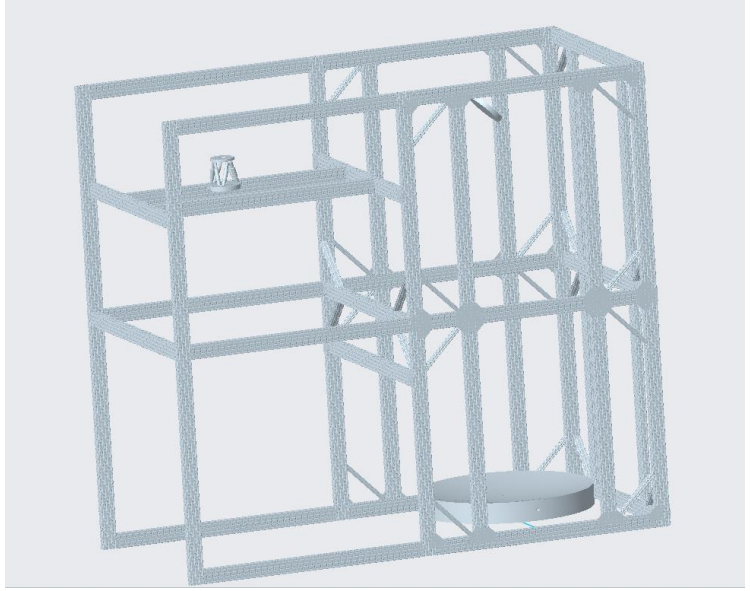
Averaging removes all test errors with angular dependence up to (N-1) Theta; and, all higher angular order errors that are not harmonics of N.

So, an N=3 rotation test will remove 2-Theta errors (i.e. coma, secondary coma, tertiary coma, etc.; and, astigmatism, secondary astigmatism, tertiary astigmatism, etc.).

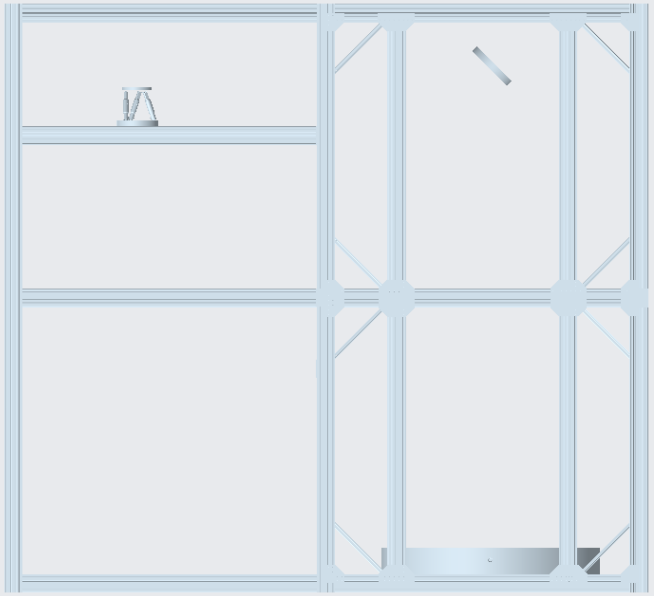
An N=6 rotation test is required to remove error terms up to 5-Theta (i.e. trefoil, tetrafoil, and pentafoil).

Vertical Testing

- Frame
  - Vibrational damping leveling feet to suppress noise
  - Easily outfitted with plastic sheets to mitigate air current
  - Rail platform with adjustable height and tilt for moving interferometer into position
  - Fold mirror assembly with digital protractors and tip/tilt adjustment for aligning to different elevation angles



- Mirror cart
  - 4000 lb capacity hydraulic lifts with vibration damping leveling feet
  - 2000 lb hydraulic lift for tip mechanism
  - Levels on frame and digital protractors for accurate elevation angles

pabilities and limitations

- Using a 50” fold mirror max focal length for a 2 m mirror is 7.14 m
  - Limited by height of tower/fold mirror aperture
- For smaller mirrors max focal length is 8 m
  - Limited by length of frame