Figure Verification of a Precision Ultra-Lightweight Mirror:
Techniques and Results

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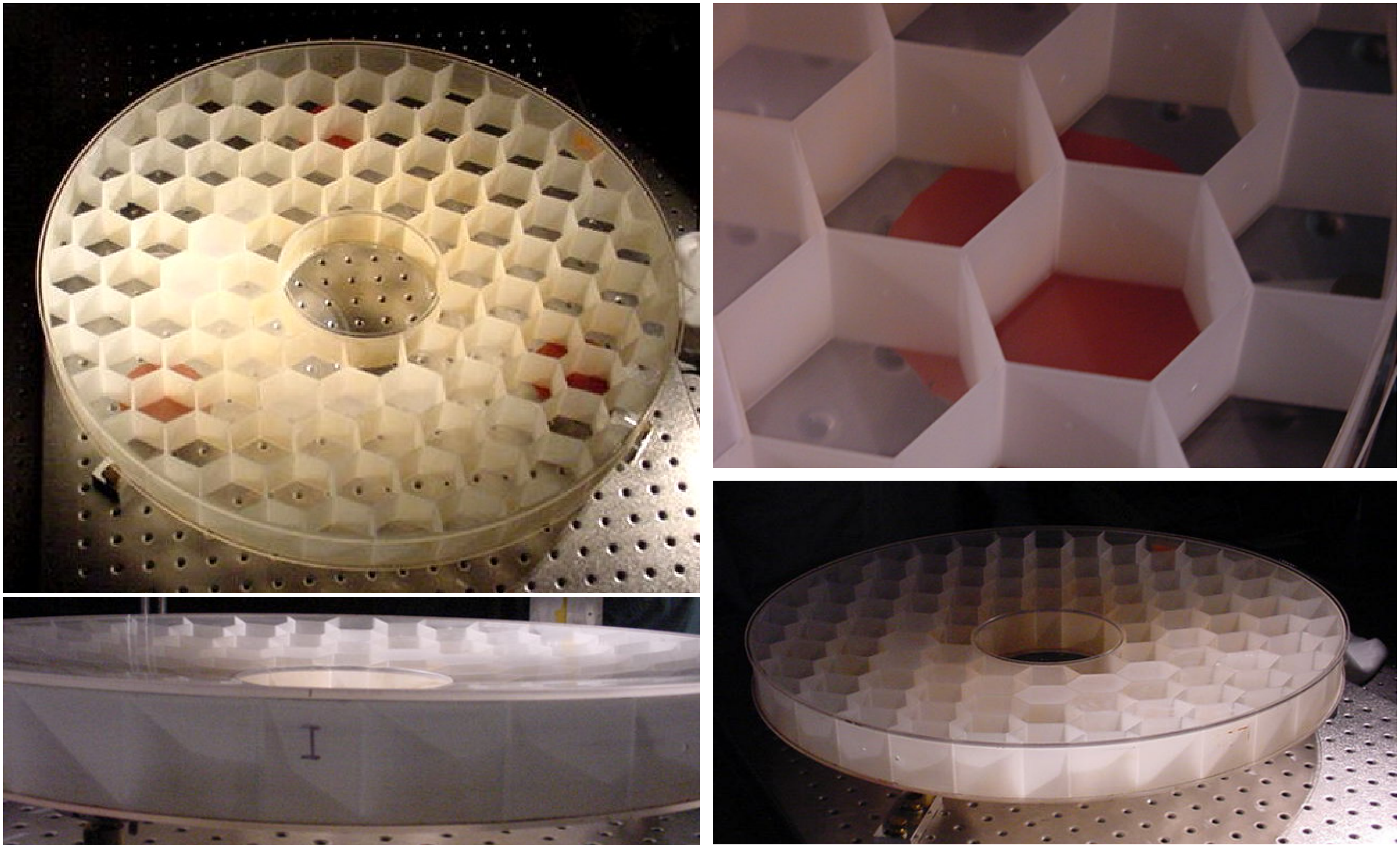
Ultra-Lightweight Mirror Technology R&D:

Developing and testing the methodologies required to incorporate cutting-edge lightweight mirror technology in spaceflight missions.

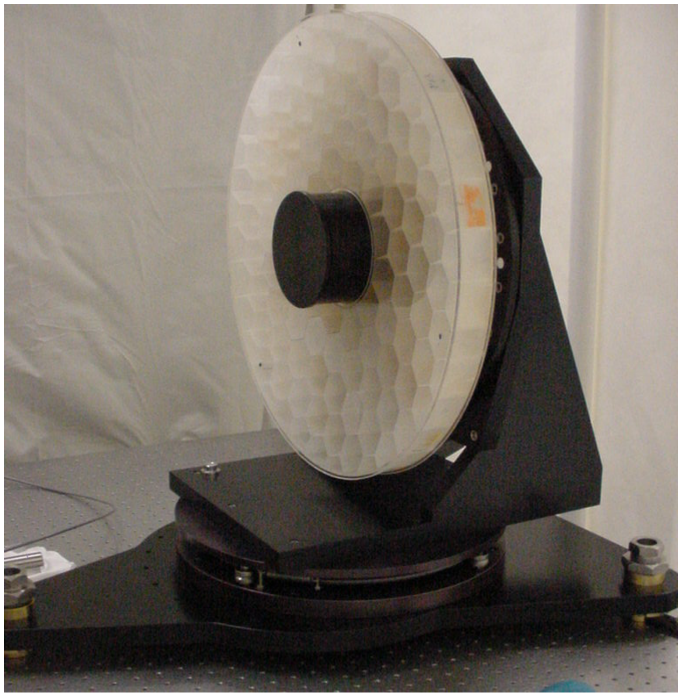
- NASA/Goddard has dedicated internal research and development resources to advance methods of verifying and utilizing ultra-lightweight mirror technologies for spaceflight use.
- To test the feasibility of using ITT Space System's ultra-lightweight ULE architecture for diffraction limited applications in the EUV (~120nm), a demonstrator mirror was fabricated, polished, and furnished to GSFC.
- At GSFC the mirror was: coated, measured, mounted, and vibration tested

Mirror Received in June 2003

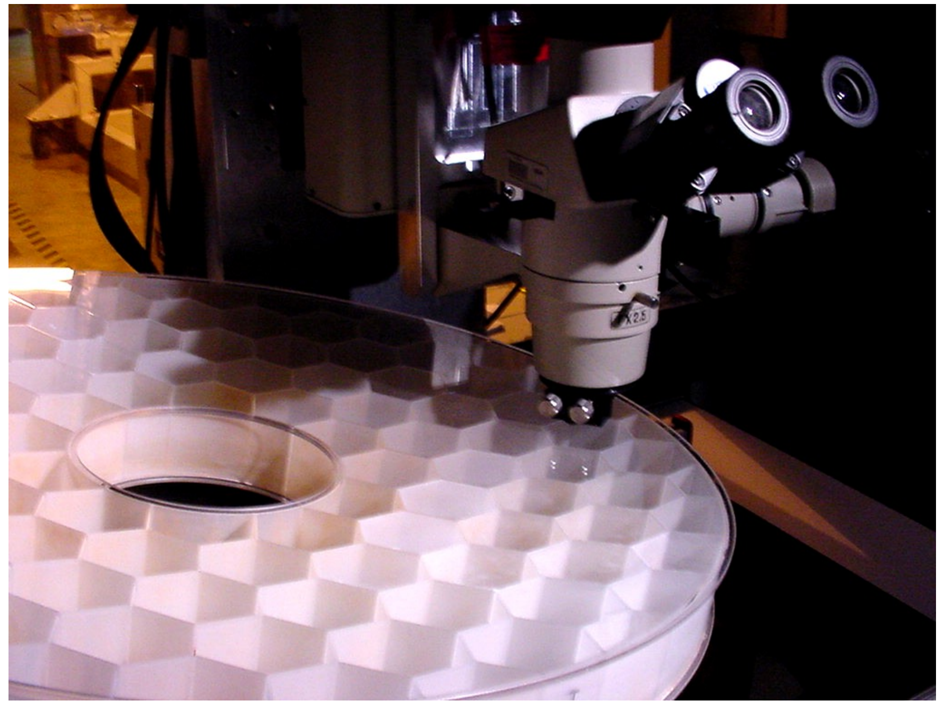


Mirror during initial inspection. Starting at upper-left and moving clockwise: (a) from above, showing overall cell pattern and mount pad locations; (b) close up of one mount pad looking through front face; (c) foreshortened view looking across flat-flat symmetry line; (d) side view showing clocking marks

Fixturing and Initial Measurements



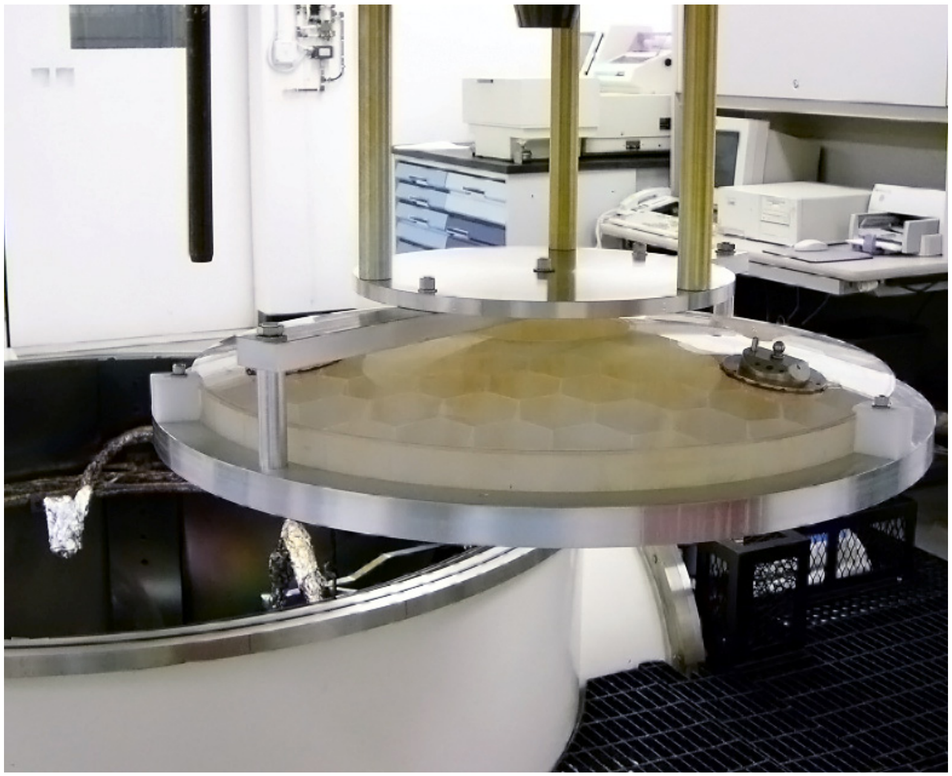
uncoated mirror in
horizontal test fixture



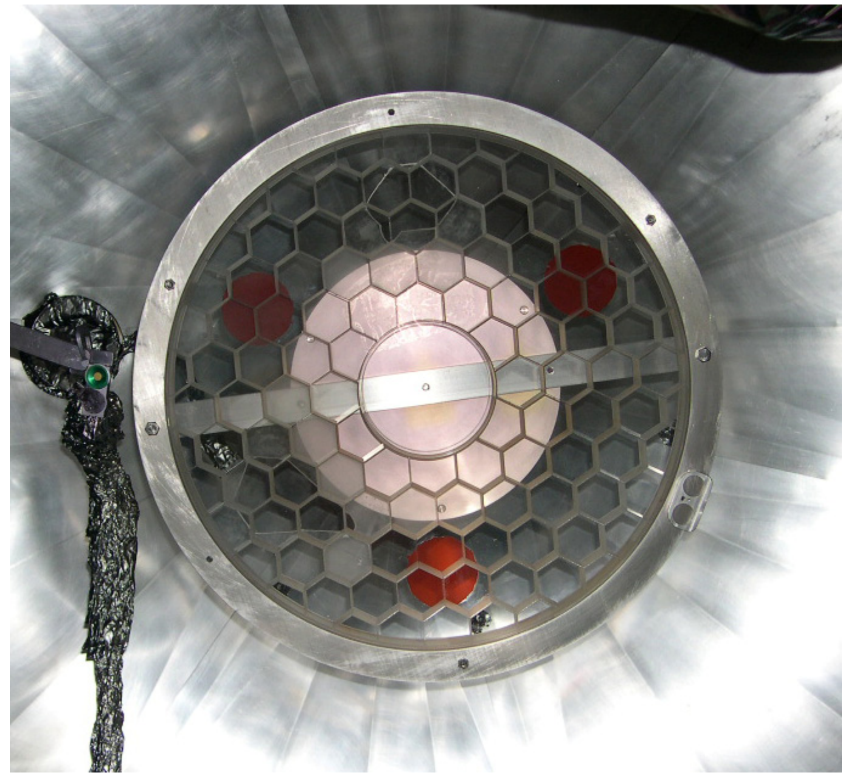
roughness measurements
(Topo2D Micro-interferometer)

Coating at Goddard

AlMgF2 and AlSiO2

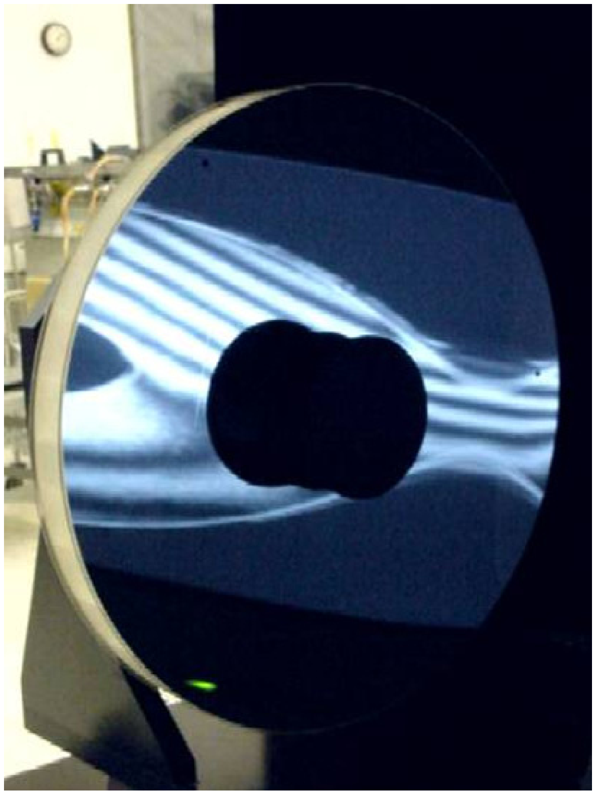


Mirror being loaded into Goddard's 2m coating chamber.

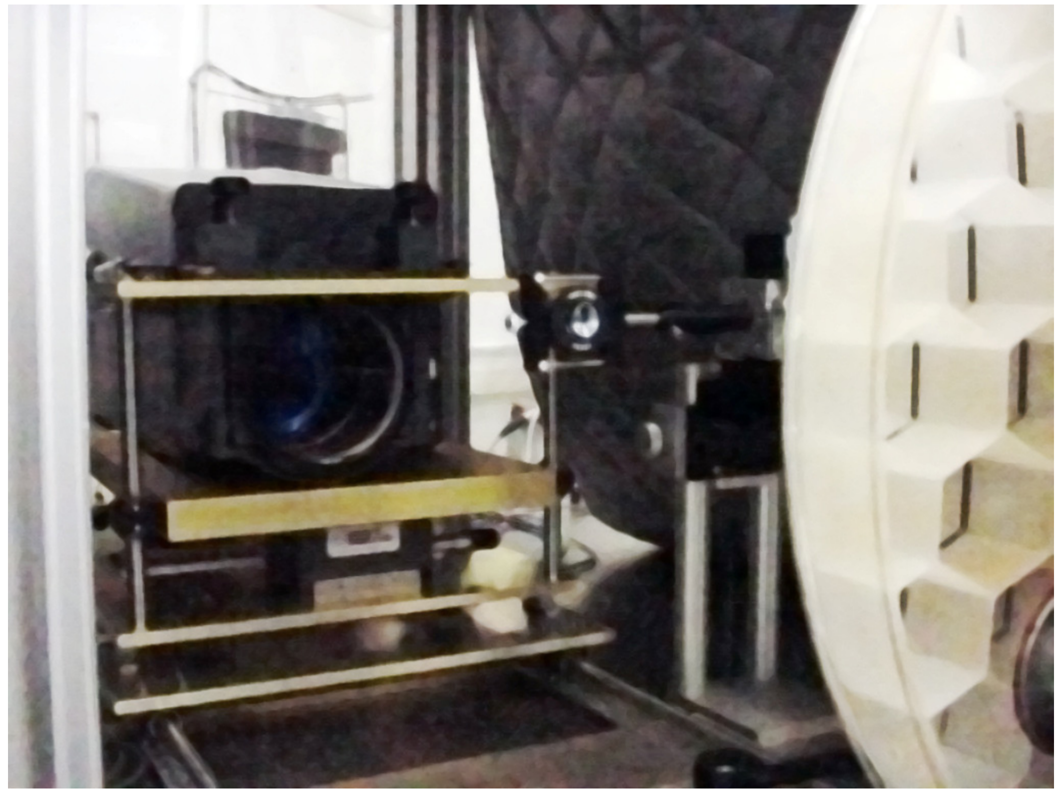


Looking up into the chamber at the mirror just before coating

Horizontal Figure Metrology

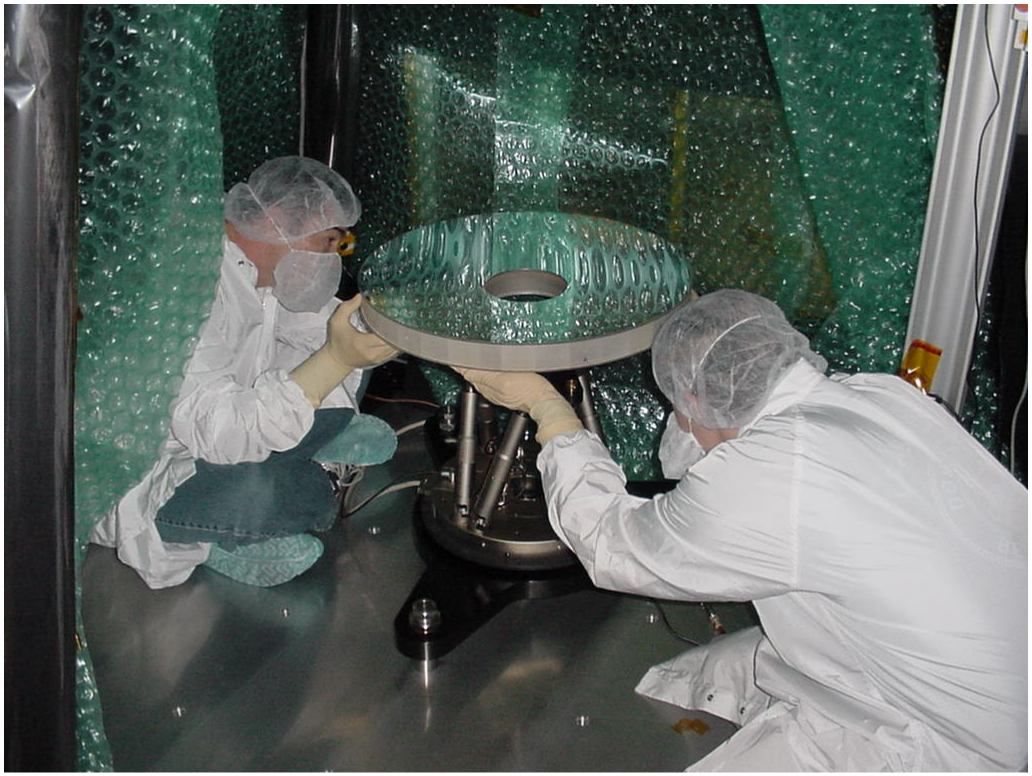


full aperture test

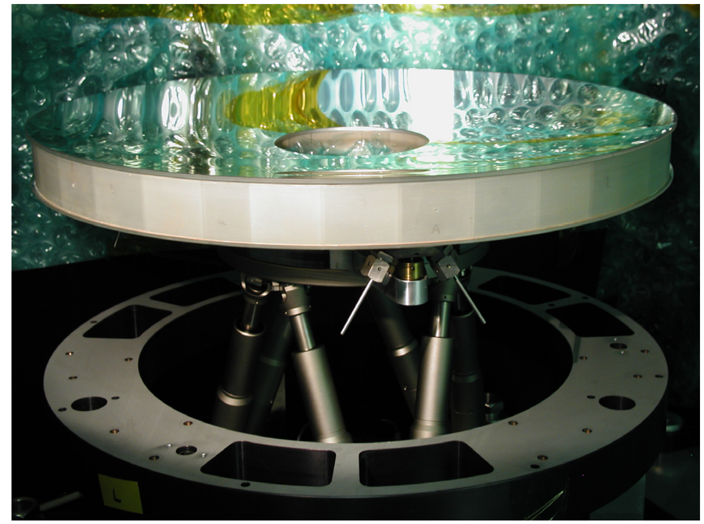


sub-aperture test

Vertical Metrology and Mount Prep.

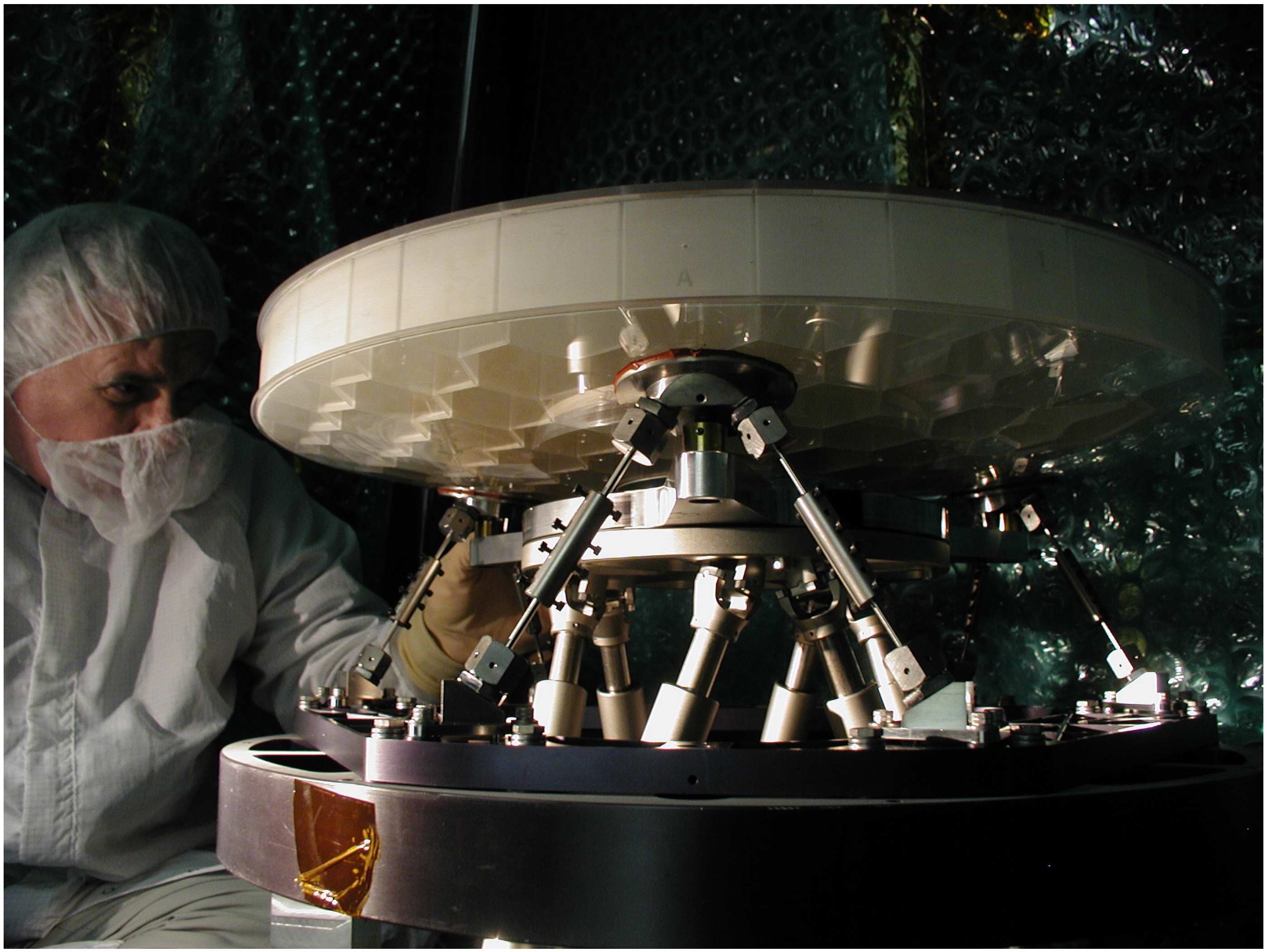


kinematic mount and hexapod positioner for vertical test

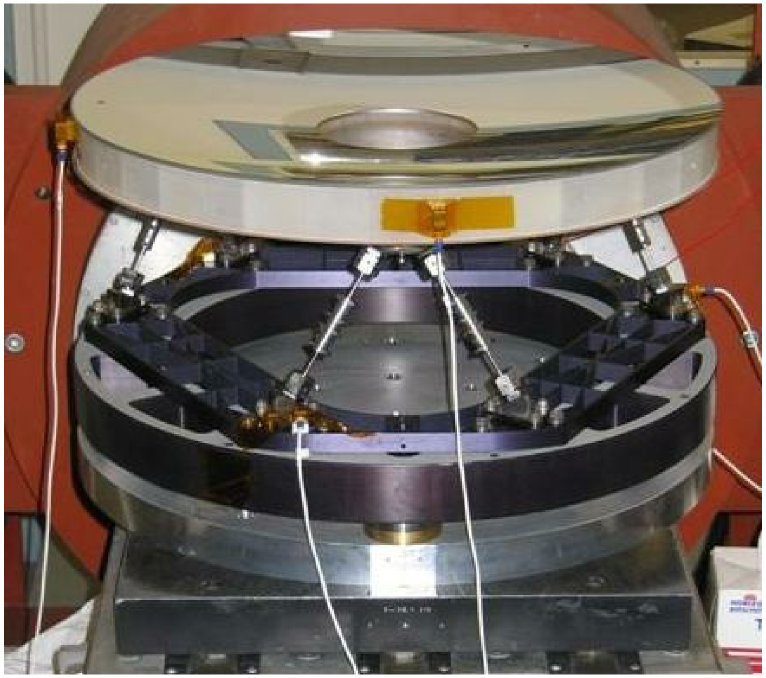


initial mounting steps

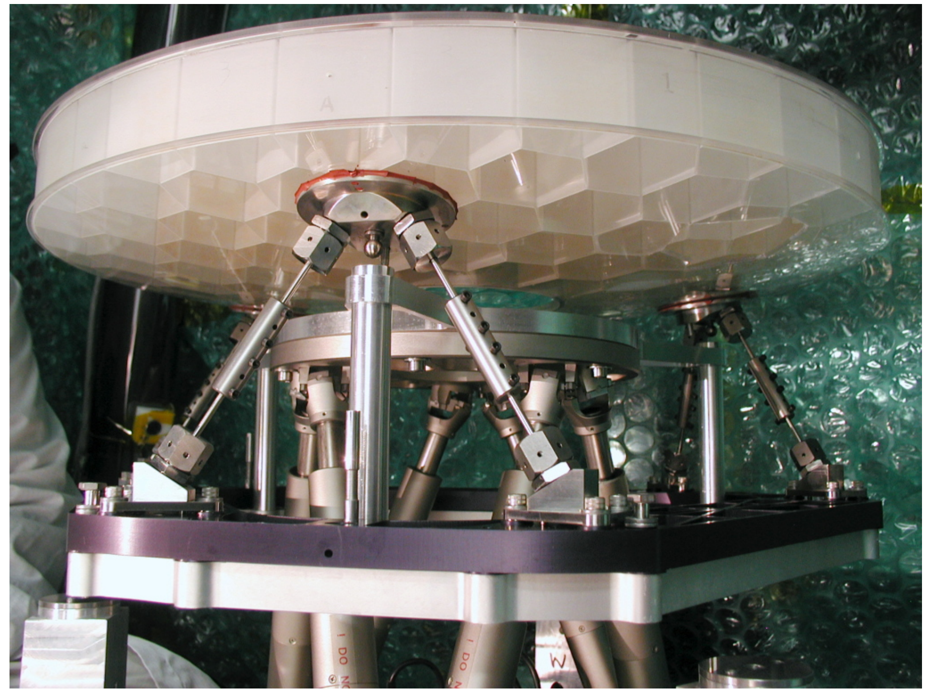
Mounting and *in situ* Testing



Qualification Tests



vibration tests at
Goddard's Wallops
Flight Facility

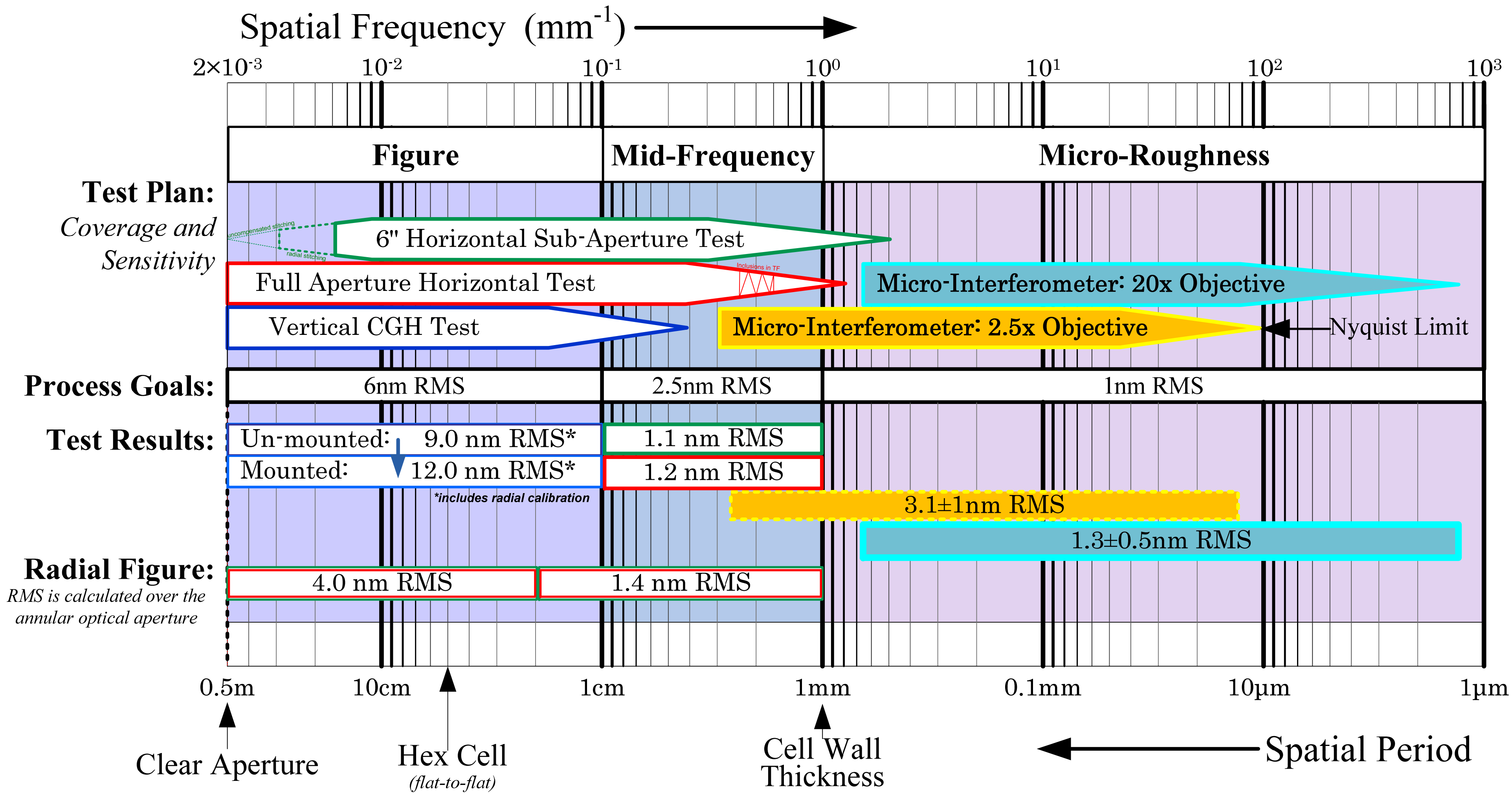


fixturing configuration for
post-mount and post-vibe
figure measurements

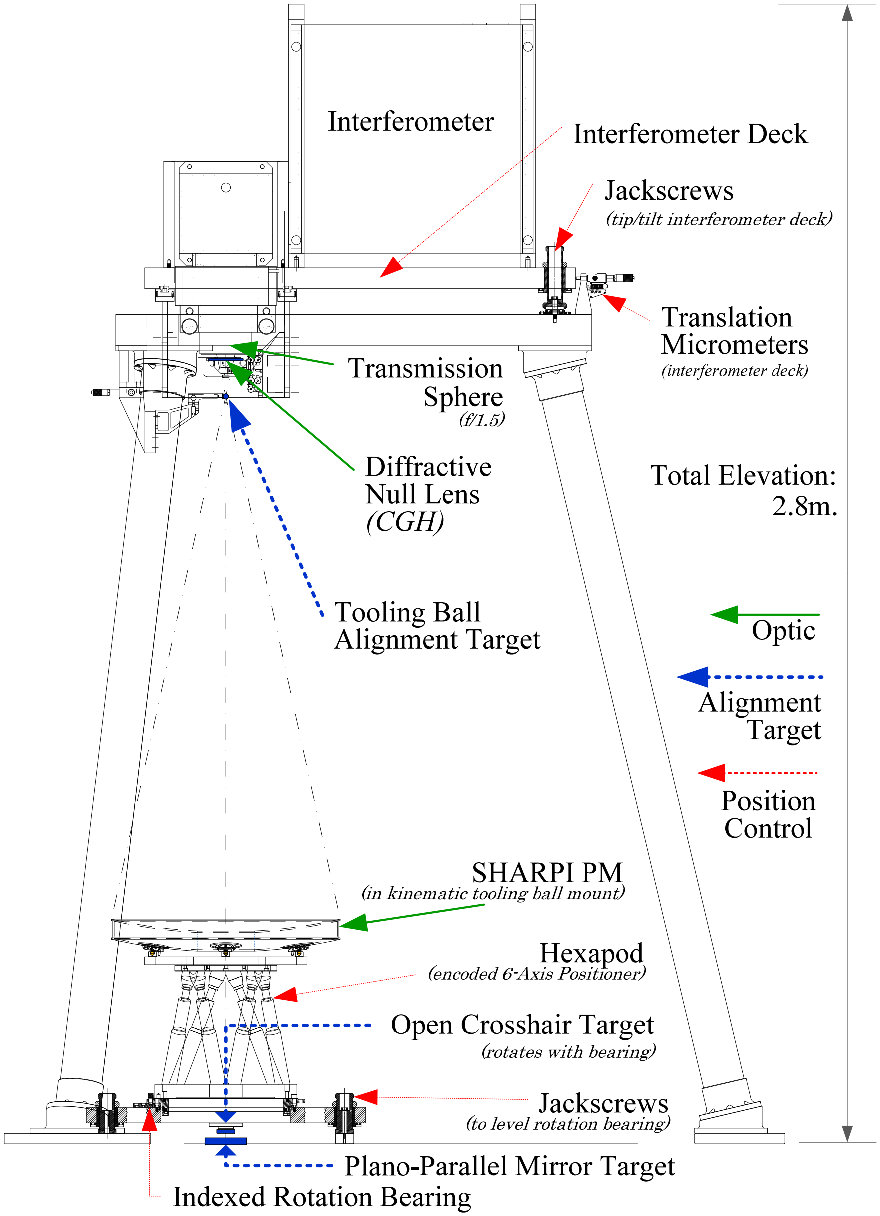
Metrology Tactics

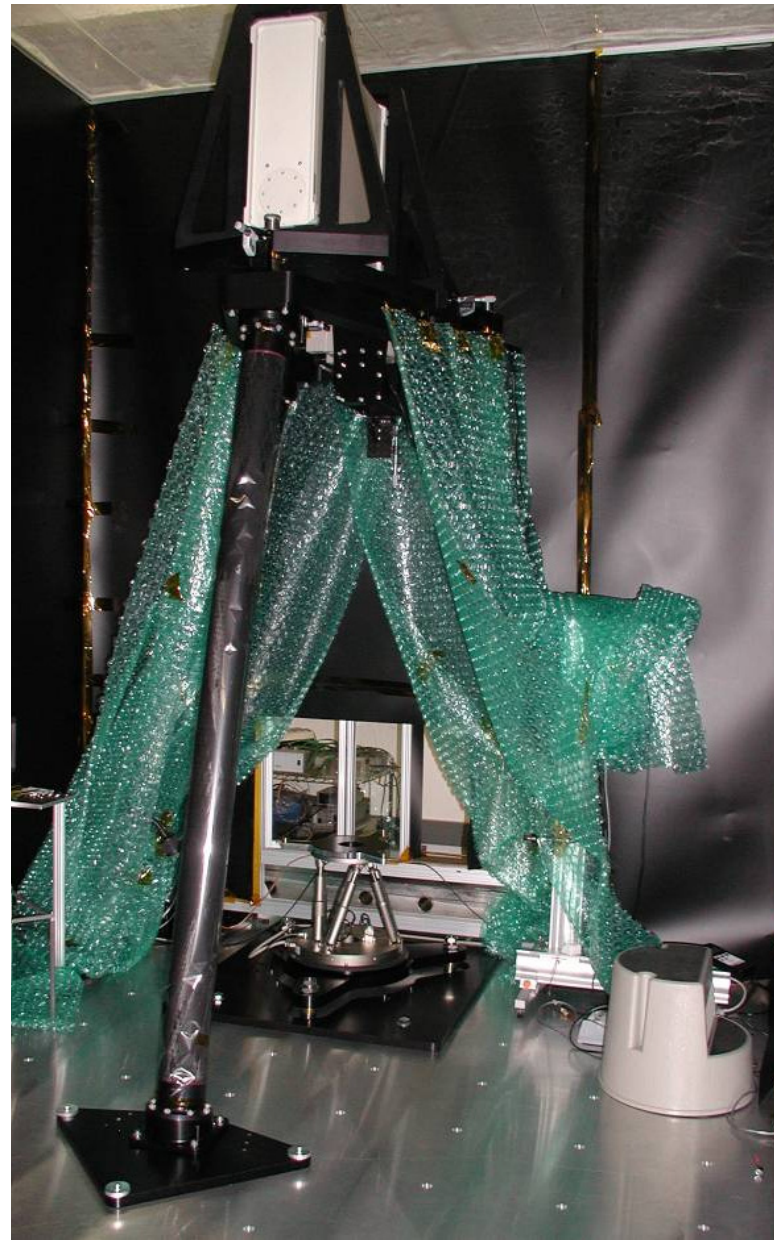
- Divide and conquer for “absolute” asphere testing
  - n-position test + independent radial test ≈ “absolute”
  - test in vertical and horizontal orientations
  - test with an aspheric CGH null and by auto-collimation
- Split spatial frequency test requirements between separate test configurations
  - Capture mid-spatial frequencies ($0.1\text{-}1\text{mm}^{-1}$) with a sub-aperture test
- Recovery: when good mirrors go bad
  - “forensic interferometry”

Test Coverage and Results:
Figure, Mid-Frequency, and Micro-roughness Errors



Vertical Test Tower Setup





Overview of Data Reduction: averaging, n-position rotations, and gravity backout

Initial Figure Analysis & Decomposition

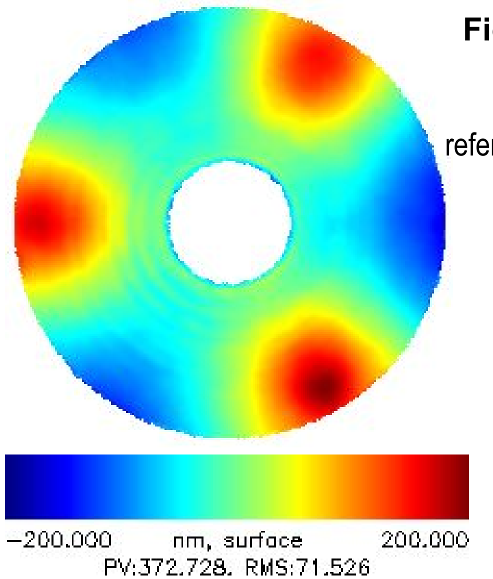
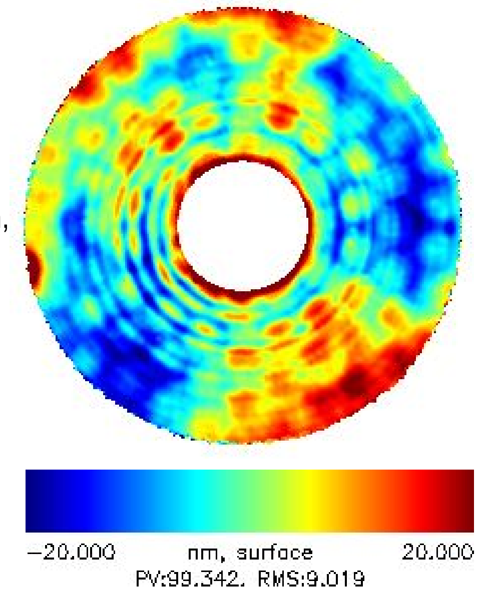


Figure Measurement *(1g)*
RMS:71.5nm±2nm
Corrections applied:
reference wavefront, pupil distortion

Figure Measurement *(0g)*
RMS:9.0nm±2nm
Corrections applied:
NASTRAN predicted 1g deformation,
CGH null radial profile calibration



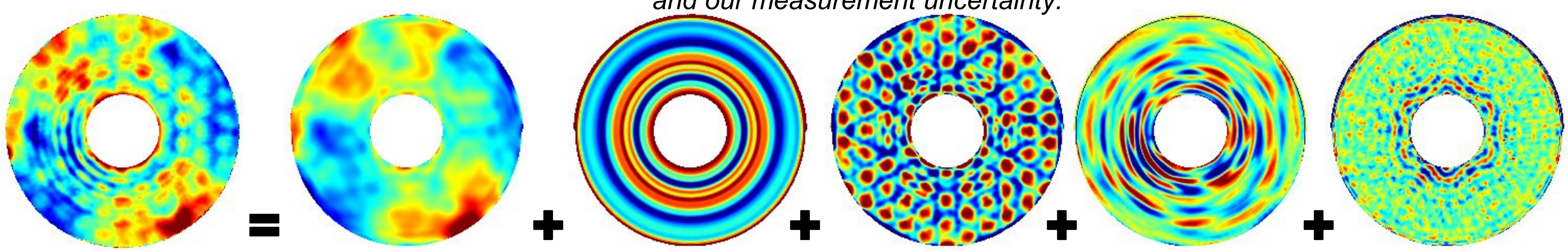
Measuring 0g Mirror Figure

Measuring precise lightweight mirrors in the presence of large gravity deformations

scale magnification: x10

Error Analysis & Decomposition

Understanding the magnitude and character of the mirror figure error and our measurement uncertainty.



Total 0g Error
RMS:9.0nm±2nm

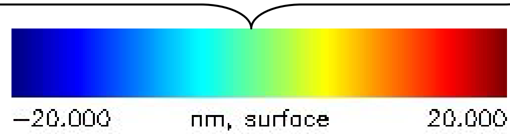
Asymmetric Figure Error
RMS:7.3nm±1nm

Symmetric Radial Error
RMS:4.0nm±0.2nm

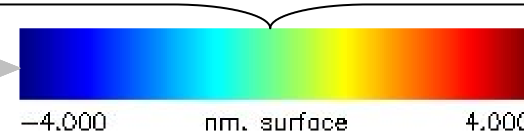
"Quilting" Error
RMS:2.3nm±0.4nm

Semi-Symmetric Error
RMS:1.9nm±0.2nm

Residual
RMS:1.1nm±0.2nm

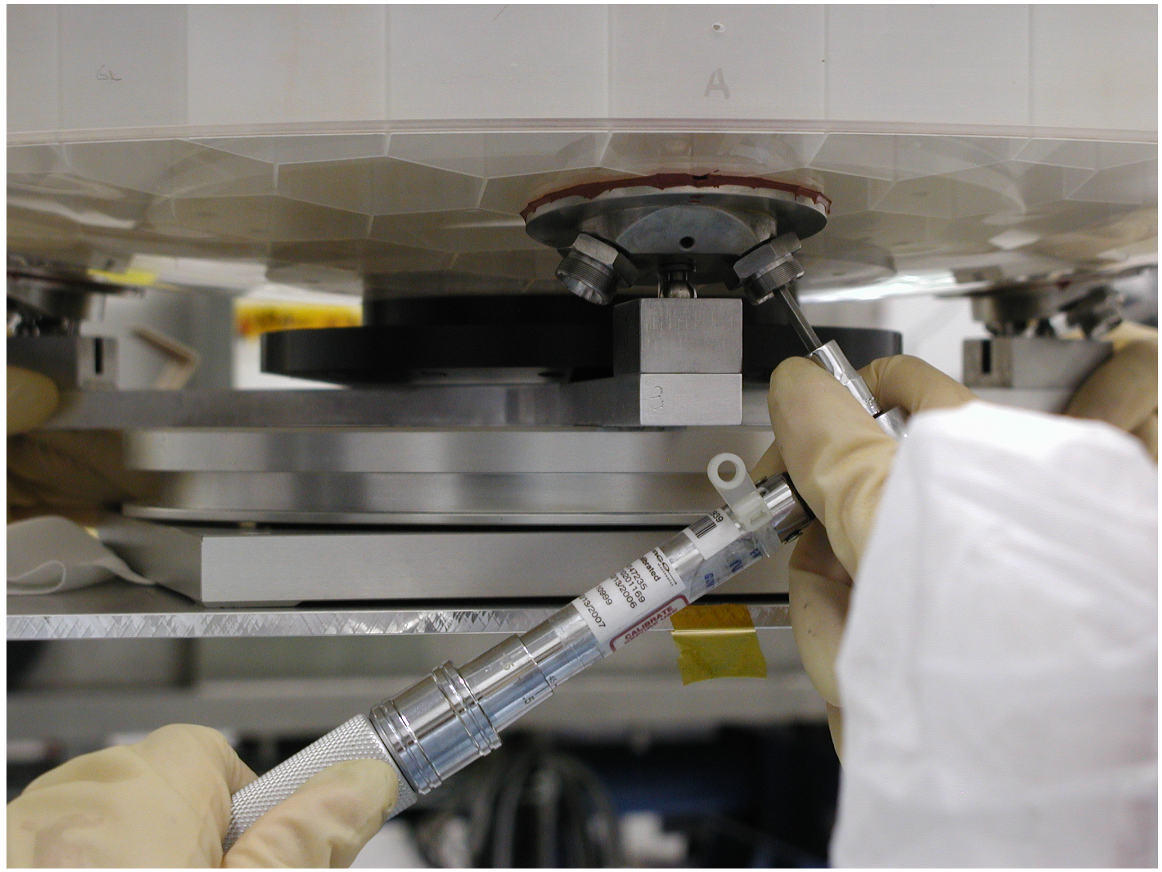


scale magnification: x5



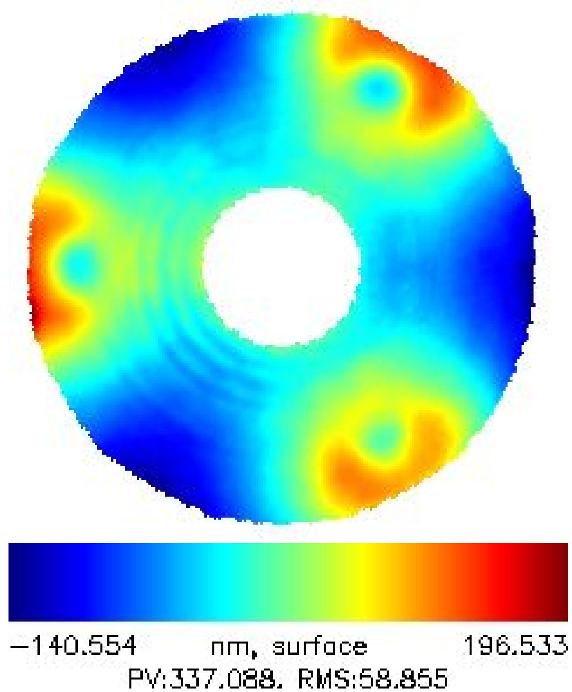
Mounting with Metrology

Mirror figure measurements taken during the mounting process immediately became an essential source of feedback.

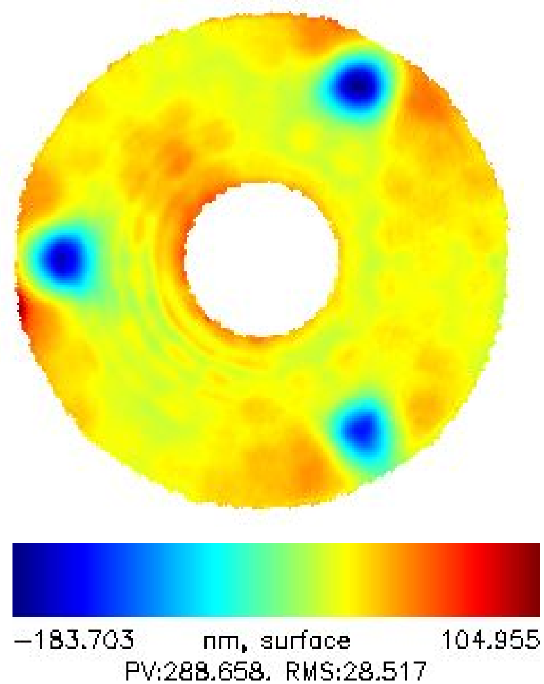


The first pieces of mount hardware attached to the mount pads were coupling sockets…

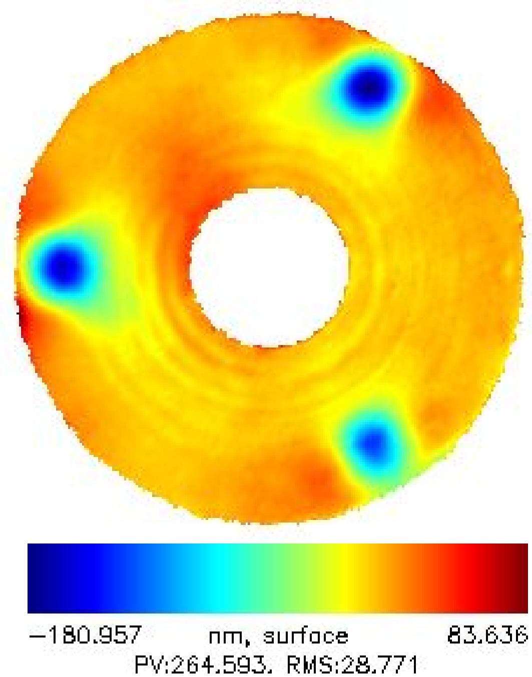
… and the mirror distorted.
from 9 nm RMS to 29 nm RMS!



Averaged 1g



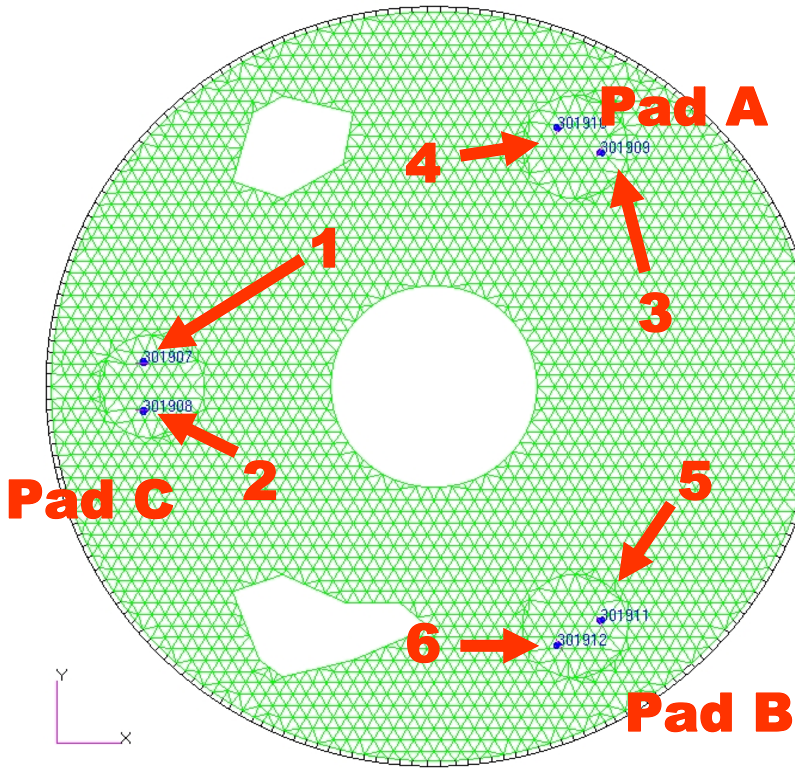
Averaged 0g



ΔFigure *from* Initial 0g

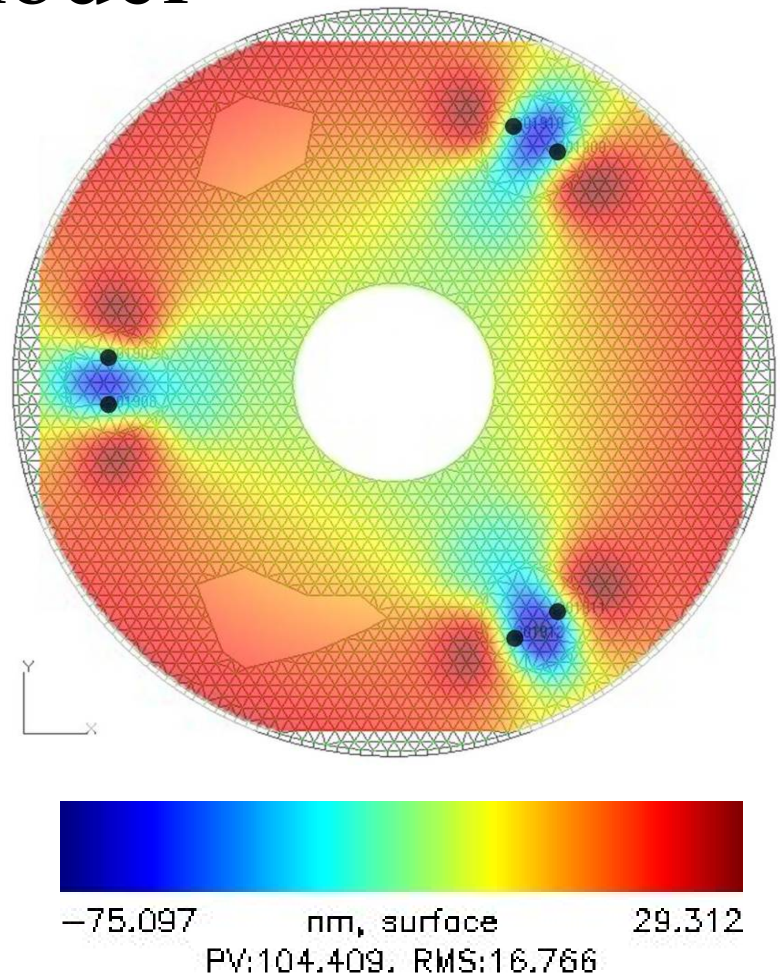
data projected onto the XY plane

Fastener stresses were added to the finite element model –



FEM Model

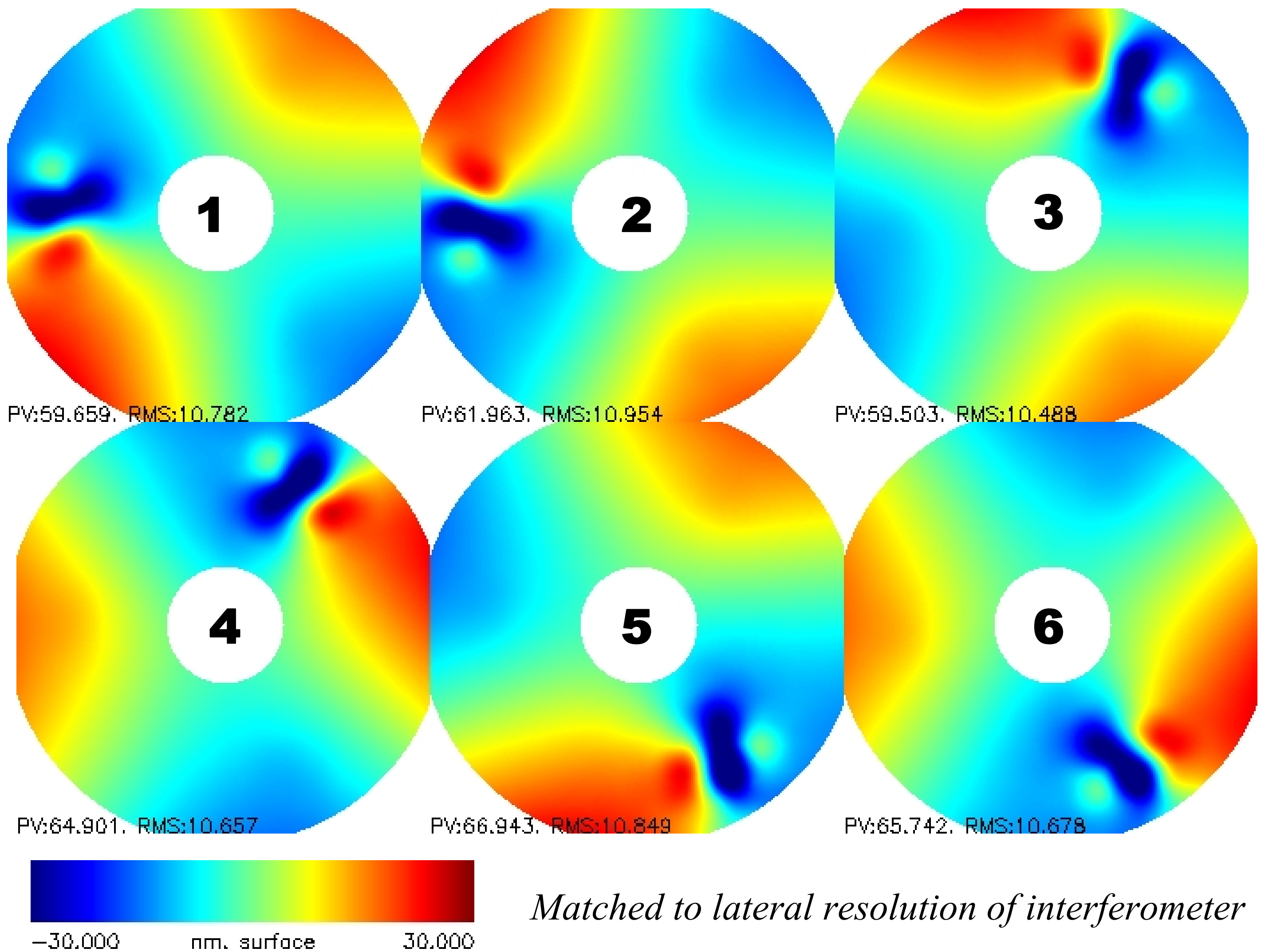
A 1000lbF preload was modeled at nodes corresponding to the location of each screws pair in each mount pad.



Distortion Prediction

(rigid body motion subtracted)

Considering each screw preloads separately, there are six "influence functions":

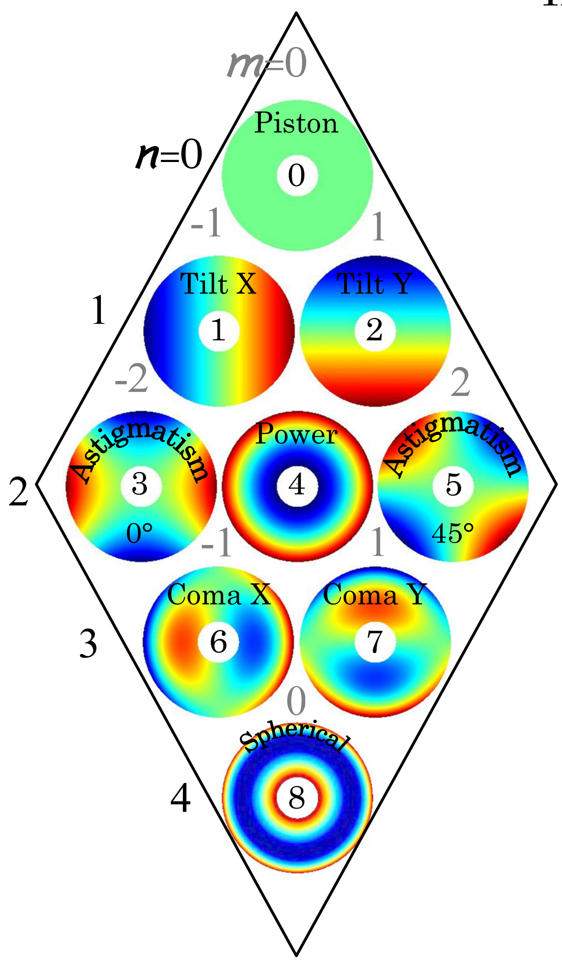


Matched to lateral resolution of interferometer

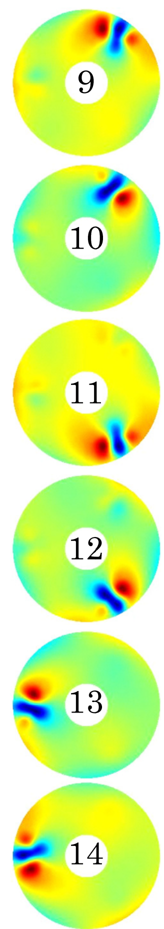
An Orthonormal “Screw” Basis:

The FEM influence functions are orthonormalized with standard Zernike terms to produce an analysis tool that correlates wavefront shape to mechanical conditions.

Selected Zernike Polynomial Terms

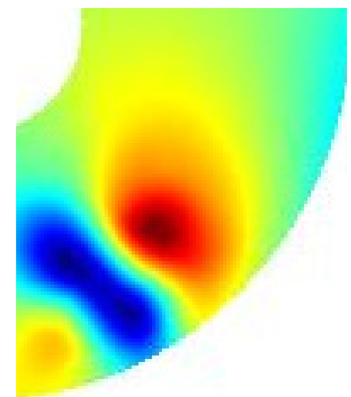


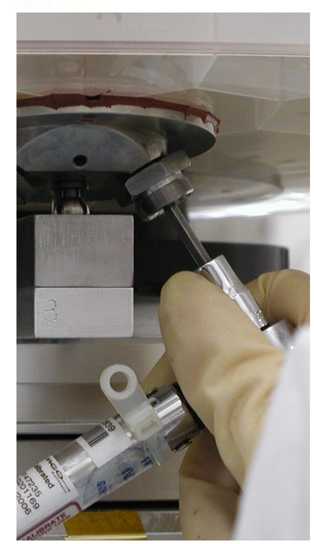
Orthogonal Screw Preload Influence Terms



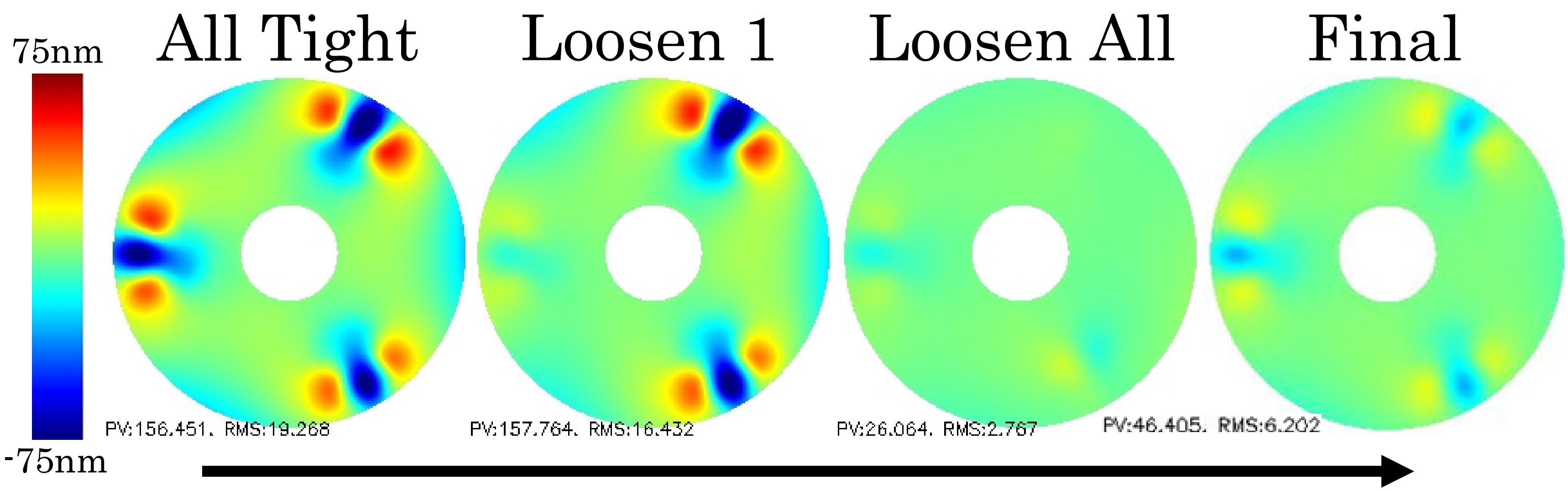
Localized Distortion

(from one screw)





Using the FEM Basis for Visualization and Prediction

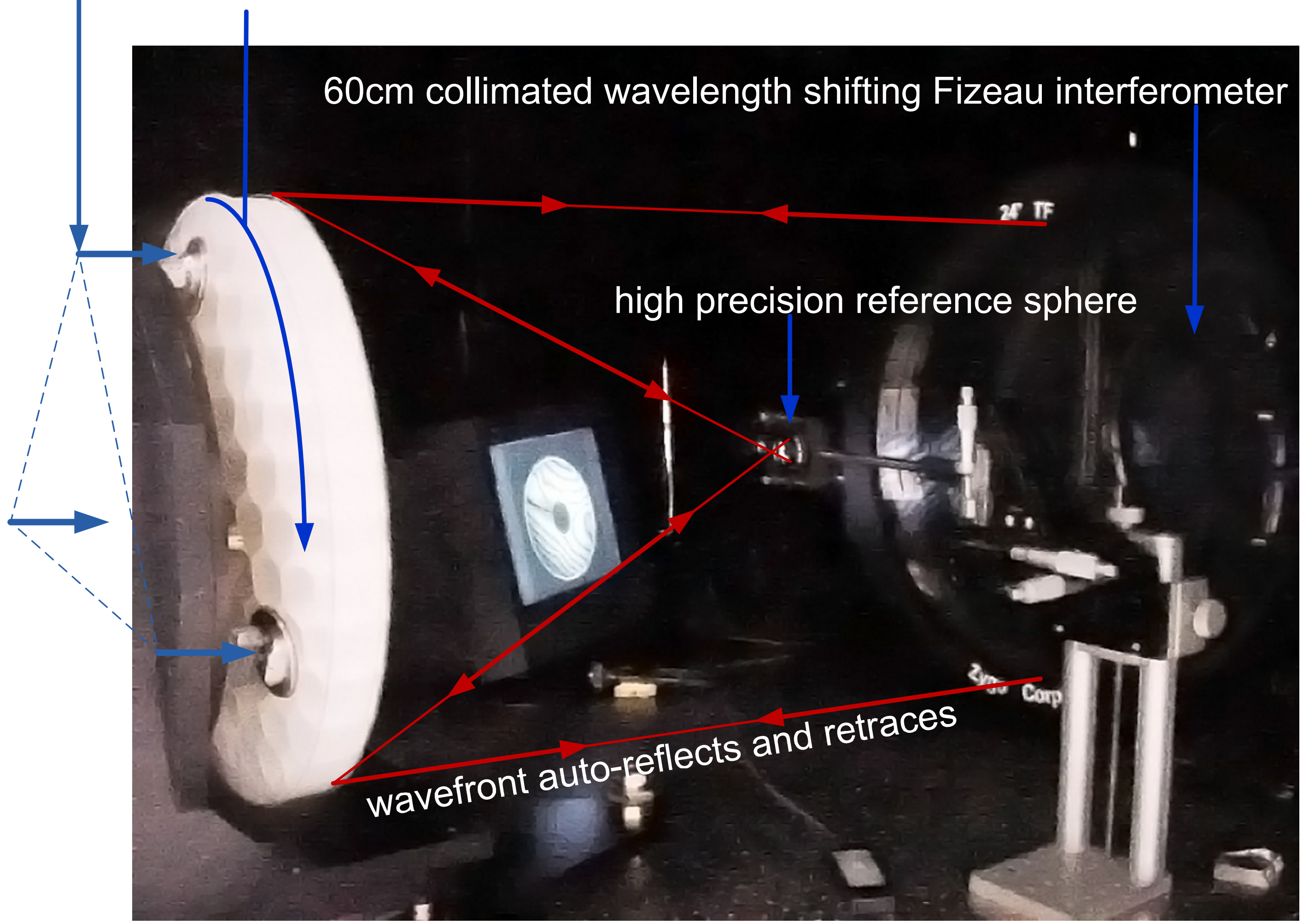


Using this FEM decomposition, the basis coefficients corresponding to screw-induced distortions show a linear dependence on the torque preload. With a few calibrated steps, it was possible to empirically determine the coupling and derive an acceptable torque value along with a prediction of the final surface figure. Over these FEM basis coefficients, the predicted distortion matched the final distortion within 1nm RMS

Horizontal Full-Aperture Testing

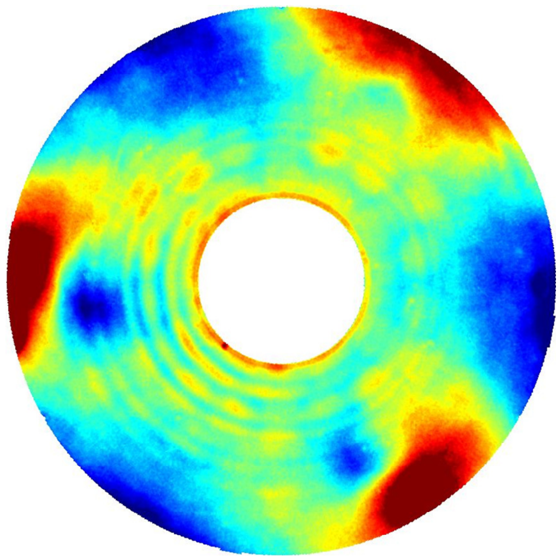
Three mount to tooling ball interfaces

Bearing on mount can clock the mirror into 24 orientations in 15° increments



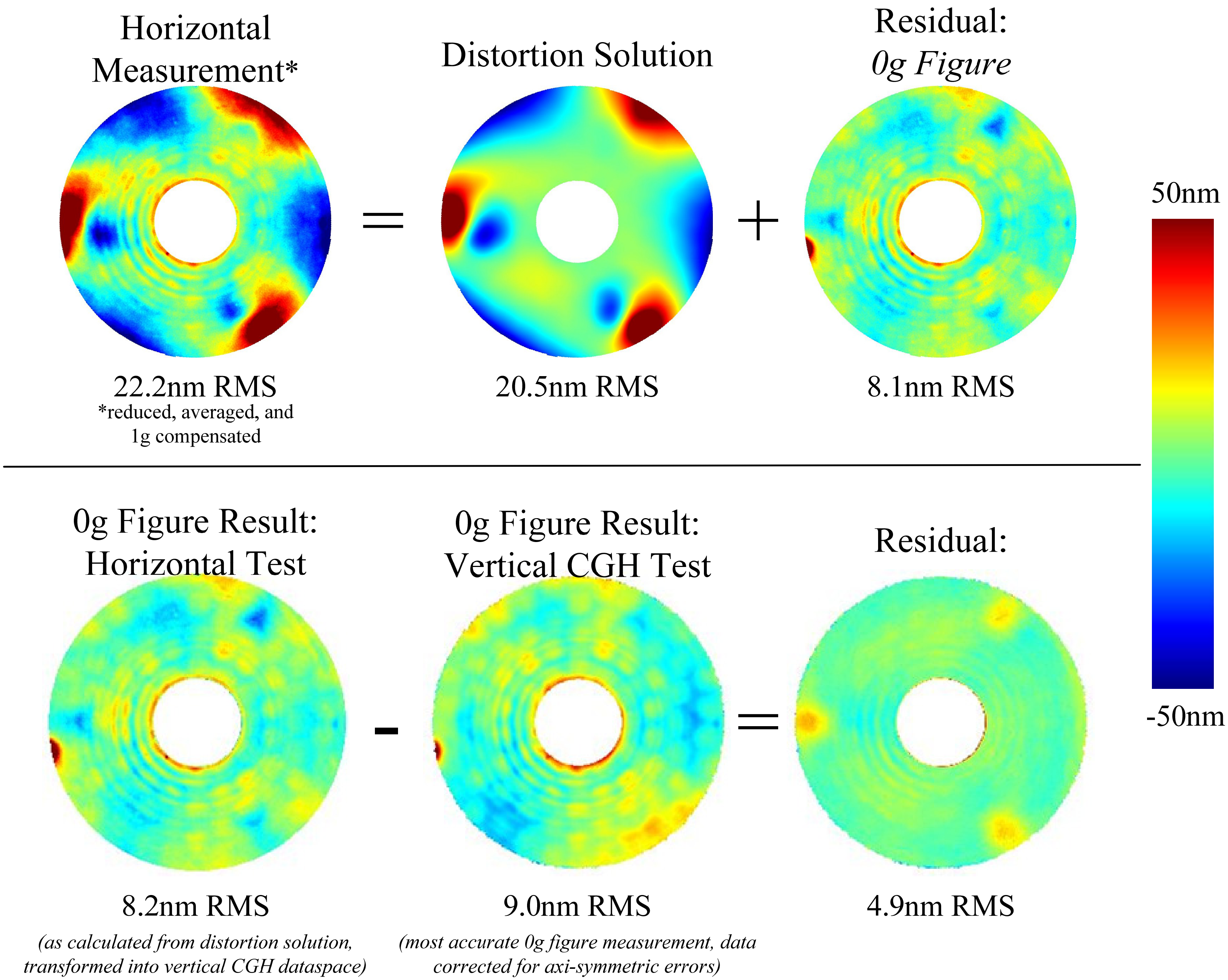
… another case for forensics

- The process of capturing the mirror in the horizontal fixture captured an unknown strain and resulted in a significant amount of mirror distortion during horizontal testing
- Vertical test data confirmed the horizontal mount was the culprit, but horizontal metrology was our only planned independent measurement of radial figure.
- Using a similar FEM-basis analysis, it was possible to separate the mount-induced distortion from mirror figure and confidently determine the radial figure.



22.2nm RMS

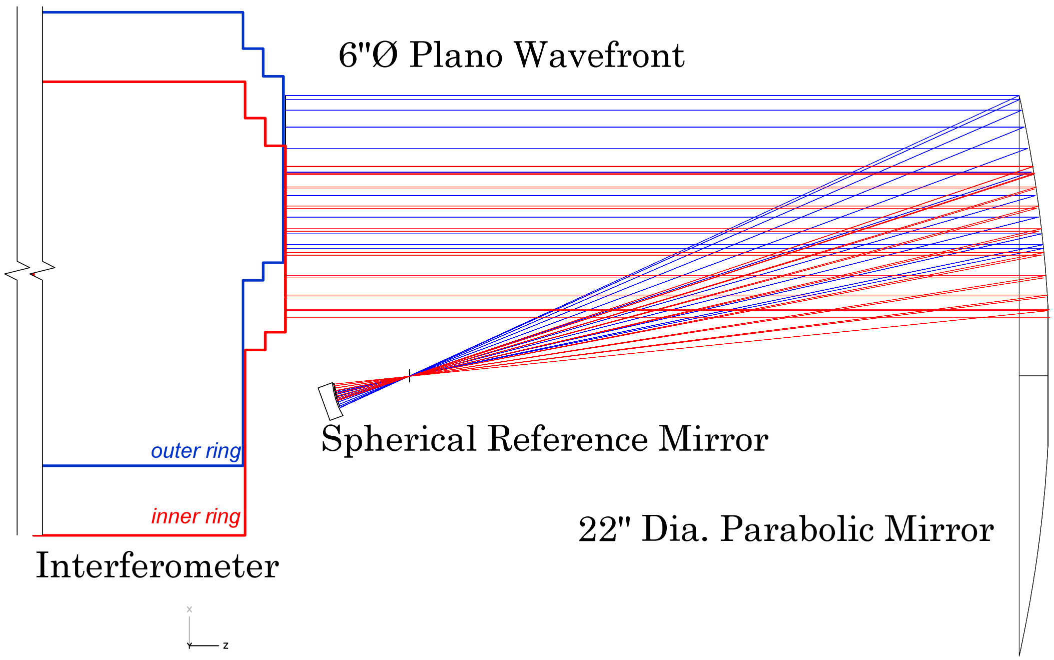
24x15° n-position test, averaged, and 1g backout applied



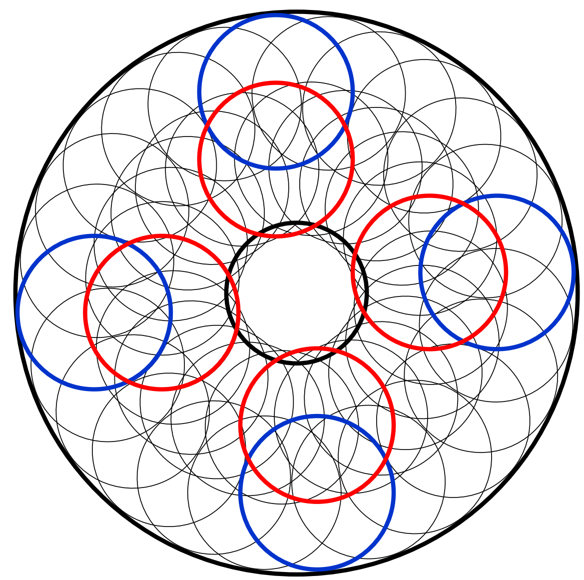
Horizontal Measurement*
Distortion Solution
Residual: 0g Figure
=
+
22.2nm RMS
*reduced, averaged, and 1g compensated
20.5nm RMS
8.1nm RMS
50nm
-50nm
0g Figure Result: Horizontal Test
0g Figure Result: Vertical CGH Test
Residual:
-
=
8.2nm RMS
(as calculated from distortion solution, transformed into vertical CGH dataspace)
9.0nm RMS
(most accurate 0g figure measurement, data corrected for axi-symmetric errors)
4.9nm RMS

Horizontal Sub-Aperture Tests

- Measurement of mid-spatial frequency errors
- Higher resolution radial figure measurement, overlap with full-aperture result



Layout



Sub-Aperture Coverage

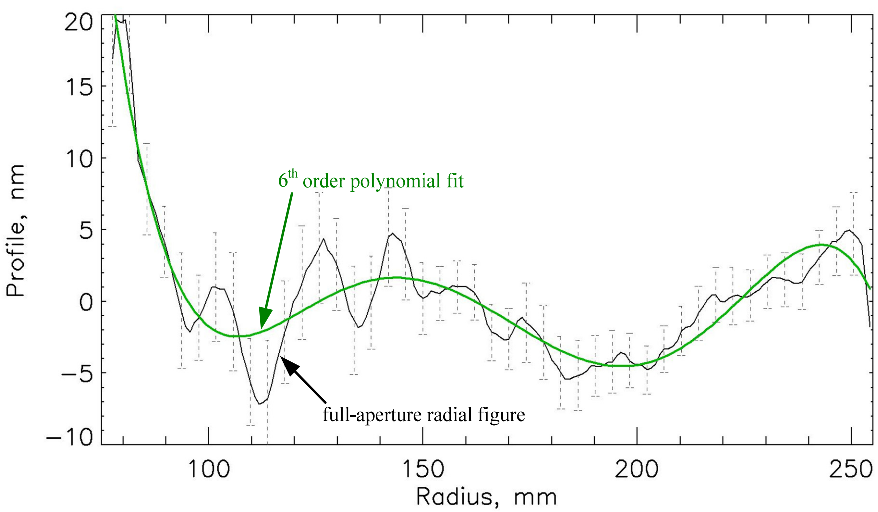
Sub-Apertures Total: 48

24 measurements on inner (red) and outer (blue) ring in 15° increments about the parent vertex

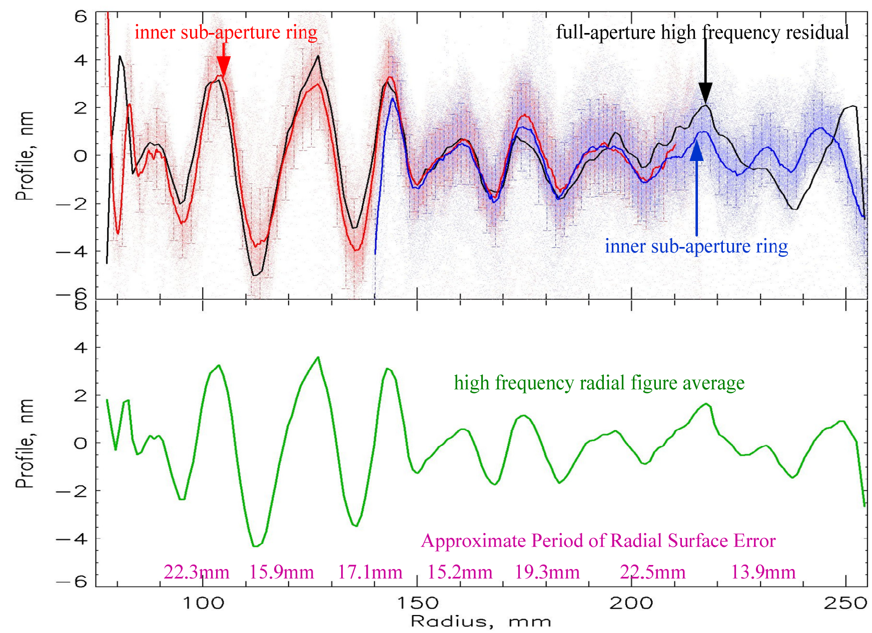
Total Radial Profile Derived from the Low Frequency Radial Figure and the High Frequency Radial Figure

Low Frequency Radial Figure

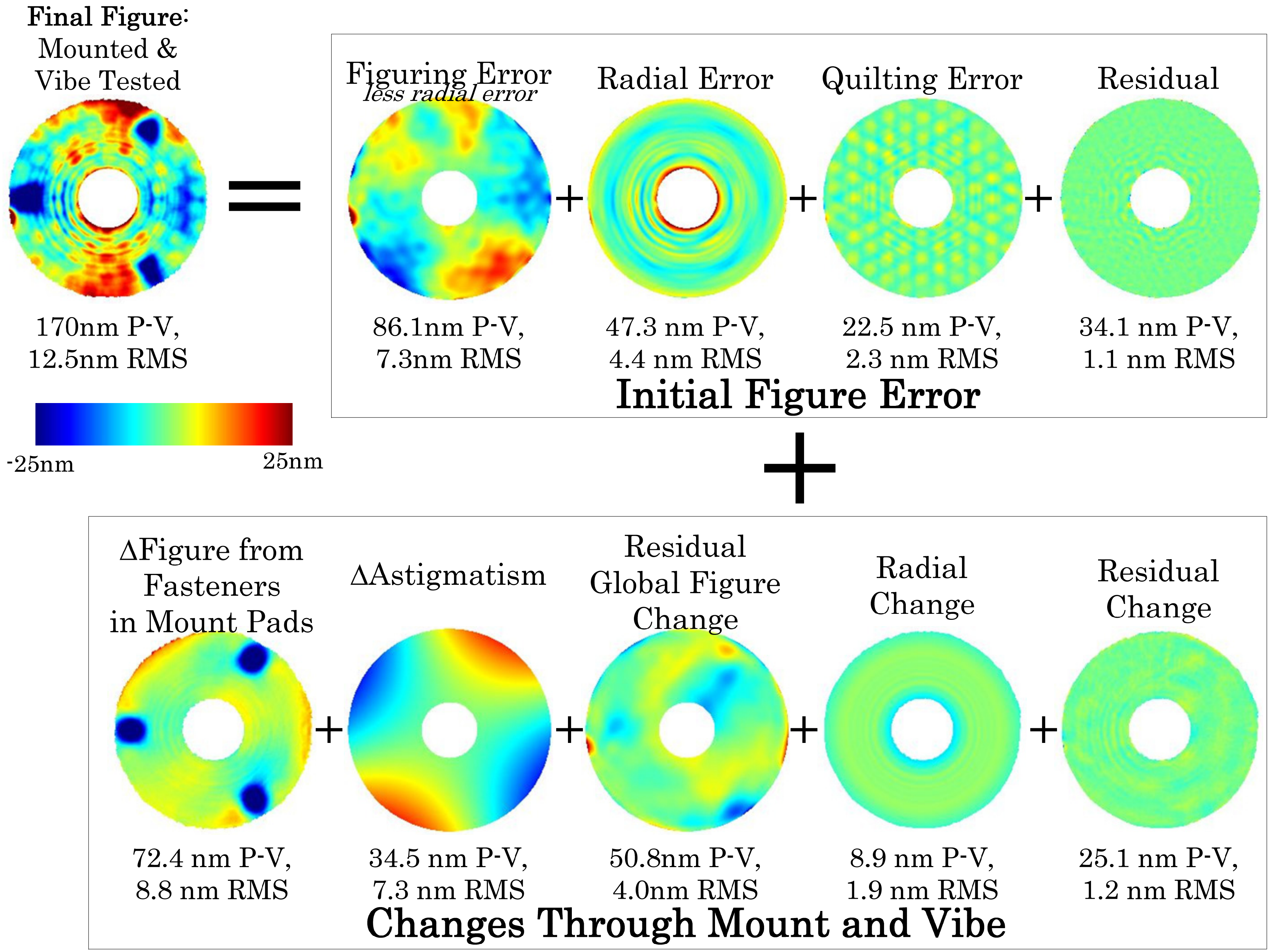
from the full-aperture horizontal test



High Frequency Radial Figure



Full-aperture horizontal test data and sub-aperture test data are combined to give an independent measurement of the radial figure over a large spatial frequency range.



Final Figure:
Mounted &
Vibe Tested
170nm P-V,
12.5nm RMS
-25nm
25nm
Figuring Error
less radial error
86.1nm P-V,
7.3nm RMS
Radial Error
47.3 nm P-V,
4.4 nm RMS
Quilting Error
22.5 nm P-V,
2.3 nm RMS
Residual
34.1 nm P-V,
1.1 nm RMS
Initial Figure Error
ΔFigure from
Fasteners
in Mount Pads
72.4 nm P-V,
8.8 nm RMS
ΔAstigmatism
34.5 nm P-V,
7.3 nm RMS
Residual
Global Figure
Change
50.8nm P-V,
4.0nm RMS
Radial
Change
8.9 nm P-V,
1.9 nm RMS
Residual
Change
25.1 nm P-V,
1.2 nm RMS
Changes Through Mount and Vibe

Accomplishments:

- Successfully adapted existing capabilities and facilities
  - coating, roughness metrology, fixture design and fabrication
- Performed an absolute 0g figure test on an ultra-lightweighted aspheric mirror with ~2nm RMS accuracy.
  - Addressed aspheric null certification, gravity back-out verification, and much more…
- Mounted mirror to a flight interface without inducing significant distortion, passed component vibration testing, and maintained surface figure through vibe

Thanks…

- Our success would not have been possible without the dedicated efforts of: David Content, Doug Rabin, Thomas Wallace, Shane Wake, Jeff Bolognese, Sandra Irish, Craig Stevens, Jeff Gum, and many more…
- Funding provided by NASA/Goddard Space Flight Center IRAD program. Telescope I&T funds provided through PICTURE sounding rocket project, managed through Boston University.
- Questions?
  - I would be happy to answer additional questions by email:
    - Scott.Antonille@nasa.gov

Backup Slides…

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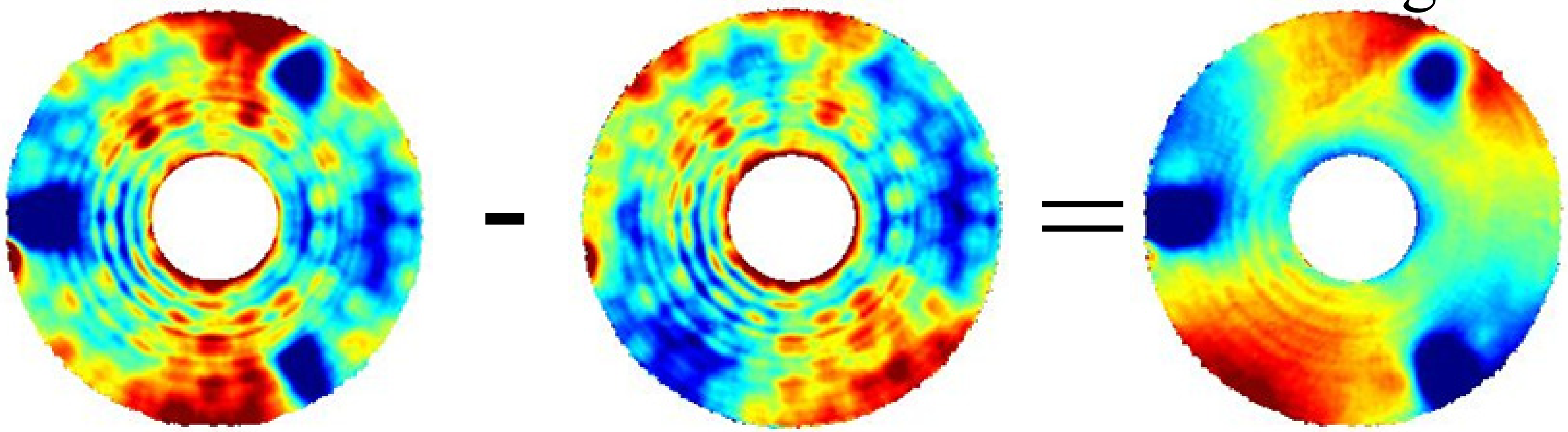
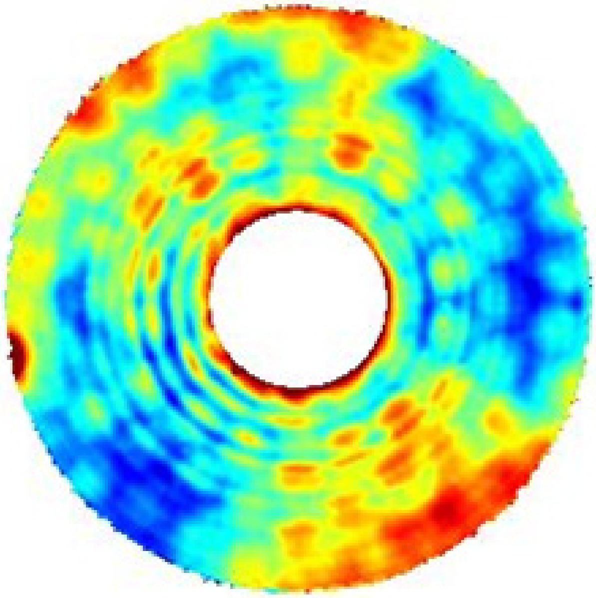
Total Figure Change:

Mounted, Vibr. Tested | Un-Mounted | Measured Figure Change

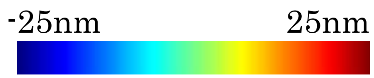


12.5nm RMS | 8.9nm RMS | 11.8nm RMS

Initial

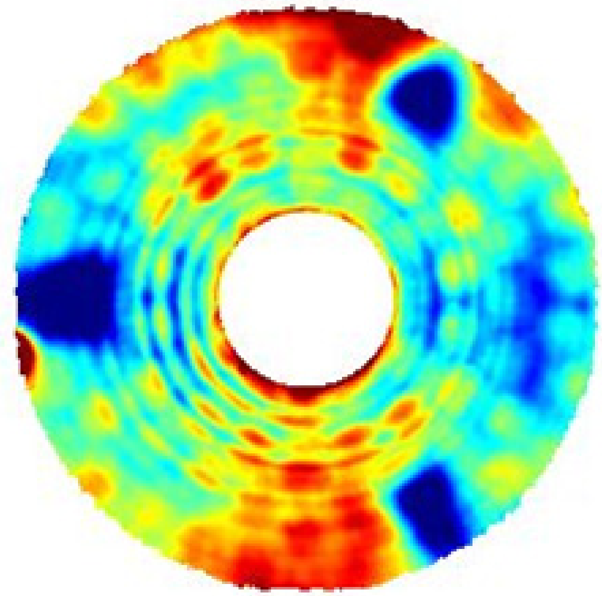


95.1 nm P-V,
8.9nm RMS



- Initial Vertical CGH measurement.
- Gravity sag subtracted.
- Radial CGH figure correction applied.
- Data has been transformed into the final measurement coordinate system, and therefore there are minor changes in RMS and PV from the initial measurements as reported in their initial coordinate frame
- This result includes all error terms except rigid body motion and the Zernike power term as normalized over the discretely sampled annular aperture.

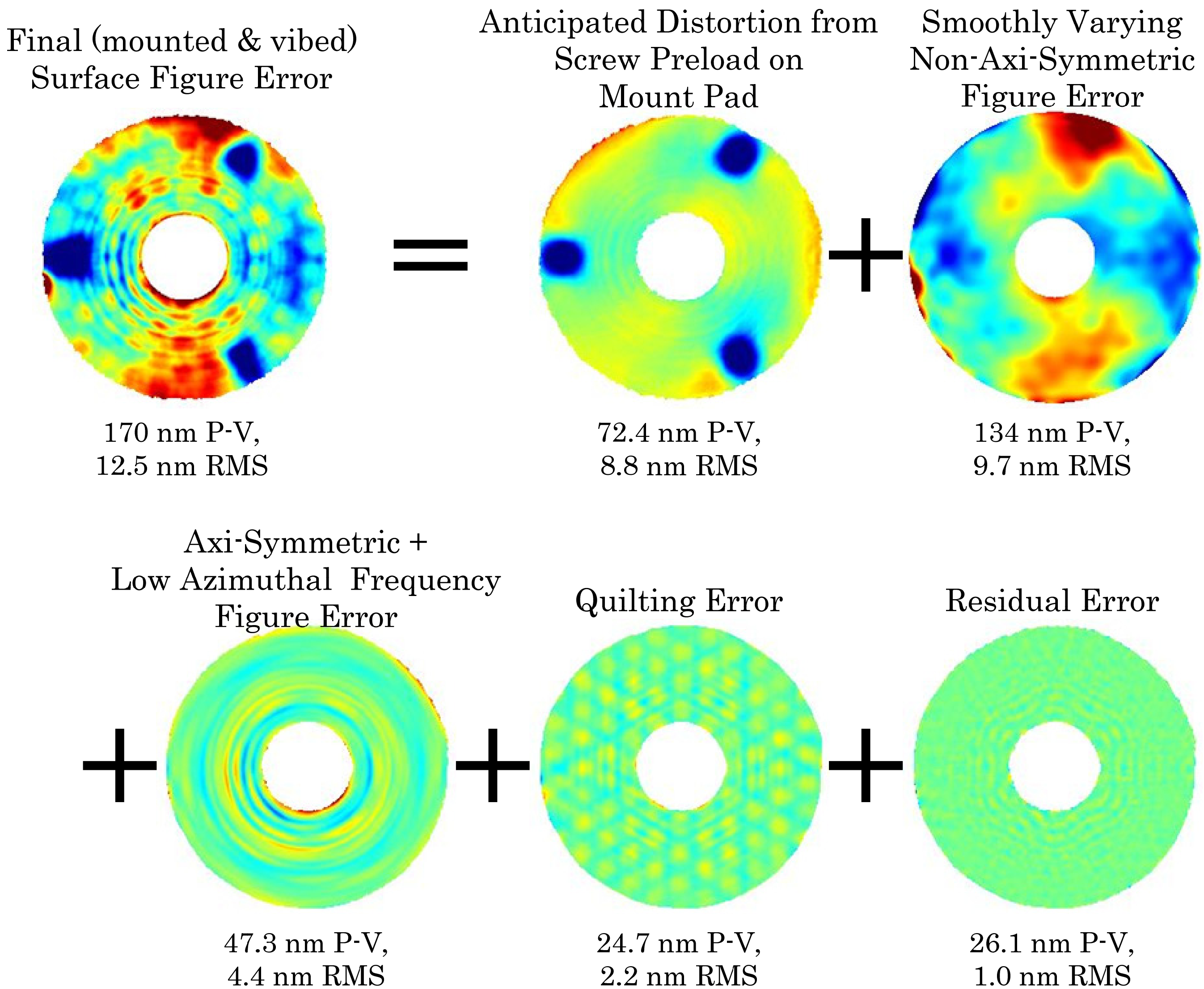
Final



170 nm P-V,
12.5 nm RMS

- Post-Mount, Post-Vibe Test Vertical CGH measurement.
- Gravity sag subtracted.
- Radial CGH figure transformed into final data space and applied. Result includes any changes in radial figure.
- This result includes all error terms except rigid body motion and the Zernike power term as normalized over the discretely sampled annular aperture.

Decomposition of Final Surface Figure



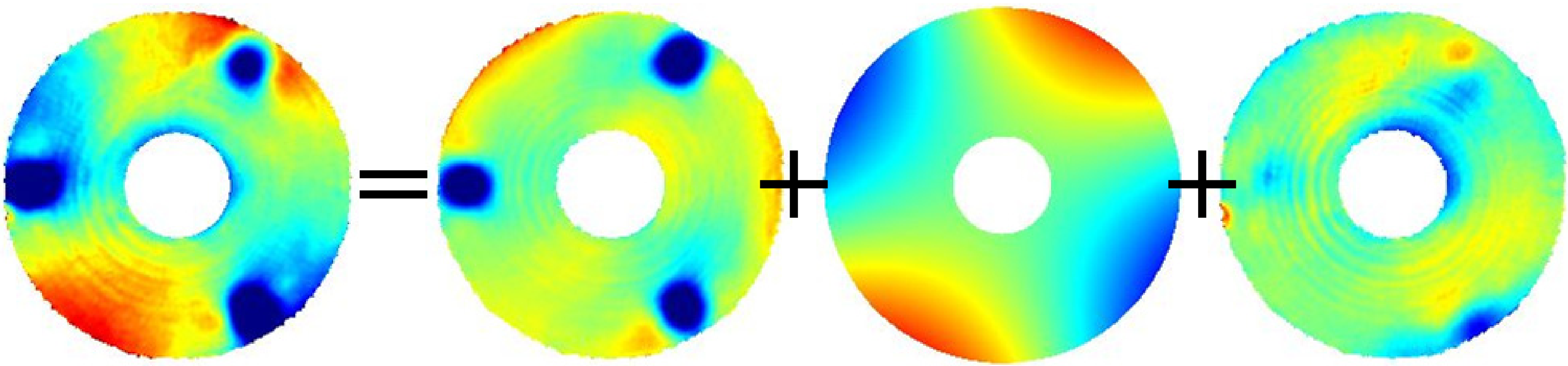
Changes Through Mount and Vibe

Total Change:
from pre-mount
to post-mount, post-vibe

ΔFigure from Fasteners in Mount Pads

ΔAstigmatism

Residual change after subtracting fastener distortion and astigmatism

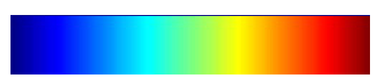


92.9 nm P-V,
11.7 nm RMS

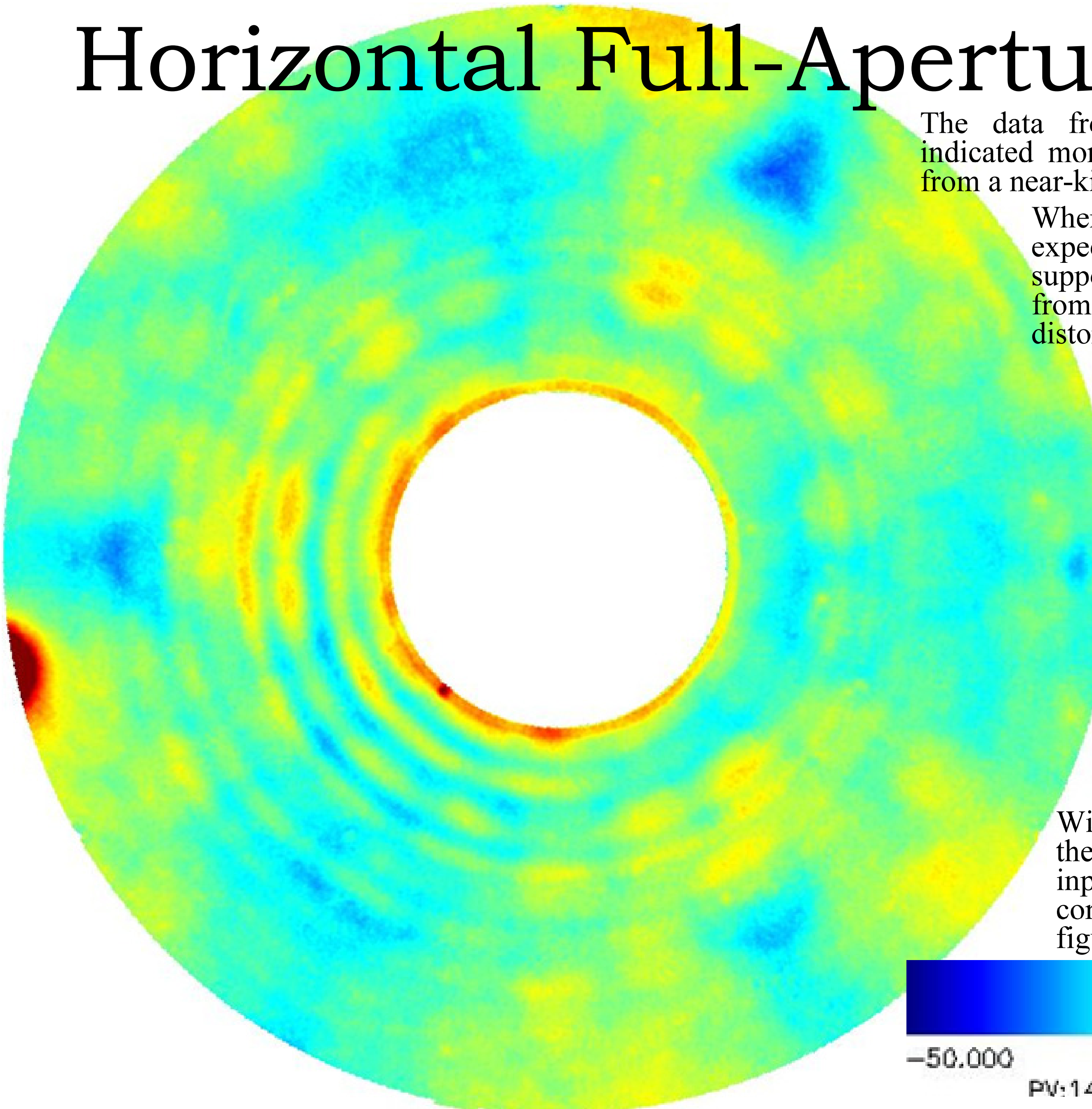
72.4 nm P-V,
8.8 nm RMS

34.5 nm P-V,
7.3 nm RMS

46.2 nm P-V,
4.4 nm RMS



Horizontal Full-Aperture Test



The data from the full-aperture test indicated more distortion than expected from a near-kinematic mount.

When the the gravity distortion expected from an ideally supported mirror was subtracted from the data, an additional distortion is apparent.

Using a FEM to simulate unit force/torques in 6 DOF at each mount interface, a set of input force/torques were found to match the observed distortion. Subtracting that solution yields this illustration of the 0g figure error.

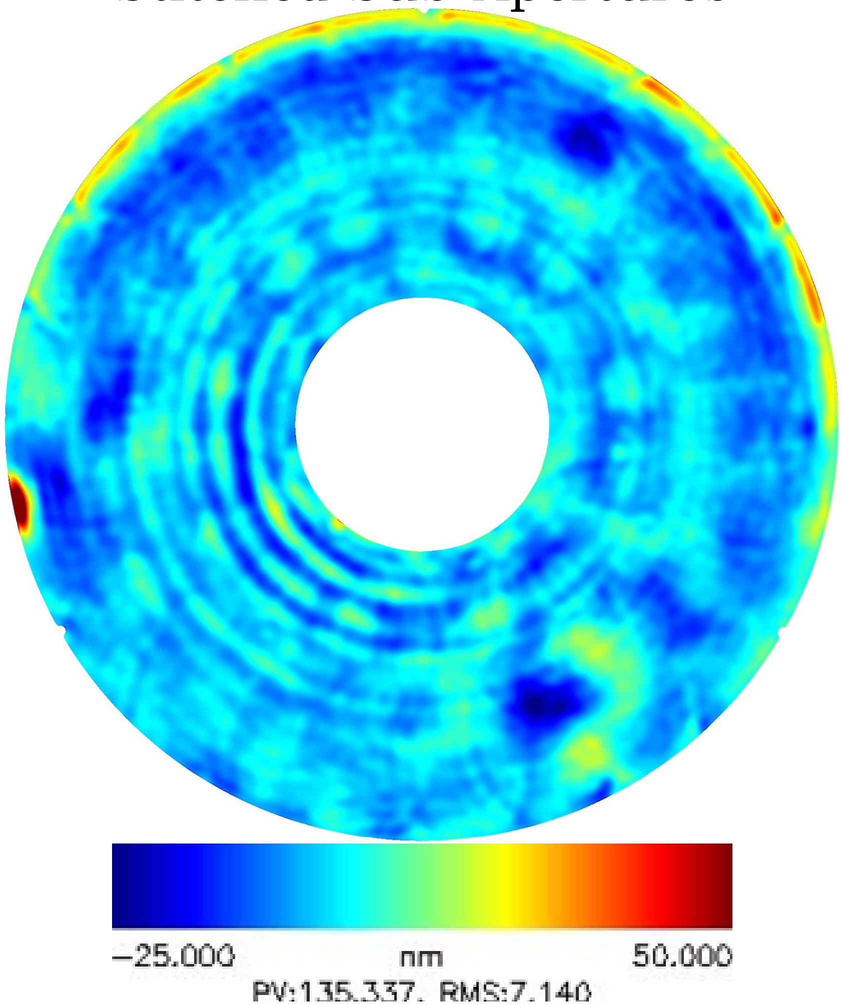
This 0g mirror figure solution matches well with the results taken with the mirror in a kinematic mount.

Without a priori knowledge of the boundary conditions, the input force solution has correctly determined the 0g figure.

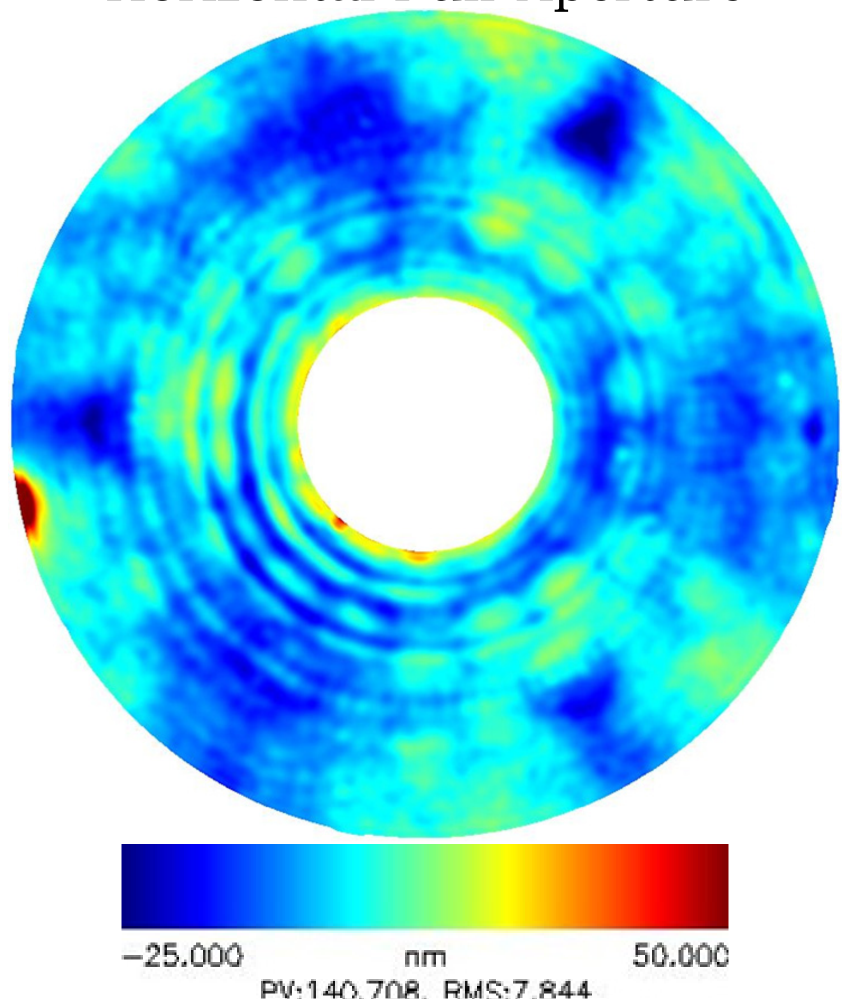
Low-Frequency Error

(lowpass filter >10mm)

Stitched Sub-Apertures



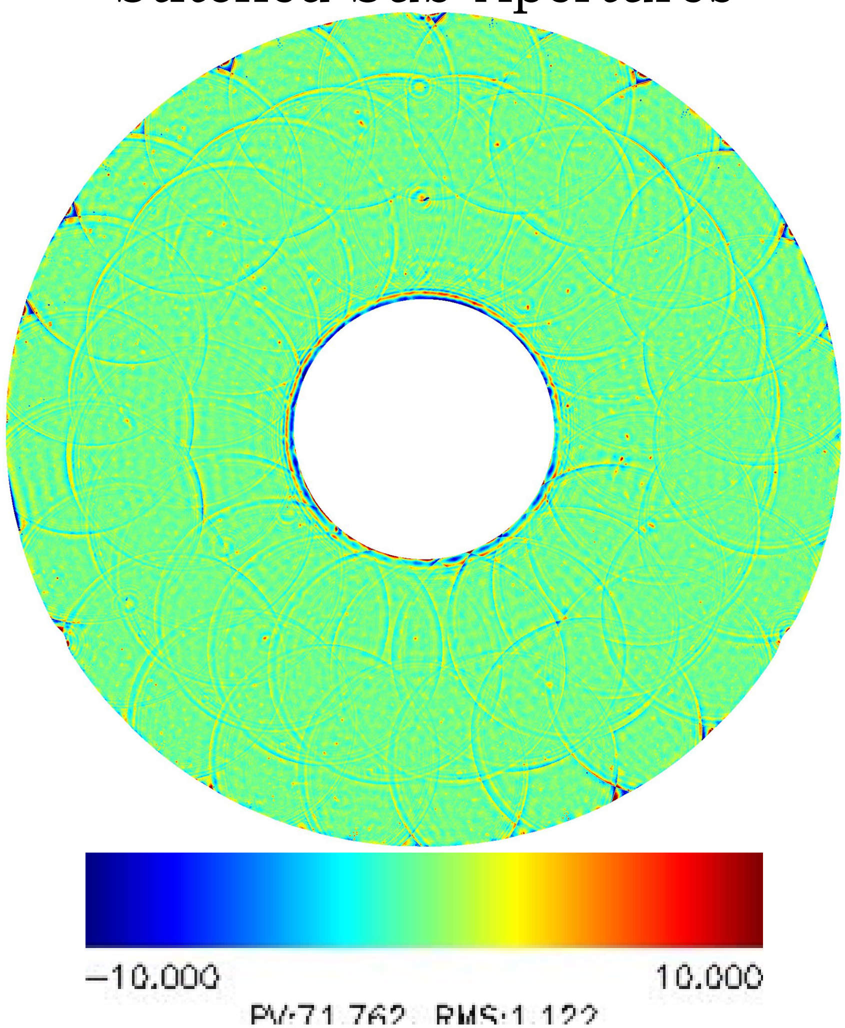
Horizontal Full-Aperture



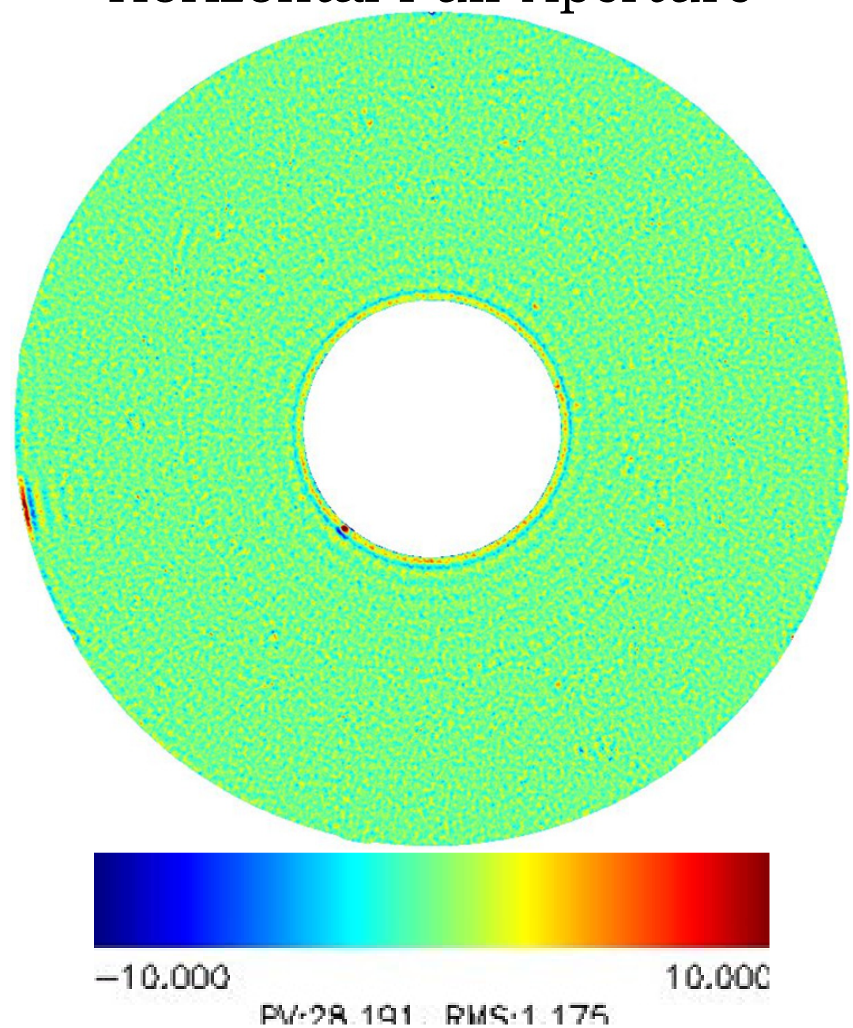
Mid-Frequency Error

(bandpass filter 1-10mm)

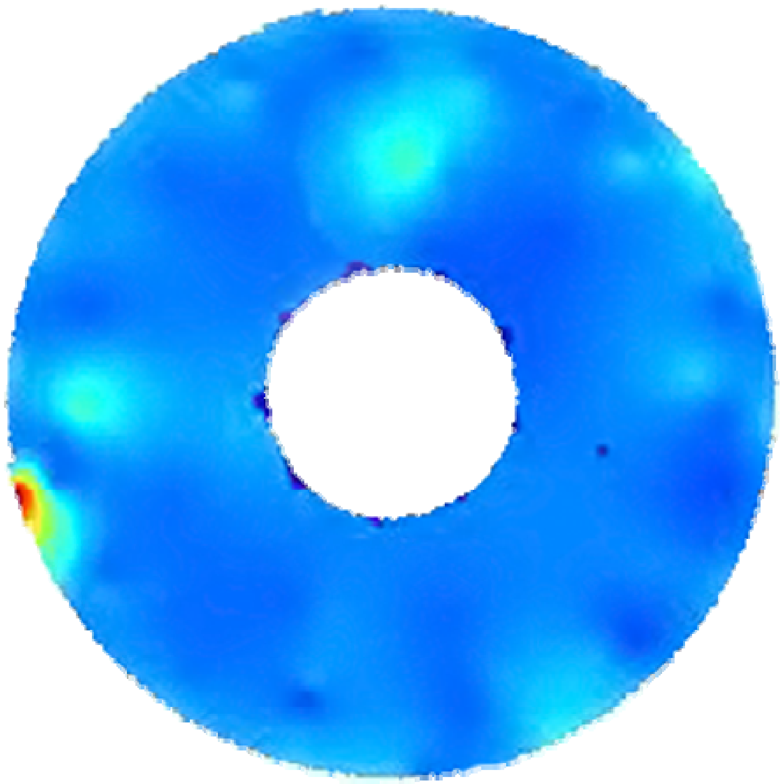
Stitched Sub-Apertures



Horizontal Full-Aperture



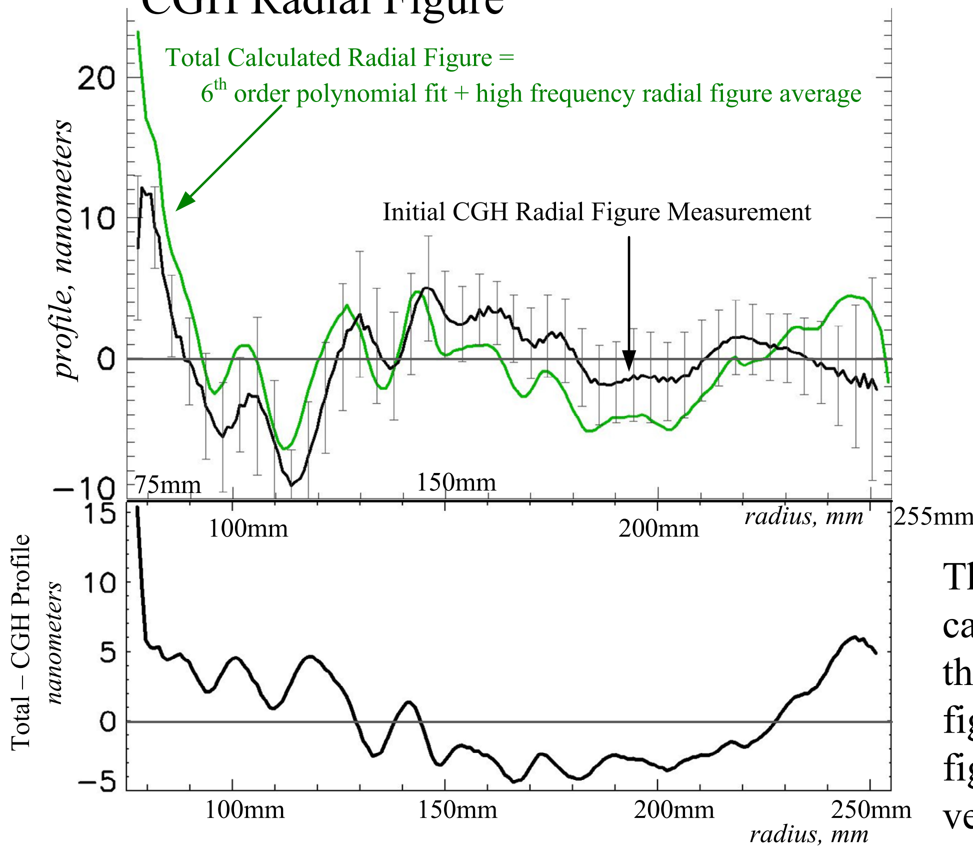
Roughness Distribution:



Map of RMS Roughness from 20x Objective Topo2D Micro-Interferometer

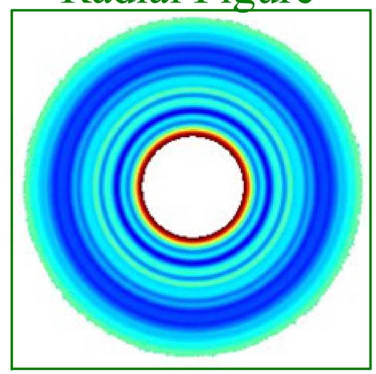
CGH Radial Figure Correction using the Total Radial Figure

Total Radial Figure vs. CGH Radial Figure



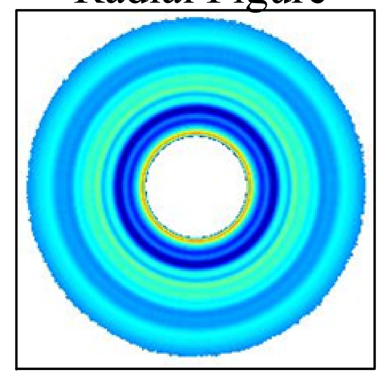
Difference (CGH Correction)

Calculated Total Radial Figure



4.6nm RMS

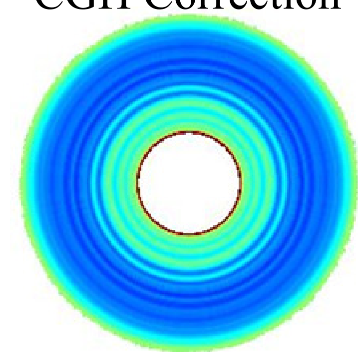
CGH Measured Radial Figure



2.9nm RMS

The difference between the calculated radial figure and the CGH measured radial figure results in a radial figure correction for the vertical CGH test.

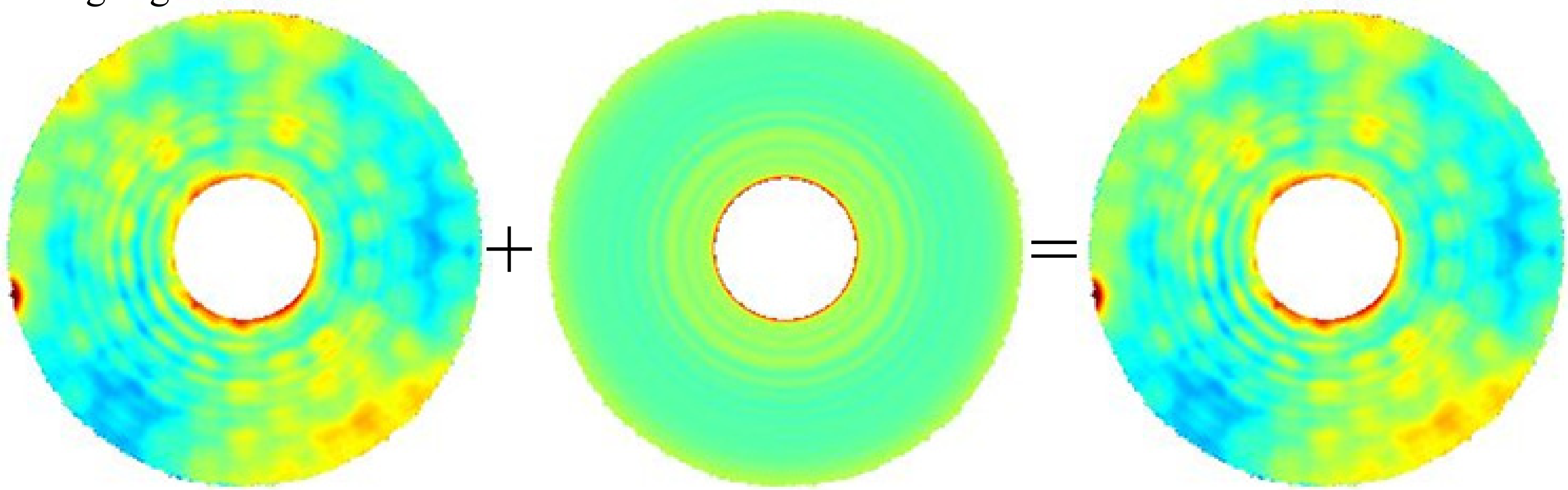
CGH Correction



4.1nm RMS

Addition of Radial Figure Correction to CGH Measured Figure Error

Initial Vertical (CGH null) 0g Figure Measurement | Radial Correction from Horizontal Measurements | Final Corrected 0g Figure



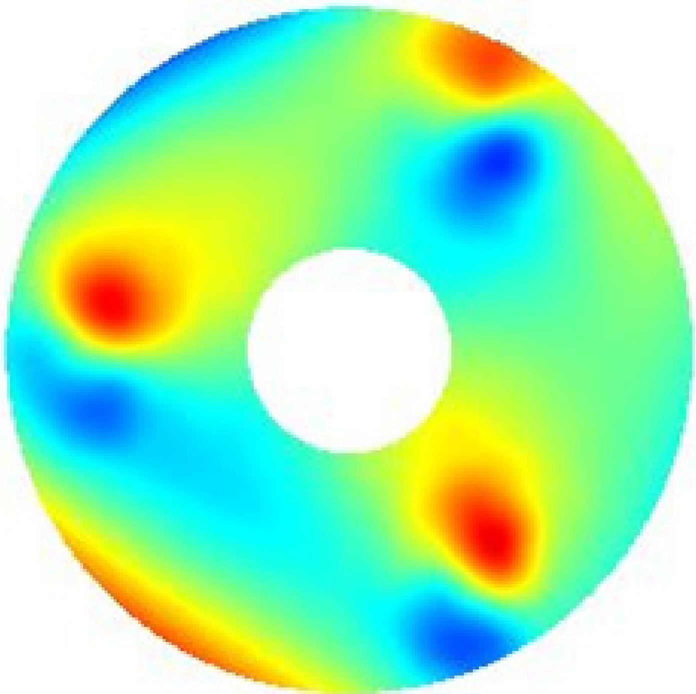
8.4nm RMS | 4.1nm RMS | 9.0nm RMS

The independent measurement of the radial figure is required to fill the blindspot in the n-position asphere test.

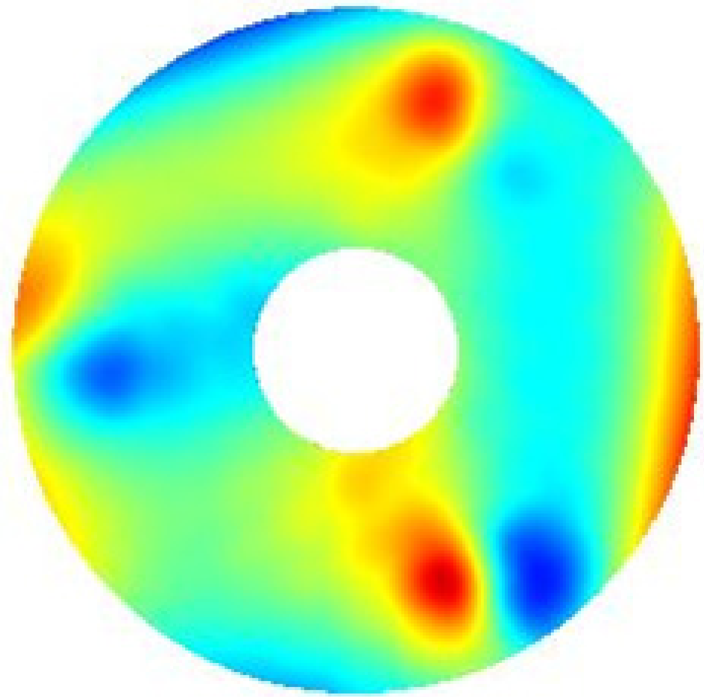
Mounting in Vertical Test Tower

- Tower configuration allowed for *in situ* measurements of mirror figure during the rigidization of the bipod mount.
- Figure data was analyzed with finite element model predictions to help understand process errors.
- Rather than using set boundary conditions to predict a mirror figure distortion, 6DOF forces/torques were applied at mount-mirror interface points, generating an array of potential distortions.
- With some care, orthonormal influence functions were generated out of these FEM test cases and then combined with low order Zernike functions correlated with misalignment.
- Fit coefficients to these influence functions were monitored during the mounting process.
- During mounting, variations in the FEM-basis coefficients were concentrated in only two influence functions

Orthonormal Functions: FEM #1/2



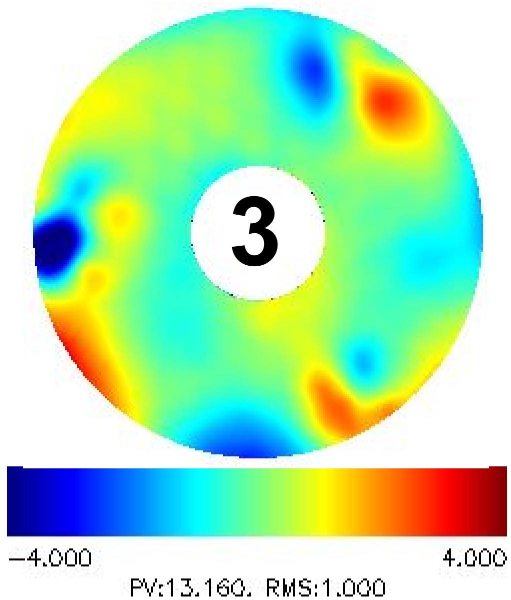
FEM Influence Function #1

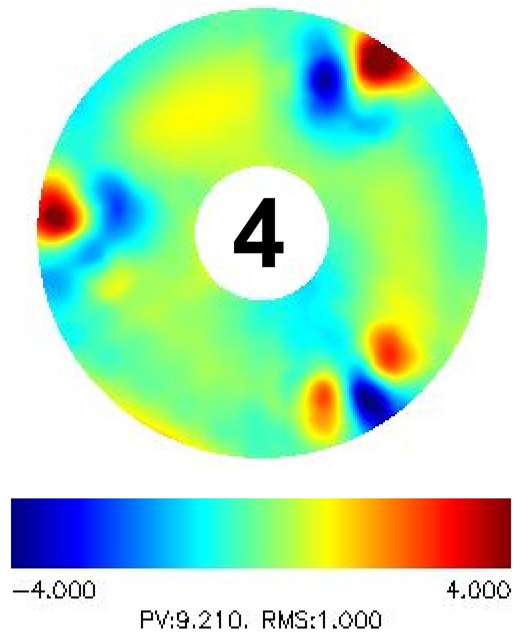


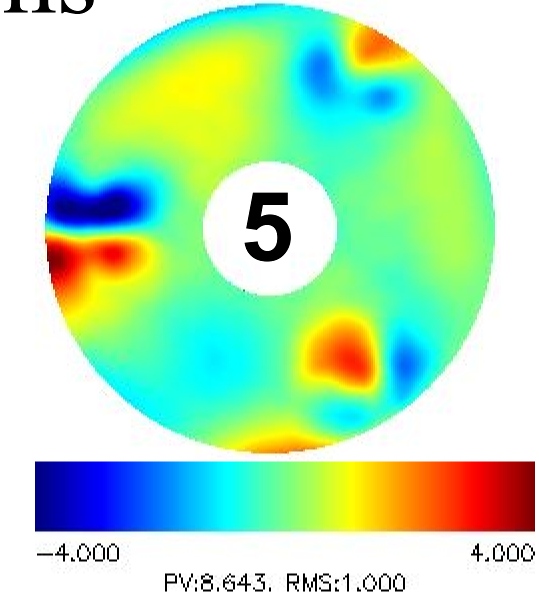
FEM Influence Function #2

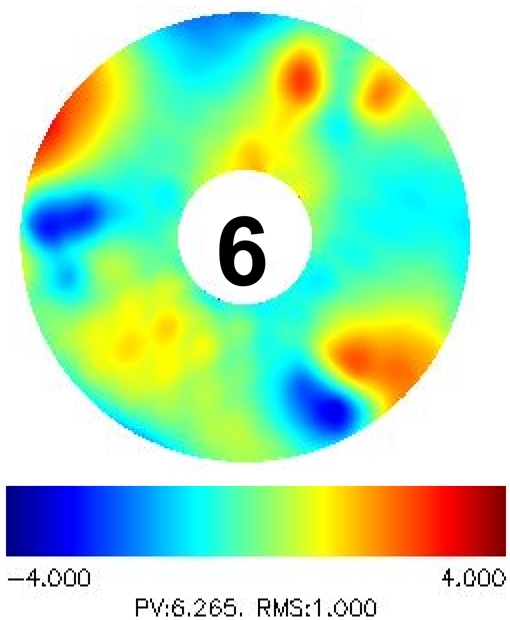
Influence functions are normalized to 1nm RMS.

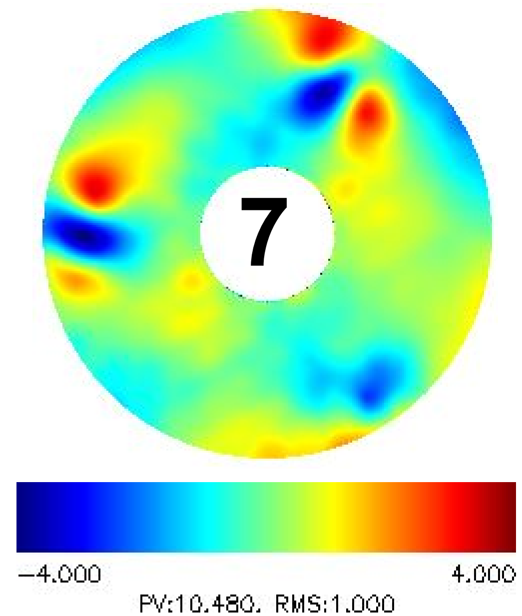
FEM Basis Functions
FEM #3-7



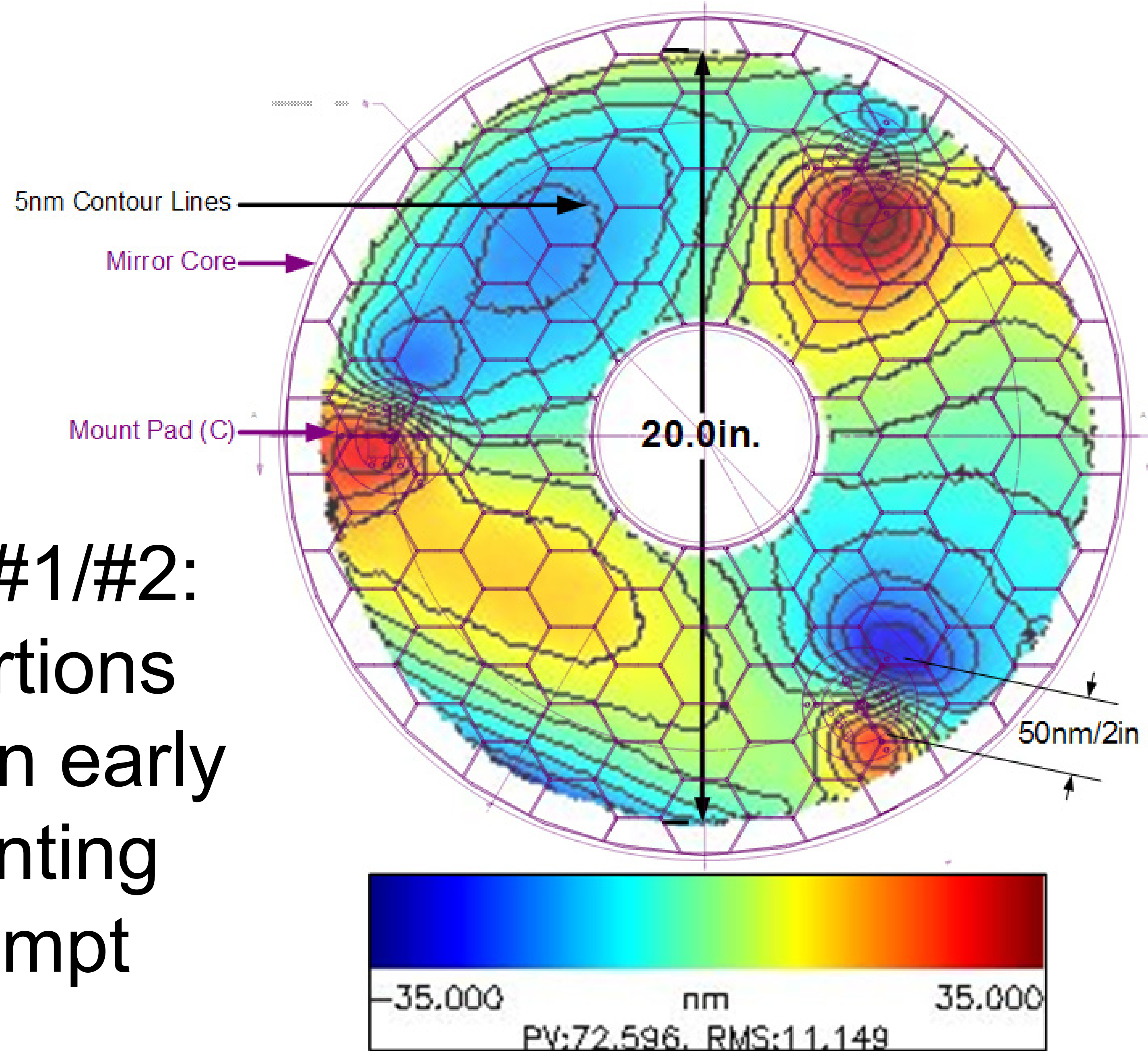


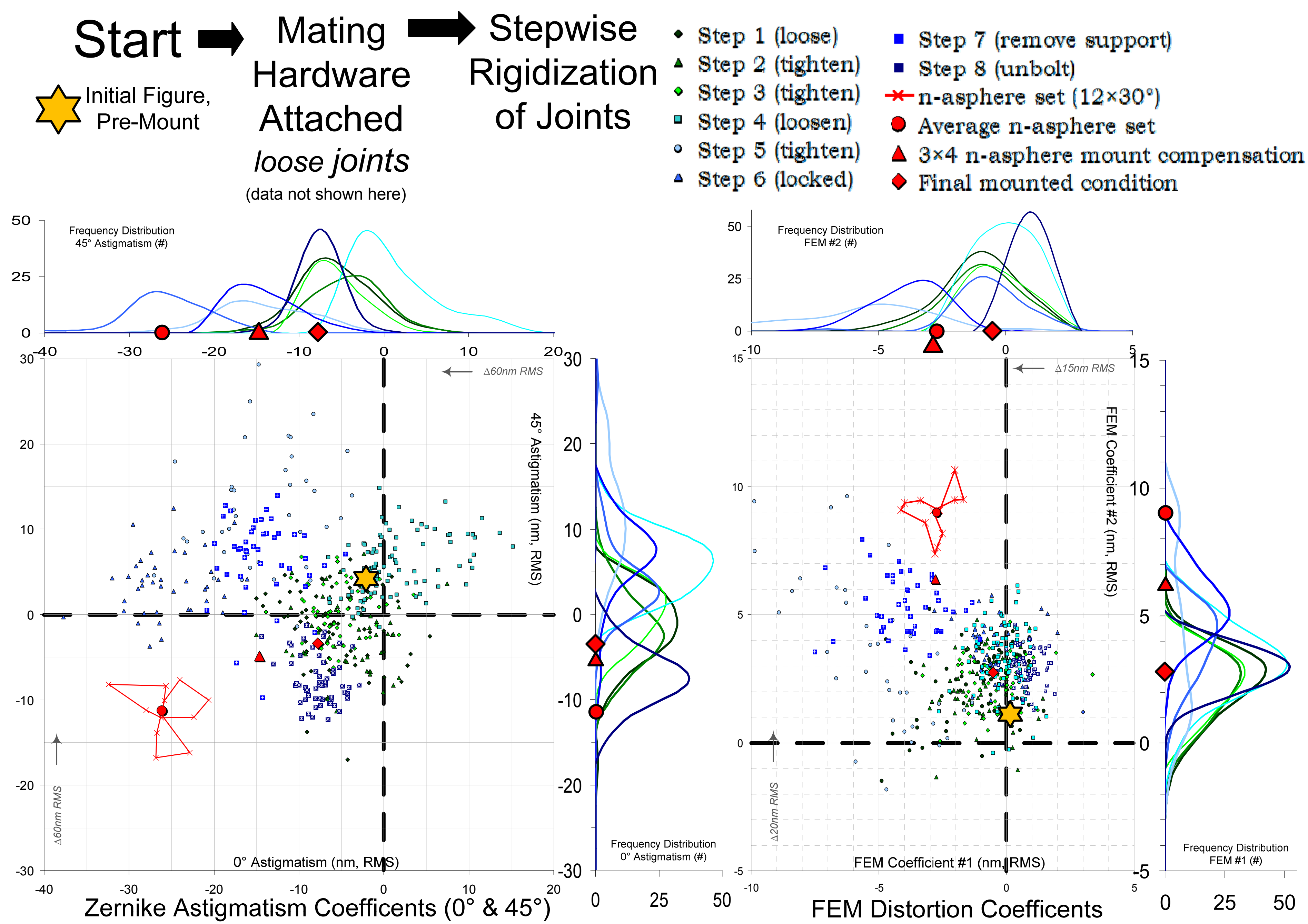






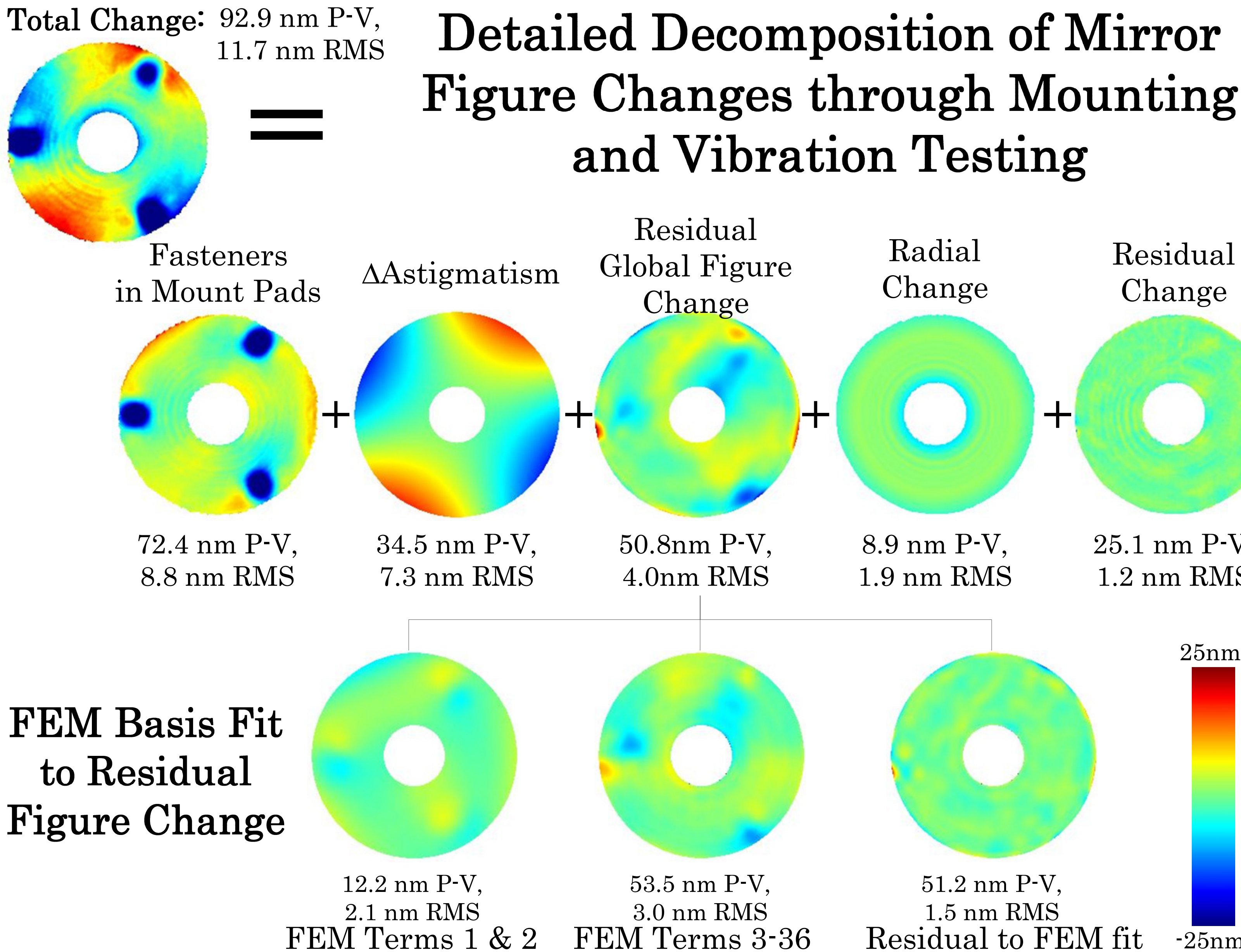
FEM #1/#2: distortions from an early mounting attempt



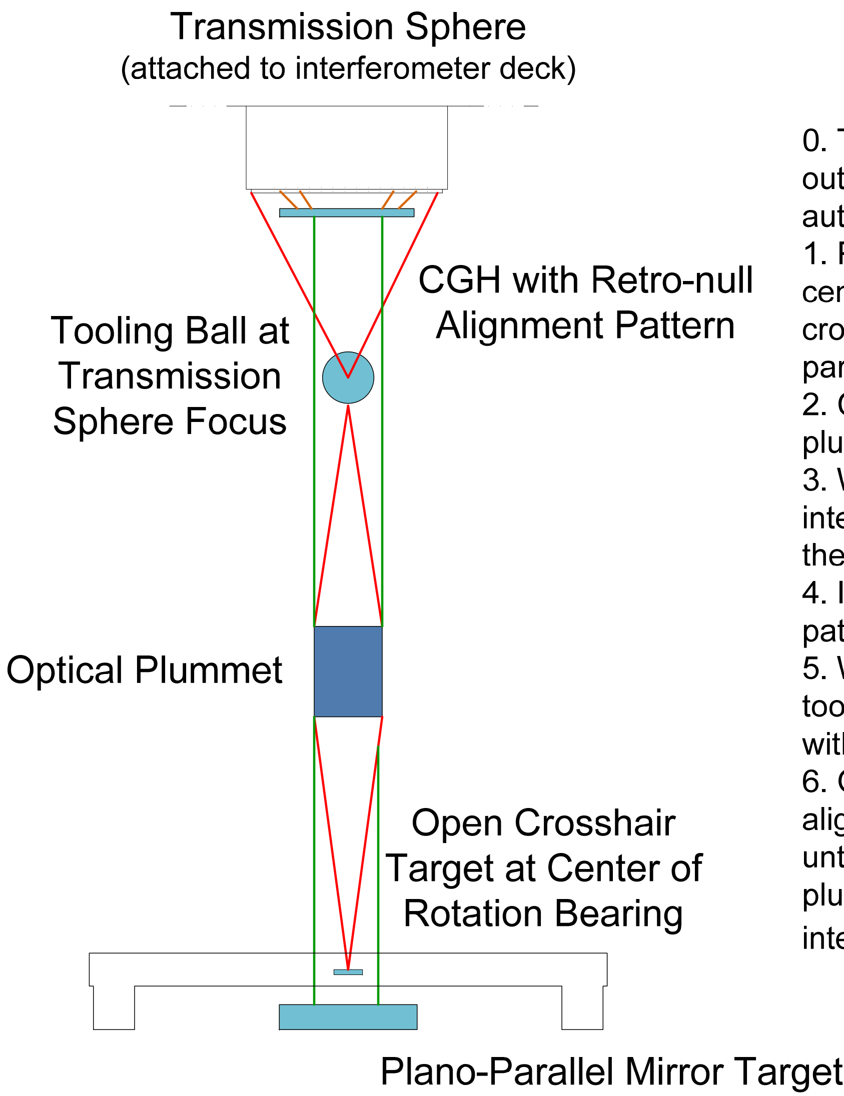


Start
Mating Hardware Attached
loose joints
(data not shown here)
Stepwise Rigidization of Joints
Initial Figure, Pre-Mount
Step 1 (loose)
Step 2 (tighten)
Step 3 (tighten)
Step 4 (loosen)
Step 5 (tighten)
Step 6 (locked)
Step 7 (remove support)
Step 8 (unbolt)
n-asphere set (12×30°)
Average n-asphere set
3×4 n-asphere mount compensation
Final mounted condition
Frequency Distribution 45° Astigmatism (#)
Δ60nm RMS
45° Astigmatism (nm, RMS)
0° Astigmatism (nm, RMS)
Frequency Distribution 0° Astigmatism (#)
Zernike Astigmatism Coefficents (0° & 45°)
Frequency Distribution FEM #2 (#)
Δ15nm RMS
Δ20nm RMS
FEM Coefficient #2 (nm, RMS)
FEM Coefficient #1 (nm, RMS)
Frequency Distribution FEM #1 (#)
FEM Distortion Coefficents

Detailed Decomposition of Mirror Figure Changes through Mounting and Vibration Testing



Alignment of Tower



0. Tip/tilt interferometer deck so that laser output with no transmission element autoreflects off of plano-parallel.
1. Position optical plummet so that it is centered with the rotation bearing crosshair, and normal to the plano-parallel mirror on the table.
2. Center the tooling ball with the optical plummet.
3. With the CGH removed, move interferometer assembly until nulled on the tooling ball.
4. Install CGH and null CGH alignment pattern.
5. With laser aperture stopped, remove tooling ball and tip/tilt CGH until normal with plummet.
6. Open laser aperture and re-null CGH alignment pattern. Repeat steps 5 and 6 until CGH is both normal to the optical plummet and aligned with the interferometer.