SHARPI mirror development program – taking the next step in precision lightweight optics

NASA GSFC IR&D task - Team List

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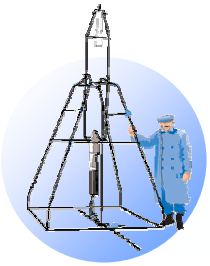
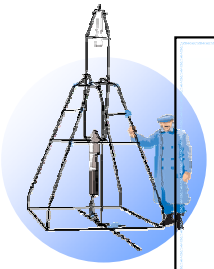


Outline

- Overview
- Science drivers
- Requirements
- Mirror blank fabrication history
- Review of Kodak data
- In-house metrology
  - Roughness
  - Mid frequency (planned)
  - Figure (planned)
- Conclusion

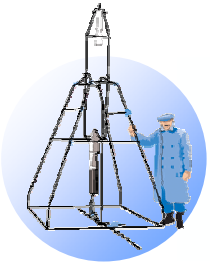


Precision Lightweight Mirrors for Ultraviolet Solar Physics and Astronomy

Task Overview

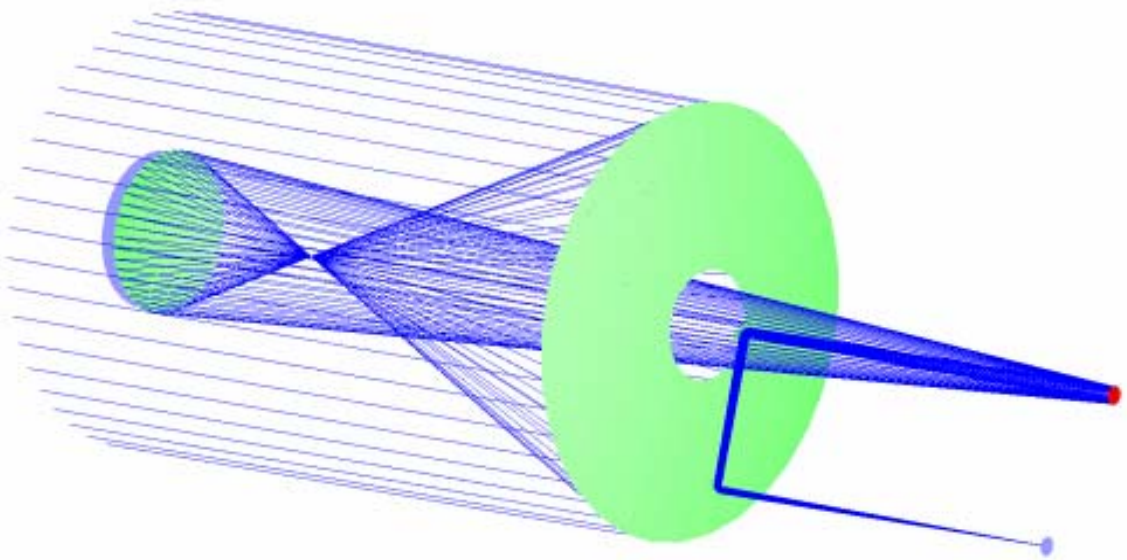
- Carry out in-house testing of a 50-cm primary specified to be the best lightweight FUV mirror ever made.
- Design and fabricate a flight-capable mount for this mirror and demonstrate that it could survive launch and support the mirror without significant distortion.
- Develop state-of-the-art facilities and expertise necessary to space-qualify large-aperture, smooth, ultraprecise lightweight optics.

  - Lightweight: < 15 kg m^{-2}
  - FUV: < 200 nm
  - Smooth: < 1 nm microroughness
  - Ultraprecise: $< \lambda / 50$ rms figure error @ 630 nm

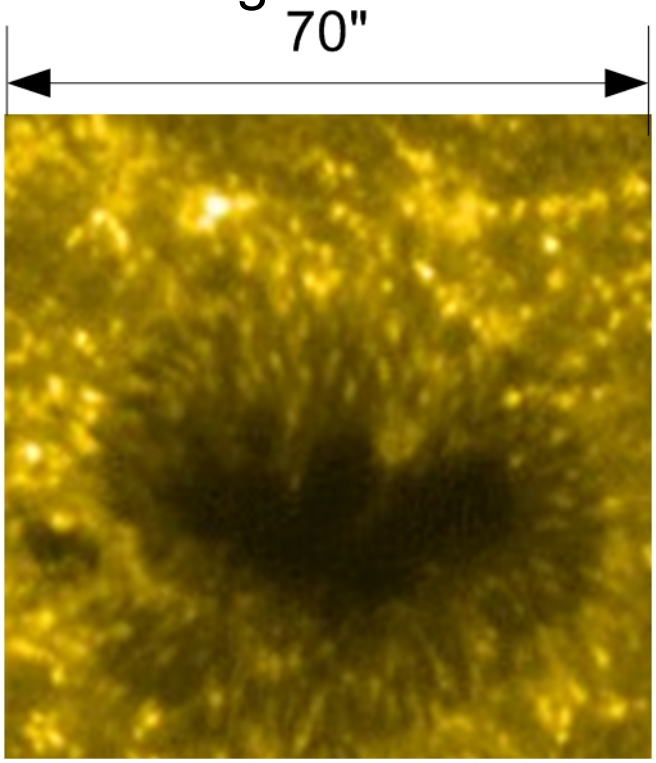


Solar High Angular Resolution Photometric Imager (SHARPI)

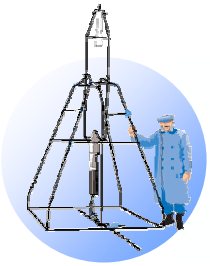
- Sounding rocket telescope for 0.2” solar imaging over 70” in the far ultraviolet (160nm)
- Primary Surface figure error budget allocation range 6-7.5nm RMS



SHARPI optical layout

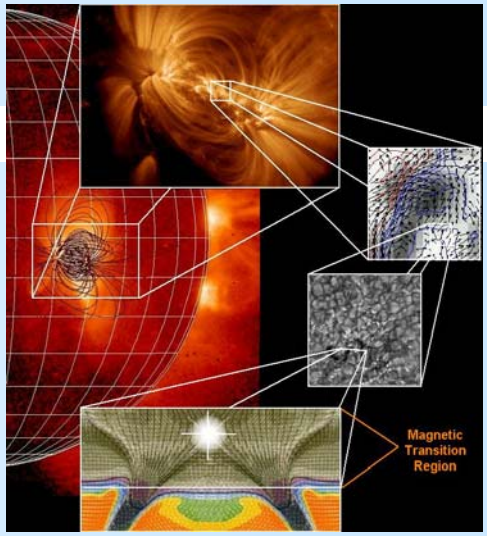


TRACE image of sunspot
160nm, 1" resolution

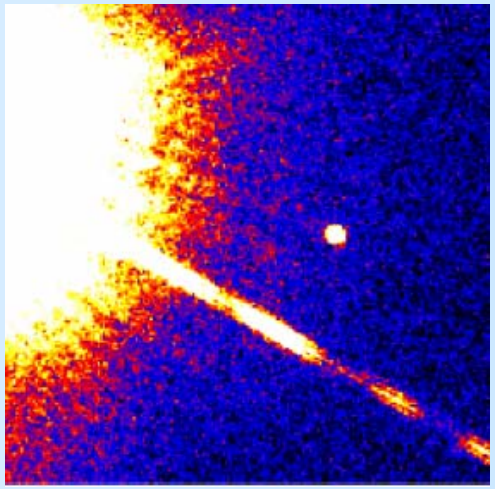


Science Drivers

- Science Challenges
  - Probing the origins of solar and stellar activity by studying the dynamic microstructure of stellar atmospheres
  - Detecting planets around other stars
  - Understanding the structure of galaxies and the media between stars and galaxies
- Method
  - high angular resolution, high contrast imaging and spectroscopy from optical to far ultraviolet (FUV) wavelengths



RAM & MTRAP

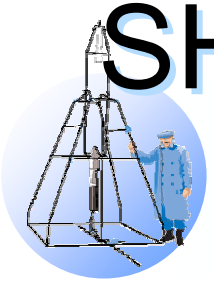


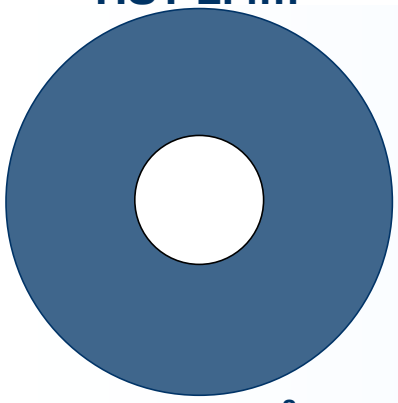
TPF Coronagraph

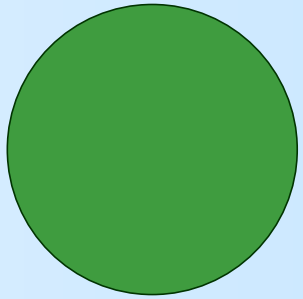
Science Drivers

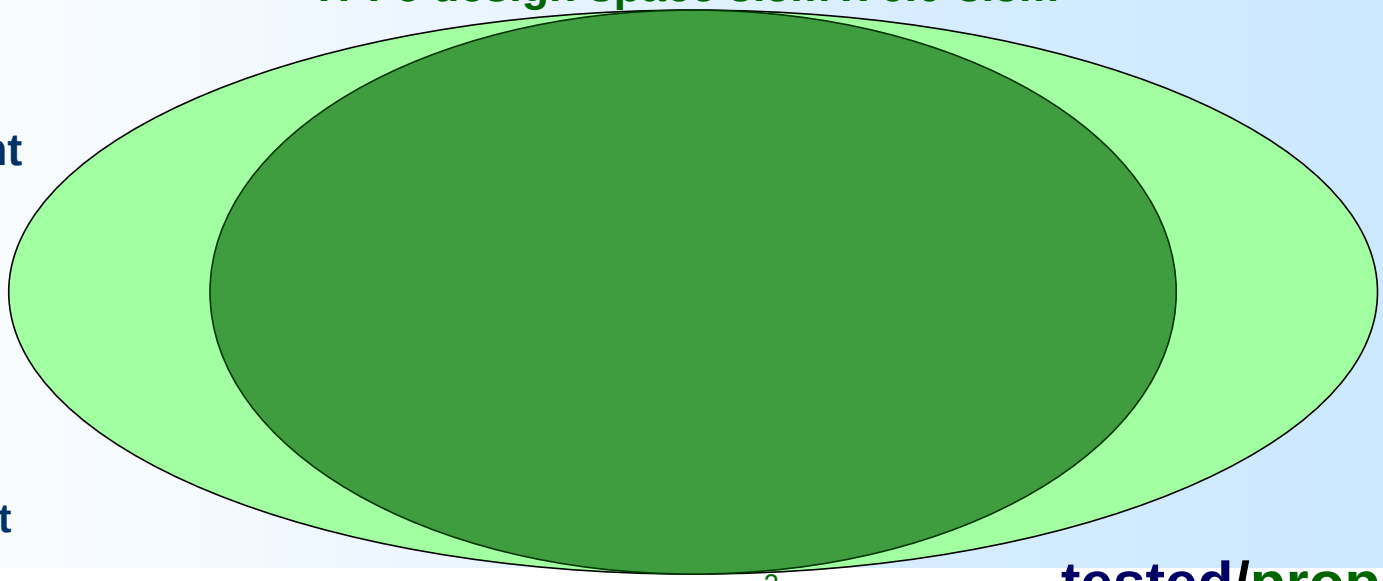
- Targeted 2003 Roadmap Missions
  - Reconnection and Microscale (RAM)
  - Terrestrial Planet Finder (TPF coronagraph concept)
  - Next Large UV/Optical Telescope (“NHST”)
  - Magnetic Transition Region Probe (MTRAP)
  - Solar Connections Observatory for Planetary Environments (SCOPE)
  - Stellar Imager (SI)

SHARPI PM versus other smooth, precise, lightweight mirrors

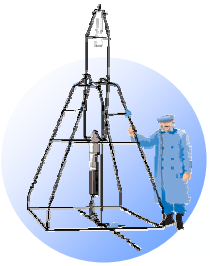






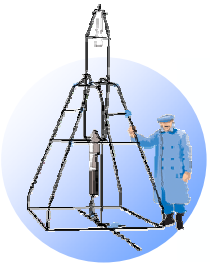


tested/proposed



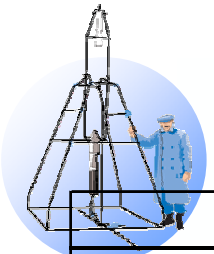
Requirements

- Extremely lightweight for a precision optic
  - (20 kg/m^2, 4.5kg)
- 0.01 wave (@633nm) or 6.3nm rms surface figure requirement
- 2.5 nm rms midfrequency surface accuracy (1-10mm)
- 1.0 nm rms microroughness (1-1000 μm)
- Ready for kinematic, minimal mounting stress mount



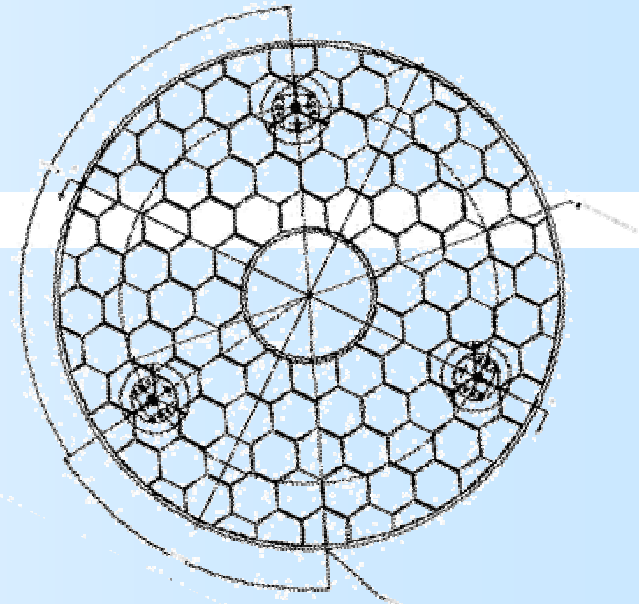
Mirror blank fabrication

- Kodak fabrication through non-slumped LTF (contract predates AMSD development of slumping aspheres)
  - Previously reported at TechDays by G. Matthews/Kodak & R. Keski-Kuha/GSFC
- Delivered FY2003
  - CA reduced from 21” to 20” diameter
  - Final surface figure rms ~7 nm vs. 6.3
- Pushed Kodak in areas of metrology, midfrequency polishing, roughness

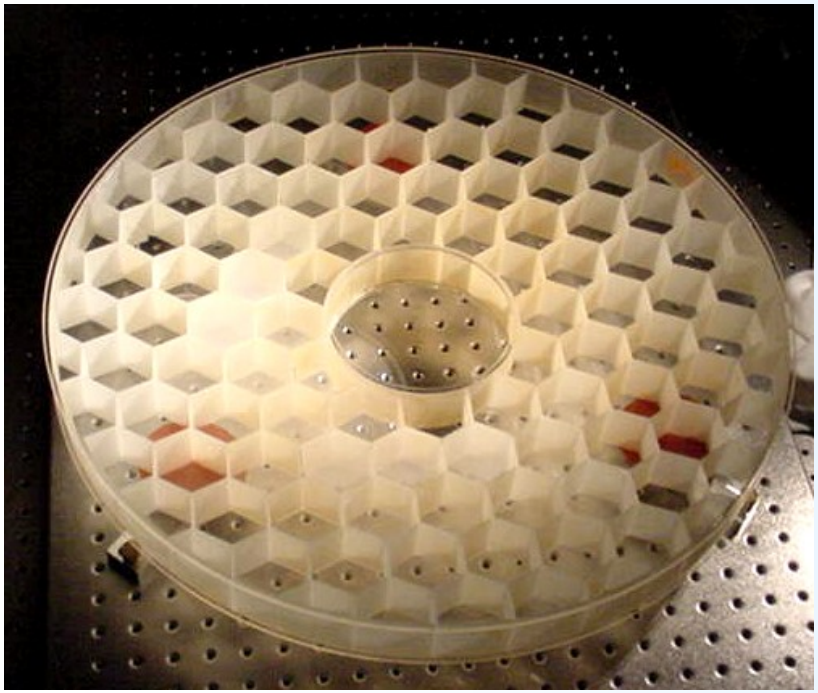


SHARPI PM

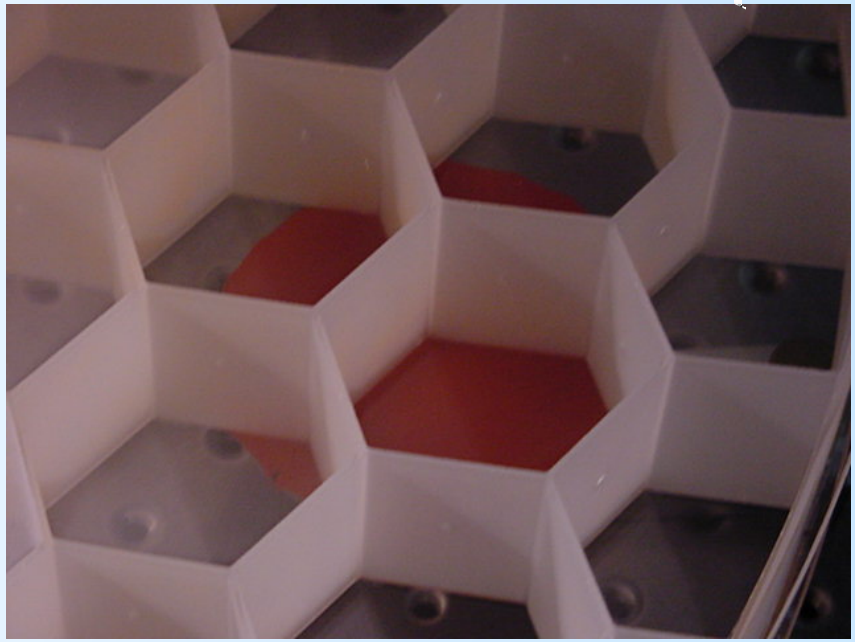
SHARPI Primary Mirror: specifications			
Material / construction		ULE / LTF	
Total mass		4.54	*kg*
Areal density		19.75	*kg/m*^{2}
Light weighting		92	%
Figure specifications			
Global surface figure error	(>10mm)	6.3	*nm* RMS
Microroughness	(1mm-1mm)	1	*nm* RMS



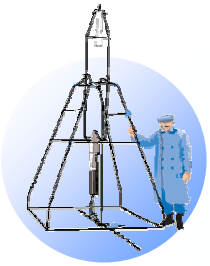
drawing, from top



under inspection at Goddard



View from above, looking down at mount pad

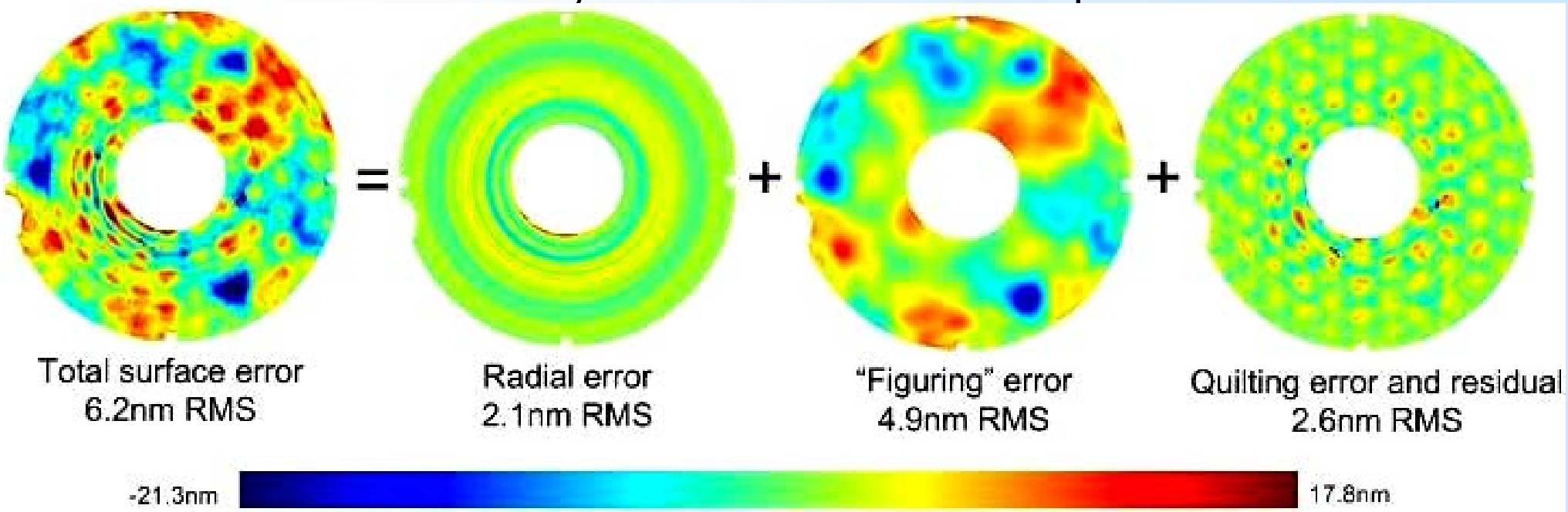


Review of Kodak data

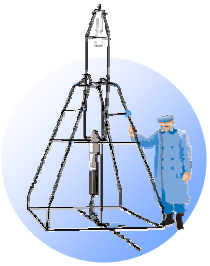
Analysis of surface figure data from Kodak's fabrication metrology

{S. Antonille}

- Kodak uses vertical test stand with gravity compensated (ion figured) 0.5m fold flat – ideal test for parabolic 0.5m optics
- Gravity deflection and outlying feature removed for analysis
- Data was iteratively filtered and fit to decompose error



Simulations of SHARPI PSF are expected to support the SHARPI science goals

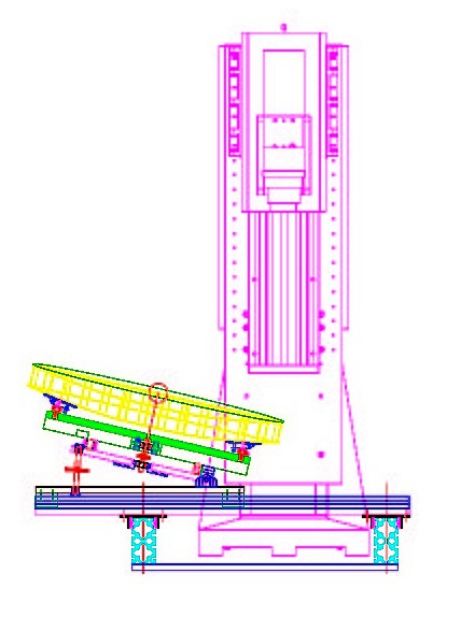


Additional Kodak data

- Roughness ~ 1.0 nm rms (at spec. leve)
  - 80 um filter, i.e. 1-80 um bandpass
  - Chapman profilometer used
- Pixel spacing on figure data is ~1mm
- No data between 2mm and 0.08mm spatial frequencies taken by Kodak

In-house metrology at GSFC

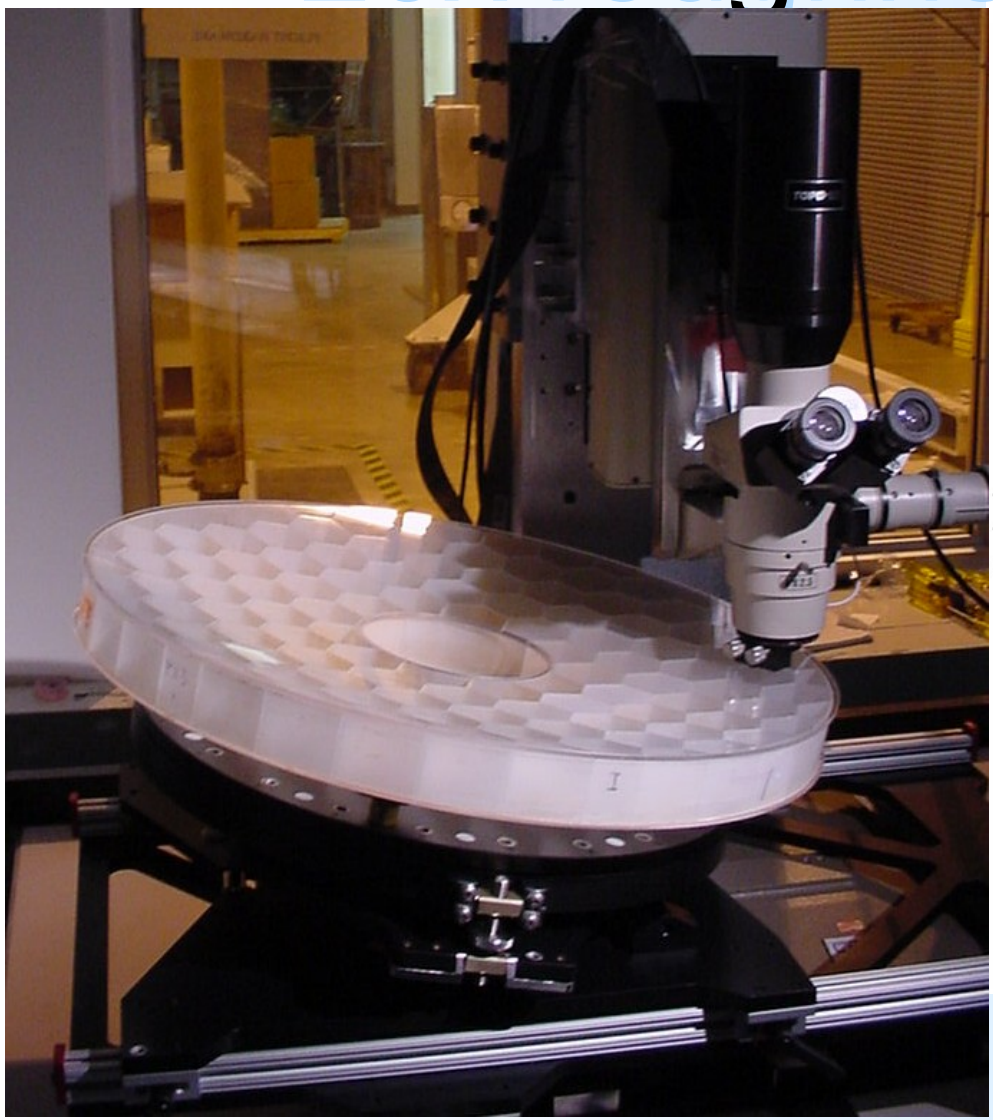
- GSFC optics branch has facilities and experience across many programs for precision metrology
  - X-ray to far-IR
- First work is to map microroughness
- 2nd – attempt to fill in gap in PSD from 0.08 to 2mm
- Finally – verify surface figure



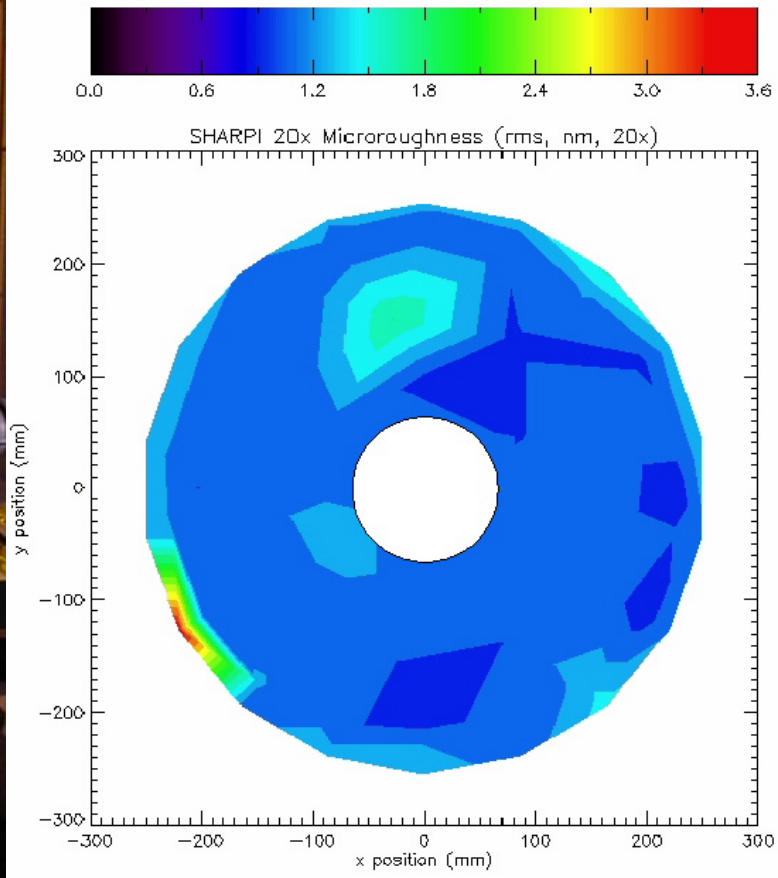
CAD view of Mirror on roughness stand

Subaperture test mirror on completed roughness metrology mount

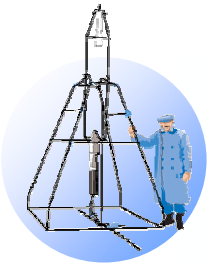
20x roughness results



SHARPI PM being scanned for 20x roughness



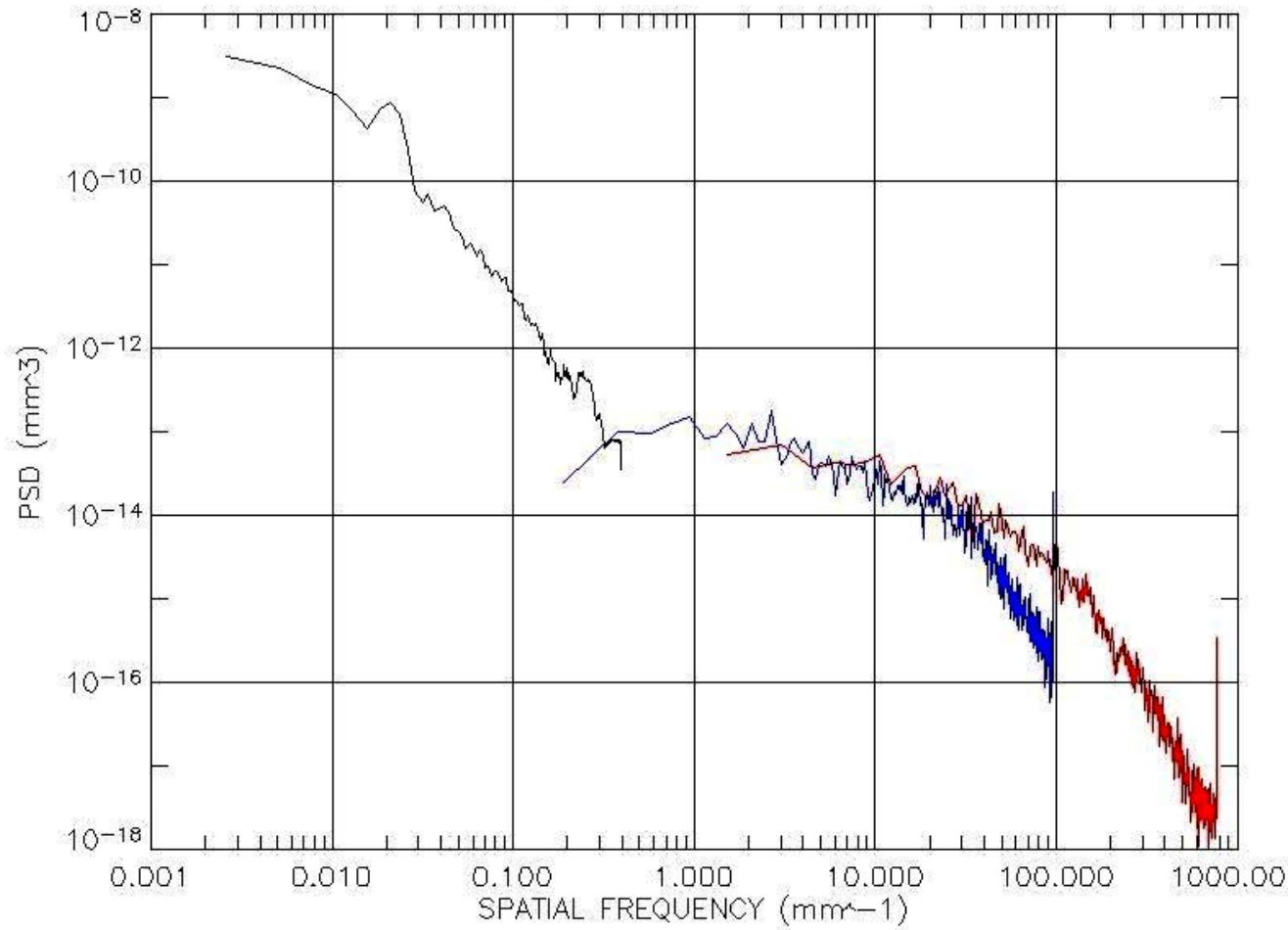
Roughness map: 1.3nm rms @20x (acceptable for SHARPI science but out of 1.0nm specification)
Feature at 210° matches area of worst figure



2.5x roughness results (July04)

- Raw roughness is ~3.1nm rms
- 4th order dominates, but too much to be explained by parabolic sag difference from best fit sphere
- This PSD comparison has 4th order removed from 2.5x (blue), 20x (red), and figure(black)

Power spectral density from 50mm to 1um



Spatial period (mm): 50 10 1 0.1 0.01 0.001

Midfrequency metrology

- Map ≥50mm areas to measure print-through (~2nm rms) to overlap with figure data
- Concept is to mount SHARPI PM horizontally in roughness fixture and use 100-150mm small aperture of our upgraded 60cm aperture Zygo
  - Allows multiple samples and easy adjustment

60cm aperture Zygo (wavelength shifting, no moving parts); small aperture in foreground

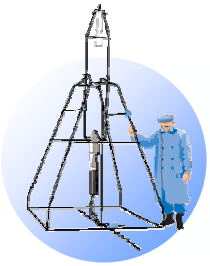
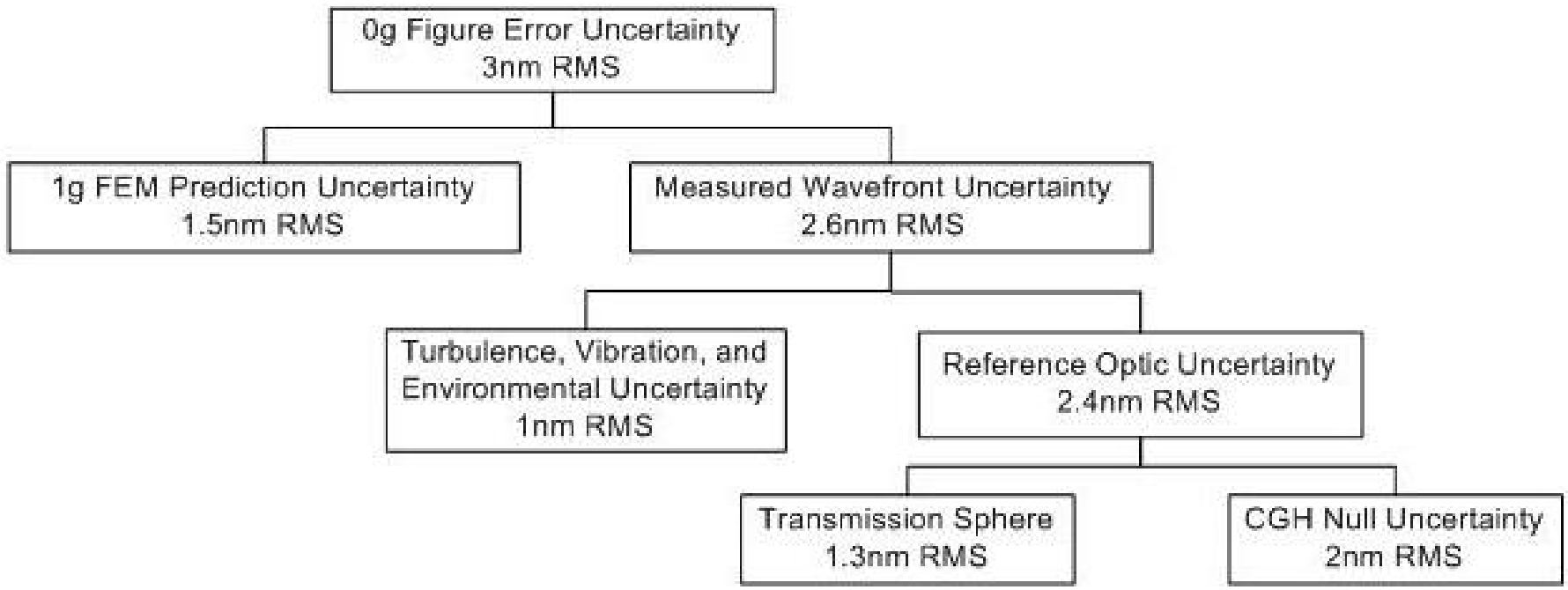


Figure Metrology uncertainty budget

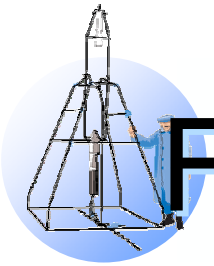
Retrieve 0g figure error by subtracting systematic contributions.

Total uncertainty in subtraction should not exceed 3nm RMS.



Our test plan is entirely independent from Kodak's, but requires

1) ***Careful calibration of gravity sag and correlation of gravity sag models***
2) ***calibration of CGH test at unprecendented levels***

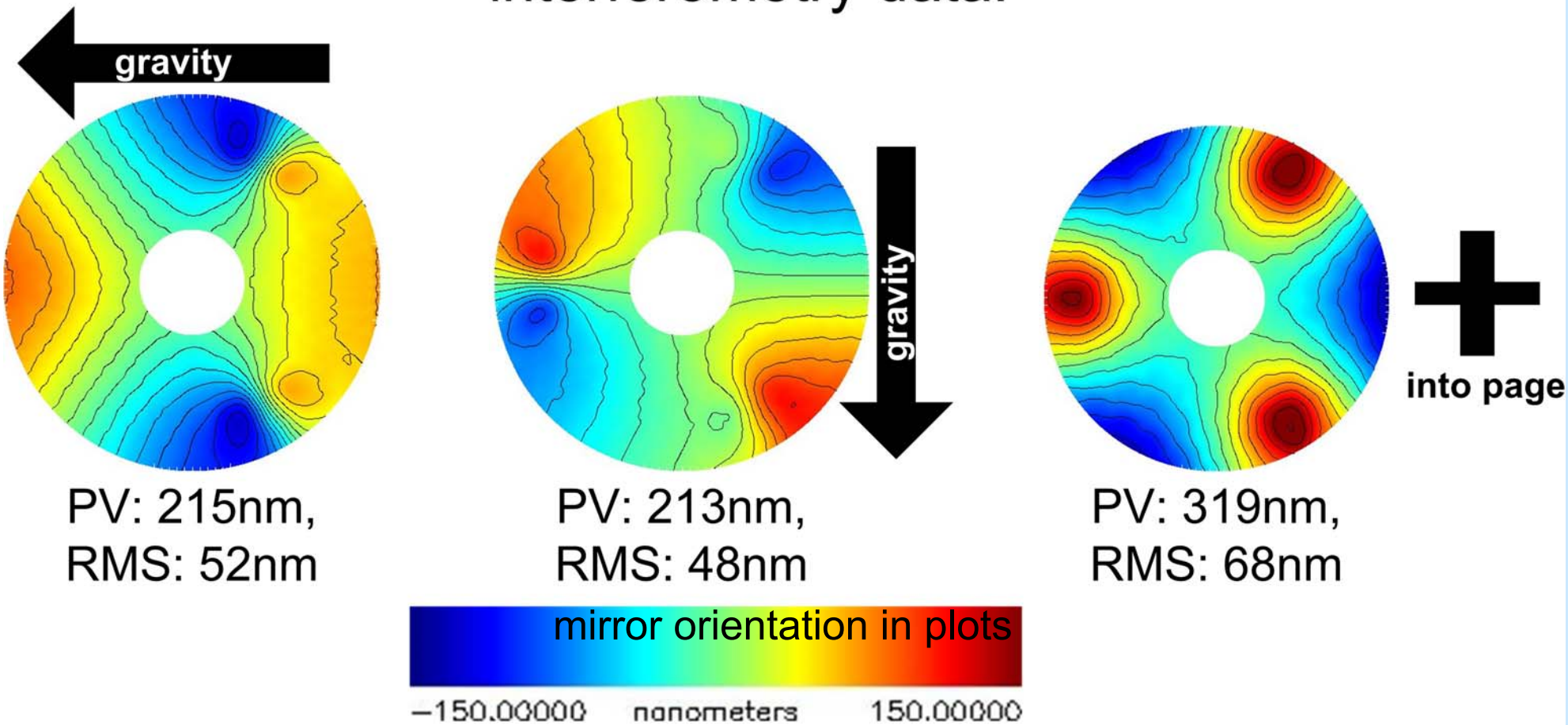


FEM Gravity Sag Correlation

- Lightweight mirror sags due to gravity
- Spec. is 6.3nm RMS 0g surface figure error
- Subtract FEM prediction from data
- FEM needs to be accurate to ~2%, 1.5nm RMS
- FEM correlation planned for axial and lateral directions

FEM 1g deflection predictions

Modeled sags need to be subtracted from interferometry data.



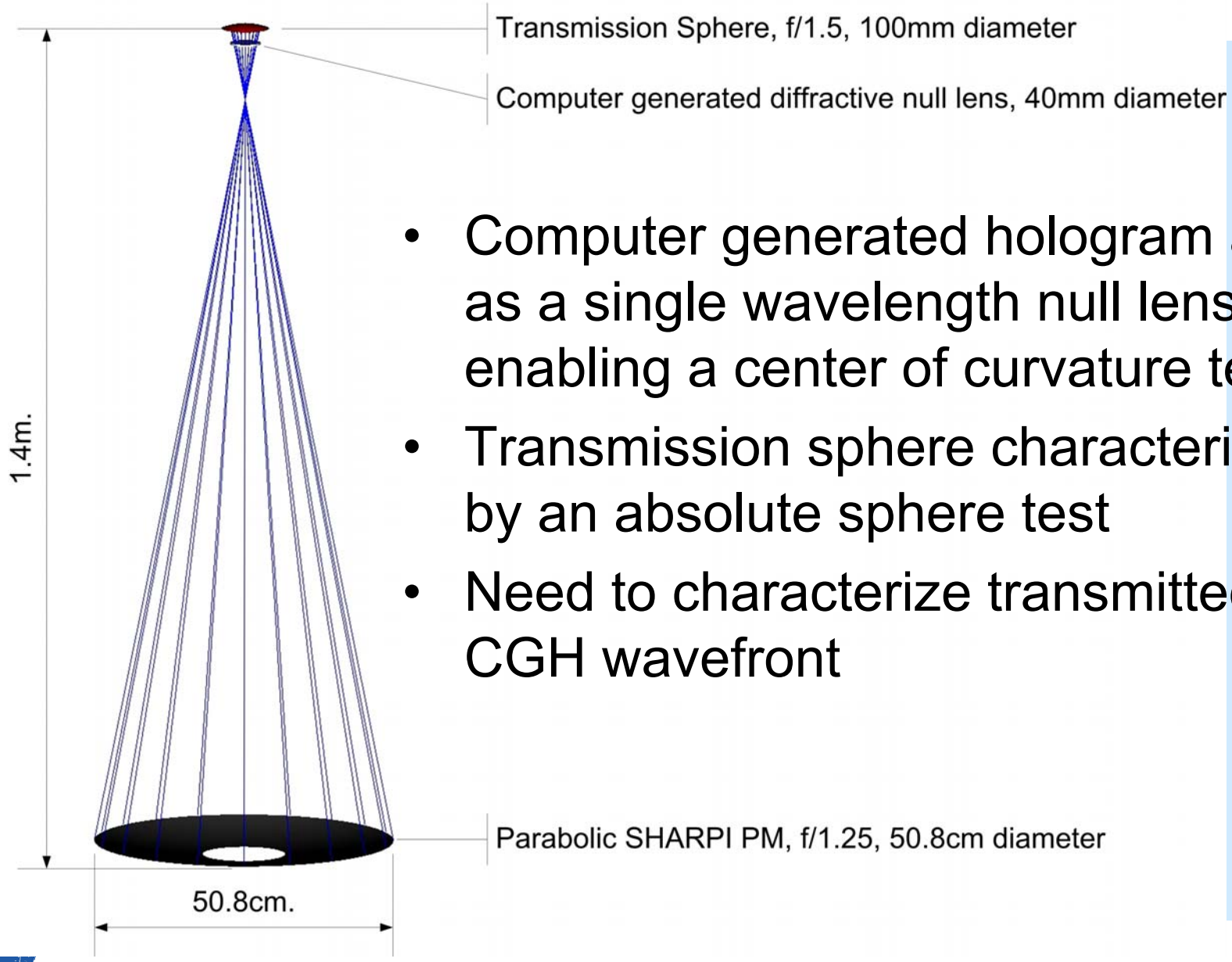
PV: 215nm, RMS: 52nm

PV: 213nm, RMS: 48nm

PV: 319nm, RMS: 68nm

facing mirror, same clocking orientation
contour lines mark 20nm elevation increments

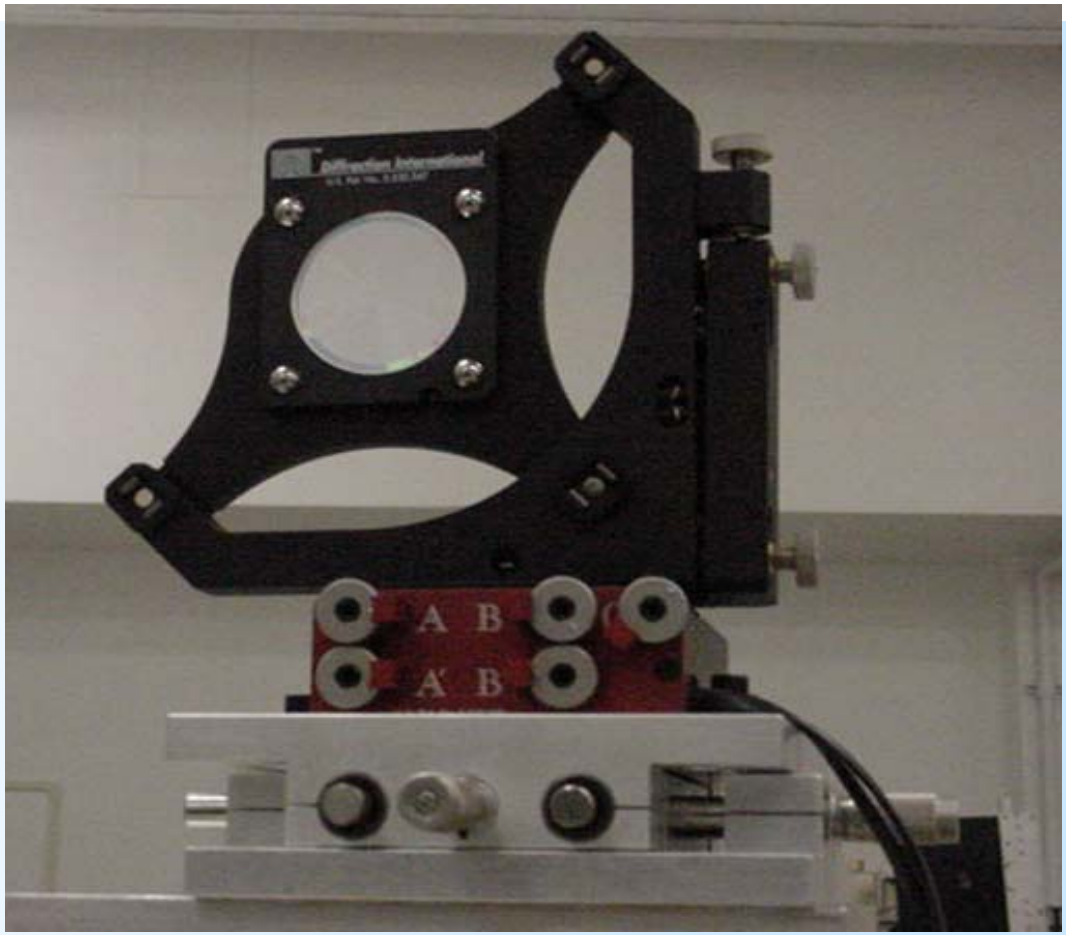
CGH Null Test - overview



- Computer generated hologram acts as a single wavelength null lens, enabling a center of curvature test
- Transmission sphere characterized by an absolute sphere test
- Need to characterize transmitted CGH wavefront

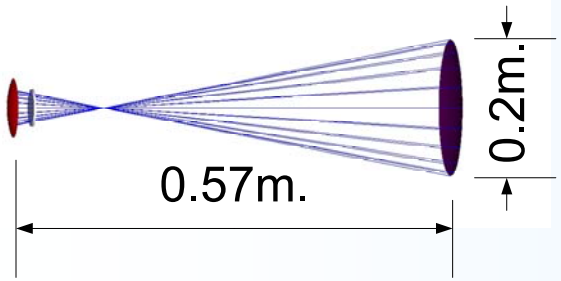
Figure Metrology plan & equipment

Figure metrology layout (in fabrication)



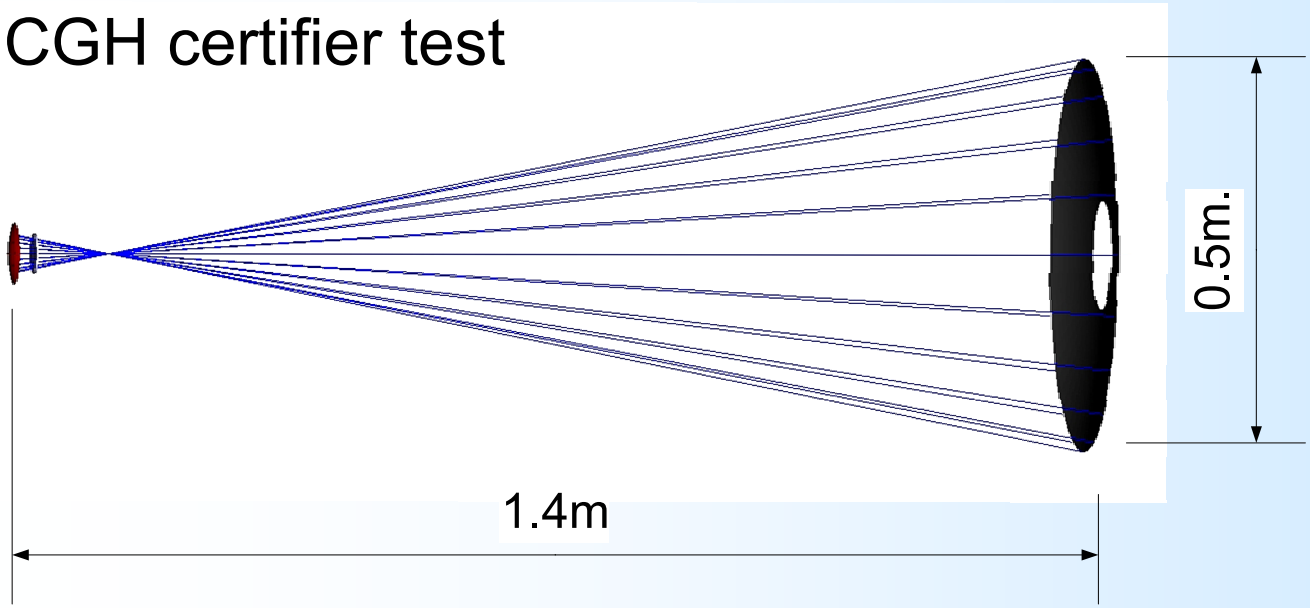
Custom computer-generated hologram in 5-axis adjustable mount

CGH Certifier Test



CGH certifier test

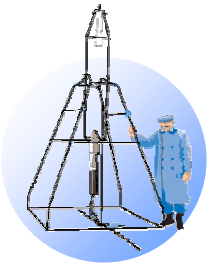
Highly aspheric “certifier” mirror reproduces ideal reflected wavefront from SHARPI PM.



SHARPI PM test

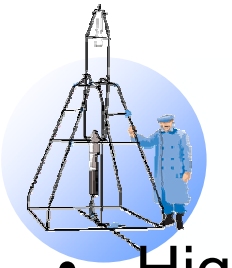
Develop a means of using a >3nm RMS certifier mirror to characterize the CGH wavefront to <3nm RMS.

Relatively inaccurately figured certifier can be made in-house using DTM or made commercially



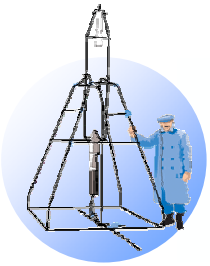
Future Work

- Fabricate figure metrology tower, perform measurements, and report in open literature.
- Fabricate flight mount, carry out mounted measurements and vibrate with mirror simulator.
- Carry out conceptual design of a 0.5-m telescope for high angular resolution observations of the Sun.
- Propose for flight opportunity to lay the groundwork for Roadmap level missions
  - Possible testbed for TPFc high contrast demo using lightweight precision large optics



Conclusion

- Highly precise lightweight mirror fabricated, delivered, and is being tested and mounted at GSFC
- Roughness has been tested, some analysis underway. While slightly out of specification, we believe the mirror as delivered supports the SHARPI science goals
- Surface figure deflection due to gravity has been modeled, and correlation tests are planned.
- Plan to verify and map the surface error to 3nm RMS using a diffractive CGH null lens test, including a novel calibration of the diffractive null lens.
- Tests will be used to monitor surface figure during mounting process to minimize distortion from induced strain
- Verify this state of the art high precision, lightweight, UV capable mirror: for SHARPI mission and as a proof of concept for this class of precision mirrors to be followed by significantly larger apertures



Acronyms

- AMSD: Advanced Mirror Systems Demonstrator, *ULE version-Kodak*
- CGH: Computer Generated Hologram
- FEM: Finite Element Model
- FUSE: Far Ultraviolet Spectroscopic Explorer
- JMEX: Jupiter Magnetospheric Explorer
- PSF: Point spread function
- SBMD: Sub-scale Beryllium Mirror Demonstrator, *Ball Aerospace*
- SHARPI: Solar High Angular Resolution Photometric Imager
- SMEX: Small Explorer program
- TDM: Technology Demonstrator Mirror, a TPFc technology pathfinder
- TPFc: Terrestrial Planet Finder, Coronograph option
- TRACE: Transition Region and Coronal Explorer
- ULE: Ultra-Low Expansion Fused Silica