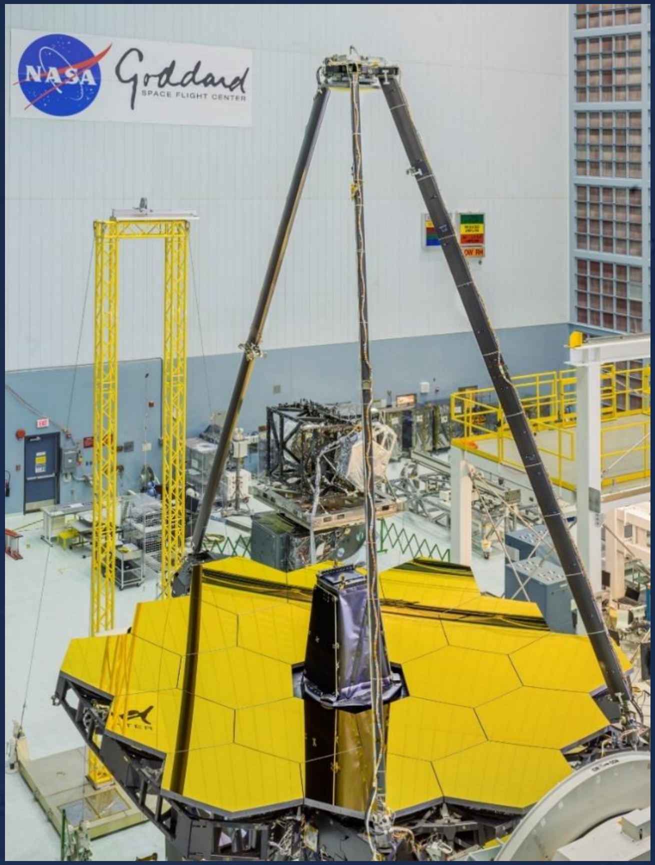
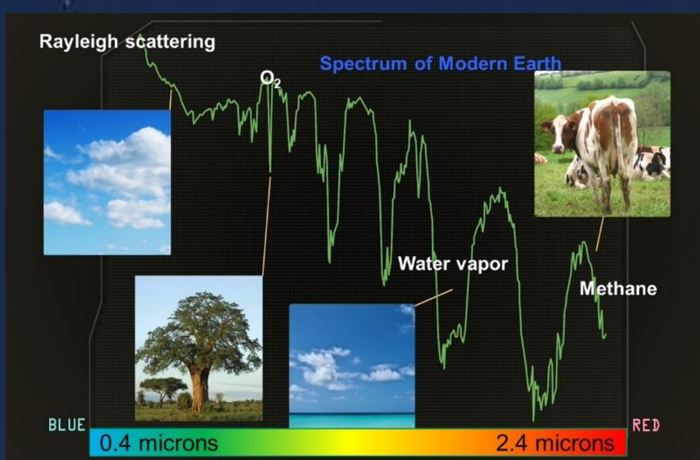


Breakthroughs in Picometer Ultra-stable Spatial Metrology Systems for Next Generation Telescopes

Lee Feinberg, Babak Saif
NASA Goddard Space Flight Center

Why large ultra-stable telescopes?

Credit: L. Pueyo / M. N'Diaye / A. Roberge

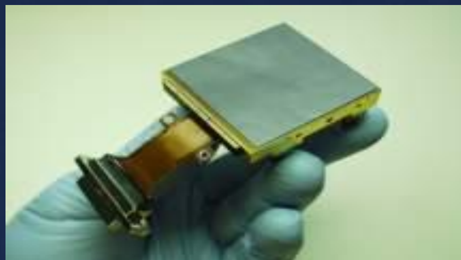


- Goal is to discover and characterize habitable planet candidates around Sun-like stars
- Need 10^-10 contrast between reflected earth like planet and sun like star
- Options are internal Coronagraphs (LUVOIR and Habex) and large starshades (Habex) which each have pros and cons
- Coronagraphs require 10^-11 contrast stability which means the primary mirror must be stable to roughly 10 picometers RMS wavefront over an exposure (minutes)
    - Simplistically: Primary mirror instabilities of 10 picometers in certain spatial frequencies look like planets!

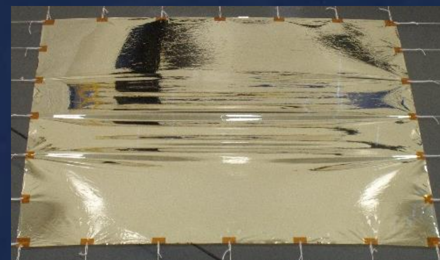
How did we get here?

- During the testing of the primary mirror segments for Webb, our team realized that some of the tools and techniques we had developed could be pushed further to achieve picometer resolution
- We began developing incremental techniques for measuring, controlling, sensing to picometer levels
- Several recent peer reviewed papers have shown that we can measure this level of change, control it with actuators, and potentially even develop active architectures using these ideas
- To understand this work, we will review the history of what we did on Webb, show how it evolved to systems applicable to measure picometer and even sub-picometer levels, show the results, and discuss implications for future telescope like LUVOIR and Habex

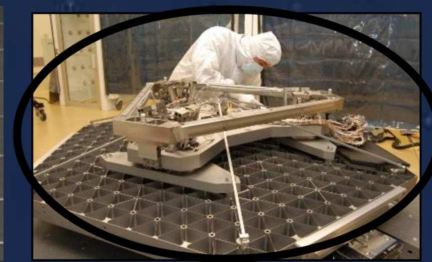
3 of 10 Webb key technologies were related to primary mirror….



Near Infrared Detectors
April 2006



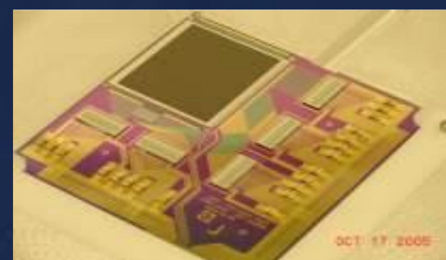
Sunshield Material
April 2006



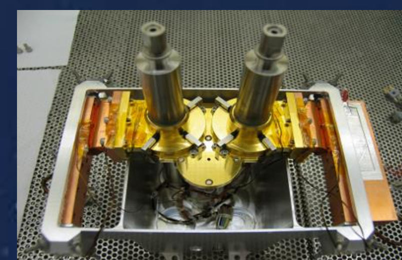
Primary Mirror Segment Assembly
June 2006

Mid Infrared Detectors
July 2006

Cryo ASICs
August 2006

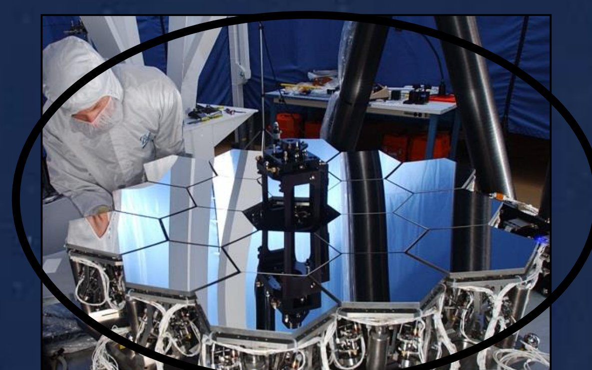


Microshutter Arrays
August 2006



Heat Switches
September 2006

Large Precision Cryogenic Structure
November 2006



Wavefront Sensing & Control
November 2006

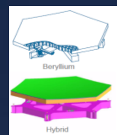
Cryocooler
December 2006

The hardest part of making a mirror is measuring it….

JWST Mirror History Enabled by Metrology

1996 | 1998 | 2000 | 2002 | 2004 | 2006 | 2008 | 2010 | 2012 | 2014

Advanced Mirror System Demonstrator (AMSD)
Collaboration among 3 government agencies
15Kg/m2, 1.2M diameter segments



Medium **Authority** Glass (ULE)

Low Authority **Beryllium**

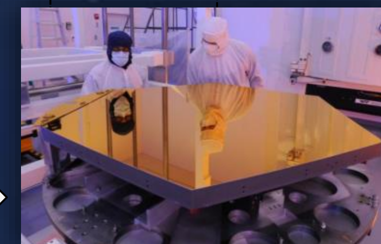
Technology Readiness Level-6 Demonstrated:
All key requirements and environments demonstrated

Onset of
James Webb Space Telescope

AMSD Phase 1:
8 Mirror Designs

AMSD Phase 2:
3 mirrors developed

AMSD Phase 3/Six Sigma Study
Be manuf. and process improvements



OTE Optics Review (OOR): Beryllium Selected

Engineering Design Unit.

Subscale Beryllium Mirror Demonstrator (SBMD):
.5 meter diameter,

PM Manufacturing of 18 segments

Primary Mirror Segment Assemblies Complete

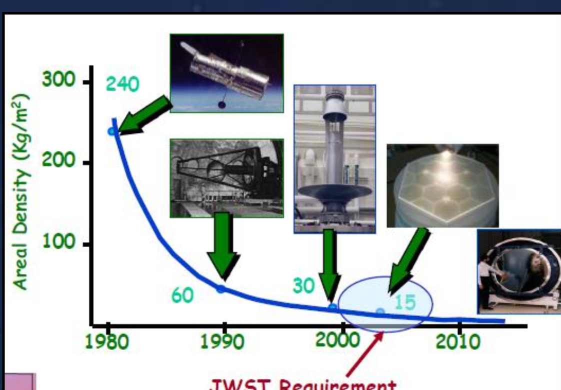
Machining Facility Complete

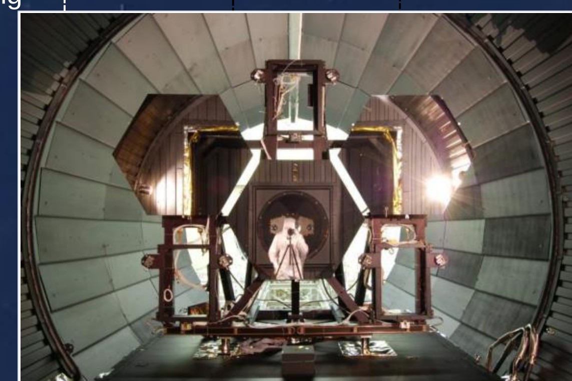
Cryo Testing

Low Areal Density Mirrors Identified as Key Enabling Technology for 25 Square Meter Space Telescope

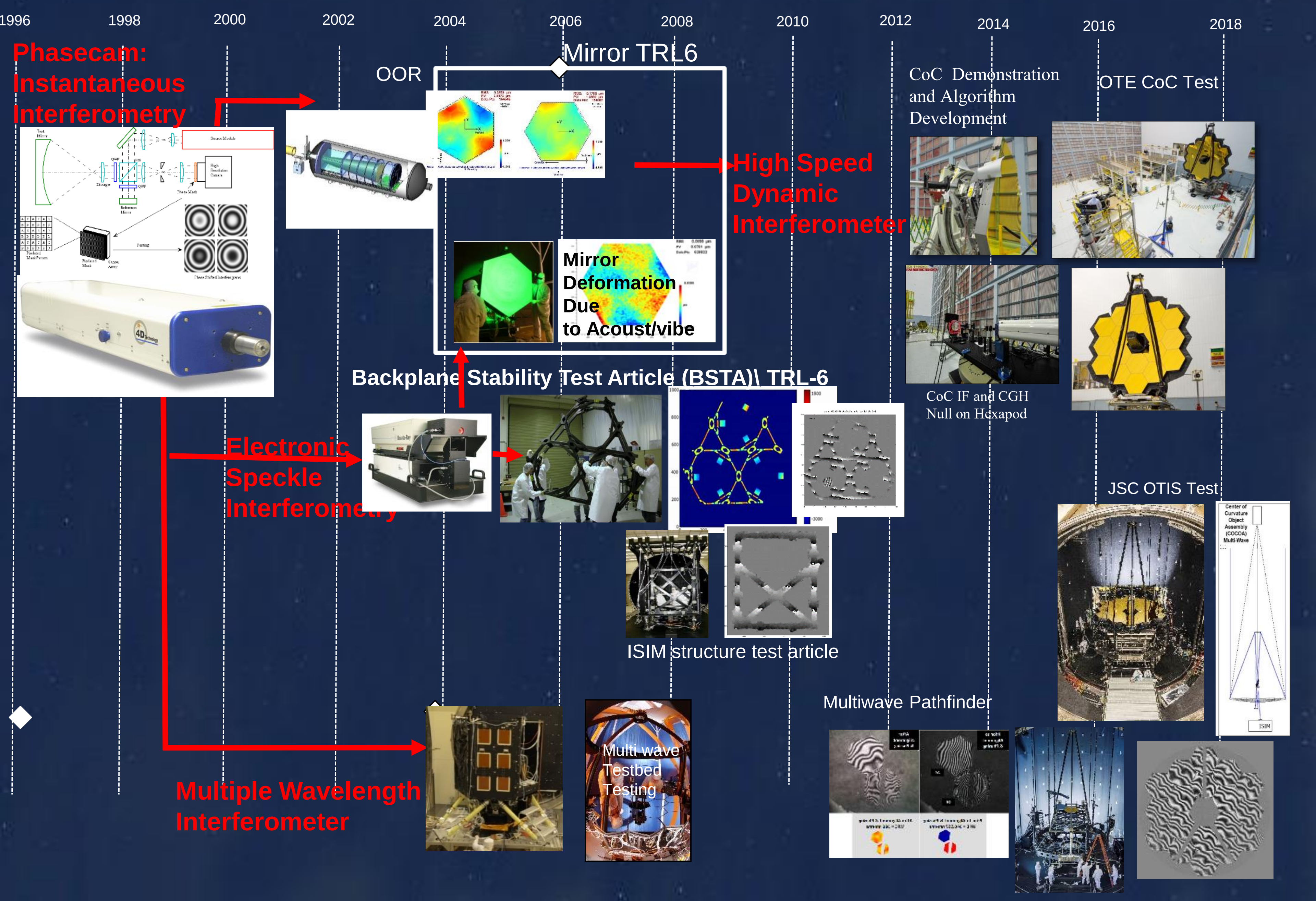
NGST Mirror System Demonstrator (NMSD): Other architectures that were not successful

Polishing Facility Complete



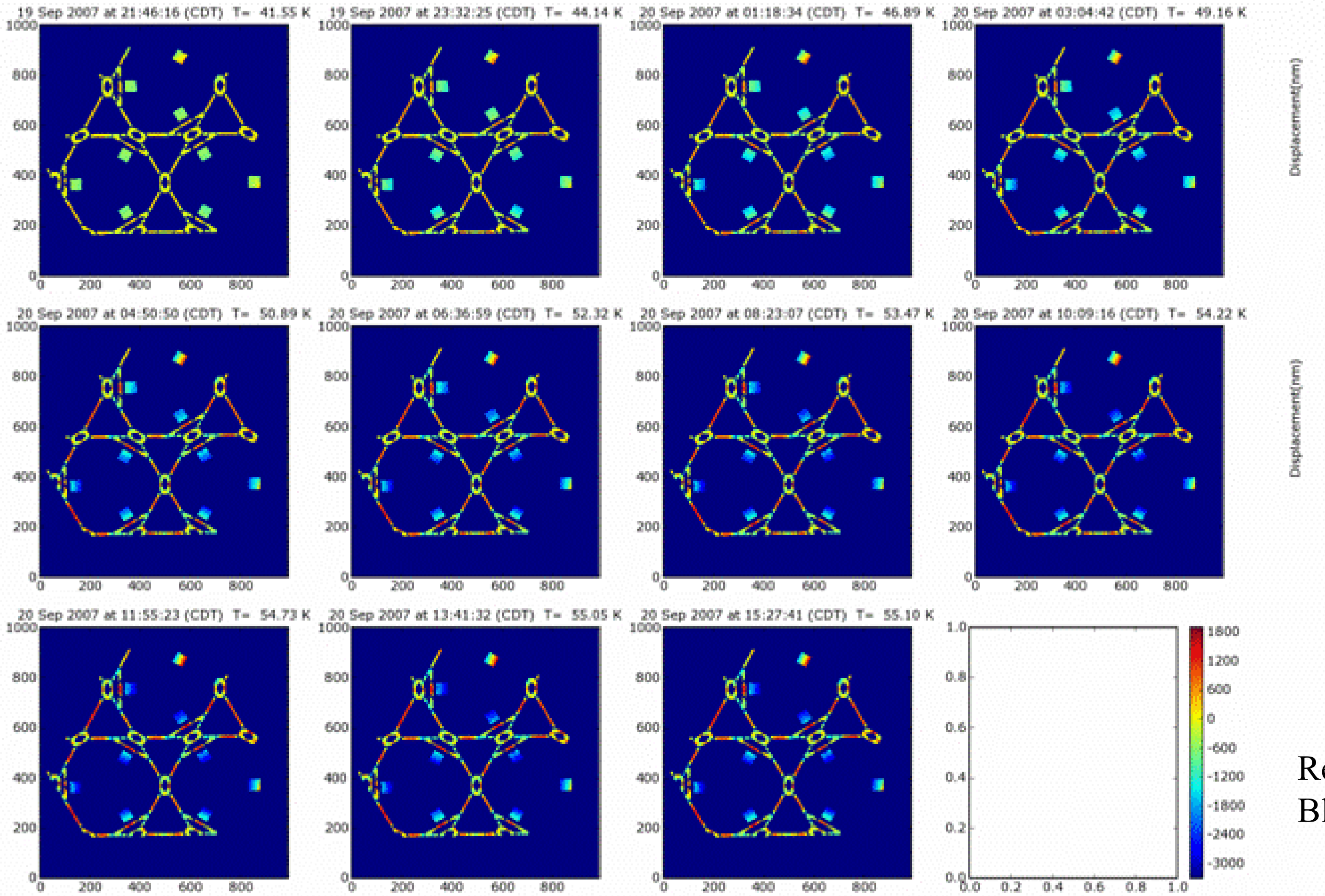


Ancillary Technology: Webb Interferometry History



BSTA Distortion

Compared Pad motions to Structural-Thermal Optical Model



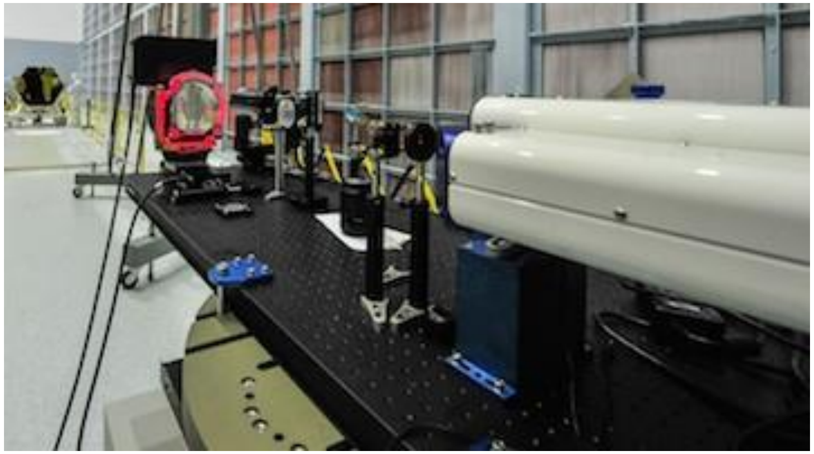
Red ~1800 nm
Blue ~ -3000 nm

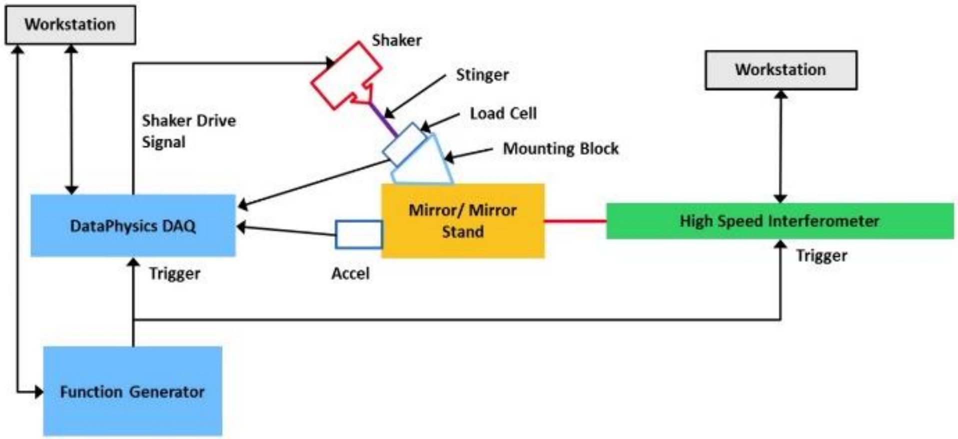
High Speed Interferometer Built to Assess Webb Mirror Dynamics

•780x780 CMOS, Spatially Phase Shifted, Spatially and Temporal phase Unwrapping. Its noise floor is like regular phase CAMs, repeatability of 4 nm RMS. Highest frequency for this number of pixels is 500 Hz.

•Allows Rigid Body Measurements to get the modes and change in the modes shape and frequencies.

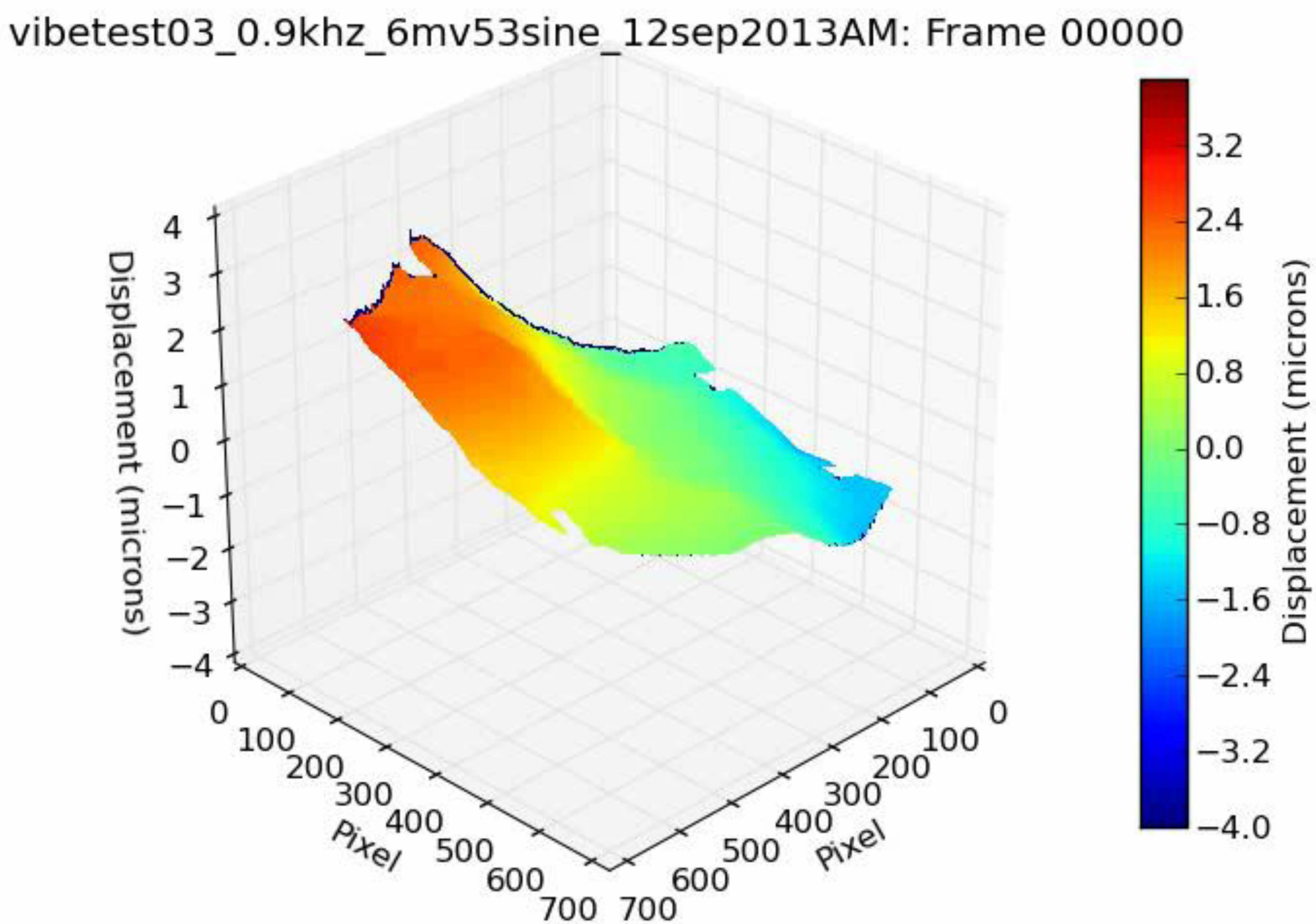
•Allows Deformation measurements such as Astigmatism at 250 Hz and deformation due to inertia of the mirror to rigid body motions.



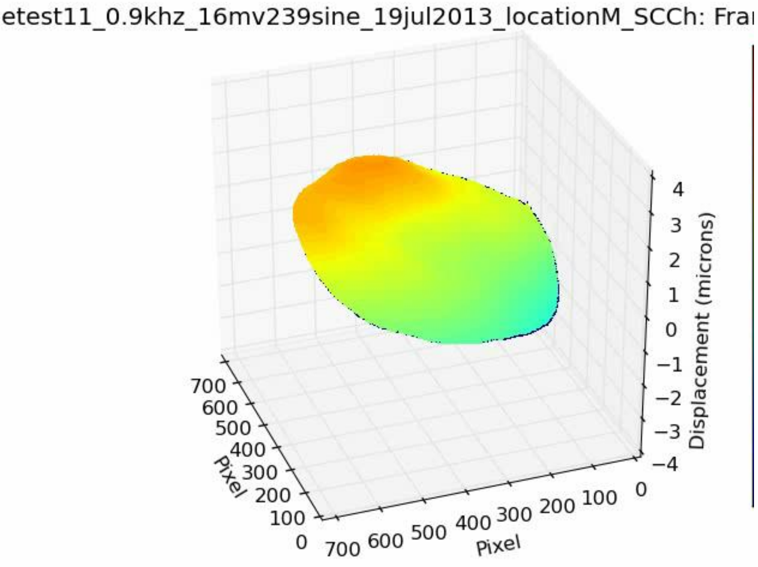


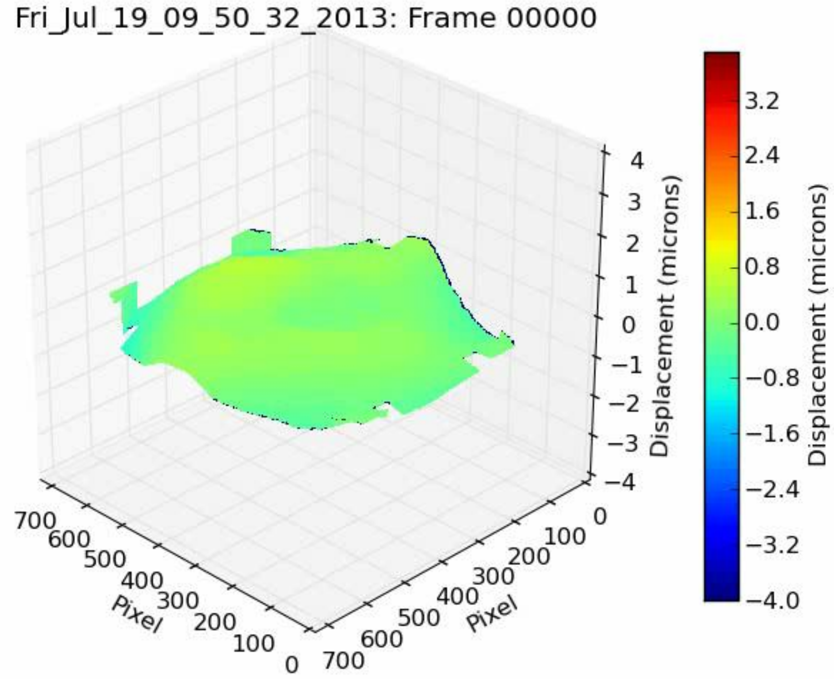
This schematic diagram shows the relationship of the components of the test setup.

Video of Mirror Motion
Tip/tilt at 53hz and a piston mode



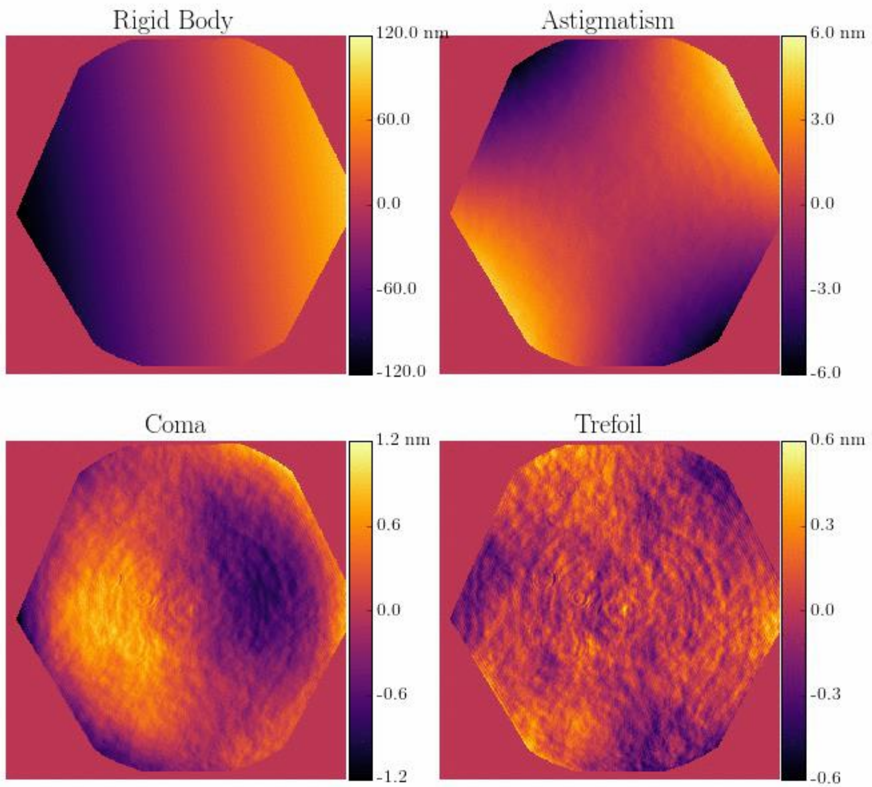
JWST Segment dynamics



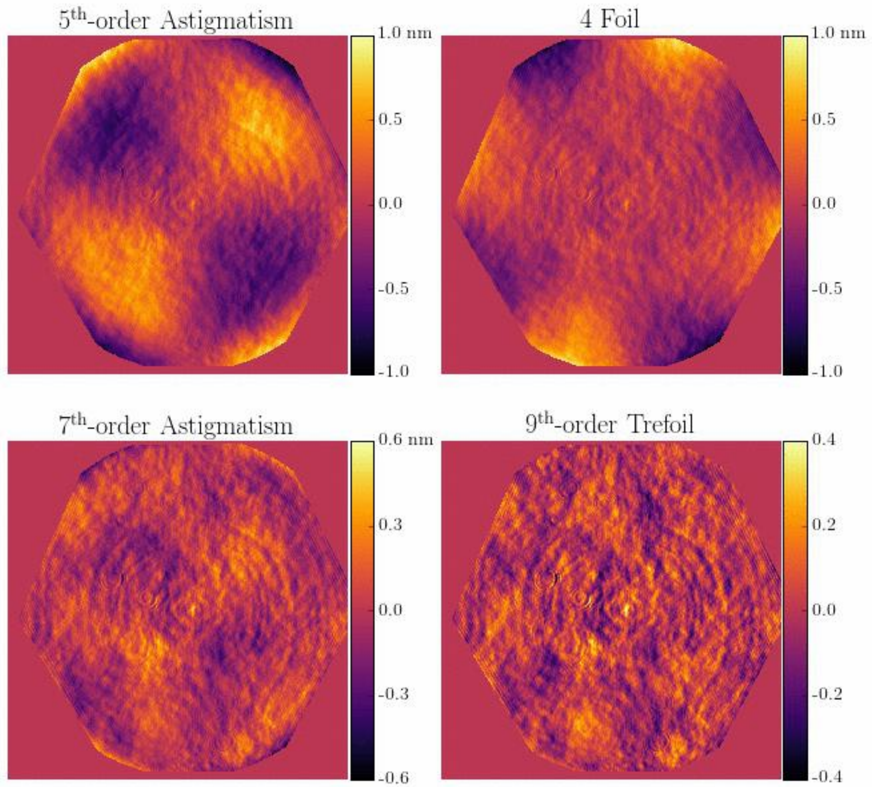


1 second of data for a measurement taken with 239Hz Sine excitation. One animation shows the raw surface motions, while the other shows the motions from the same data *after* removing the linear motions (piston, tip, and tilt) to bring out the non-linear motions in the mirror. Measurements were taken at 900Hz and the movie is animating that data at 30Hz, effectively showing the data 30x slower than real time, such that a 239Hz signal shows as a 8Hz vibration in the animation.

Animation


Rigid Body
120.0 nm
60.0
0.0
-60.0
-120.0
Astigmatism
6.0 nm
3.0
0.0
-3.0
-6.0
Coma
1.2 nm
0.6
0.0
-0.6
-1.2
Trefoil
0.6 nm
0.3
0.0
-0.3
-0.6

Animation


5th-order Astigmatism
4 Foil
1.0 nm
0.5
0.0
-0.5
-1.0
1.0 nm
0.5
0.0
-0.5
-1.0
7th-order Astigmatism
9th-order Trefoil
0.6 nm
0.3
0.0
-0.3
-0.6
0.4
0.2
0.0
-0.2
-0.4

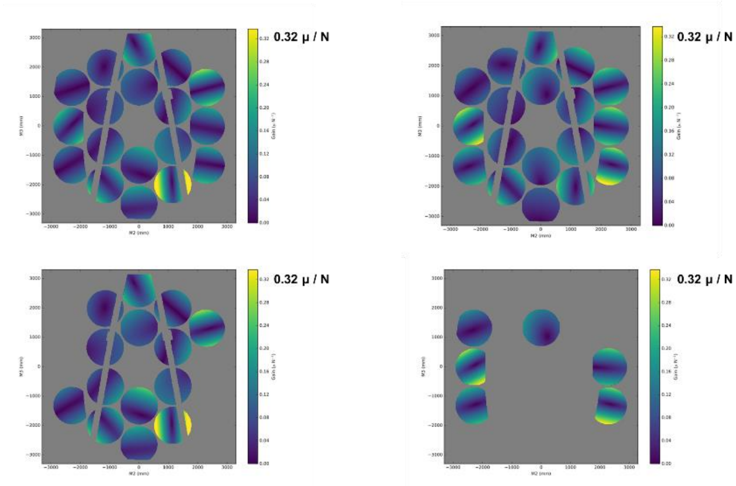
Example of Primary Mirror Response

Rigid Body (Z1-Z3) at 43.0Hz
Transfer Function Gain

Preshake | Postshake

Nominal

Reproducibility

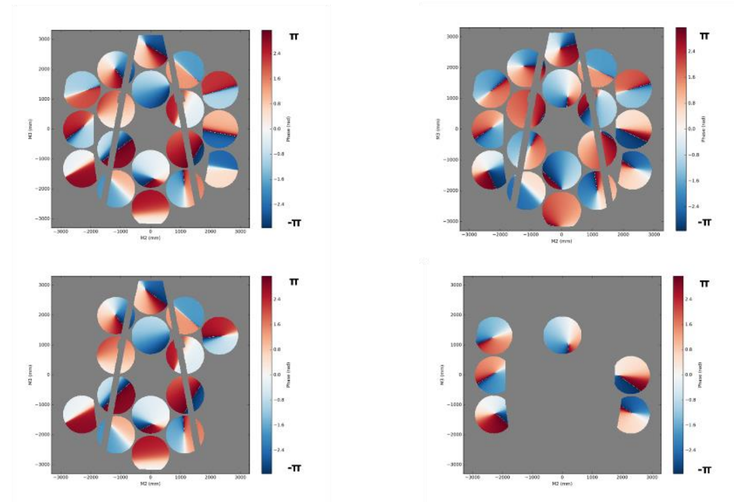


Rigid Body (Z1-Z3) at 43.0Hz
Transfer Function Phase

Preshake | Postshake

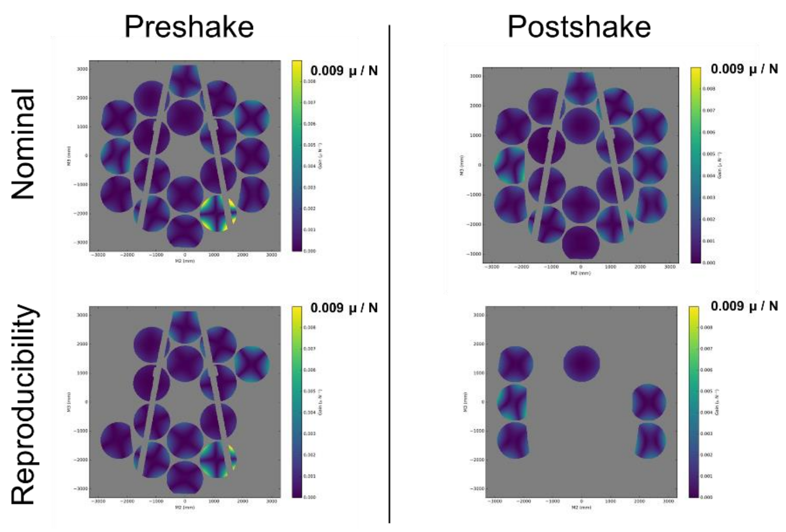
Nominal

Reproducibility

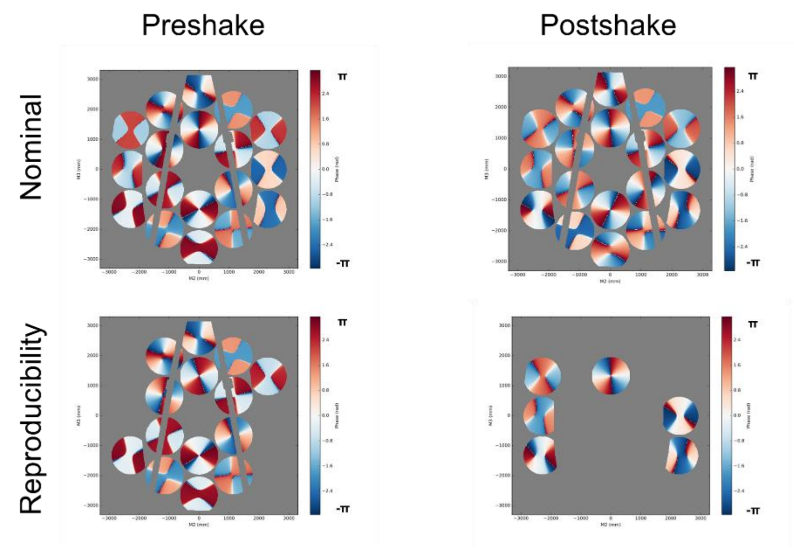


Example of Primary Mirror Response

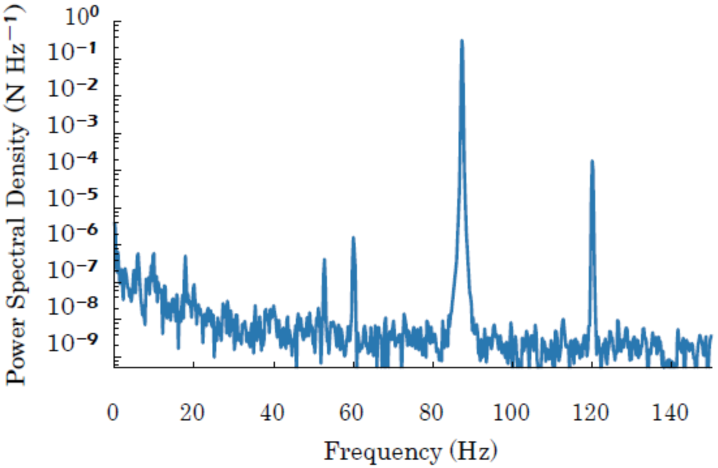
Astigmatism (Z5-Z6) at 43.0Hz
Transfer Function Gain



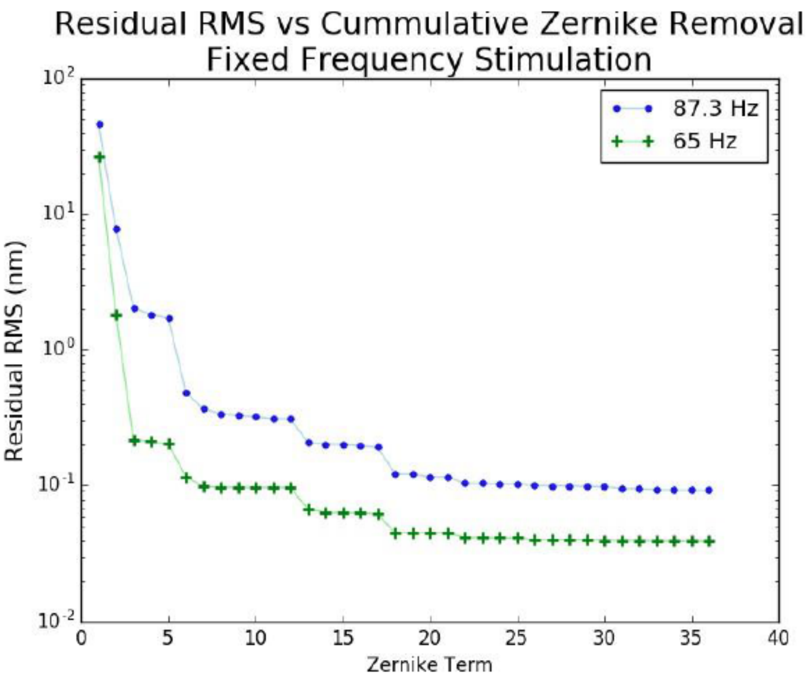
Astigmatism (Z5-Z6) at 43.0Hz
Transfer Function Phase



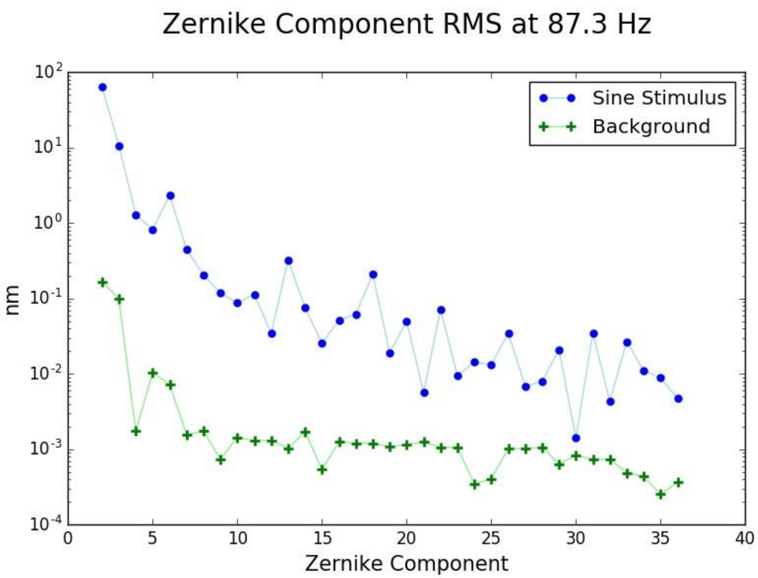
Segment Data Analysis



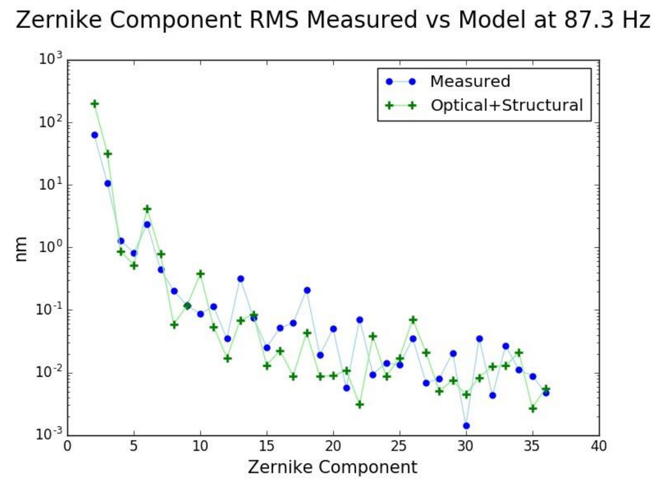
Sine Dwell at 87.3 Hz



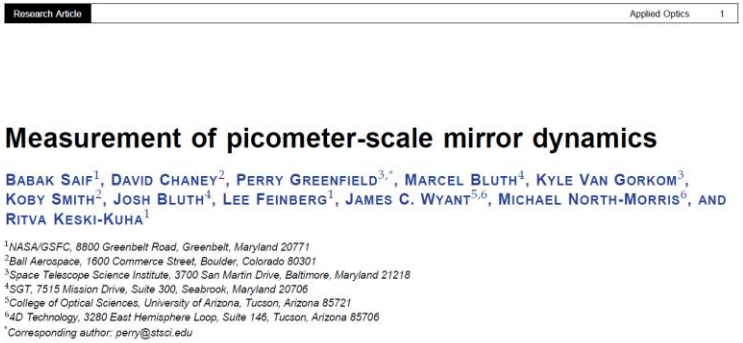
Segement Dynamic Picometer Results



Plotted are the dynamic Zernike term RMS values for 2 different cases: 1) the case where a fixed frequency sinusioidal stimulus is present, and 2) the case where no such stimulus is present.



Plotted is the comparison between the measured Zernike RMS terms and the sum of the corresponding opti- cal and structural dynamic models terms.


Research Article Applied Optics 1

Measurement of picometer-scale mirror dynamics

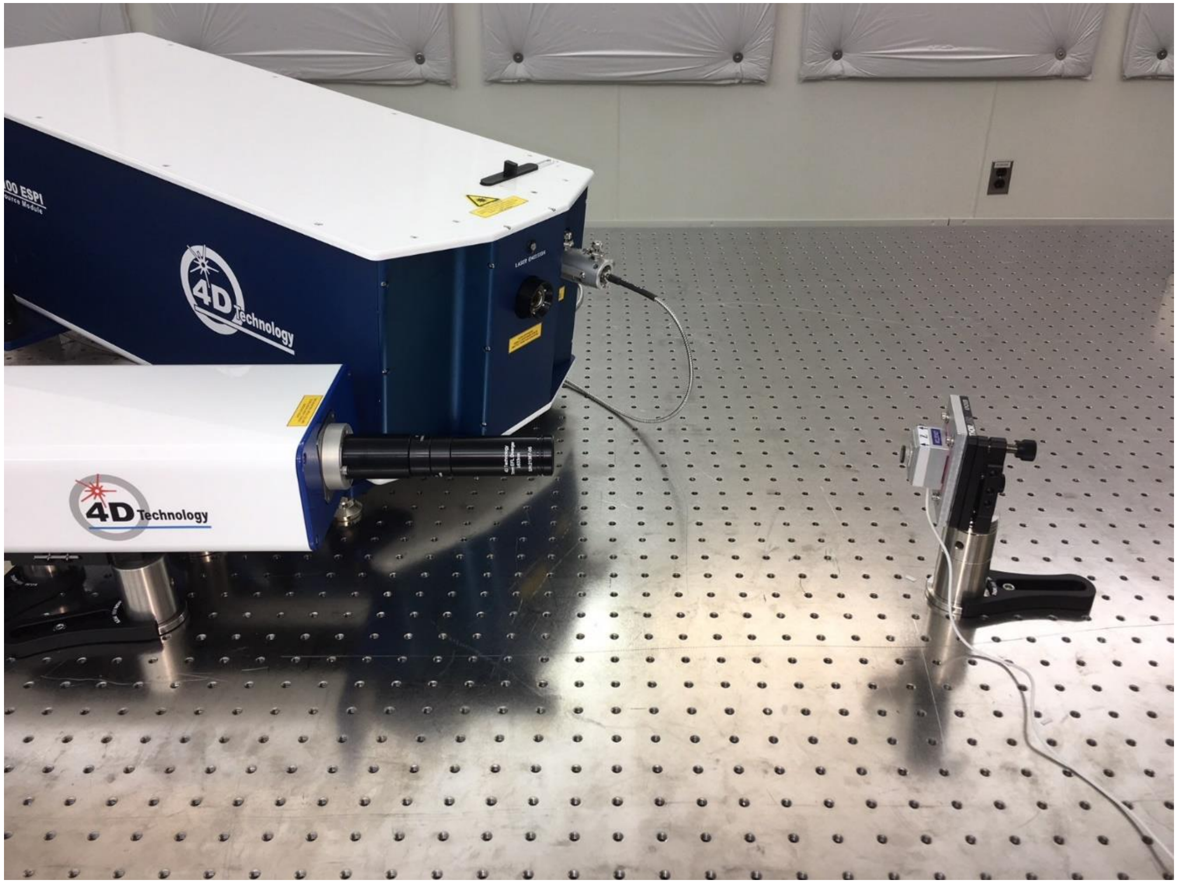
BABAK SAIF[1], DAVID CHANEY[2], PERRY GREENFIELD[3,*], MARCEL BLUTH[4], KYLE VAN GORKOM[3], KOBY SMITH[2], JOSH BLUTH[4], LEE FEINBERG[1], JAMES C. WYANT[5,6], MICHAEL NORTH-MORRIS[6], AND RITVA KESKI-KUHA[1]

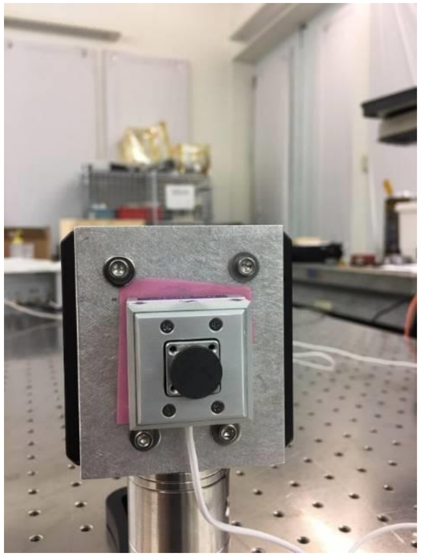
[1]NASA/GSFC, 8800 Greenbelt Road, Greenbelt, Maryland 20771
[2]Ball Aerospace, 1600 Commerce Street, Boulder, Colorado 80301
[3]Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, Maryland 21218
[4]SGT, 7515 Mission Drive, Suite 300, Seabrook, Maryland 20706
[5]College of Optical Sciences, University of Arizona, Tucson, Arizona 85721
[6]4D Technology, 3280 East Hemisphere Loop, Suite 146, Tucson, Arizona 85706
*Corresponding author: perry@stsci.edu

Ultrastable SAT

- Based on the JWST mirror segment results indicating we can detect picometer changes, we proposed to the SAT program to study Ultrastable systems to the picometer level
  - New Interferometer
  - Ultrastable chamber with window
  - Calibrators and Algorithms
- Measure the building blocks of segmented telescope to picometer levels:
  - Composites
  - Mirror samples
  - Actuators
  - Joints
- Establish that we can actually measure to the levels needed and assess if the components and building blocks can be made stable enough

New Interferometer ESPI+HSI in One Device

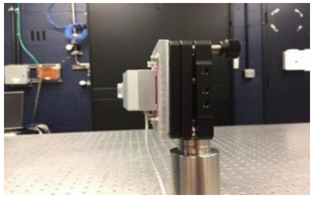


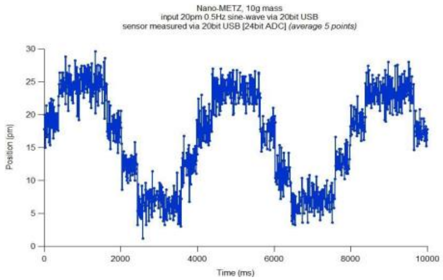


National Aeronautics and Space Administration
Goddard Space Flight Center

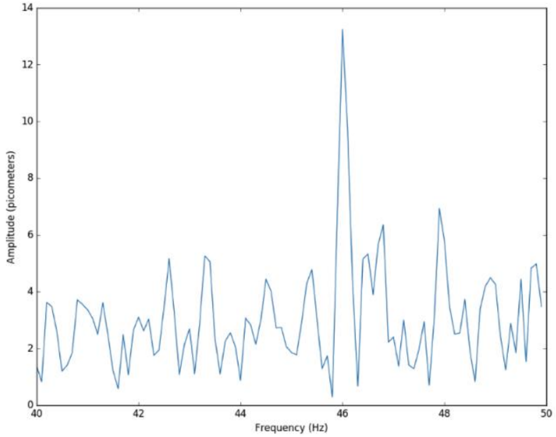
Picometer Actuator Characterization

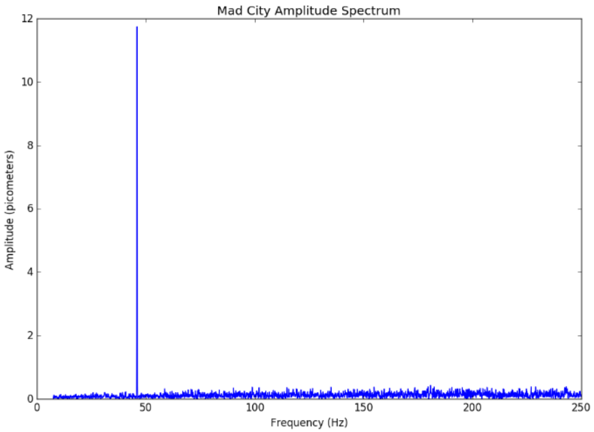
- We identified an actuator that we planned to use as a calibrator
- Closed loop piezo actuator being characterized using the same methods used on segments
  - Was measured at vendor using an AFM
  - Provides crosscheck of the temporal phase unwrapping methodology
- Results were so promising, we realized this type of actuator could form the foundation of an ultrastable control system



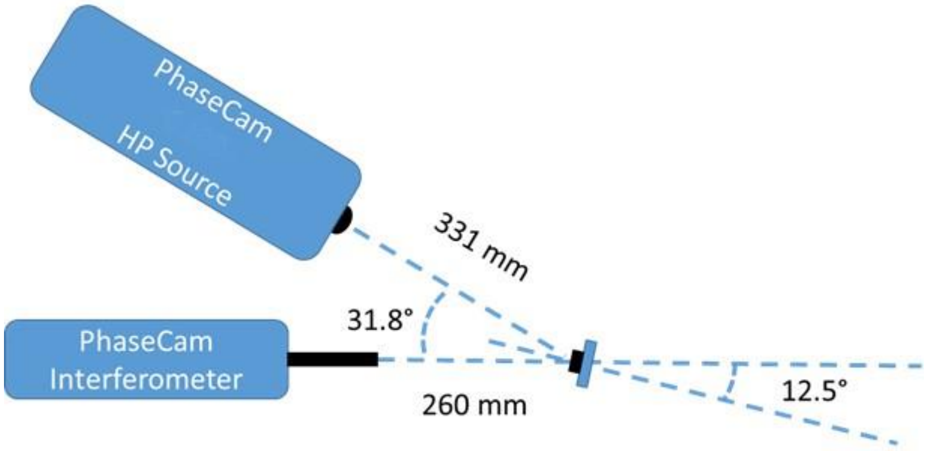


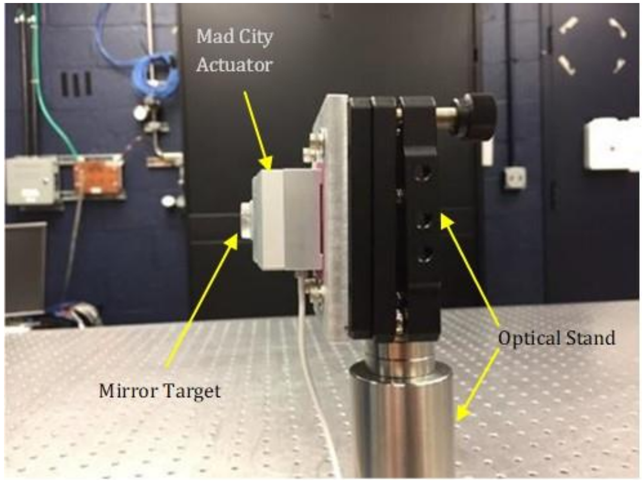
Vendor Measurements Matched our Laser Metrology

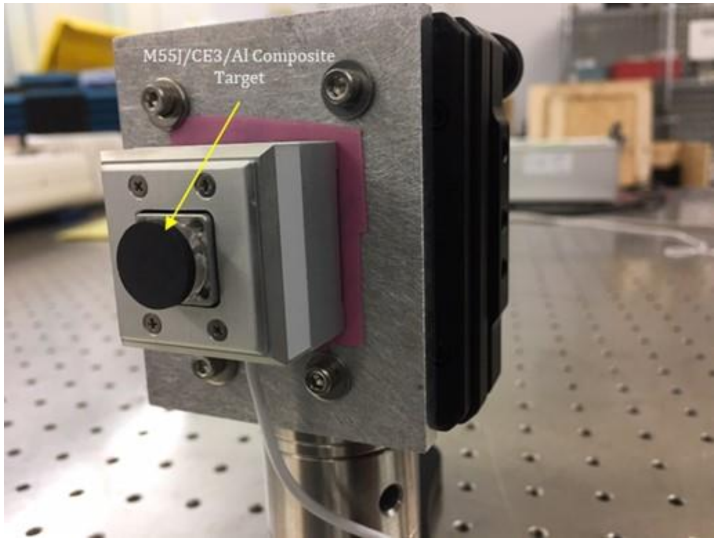


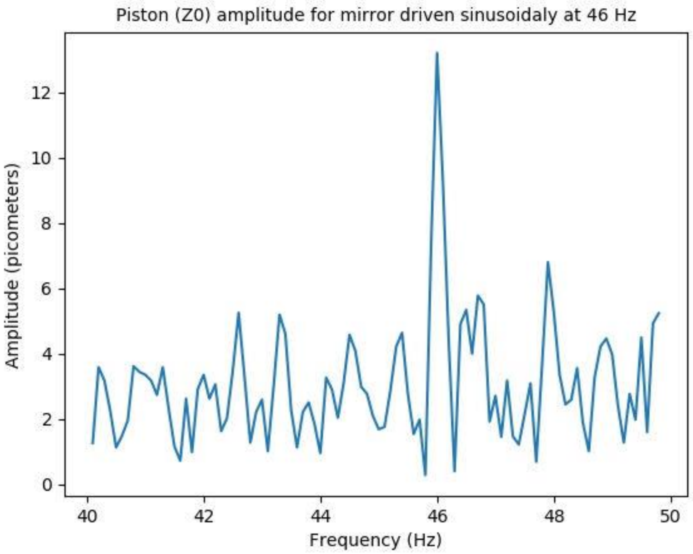


First ever picometer measurements of a non-specular surface

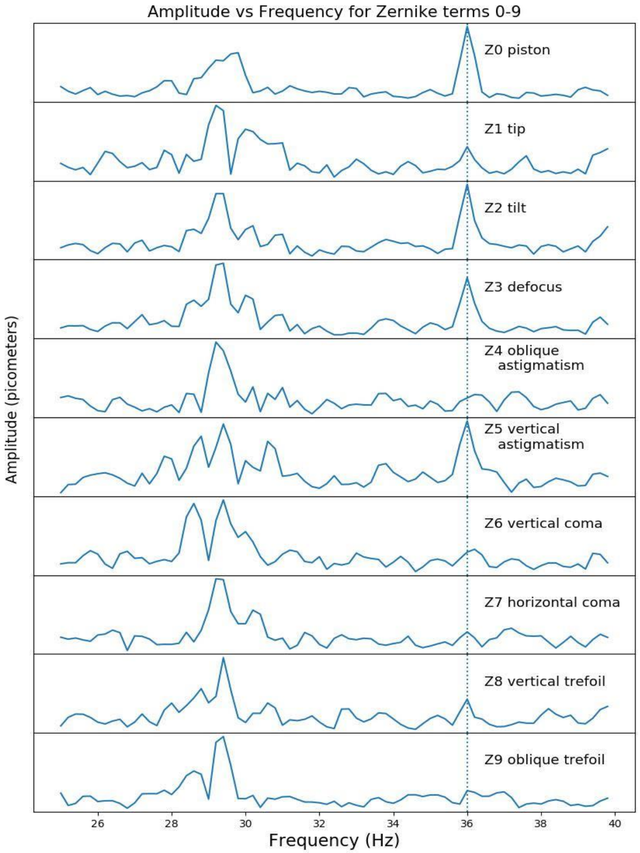








Carbon Fiber Results
100pm motion

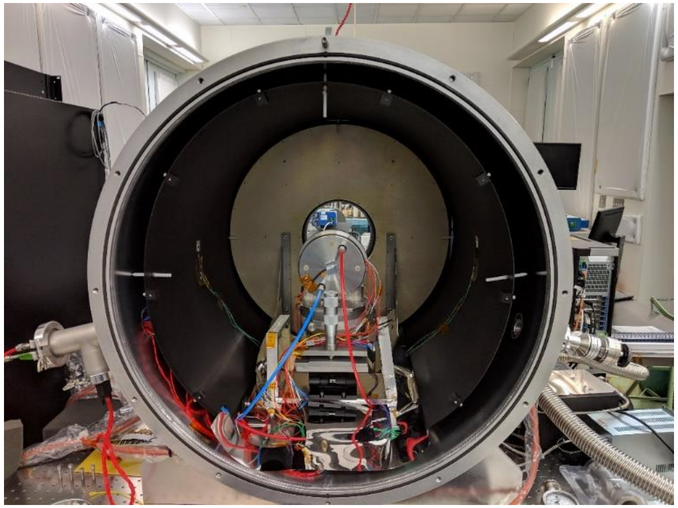


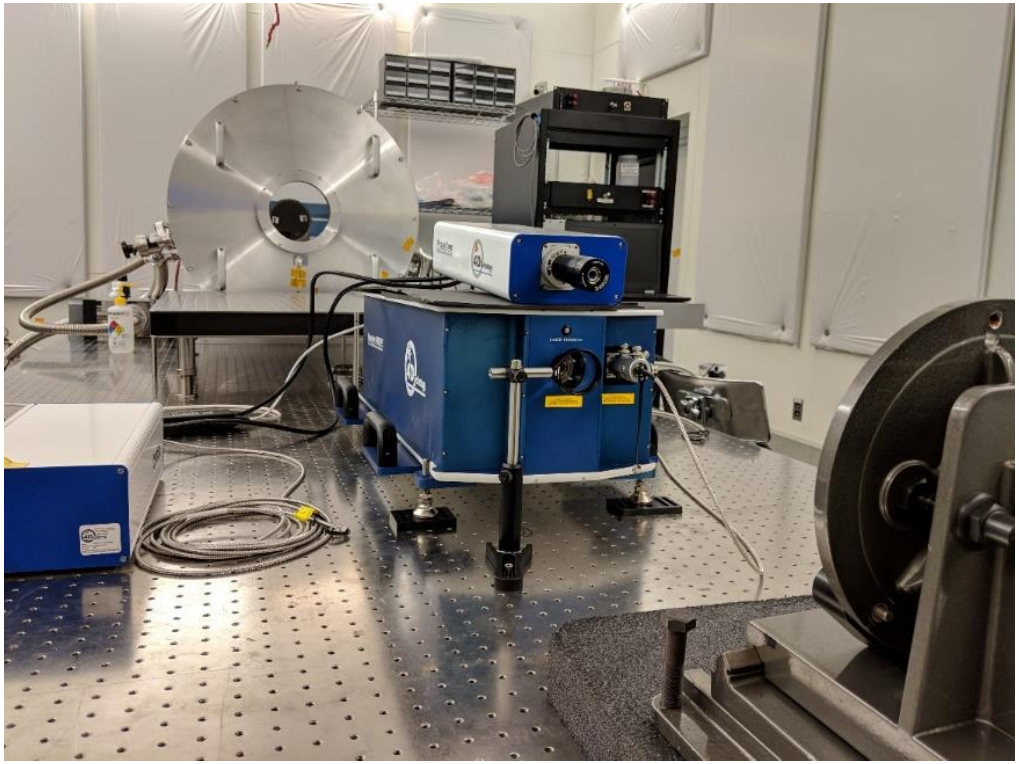
Surface Zernike Term		Amplitude (pm)	Standard Deviation (pm)	Probability of Null
Z0		82.87	4.548	0.0000
Z1		0.28	0.077	0.0012
Z2		1.23	0.151	0.0000
Z3		0.29	0.037	0.0000
Z4		0.05	0.018	0.0376
Z5		0.22	0.022	0.0000
Z6		0.02	0.013	0.4182
Z7		0.01	0.013	0.7045
Z8		0.06	0.015	0.0001
Z9		0.02	0.014	0.4048

Tabulated outcome of the surface analysis results from the test

National Aeronautics and Space Administration
Goddard Space Flight Center

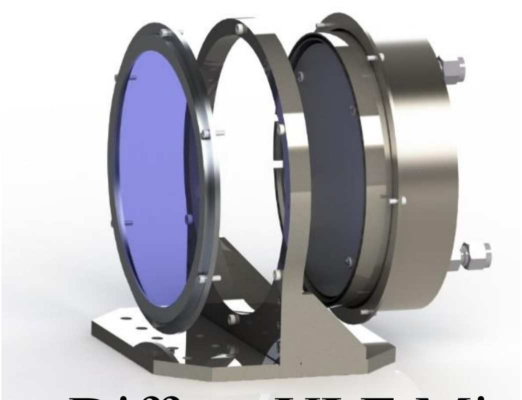
Ultra Stable Test System
Milli-Kelvin Thermal Control With Window



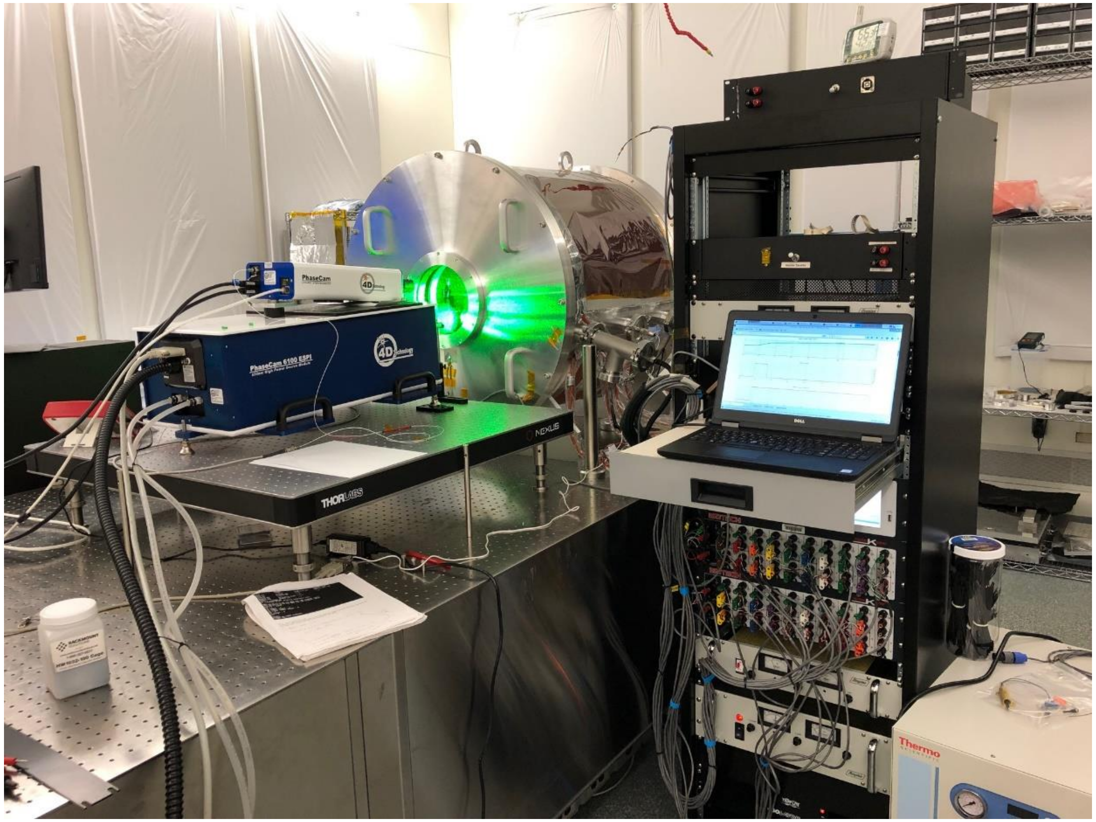


National Aeronautics and Space Administration
Goddard Space Flight Center

Ultra-Stable Chamber

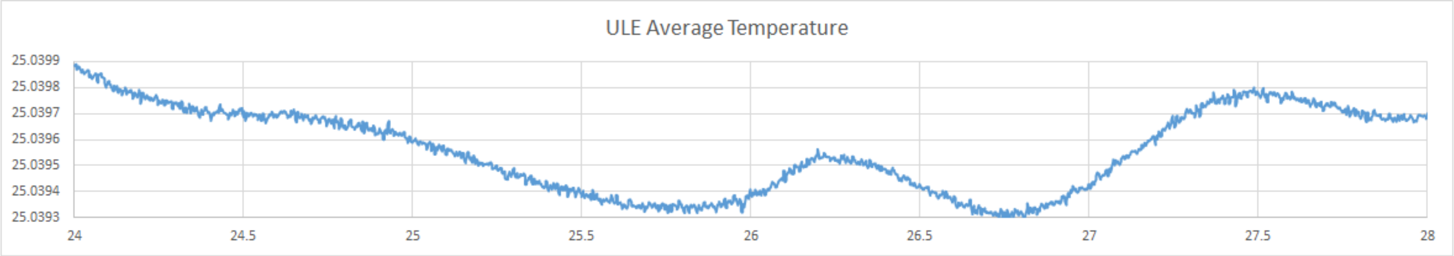


Diffuse ULE Mirror



The final thermal sensing and control functional test of ULE Test Sample resulted in the thermal stability 0.0006K (0.6mK) P-V over 4+ hours.

(This validation test data was gathered from 06 June 2019 while the Chamber sink temperature varied between 19.95 and 19.96°C or 10mK variations)



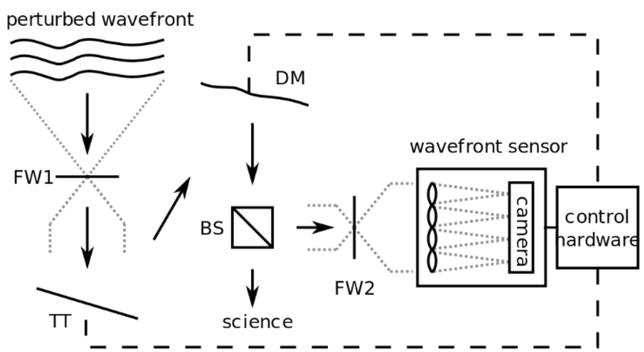
.6mK ptv
.3mK p/hr

What are the open questions?

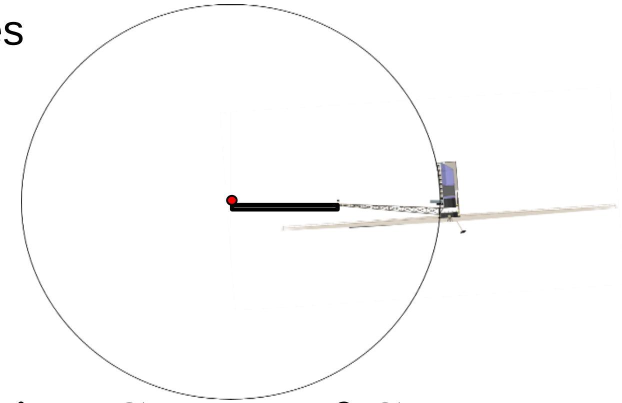
- How well can we measure long term drift?
  - Measurements in process
- Can we demonstrate controllability of segments and joints on larger systems
  - Requires higher TRL level (eg, 4-6) demonstrations (next steps)
  - Ultra RFP/Study contributing to this
- Are there ways to take what we have learned and build fully active systems that would greatly simplify verification?
  - Next slide

Active Control Possibility

- A key way to simplify the stability challenge is to utilize active controls
  - Similar to how ground telescopes using laser guide stars and adaptive optics to remove the instability of turbulence
- The basic approach being used on LUVOIR is to combine layers
- A recent idea led by K. Cahoy of MIT is to use a laser guide star on a cubesat but even this has certain complexities as you slew etc
- Now that we have demonstrated sub-pm metrology and controls, we are asking the question can we put a system like this at center of curvature of future telescope PM's as part of an active control system
  - We think this is feasible but would require demonstrating real time computation
  - The point is we can have sufficient laser power to achieve S/N at >1hz, Zernike sensors looking at the target star can take minutes



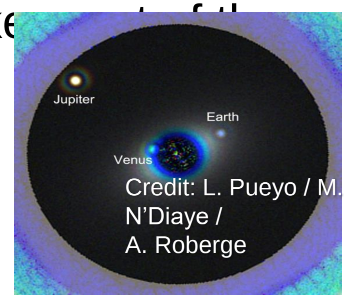
Ground Telescope AO



Active Center of Curvature Configuration

Summary

- The hardest part of making mirrors is measuring them and the hardest part of making stable mirror systems is likely measuring them
- Thanks to Webb and the SAT program, next generation spatial metrology is now achieving subpicometer levels
- The ability to sense and control at these levels on spatial systems have been shown at small scales, more work needed to study drift and larger system complexity
- This development is critical for coronagraphic systems part of future Exoplanet missions aimed at studying reflected Earth like planets (LUVOIR, Habex)
- While there is work to go, this work gives us confidence that picometer stability large telescopes are feasible and ultimately it will be an engineering and cost issue, not a matter of whether there is a physical limitation at these scales
- If ultimately we want to a statistically significant survery of Exo-earths, not just a few, we will need a large ultrastable telescope. This is considered the most challenging technology challenge and this work is a ke path to geth there.



National Aeronautics and Space Administration
Goddard Space Flight Center