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?

- 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
- Large Precision Cryogenic Structure: November 2006
- Wavefront Sensing & Control: November 2006
- Cryocooler: December 2006
The hardest part of making a mirror is measuring it....
Onset of James Webb Space Telescope

1996

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

1998

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

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

Low Authority Beryllium

Medium Authority Glass (ULE)

Technoogy Readiness Level-6 Demonstrated
All key requirements and environments demonstrated

2000

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

2002

AMSD Phase 2: 3 mirrors developed

Machining Facility Complete

2004

Amgen Facility Complete

2006

2008

2010

2012

2014

Primary Mirror Segment Assemblies Complete

PM Manufacturing of 18 segments

Cryo Testing

Engineering Design Unit.

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

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

JWST Requirement

Areal Density (Kg/m2)

200

100

30

60

240

300

1980

1990

2000

2010

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

Machining Facility Complete

Polishing Facility Complete
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
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

Astigmatism

Coma

Trefoil

Use of data discussed on this page is subject to restriction(s) on the title page of this document.
Animation

5th-order Astigmatism

4th-order Trefoil

Use of data disclosed on this page is subject to restriction(s) on the title page of this document.
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

Reproducibility

Reproducibility

Transfer Function Phase
Segment Data Analysis

Sine Dwell at 87.3 Hz

Residual RMS vs Cumulative Zernike Removal
Fixed Frequency Stimulation

Residual RMS (nm)

Zernike Term
Plotted are the dynamic Zernike term RMS values for 2 different cases: 1) the case where a fixed frequency sinusoidal 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 optical and structural dynamic models terms.

Measurement of picometer-scale mirror dynamics

BABAK SAIF1, DAVID CHANEY2, PERRY GREENFIELD3, MARCEL BLUTH4, KYLE VAN GORKOM5, KODY SMITH1, JOSH BLUTH4, LEE FEINBERG5, JAMES C. WYANT12, MICHAEL NORTH-MORRIS4, and RITVA KESKI-KUHA4

1JPL/Caltech, 4800 Oak Grove Road, Pasadena, California 91109
2Ball Aerospace, 1600 Commerce Street, Boulder, Colorado 80301
3Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, Maryland 21218
4JHU/APL, 3501 Mission Drive, Suite 300, Seabrook, Maryland 20708
5College of Optical Sciences, University of Arizona, Tucson, Arizona 85721
6Jacobs Technology, 5000 East Hemisfair Plaza, Suite 140, Tucson, Arizona 85706

Corresponding author: perry@csail.mit.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
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

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

Tabulated outcome of the surface analysis results from the test
Ultra Stable Test System
Milli-Kelvin Thermal Control With Window

Average surrogate test article thermal stability achieved: 23.5°C ±0.0004/0.0002°C over 80+ hours (+0.4mK/-0.2mK)
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)

.png

.png

.png
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 Configuration](image)
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 survey 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 key part of the path to get there.

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