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

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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....
JWST Mirror History Enabled by Metrology

Onset of James Webb Space Telescope

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

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

AMSD Phase 2: 3 mirrors developed
- Medium Authority Glass (ULE)

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

OTE Optics Review (OOR): Beryllium Selected

Engineering Design Unit.

PM Manufacturing of 18 segments

Primary Mirror Segment Assemblies Complete

Cryo Testing

Machining Facility Complete

Polishing Facility Complete

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

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

5th-order Astigmatism

4th-order Trefoil

7th-order Astigmatism

9th-order Trefoil

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Example of Primary Mirror Response

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

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

Power Spectral Density (\( \text{N Hz}^{-1} \))

- Frequency (Hz)
- Sine Dwell at 87.3 Hz

Residual RMS vs Cumulative Zernike Removal
Fixed Frequency Stimulation

- 87.3 Hz
- 65 Hz
Segement Dynamic Picometer Results

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.

Measurement of picometer-scale mirror dynamics

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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
• 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>Zernike Term</th>
<th>Amplitude (pm)</th>
<th>Standard Deviation (pm)</th>
<th>Probability of Null</th>
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<tr>
<td>Z0</td>
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<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)
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
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-earth, 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.