



Ultra-stable Telescope Testbed Results and Implications

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Introduction

- The future IOUVR flagship requires high (10^{10}) contrast
- A coronagraph solution requires the primary mirror to be stable to $<10\text{nm}$ RMS over the control cycle and in spatial frequencies that impact inner to outer working angle (mostly mid to low spatial frequencies)
- To achieve this level of stability, one first needs to be able to measure it
- This means both a spatial metrology system and environmental controls to support this level of measurement – sub mK thermal, dynamics, metrology. This is the point of the ultrastable laboratory.
- Our belief is that one cannot assume systems at the picometer scale act in the same linear way as nanometer level systems so our emphasis has been on being able to measure actual picometer spatial changes – minimizing using overdrive testing as was done on JWST
 - The level of mechanical intimacy of joints matters at the picometer scale and internal stresses and the external environment can play a role that needs to be understood
- Over the last years we have progressed our system to the point that we have measured picometer spatial changes in dynamics and recent work has focused on the more difficult measurement of drift
 - We have made substantial progress on controlling to sub milli-Kelvin, actual drift measurements are next
- During the last 6 months, we have gained value insight into the stability of JWST that is directly relevant to which issues we should pursue
- This is still a work in progress, especially the drift measurements, so this will be a progress report

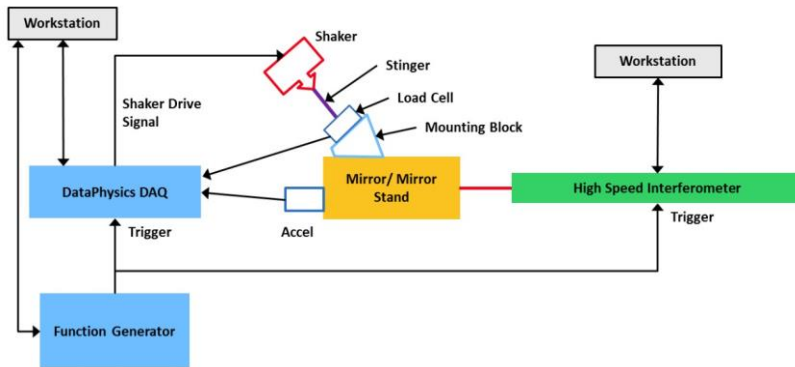
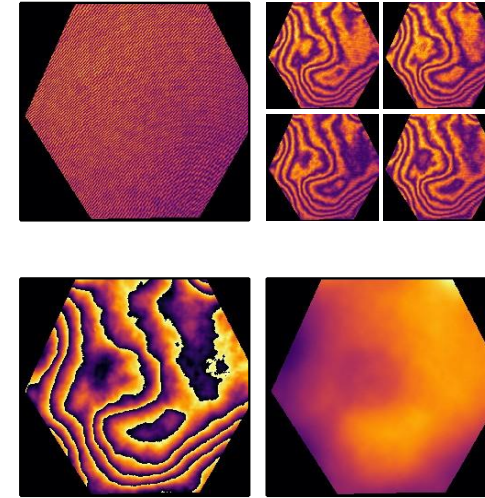


Picometer measurement of mirror dynamics



This photograph shows all the optical elements in the test setup including the HSI, CGH (framed in red), and test mirror (hexagonal mirror on the far left).

Single HSI frame comprises 4 interlaced phased- shifted interferograms which are converted (with an ellipse- to-circle correction to account for phase error) into a wrapped phase image that can be unwrapped to a surface profile.



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

Research Article

Applied Optics

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Measurement of picometer-scale mirror dynamics

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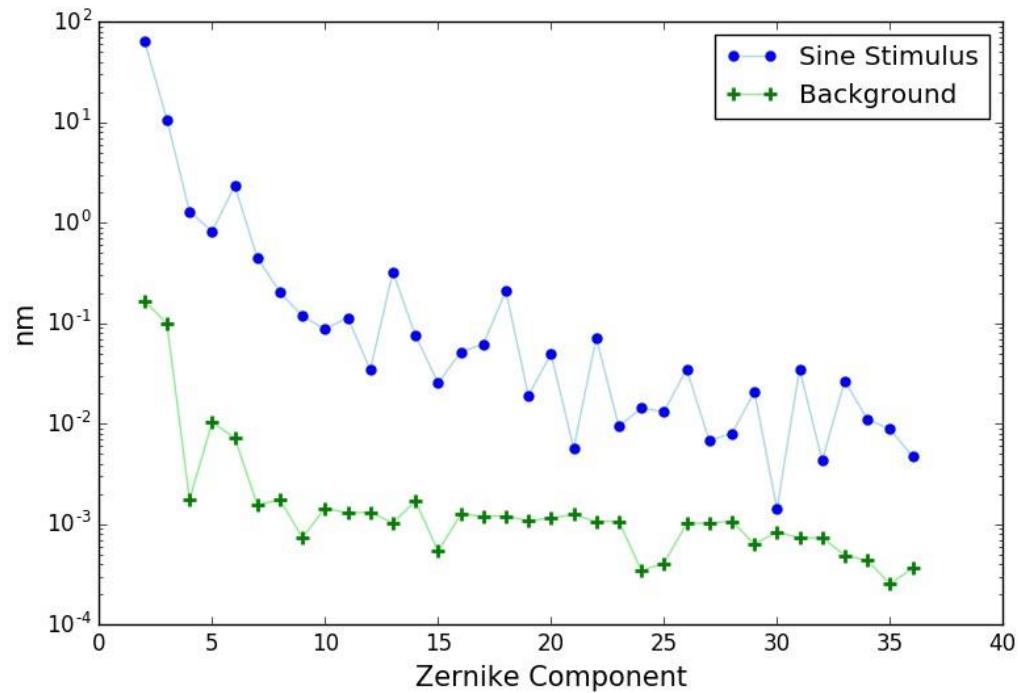
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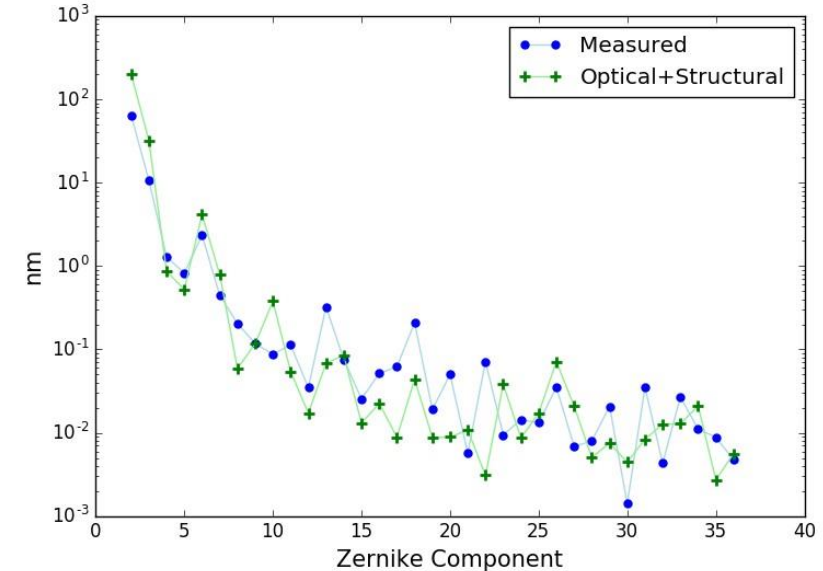
Results

Zernike Component RMS at 87.3 Hz



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.

Zernike Component RMS Measured vs Model at 87.3 Hz

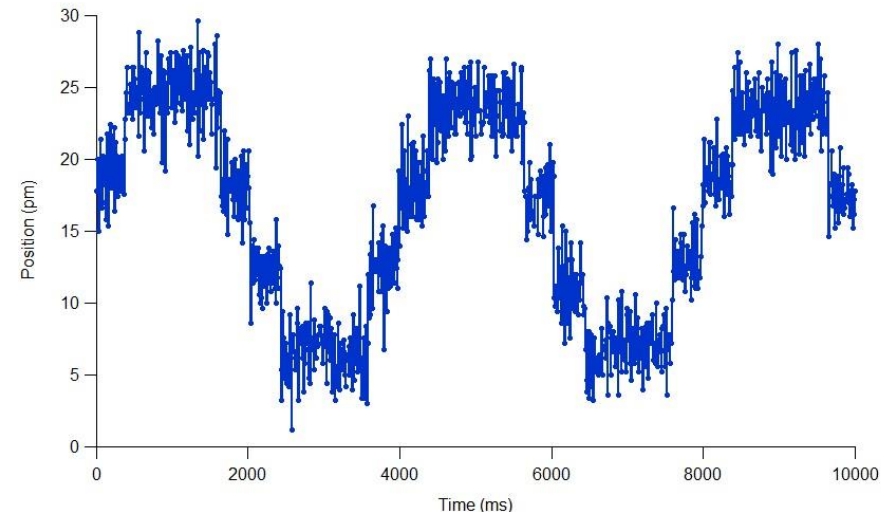
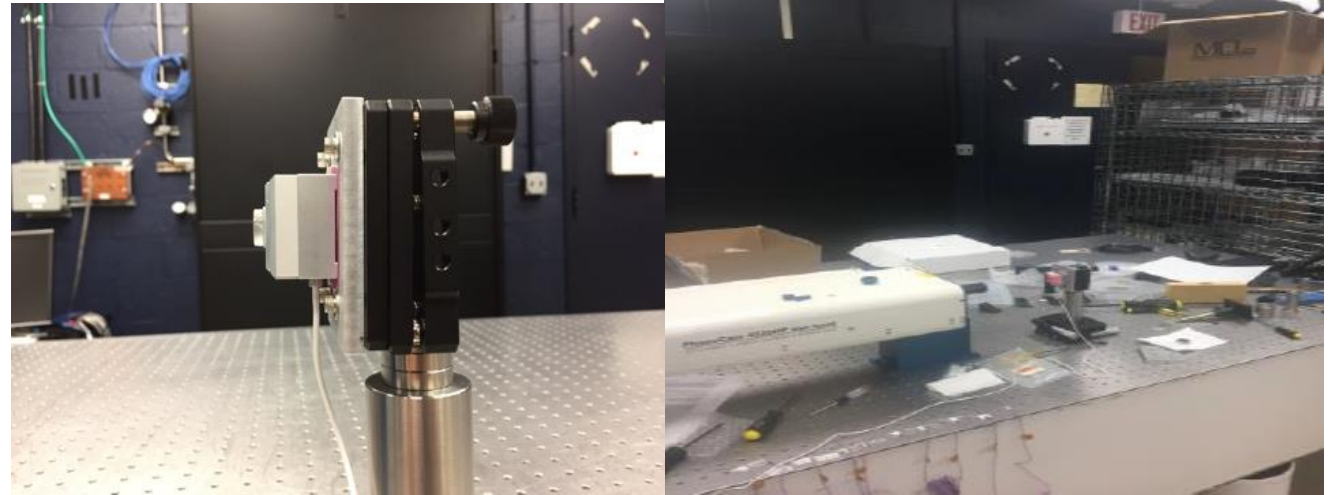


Plotted is the comparison between the measured Zernike RMS terms and the sum of the corresponding optical and structural dynamic models terms.



Picometer Actuator Characterization

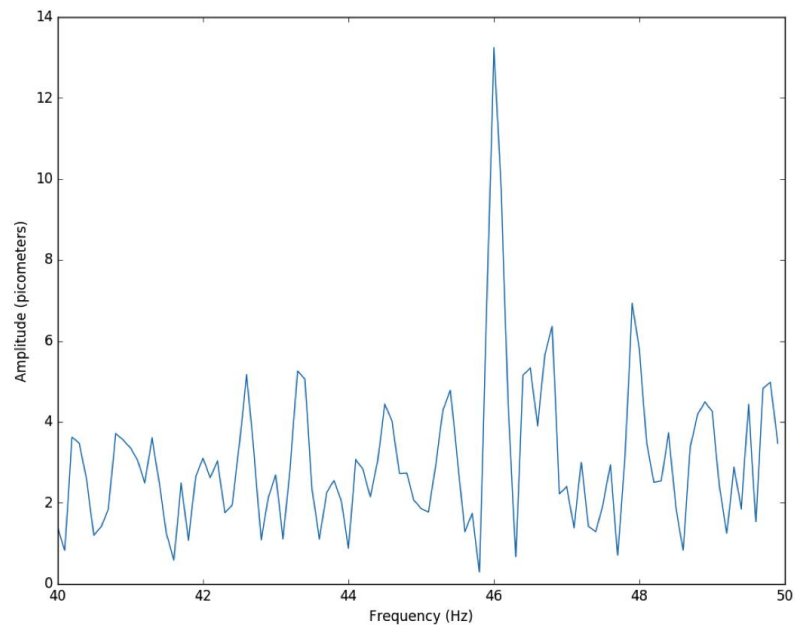
- Closed loop piezo actuator being characterized using the same methods used on segments
 - Was measured at vendor using an AFM
 - Provides crosscheck of the temporal phase unwrapping methodology
- Can provide an in situ calibration source
- Possible actuator candidate for future missions





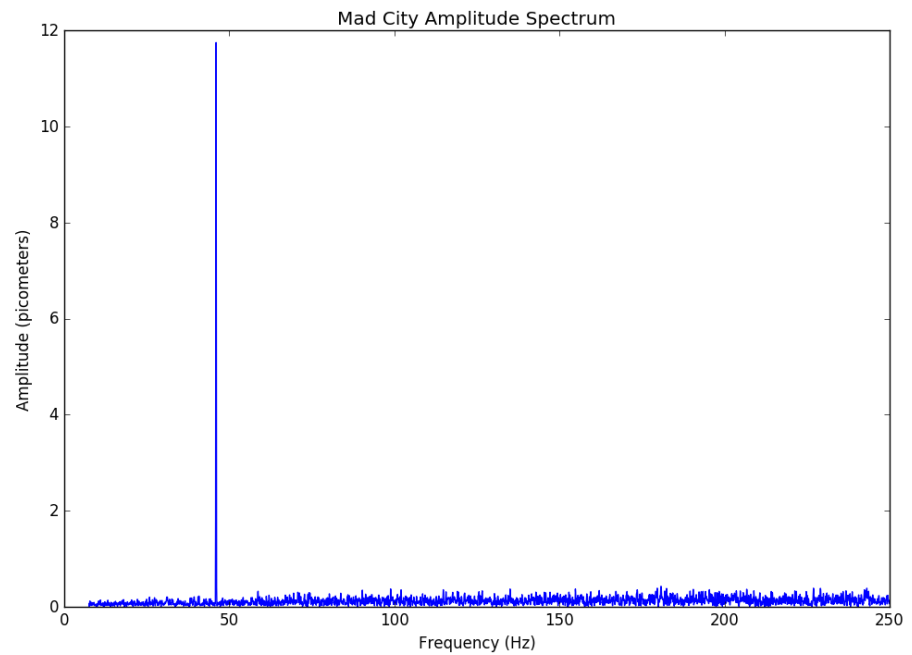
GSFC Measurements of closed loop Piezo

13+/- 2.6 pm



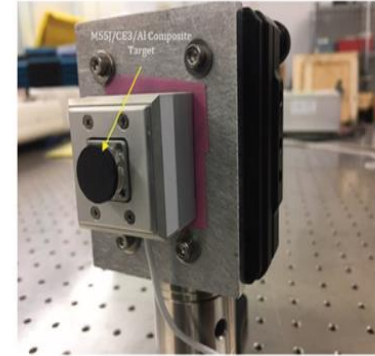
Vendor Measurements

12 Pm



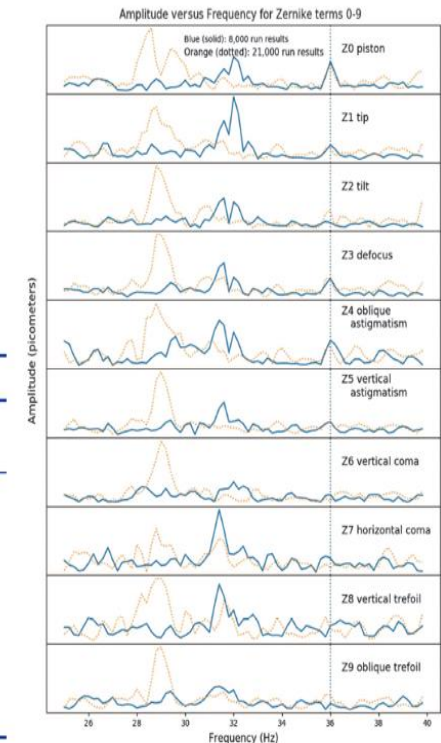
Using actuator to probe non-specular surface picometer deformations

- MCL Actuator demonstration
 - Small composite sample
 - Use High Speed Speckle Interferometry
 - Sense/detect picometer responses with HSI
 - Diffuse and Specular modes demonstrated



Tabulated Outcome of the Surface Analysis Results from both Test Campaigns at 20 μm Amplitude

Surface Zernike Term	First Set-8 K Runs			Second Set-21 K Runs		
	Amplitude (pm)	Standard Deviation (pm)	Probability of Null	Amplitude (pm)	Standard Deviation (pm)	Probability of Null
Z0	15.34	1.624	0.0000	13.84	3.456	0.0003
Z1	0.16	0.032	0.0000	0.12	0.062	0.1674
Z2	0.10	0.076	0.4400	0.30	0.112	0.0026
Z3	0.11	0.021	0.0000	0.10	0.037	0.1787
Z4	0.05	0.013	0.0005	0.04	0.018	0.0687
Z5	0.05	0.014	0.0049	0.04	0.020	0.0784
Z6	0.02	0.009	0.1800	0.00	0.011	0.0922
Z7	0.02	0.010	0.1200	0.01	0.012	0.8052
Z8	0.02	0.010	0.2800	0.01	0.011	0.5089
Z9	0.02	0.011	0.3100	0.04	0.014	0.0240



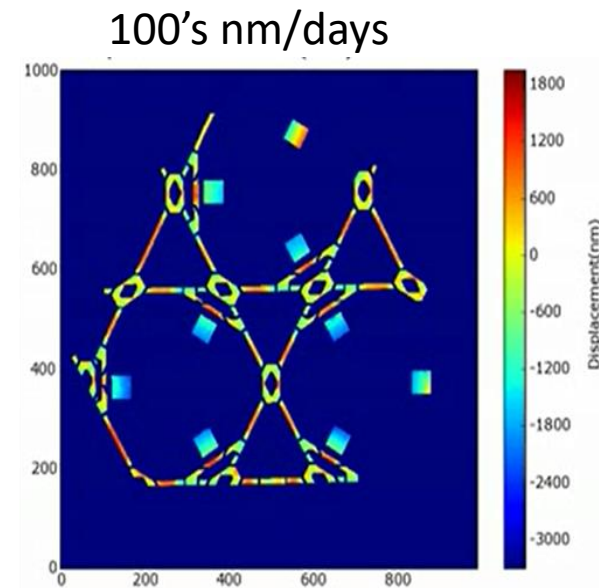
Saif, Babak, et. al, 2019 "Sub-picometer dynamic measurements of a diffuse surface", Applied Optics, 58, 12, 3156 (2019).





Structural/Thermal Strain Measurements

- Thermal response of structure key in maintaining alignment in space – dynamic range for actuation and pico-lurch
- Speckle interferometry – change in shape of diffuse structures.
- Original data from JWST was reanalyzed showing surprisingly good results which in combination with our work on small composites gives us confidence these methods will prove fruitful



Babak Saif, et al. "Measurement of large cryogenic structures using a spatially phase-shifted digital speckle pattern interferometer," Appl.

7/10/2022 Opt. 47, (2008)





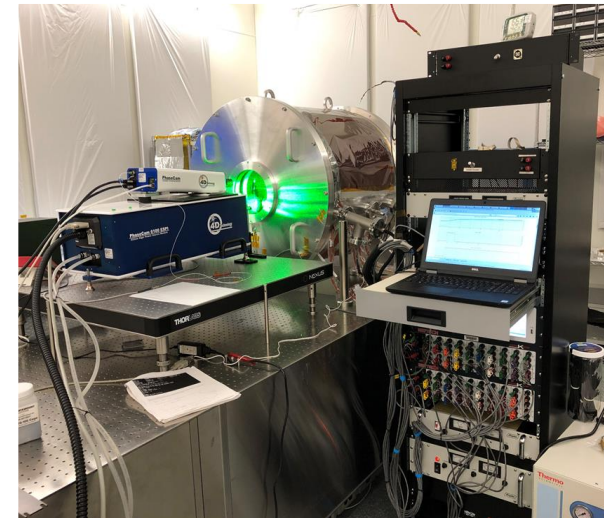
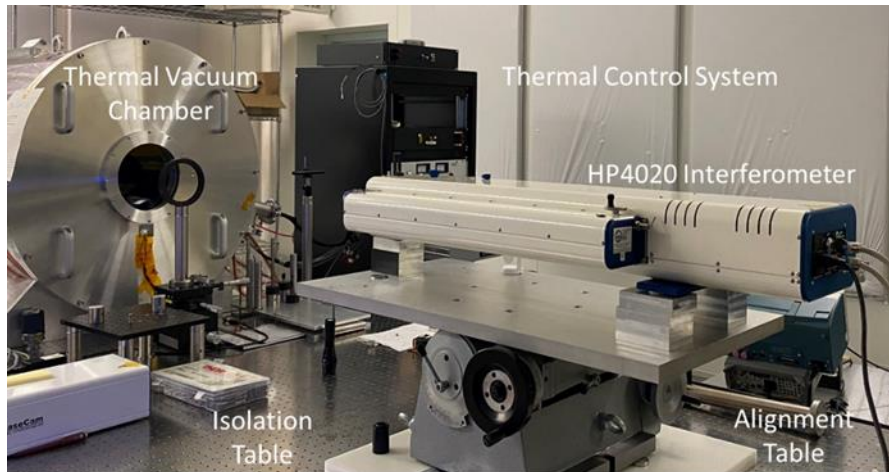
Ultrastable Lab Set Up

Modular system for flexible configurations

- Three interferometers
- Up to 2 kHz Sampling rate
- Test in air or in vacuum

Precision thermal control

- 20°C to 50°C range demonstrated
- <5 mK step change control and verification
- Stability control at sub-mK level

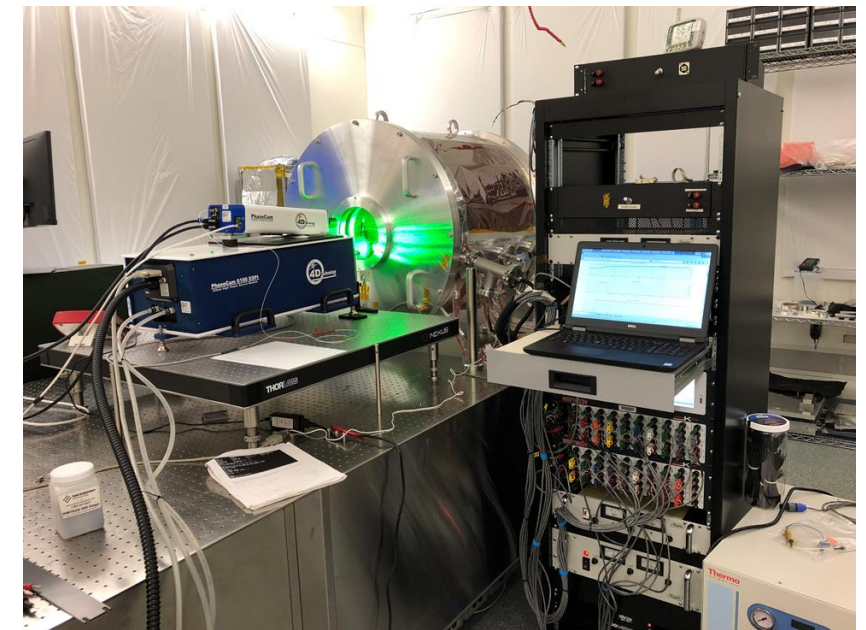




Ultra-Stable Structures (USS) Lab: High Precision Thermal Control and Thermometry System



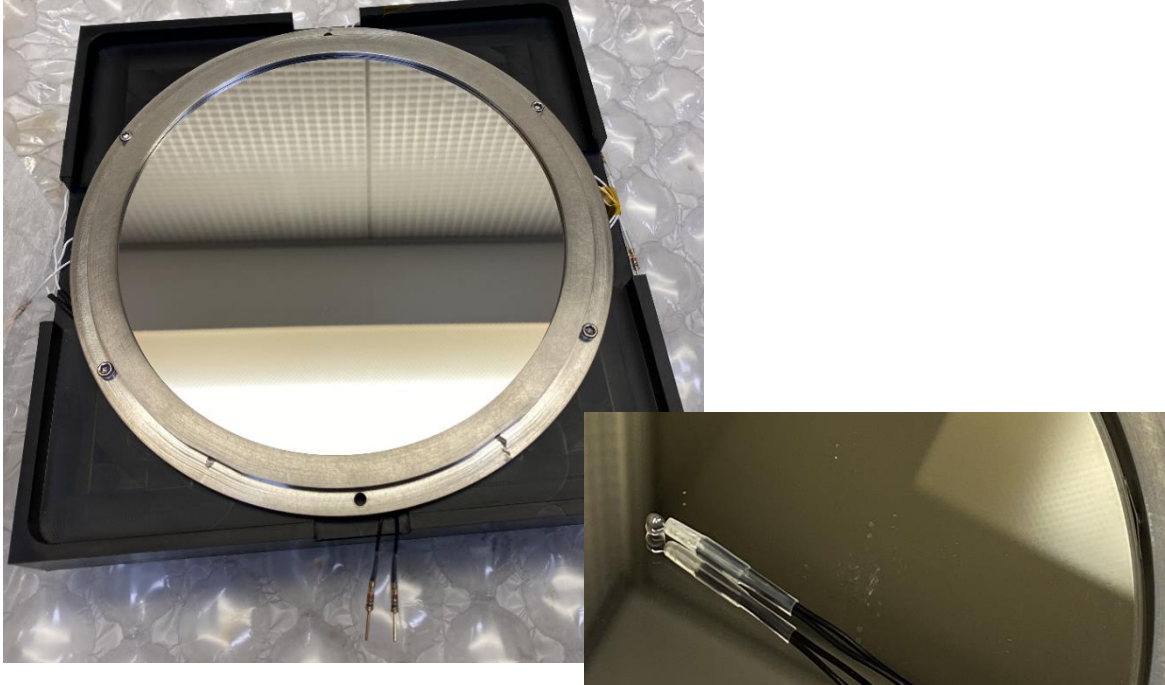
USS Vacuum Chamber and Precision Thermal Control.
Achieve Vacuum pressures at 10^{-6} Torr levels and
temperature stability below 0.001 K.



USS-lab in-test operational configuration of
the experiment set-up at the NASA GSFC
with the high power 532 nm laser source
enabled.

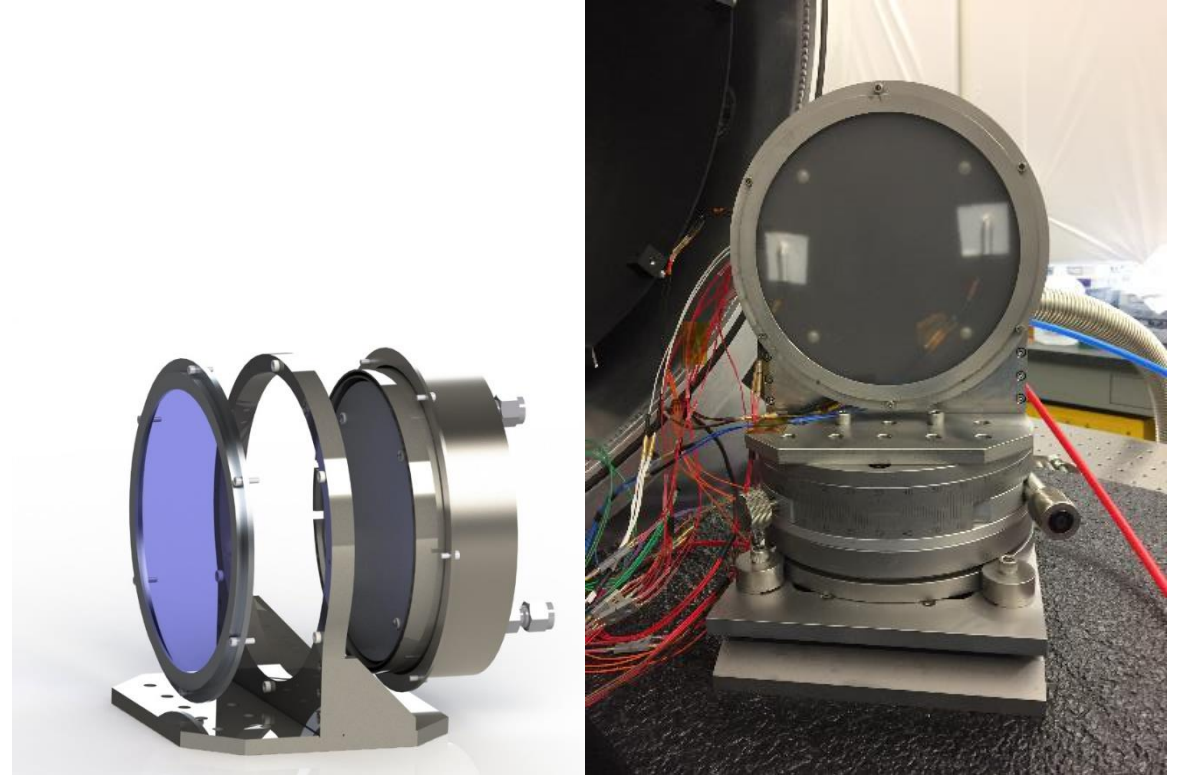


Ultra-Stable Mirror Assembly (USMA) Demonstrator:



(Left image) ULE plate mounted in Mirror bezel assembly.

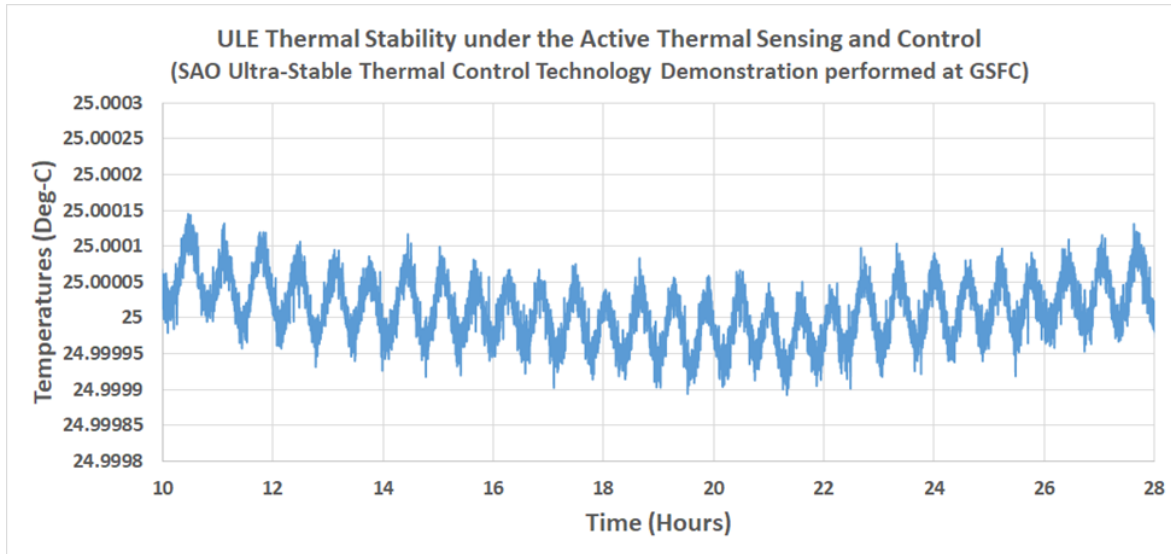
(Right image) Thermistor mounted to center of ULE plate far side.



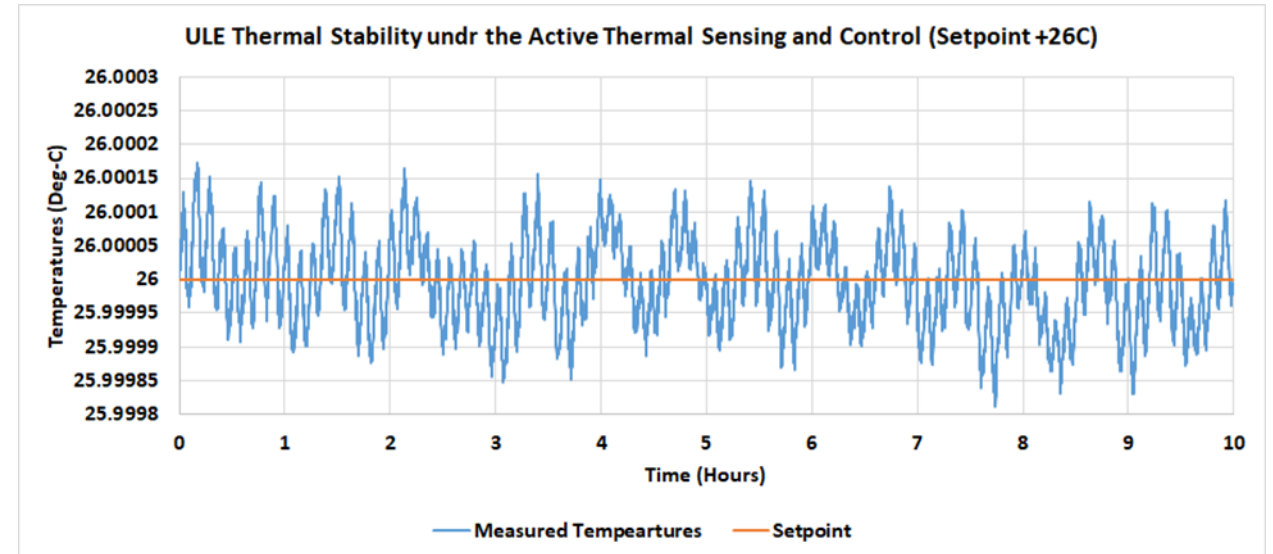
(Left image) CAD exploded view of USMA

(Right image) USMA Demonstrator with diffused ULE shown

Sub-milli-Kelvin Thermal Stability Demonstration Results



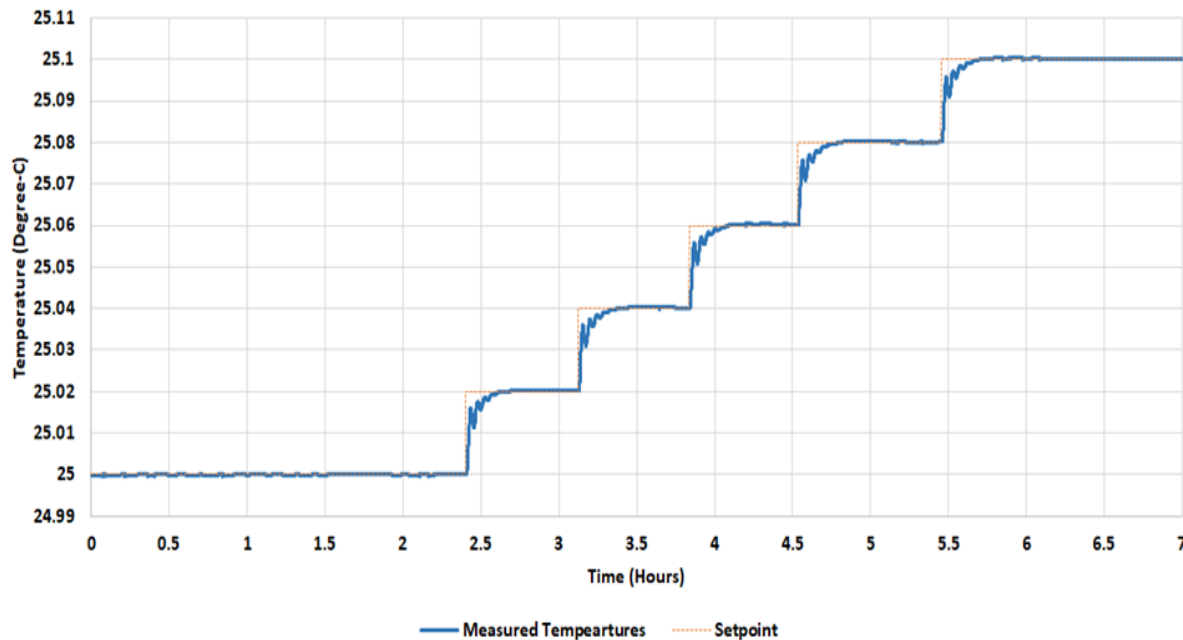
ULE thermal stability was demonstrated at **+25 °C** to **0.25mK Peak-to-Valley (P-V) over 18 hours**. At a short time span, the thermal stability was demonstrated to less than **0.15mK P-V (150uK or +/- 75 μ K) over an hour**.



ULE thermal stability test **repeated at 26°C** demonstrated **stability < 350 μ K P-V over 10 hours**.

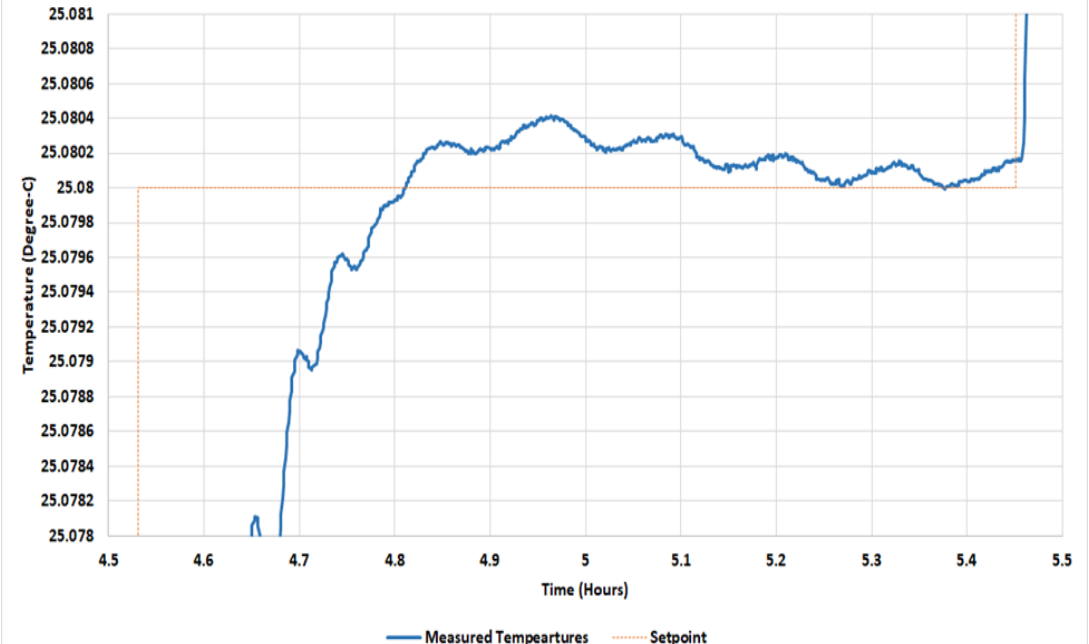
Sub-milli-Kelvin Thermal Stability Demonstration Results

Thermal Controllability at +25 deg-C Demonstration



Thermal controllability with commanded set points demonstrated at +25 deg-C with incremental increases of 20 mK.

Thermal Controllability at +25 deg-C Demonstration



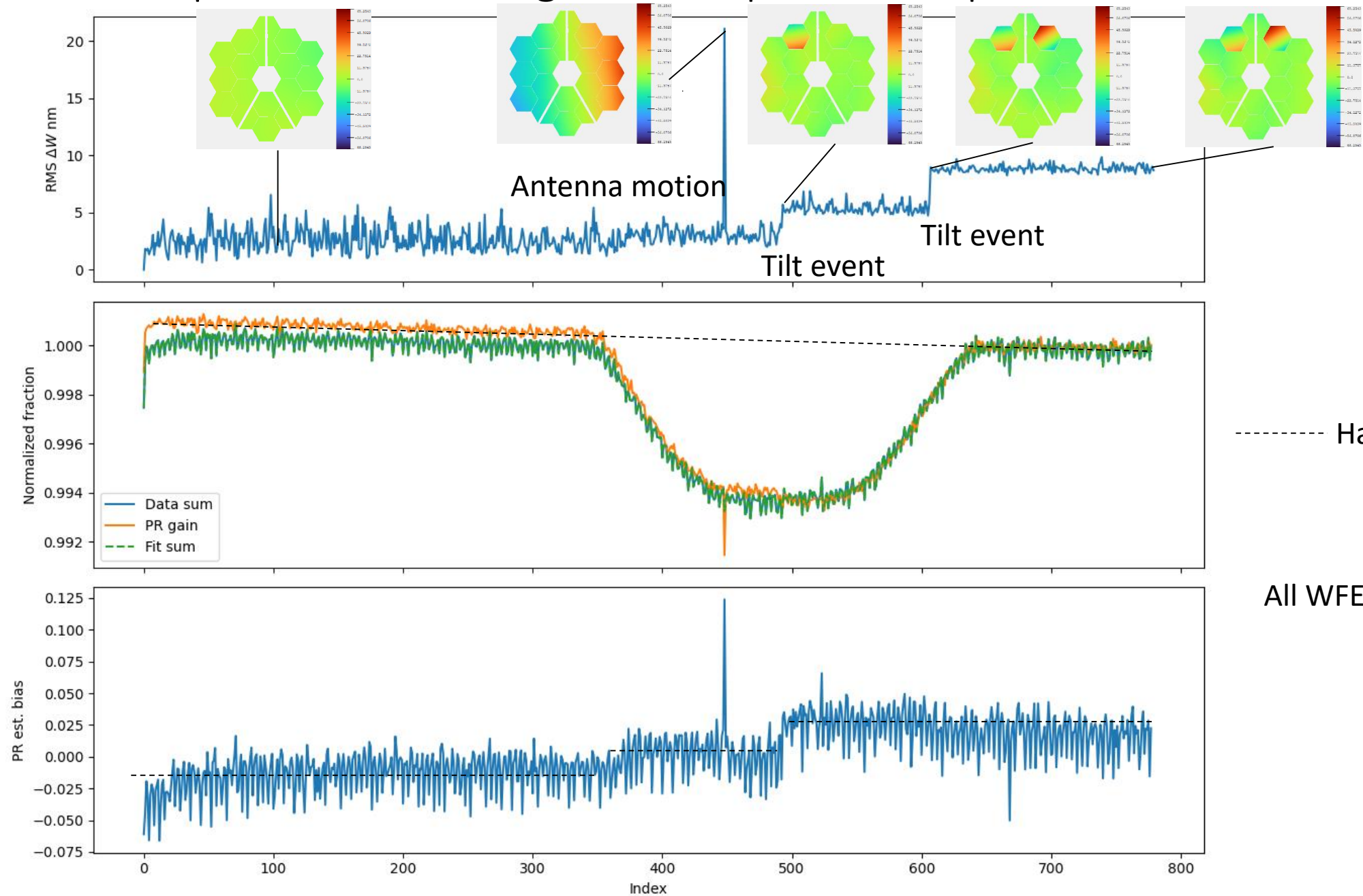
Settling characteristics of the temperature controller demonstrate 400 μ K maximum overshoot and approximately 30 minutes to settle to less than 200 μ K P-V steady condition.

Tilt events

- During the test at JSC of the telescope, we occasionally measured “tilt events” with our center of curvature metrology
 - Instantaneous change in mirror tilt that we believe resulted from strain relief (eg, small lurches as the system finds a happier mechanical state)
 - We saw a large number during cooldown, the tilt events went away by the final 5 days of the test when we did a very stable thermal balance tests
 - Due to averaging, we could only consistently discriminate 1 microradian
 - When we were quieter we didn’t see smaller tilt events
- Our expectation for flight was to see tilt events early on and they would fade
- Tilt events on Webb are nanometers and a small fraction of our encircled energy requirement.
 - Transit science which is sensitive to ppm can deal with it through a number of methods (a finding
- A key point for high contrast systems is our limitation to monitor these on JWST is nanometer scale and it seems very plausible if not likely that picometer scale lurches could occur due to:
 - Internal stress/strain relief in composite joints, interfaces, etc
 - Changes to environment especially thermal and possibly vibration



Transit performed During Peak tilt period: Captured 2 tilt events



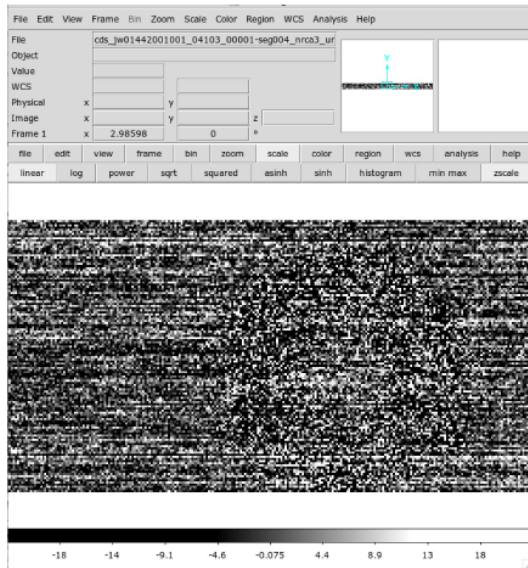
Evidence the event happens <1.35seconds

Everett Schlawin, UofAz NIRCAM team

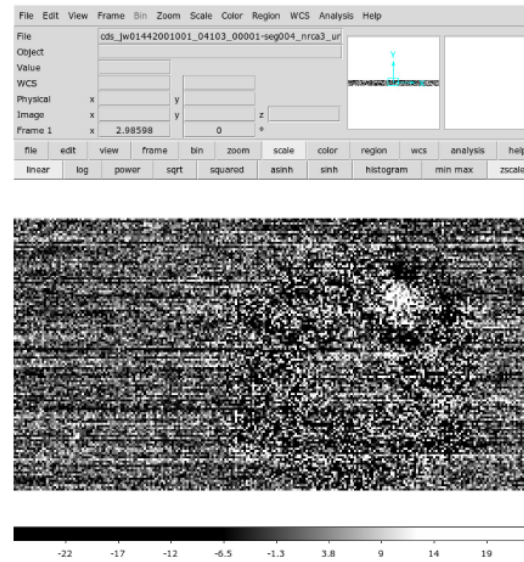
Pairwise differences for Integration 492

Tgroup=1.35194 sec, so the timescale is faster

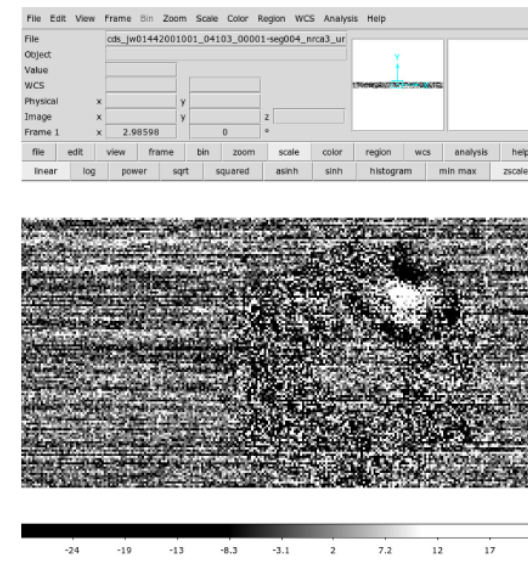
(14-13) – (1-0)



(15-14) – (1-0)

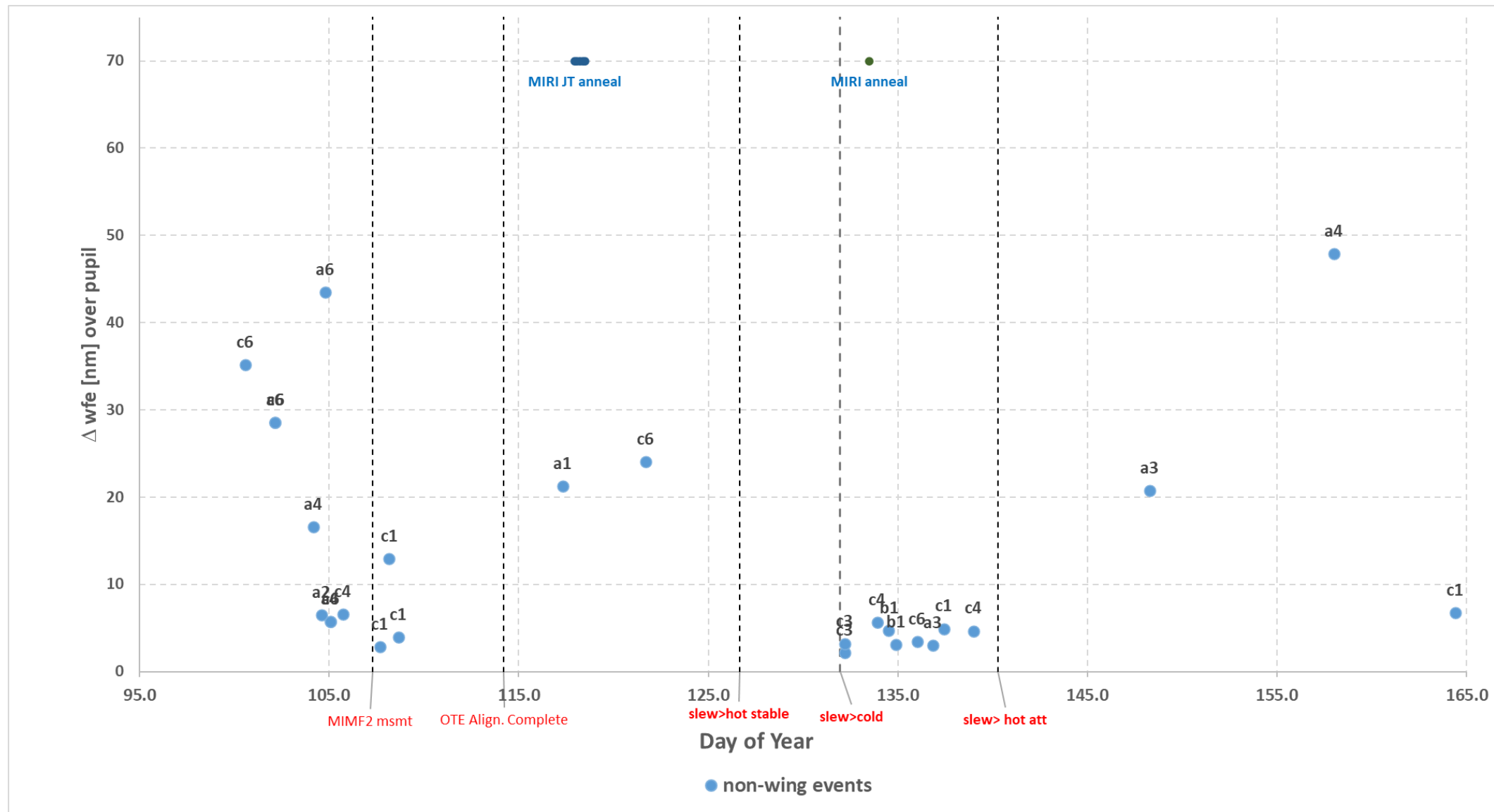


(16-15) – (1-0)



Center Section (12 mirror) segment events (26)

- Frequency of non-wing events has declined
- Includes a few non-standard thermal events



Lessons Learned from JWST for an Ultrastable Telescopes

- The safest and lowest risk approach may well be to decouple the backplane to the primary mirror wavefront
 - Composite structures are full of joints and epoxies and cable attachments and SLI attachments and their stability for picometer scale lurches is hard to know.
 - One approach is to use very stiff (eg, >500hz) mirror or mirrors, active controls that can remove tilts
 - Hubble model mirror for monolith (thick facesheet, high stiffness)
 - Stiff segments with active controls
 - RST could potentially yield important and interesting further insights into stability, a point the review panel made at the recent SIR
- While tilt events are not new, the fact is, we plan to focus on characterizing pico-lurches to the degree possible and will ultimately measure composite joints and more complex structures



Conclusion/Next Steps

- The team is making progress towards fully demonstrating the metrology and ultrastability methods needed for a IOUVR telescope
- The work to date has built confidence that picometer scale stability is measurable and controllable
- The near term priority is drift measurements to the picometer level
- Longer term goals are to increase the complexity and variety of test articles to include larger composite systems, joints
- In light of Webb's experience with tilt events, we will pursue characterizing these effects mainly for the purpose of establishing dynamic range of sense and control systems for these effects
 - Our assumption going forward is to use very stiff mirrors decoupled from the backplane

