JWST Stability

Michael McElwain
JWST Observatory Project Scientist

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Talk Outline

- JWST context for Habitable Worlds
- Stability motivation
- Architecture implementation
- JWST instabilities
- Lessons learned

JWST Telescope paper in PASP Special Issue

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The James Webb Space Telescope Mission: Optical Telescope Element Design, Development, and Performance

Michael W. McElwain[1], Lee D. Feinberg[1], Marshall D. Perrin[2], Mark Clampin[3], C. Matt Mountain[4], Matthew D. Lallo[2], Charles-Philippe Lajoie[2], Randy A. Kimble[1], Charles W. Bowers[1], Christopher C. Stark[1], D. Scott Acton[5], Charles Atkinson[6], Beth Barinek[6], Allison Barto[5], Scott Basinger[7], Tracy Beck[2], Matthew D. Bergkoetter[1], Marcel Bluth[8], Rene A. Boucarut[1], Gregory R. Brady[2], Keira J. Brooks[9], Bob Brown[5], John Byard[10], Larkin Carey[5], Maria Carrasquilla[5], Dan Chae[6], David Chaney[5], Pierre Chayer[2], Taylor Chonis[5], Lester Cohen[11,12], Helen J. Cole[13], Thomas M. Comeau[2], Matthew Coon[5], Eric Coppock[5], Laura Coyle[5], Bruce H. Dean[1], Kenneth J. Dziak[14], Michael Eisenhower[11], Nicolas Flagey[2], Randy Franck[5], Benjamin Gallagher[15], Larry Gilman[6], Tiffany Glassman[6], Joseph J. Green[7], John Grieco[14], Shari Haase[6], Theodore J. Hadjimichael[1], John G. Hagopian[16], Walter G. Hahn[14], George F. Hartig[2], Keith A. Havey[14], William L. Hayden[1], Robert Hellekson[6], Brian Hicks[5], Sherie T. Holfeltz[2], Joseph M. Howard[1], Jesse A. Huguet[14], Brian Jahne[6], Leslie A. Johnson[17], John D. Johnston[1], Alden S. Jurling[1], Jeffrey R. Kegley[13], Scott Kennard[14], Ritva A. Keski-Kuha[1], J. Scott Knight[5], Bernard A. Kulp[2], Joshua S. Levi[6], Marie B. Levine[7], Paul Lightsey[5], Robert A. Luetgens[6], John C. Mather[1], Gary W. Matthews[17], Andrew G. McKay[6], Kimberly I. Mehalick[1], Marcio Meléndez[2], Gary E. Mosier[1], Jess Murphy[5], Edmund P. Nelan[2], Malcolm B. Niedner[1], Darin M. Nol[14], Catherine M. Ohara[7], Raymond G. Ohl[1], Eugene Olczak[14], Shannon B. Osborne[2], Sang Park[11], Charles Perrygo[18], Laurent Pueyo[2], David C. Redding[7], Michael W. Regan[2], Paul Reynolds[6], Rich Rifelli[6], Jane R. Rigby[1], Derek Sabatke[5], Babak N. Saif[1], Thomas R. Scorse[19], Byoung-Joon Seo[7], Fang Shi[7], Norbert Sigrist[7], Koby Smith[5], J. Scott Smith[1], Erin C. Smith[1], Sangmo Tony Sohn[2], H. Philip Stahl[13], Randal Telfer[2], Todd Terlecki[6], Scott C. Texter[6], David Van Buren[7], Julie M. Van Campen[1], Begoña Vila[20], Mark F. Voyton[1], Mark Waldman[21], Chanda B. Walker[5], Nick Weiser[5], Conrad Wells[14], Garrett West[5], Tony L. Whitman[14], Erin Wolf[5], and Thomas P. Zielinski[1]

[1] NASA Goddard Space Flight Center, 8800 Greenbelt Road, Greenbelt, MD 20771, USA; michael.w.mcelwain@nasa.gov

JWST Context for Habitable Worlds

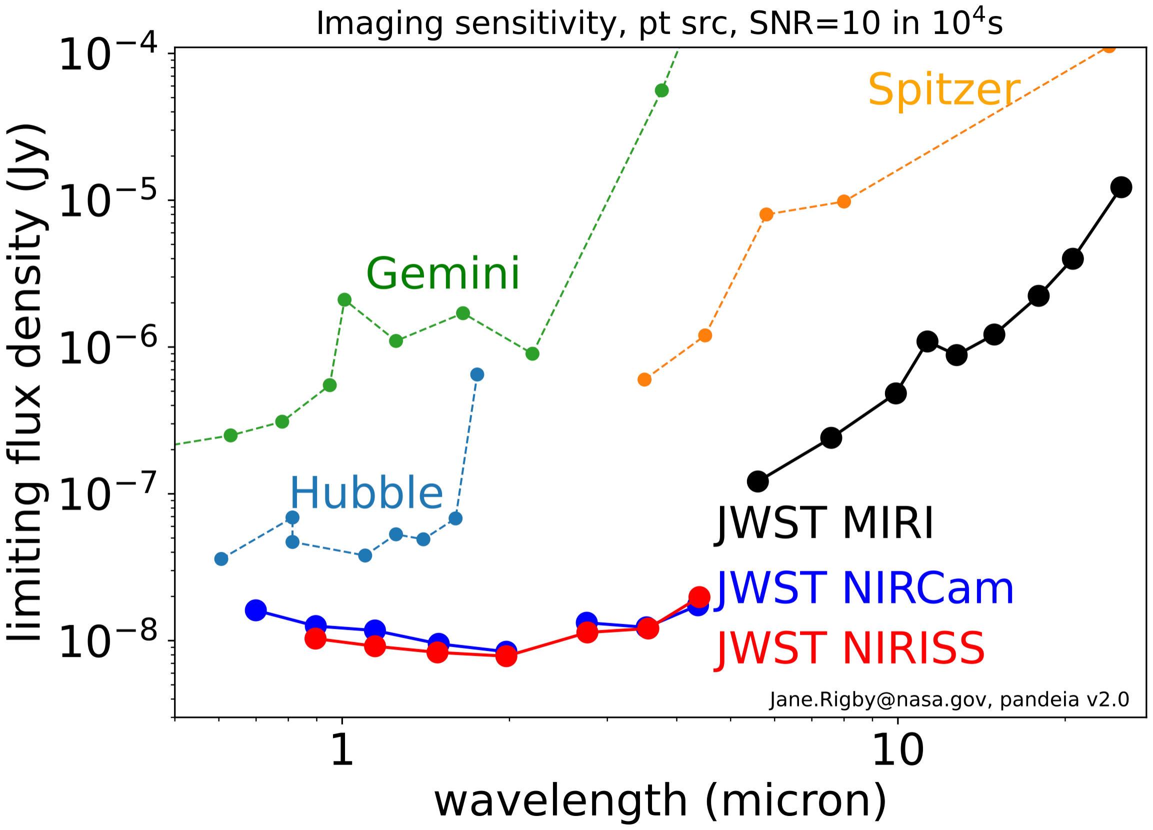
- JWST is a large, segmented telescope of comparable size to what is needed Habitable Worlds (JW 5.5m vs HWO > 6m inscribed diameter).
- JWST has passive stability that demonstrates what is achievable *now (i.e., TRL 9)*.
- JWST *does not* have the active wavefront controls planned for Habitable Worlds (e.g., edge sensors, laser truss, low order wavefront sensor).
- JWST telescope and instruments operate at cryogenic temperatures (~45 K), whereas Habitable Worlds is likely to be operated near room temperature (~300 K, actual T TBD).

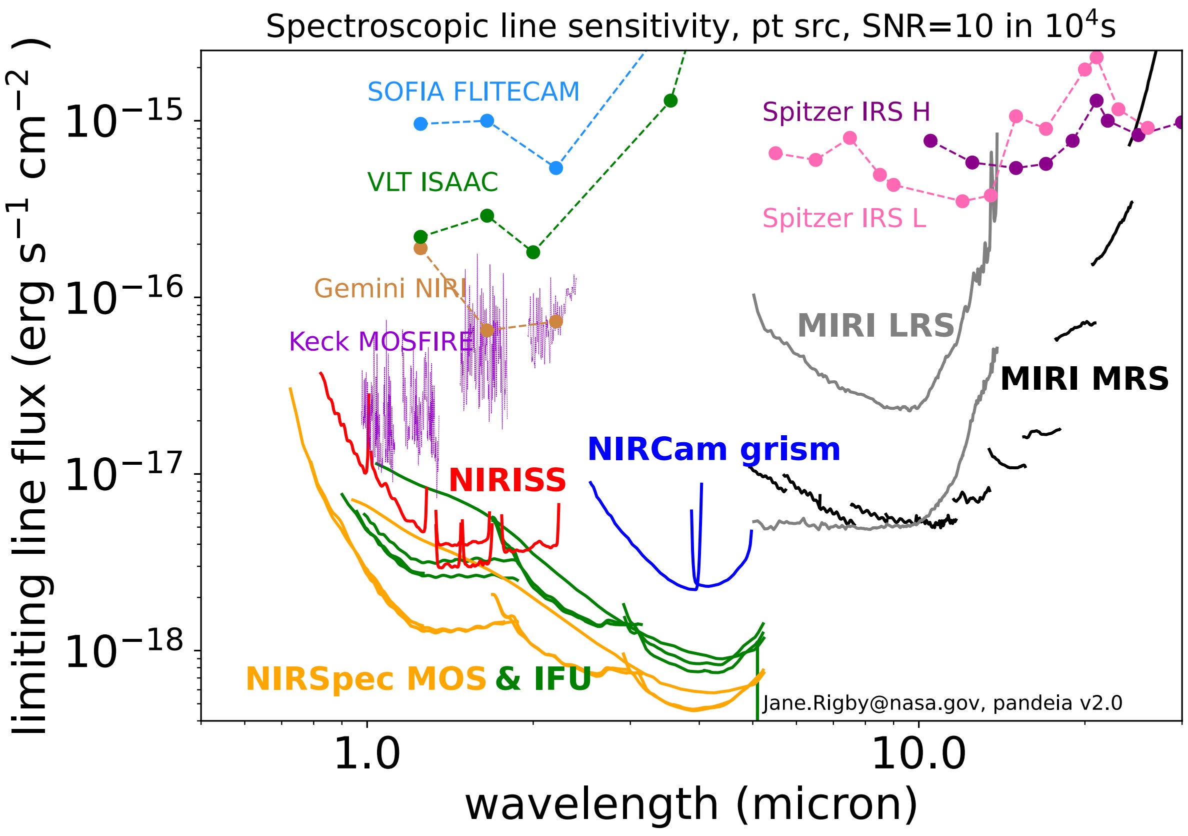
JWST Stability Motivation

Stability Motivation

- JWST science requirements built around 4 pillars: first light, assembly of galaxies, birth of stars and protostars, and planetary systems and the origins of life.
- Each of the scientific pillars required driving performance in **sensitivity** and **spatial resolution**.
  - JWST used **Strehl ratio** as the single scalar merit function for image quality to drive the allocation process.
  - Trade between wavefront error (WFE) and line of sight (LOS) jitter

Transformative Sensitivity





Rigby, Perrin, McElwain et al., 2023, PASP Special Issue

Image Quality and Stability Requirements

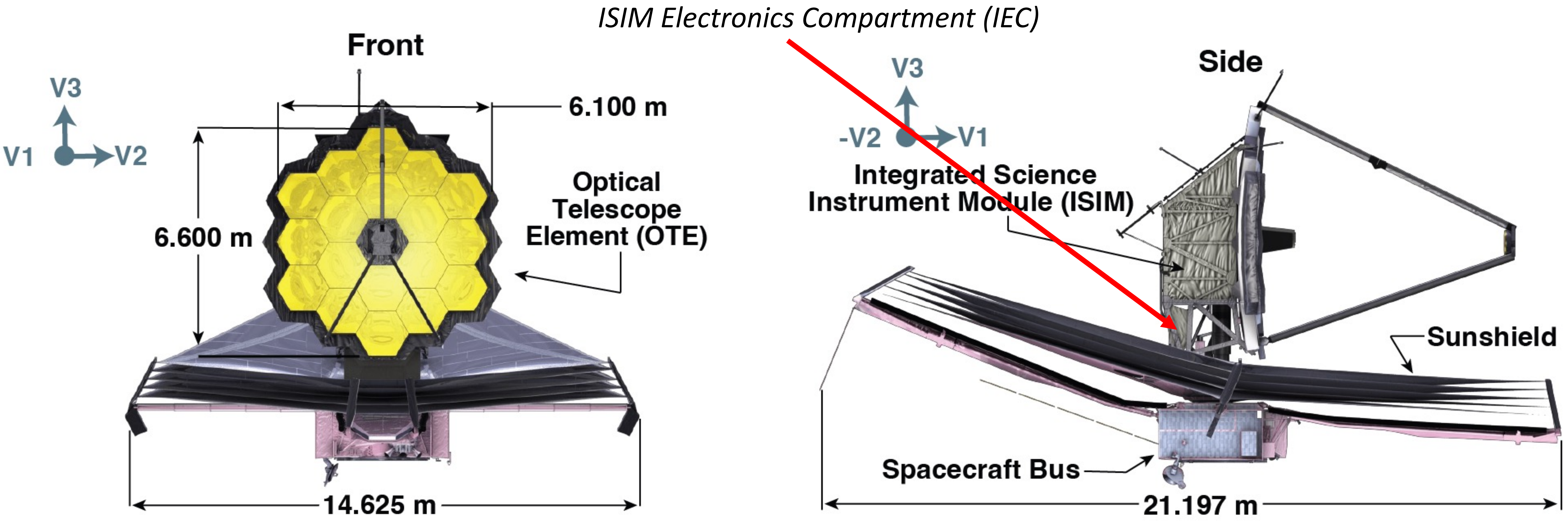
- The image quality is specified by the Strehl Ratio, *including dynamic terms*:
  - **Strehl Ratio of 0.8 at 2 um wavelength (NIRCam)** -- Equivalent to **150 nm rms WFE**
    - MR-110: "Over 80% of the FOV of each NIRCam module, the observatory shall be diffraction limited at 2 um defined as having a Strehl ratio greater than or equal to 0.8.
  - **Strehl Ratio of 0.8 at 5.6 um wavelength** (MIRI) -- Equivalent to **420 nm rms WFE**
    - MR-116: "The Observatory, over the FOV of the Mid-Infrared Instrument (MIRI) shall be diffraction limited at 5.6 um, defined as having a Strehl Ratio greater than or equal to 0.8."
  - *MR-228: "The* ***OTE WFE shall be less than or equal to 131 nm RMS*** *over the field of views of NIRCam, NIRSpec, and MIRI." MR-414: "… 150nm RMS over the field of the FGS."*
- Image quality stability is specified by *Encircled Energy (EE) stability*
  - MR-113: Specified to **change less than 2.3% at 2 µm wavelength over 24 hours**.
  - MR-115: Specified to **change less than 3.0% at 2 µm wavelength over 14 days following a worst case slew**.
    - Approximately 68 nm rms (depends on form of aberration content)

Architecture Implementation

Stability Design Considerations

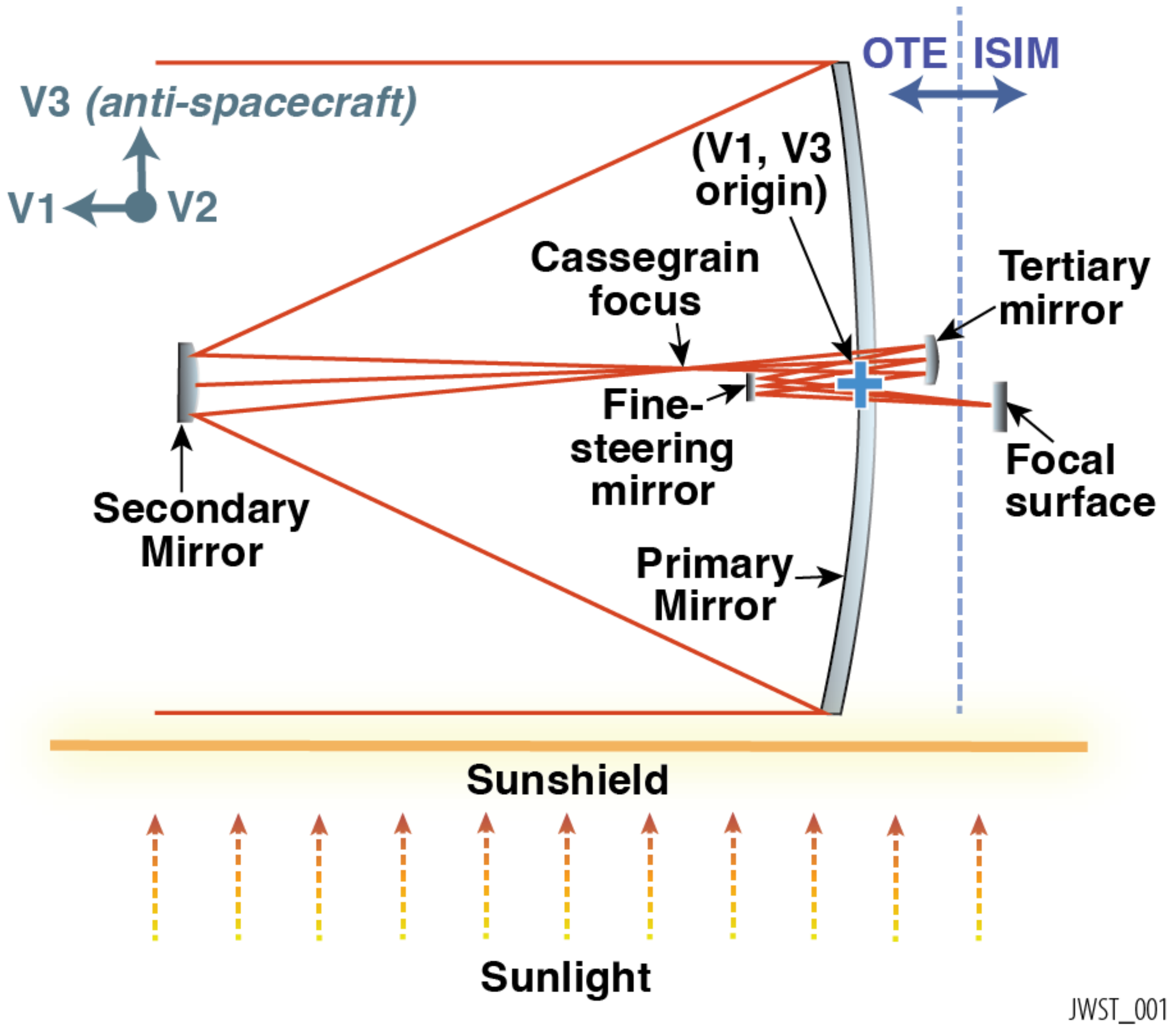
- Thermal-structural stability – Observatory thermal variations, structural thermal expansion
- Dynamic stability – vibrations and dynamical excitations, mitigations through isolation
- Space environmental effects (e.g., micrometeoroid impacts, space weathering)

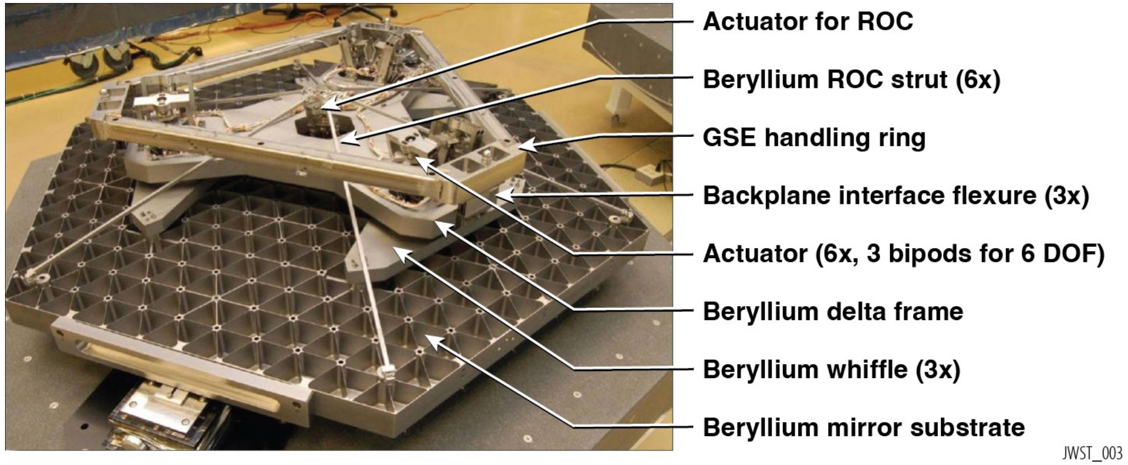
Observatory Architecture



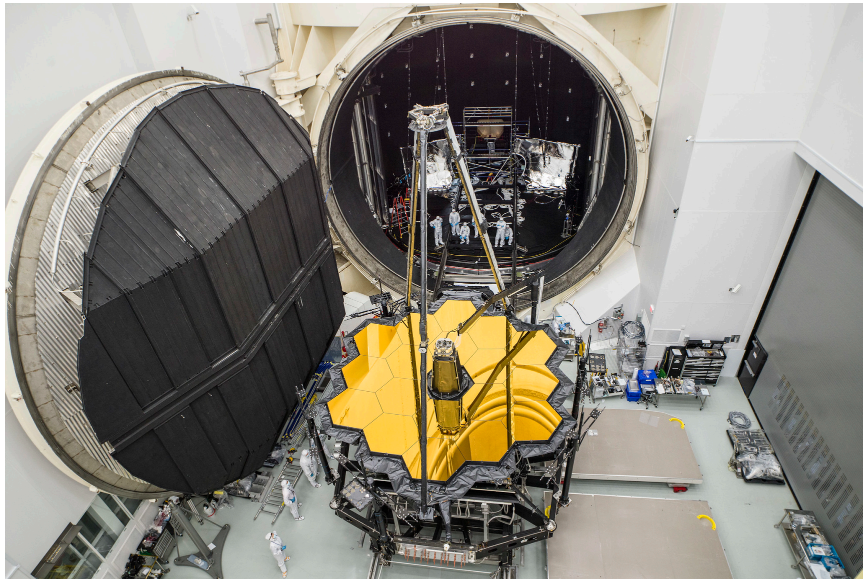
McElwain, Feinberg, Perrin, et al., 2023, PASP Special Issue
Menzel, Davis, Parrish et al., 2023, PASP Special Issue

Telescope Architecture





Primary mirror segment actuators with 7 degrees of freedom



Telescope emerges after cryogenic testing at NASA/JSC

OTE Optical Error Budget Summary

nm	System Stability			
rms	tot	lo	mid	hi
Alloc	59	45	38	1
P+U	55	41	36	0
pred	34	25	22	0
unc	21	16	14	0

nm	OTE totals			
rms	tot	lo	mid	hi
Alloc	122	92	74	30
P+U	115	83	71	37
pred	81	53	55	26
unc	74	59	37	26

nm	OTE WFC Residual			
rms	tot	lo	mid	hi
Req	81	41	63	30
P+U	78	33	60	37
pred	60	21	50	26
unc	51	29	34	26

nm	OTE Stability			
rms	tot	lo	mid	hi
Alloc	57	43	38	0
P+U	54	40	36	0
pred	34	25	22	0
unc	21	15	14	0

nm	OTE Steady State Vibe			
rms	tot	lo	mid	hi
Alloc	13	11	7	0
P+U	7	0	7	0
pred	3	0	3	0
unc	3	0	3	0

nm	Image Motion Equ.			
rms	tot	lo	mid	hi
Req	69	69	0	0
P+U	64	64	0	0
pred	41	41	0	0
unc	49	49	0	0
Req	los	6.2 mas		
P+U	los	5.7 mas		
pred	los	3.7 mas		
unc	los	4.3 mas		

System Image motion	
Req	6.6 mas
P+U	5.7 mas
pred	3.7 mas
unc	4.3 mas

System Image motion	
Req	6.2 mas
P+U	5.7 mas
pred	3.7 mas
unc	4.3 mas

LOS budget margin	
Req	2.3 mas
P+U	0.0 mas
pred	0.0 mas
unc	0.0 mas

LOS dynamics > fg bw	
Req	2.8 mas
P+U	2.6 mas
pred	1.3 mas
unc	2.3 mas

LOS jitter in fg bw	
Req	4.0 mas
P+U	3.5 mas
pred	2.5 mas
unc	2.5 mas

Inter-instr boresight motion	
Req	1.8 mas
P+U	1.8 mas
pred	1.1 mas
unc	1.4 mas

Cross term	
Req	3.3 mas
P+U	3.2 mas
pred	2.1 mas
unc	2.4 mas

nm	OTE Stability			
rms	tot	lo	mid	hi
Alloc	57	43	38	0
P+U	54	40	36	0
pred	34	25	22	0
unc	21	15	14	0

nm	ISIM Stability			
rms	tot	lo	mid	hi
Alloc	13	13	1	1
P+U	8	8	0	0
pred	5	5	0	0
unc	4	4	0	0

nm	Alignment Vibrate			
rms	tot	lo	mid	hi
Alloc	5	5	0	0
P+U	0.3	0	0	0
pred	0.1	0	0	0
unc	0.1	0	0	0

nm	Alignment Drift			
rms	tot	lo	mid	hi
Alloc	10	10	0	0
P+U	8	8	0	0
pred	4	4	0	0
unc	4	4	0	0

nm	ISIM Struct Stab			
rms	tot	lo	mid	hi
Alloc	8	8	0	0
P+U	7	7	0	0
pred	5	5	0	0
unc	2	2	0	0

nm	NIRCam Stability			
rms	tot	lo	mid	hi
Alloc	10	10	1	1
P+U	3	3	0	0
pred	0	0	0	0
unc	3	3	0	0

nm	Figure Vibrate			
rms	tot	lo	mid	hi
Alloc	13	2	13	0
P+U	12	2	12	0
pred	6	1	6	0
unc	6	1	6	0

nm	Figure Drift			
rms	tot	lo	mid	hi
Alloc	55	41	36	0
P+U	52	39	35	0
pred	33	25	22	0
unc	20	15	13	0

nm	OTE-ISIM Stability			
rms	tot	lo	mid	hi
Alloc	1	1	0	0
P+U	0	0	0	0
pred	0	0	0	0
unc	0	0	0	0

nm	PM w/ frill & IEC effects			
rms	tot	lo	mid	hi
Alloc	55	41	36	0
P+U	52	39	35	0
pred	33	25	22	0
unc	20	15	13	0

nm	SM			
rms	tot	lo	mid	hi
Alloc	1	1	0	0
P+U	0	0	0	0
pred	0	0	0	0
unc	0	0	0	0

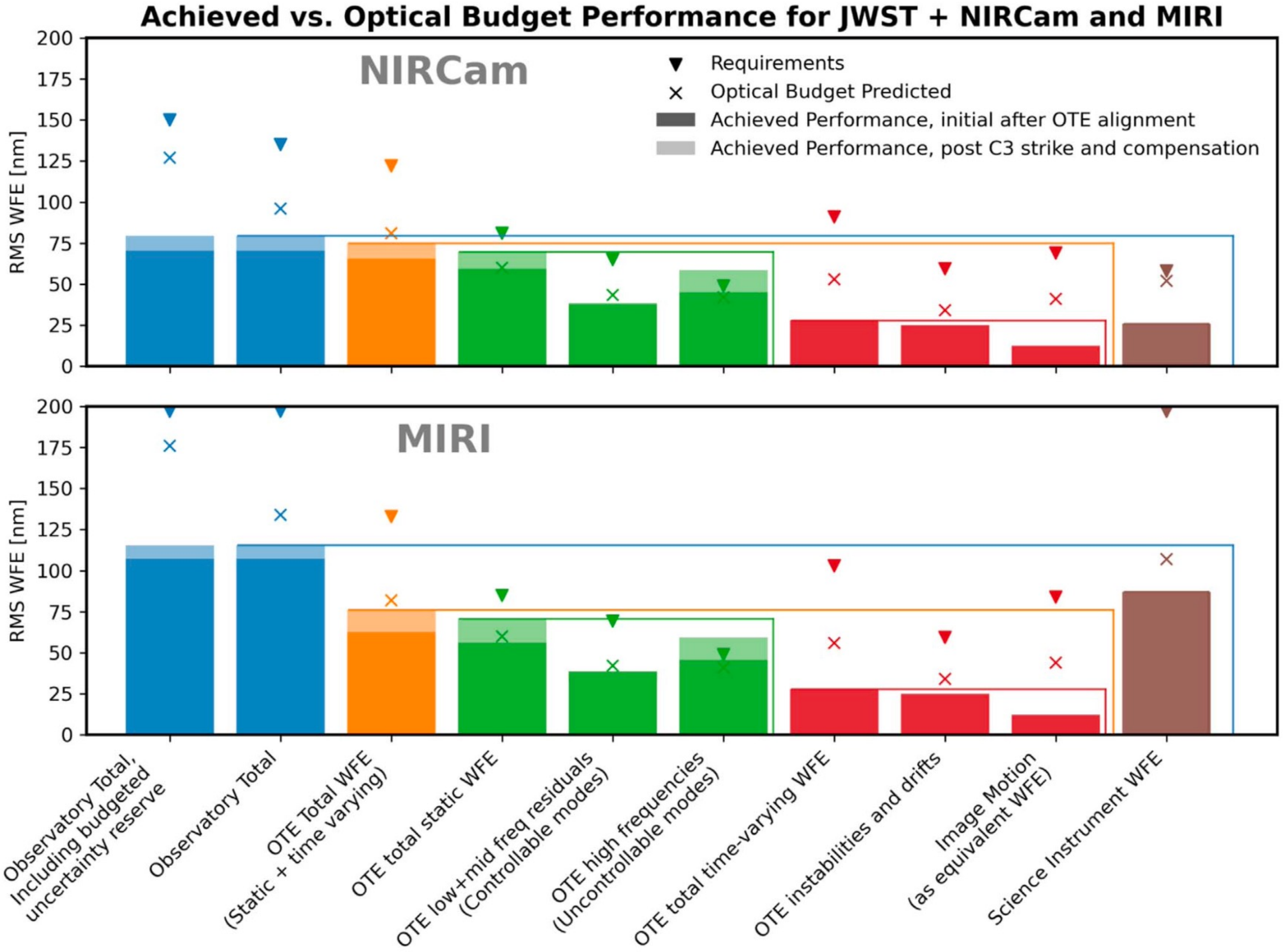
nm	TM			
rms	tot	lo	mid	hi
Alloc	1	1	0	0
P+U	0	0	0	0
pred	0	0	0	0
unc	0	0	0	0

nm	FSM			
rms	tot	lo	mid	hi
Alloc	1	1	0	0
P+U	0	0	0	0
pred	0	0	0	0
unc	0	0	0	0

Feinberg, McElwain, Bowers, et al. 2023, JATIS (submitted)

JWST Performance

Webb Telescope Team at Completion of Alignment



Rigby, Perrin, McElwain et al., 2023, PASP Special Issue

Telescope Static Error

- Telescope alignment, the correctable ***static*** wavefront error, is nearly perfect. There were no modifications to the alignment that would have gained material improvements (< 1% EE change at any field point).
  - NB: micrometeoroid impacts *are* slowly degrading the static wavefront error (see Menzel's presentation).
  - OTE wavefront error is currently 62nm; NIRCam WFE is 32nm at control field point
- We carry out wavefront measurements every 2 days and correct the telescope alignment less frequently as needed to maintain the ***static*** alignment (corrections planned for a 14 day cadence and currently needed significantly LESS frequently).
  - We do *not* plan to correct the dynamic drifts but rather the systematic drifts due to the telescope's deformations.

Encircled Energy Stability Meets Requirements

Encircled Energy Stability	24 Hour (%)	14 Day (%)
Requirement	< 2.3%	<3.0%
BOL Thermal Test	0.2	0.53
EOL Estimate	0.4	2.4

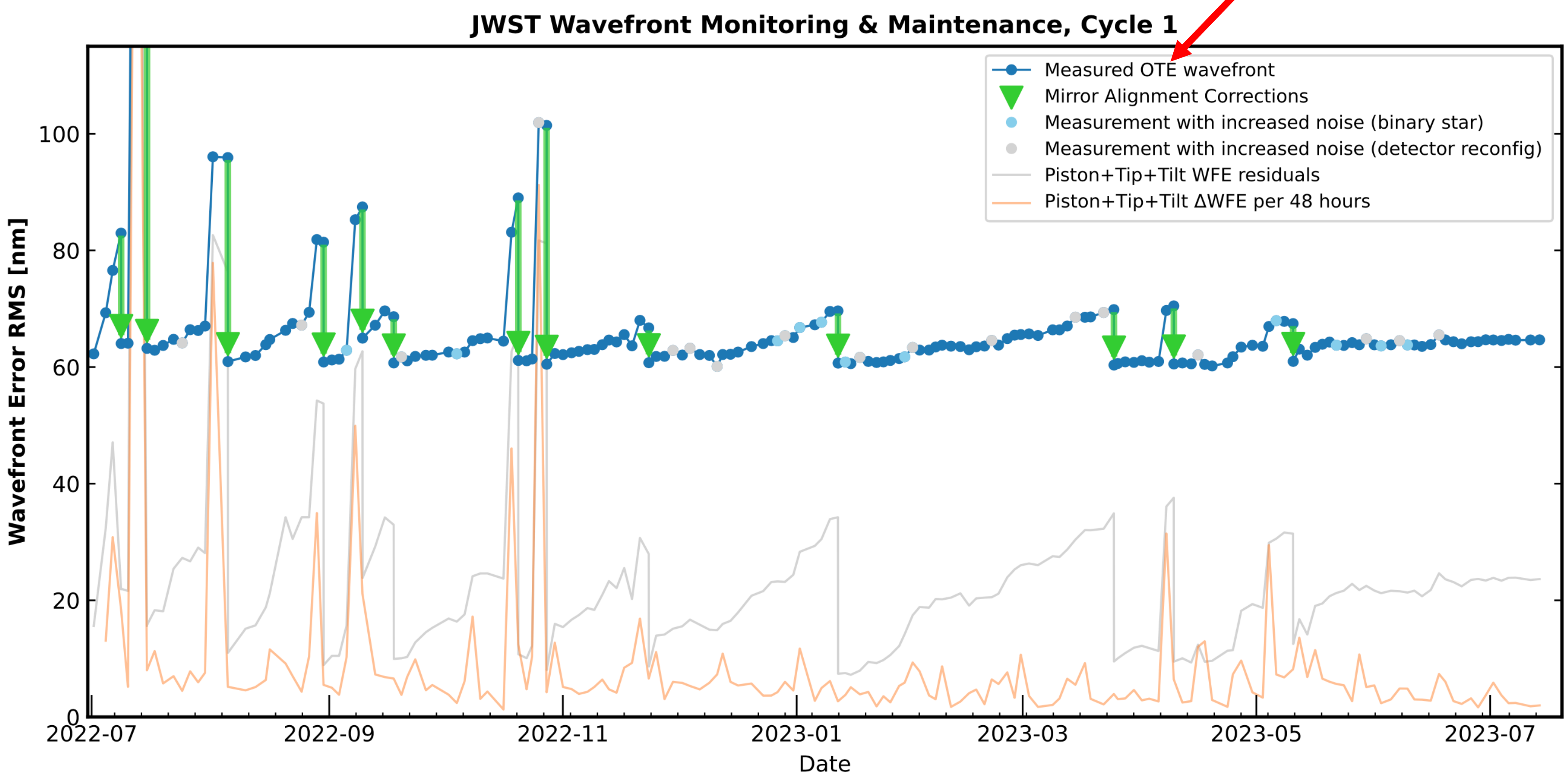
Evaluation assumptions

- BOL to EOL extrapolations are valid.
- Thermal slew data matches the BOL prediction.
- Tilt events are small contributors relative to thermal and dynamics.
- Line of sight is bounded by high speed jitter (observed every 2 days with wavefront monitoring) and image motion measurements from the thermal stability test.
- Form of the static wavefront error is consistent with the encircled energy stability models.

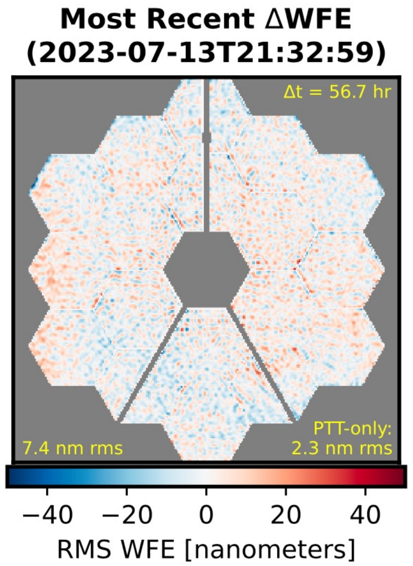
Knight & Lightsey, 2022, SPIE

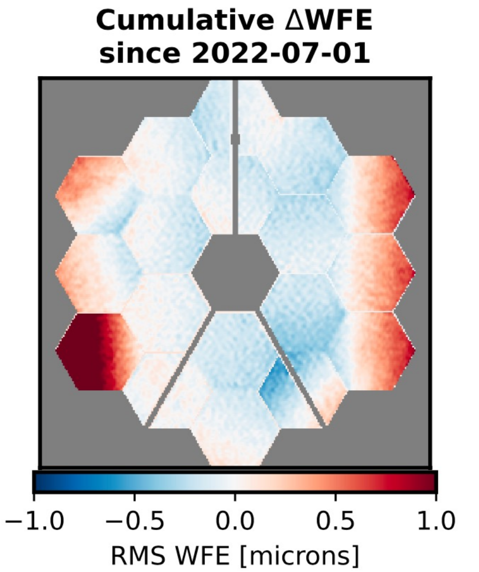
JWST Cycle 1 Wavefront Trending

Wavefront errors reported for telescope only (not OTE+NIRCam).



2 day WFS interval





Over the last 2 days, drift over that time interval was 2.5 pm/min

Lajoie, Lallo, Meléndez, et al., 2023; arXiv:207.11179

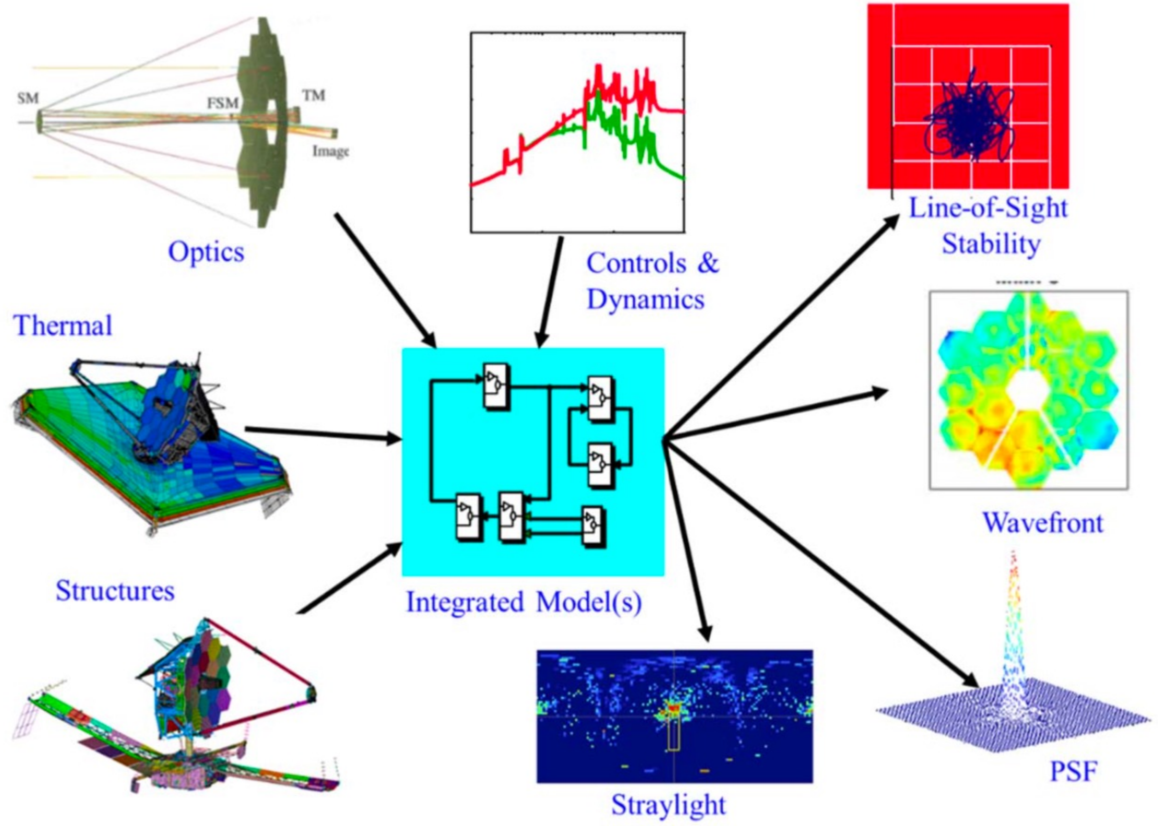
JWST Instabilities

Instabilities -- Knowns and Unknowns

- **Design drifts**: When a large slew in pitch (i.e., toward or away from the sun) is made, thermal changes on the spacecraft and OTE contribute to optical stability changes.
  - *Pointing instability*: from thermal changes to the star tracker assembly and OTE which affect the relative coordinates, resulting in a roll about the boresight (i.e., not sensed or corrected by the fine guidance sensor loop). HWO could control roll with more than one guide star.
  - *OTE thermal distortion*: from structural displacements to the OTE backplane and secondary mirror motion, resulting in a change in the wavefront error. HWO will be active; the JWST is a benchmark for dynamic range and time constants for active control.
- **As-built drifts**: During OTIS cryovacuum testing, three additional instabilities were observed:
  - *PMSA tilt events:* unpredictable tilt events, likely due to backplane stress relief from the structural cooldown to operational temperatures. Several events were identified during OTIS cryo-stable but had plausible non-flight contributors. HWO will be sensitive at picometer level for HWO (need active controls, PSF calibrations); HWO room temperature so less built in strain.
  - *IEC cyclic wavefront drifts*: from the IEC radiator panel heater turn on/off which coupled into the backplane through the harness. *HWO will use variable heater control (not bang-bang), harnesses will be designed to mitigate mechanical interactions (e.g., splayed cables, service loops), and thermal control loop should be modeled.*
  - *Frill & PMSA close-out thermal distortion*: from frill and PMSA installations that did not have the requisite slack to operate across the OTE temperature range without imparting forces on the backplane. *HWO design* should avoid using a frill (e.g., a telescope barrel decoupled from mirrors/backplane).
- Micrometeoroid damage will degrade the OTE static wavefront error over time. *HWO can use a barrel to protect from micrometeoroids and contamination.*

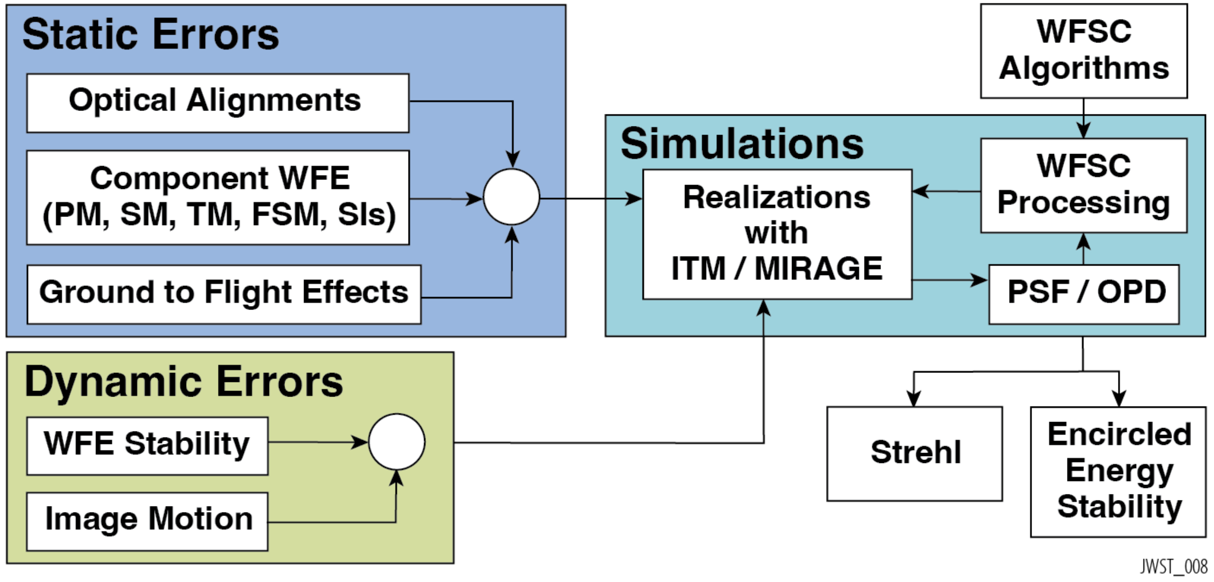
Performance Verification often by Analysis

Integrated Modeling



Menzel, Davis, Parrish et al., 2023, PASP Special Issue

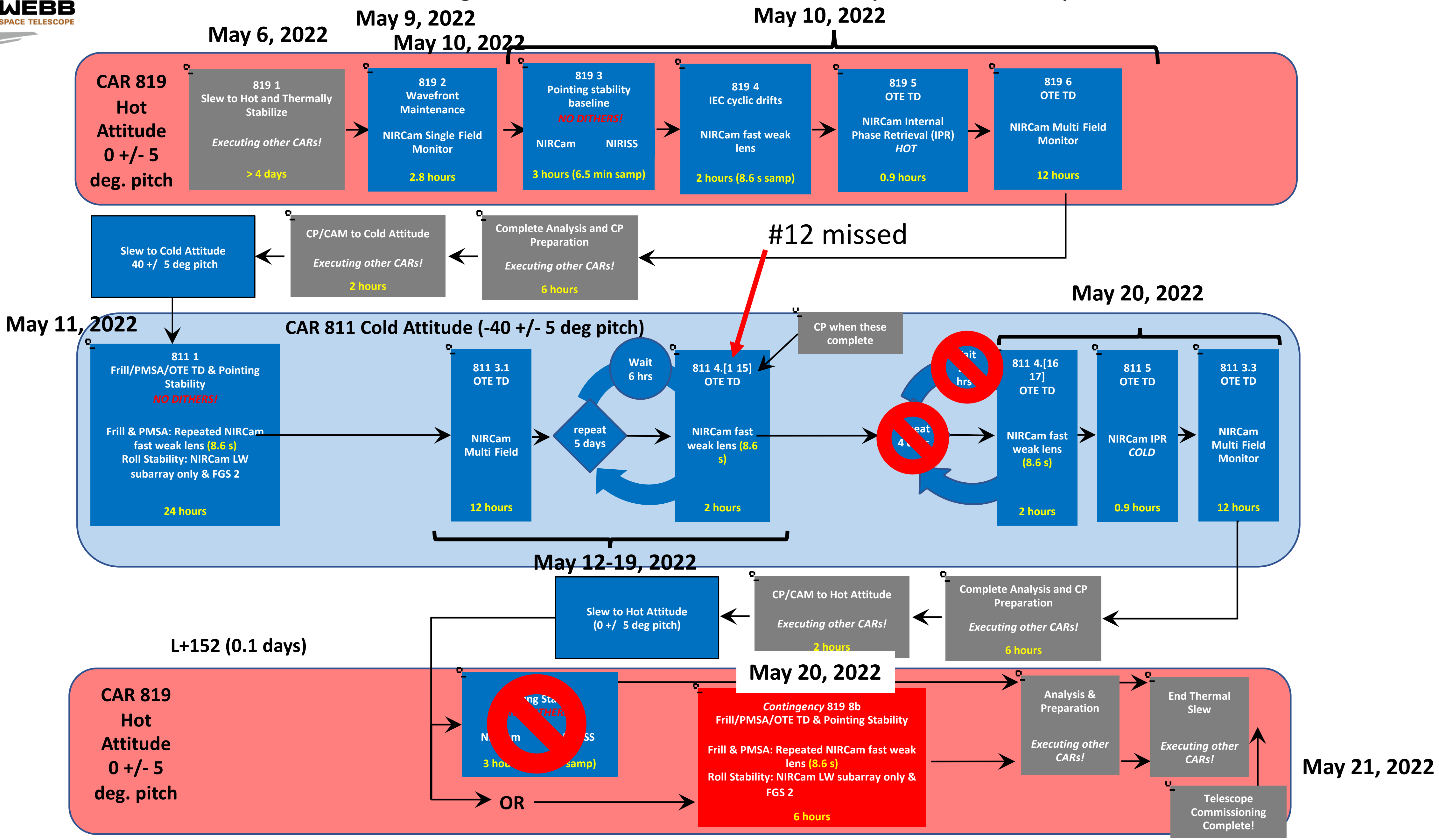
Optical Modeling



McElwain, Feinberg, Perrin, et al., 2023, PASP Special Issue

See Marie Levine keynote talk “Integrated modeling of the James Webb Space Telescope: flight performance and lessons learned” at SPIE Optics + Photonics August 20-24, 2023.

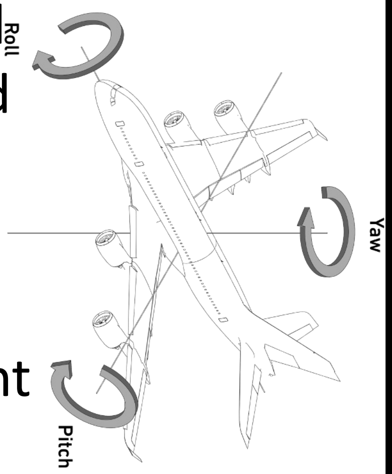
Commissioning thermal stability activity flowchart

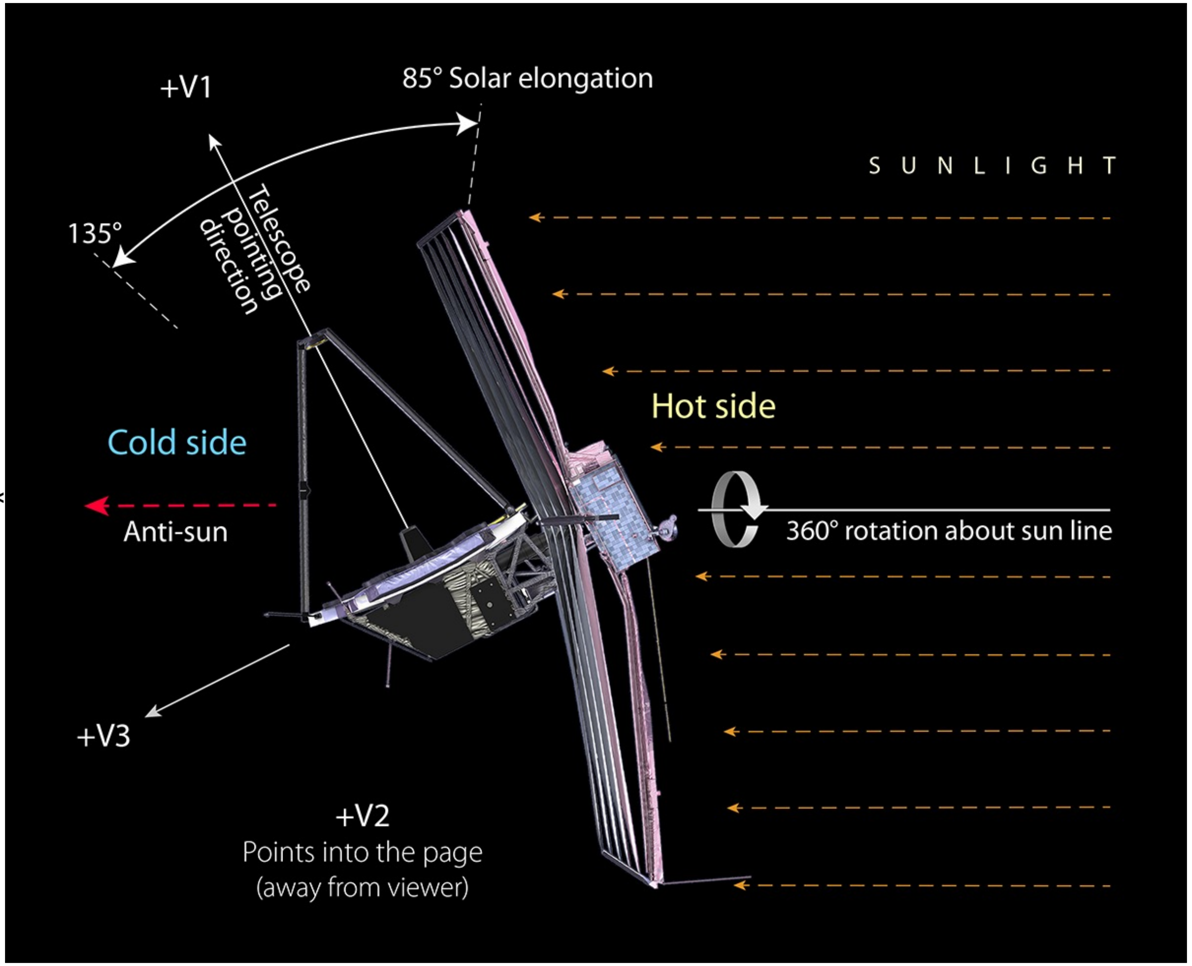


Thermal Distortion:
Telescope, Frill, and PMSA Closeout

Thermal Distortion Overview

- Pointing within the field of regard changes solar heating, causing temperature changes (< 100 mK, < 50nm drift EOL), causing wavefront drift.
- JWST is *passively* stable with thermal isolation from the spacecraft bus and low CTE components on the telescope.
- JWST designed to meet the 14 day encircled energy stability requirement without any mirror control – that is, the wavefront active control does not correct thermal distortion but rather systematic drifts (e.g., tilt events, mechanical creep).

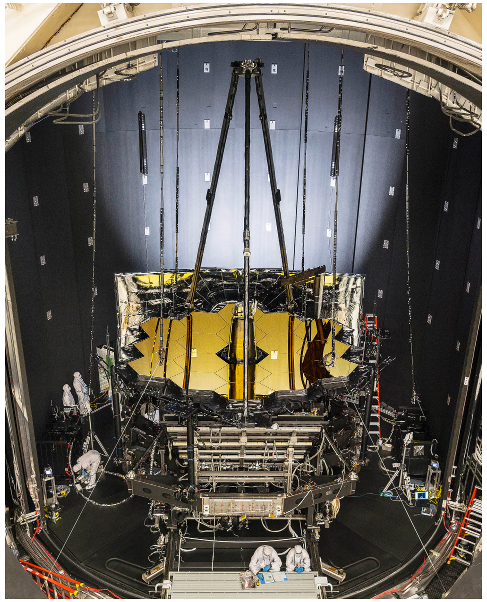




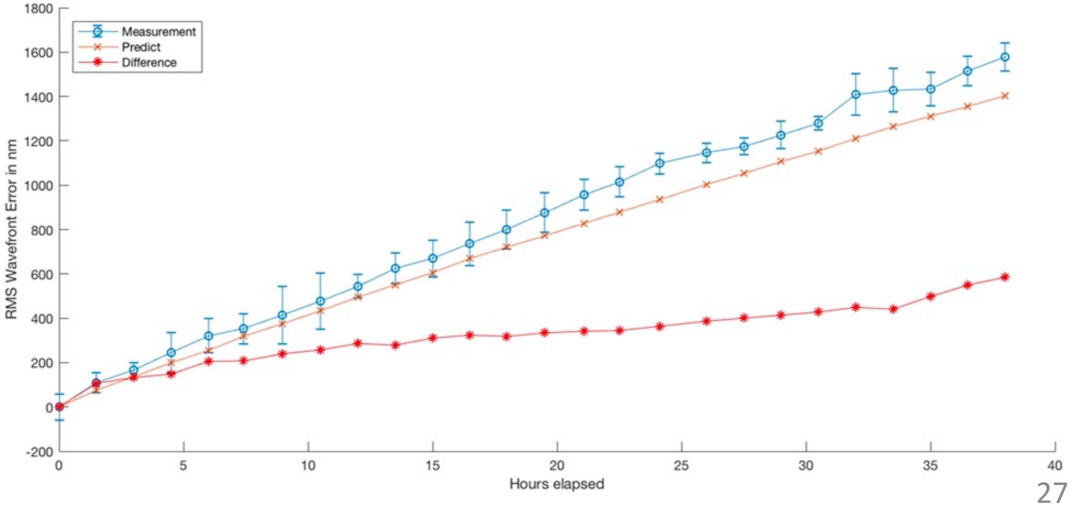
Thermal Distortion Ground Tests

- Thermal distortion predictions from integrated modeling, anchored in tests at the component and assembly levels.
- OTIS cryovacuum testing measured alignment drifts and figure drifts, using overdrive tests that were ~100x larger temperatures than the flight conditions.
  - Confirmed structural displacements due to temperature changes, making use of high precision ground test temperature sensors
  - Repeated tests on cooldown and warm up; independent team analyses
- Verified flight telescope performance within integrated modeling predictions
- Discovered unexpected wavefront drifts, later attributed to interactions with soft structure and harnesses.

OTIS in JSC Chamber A

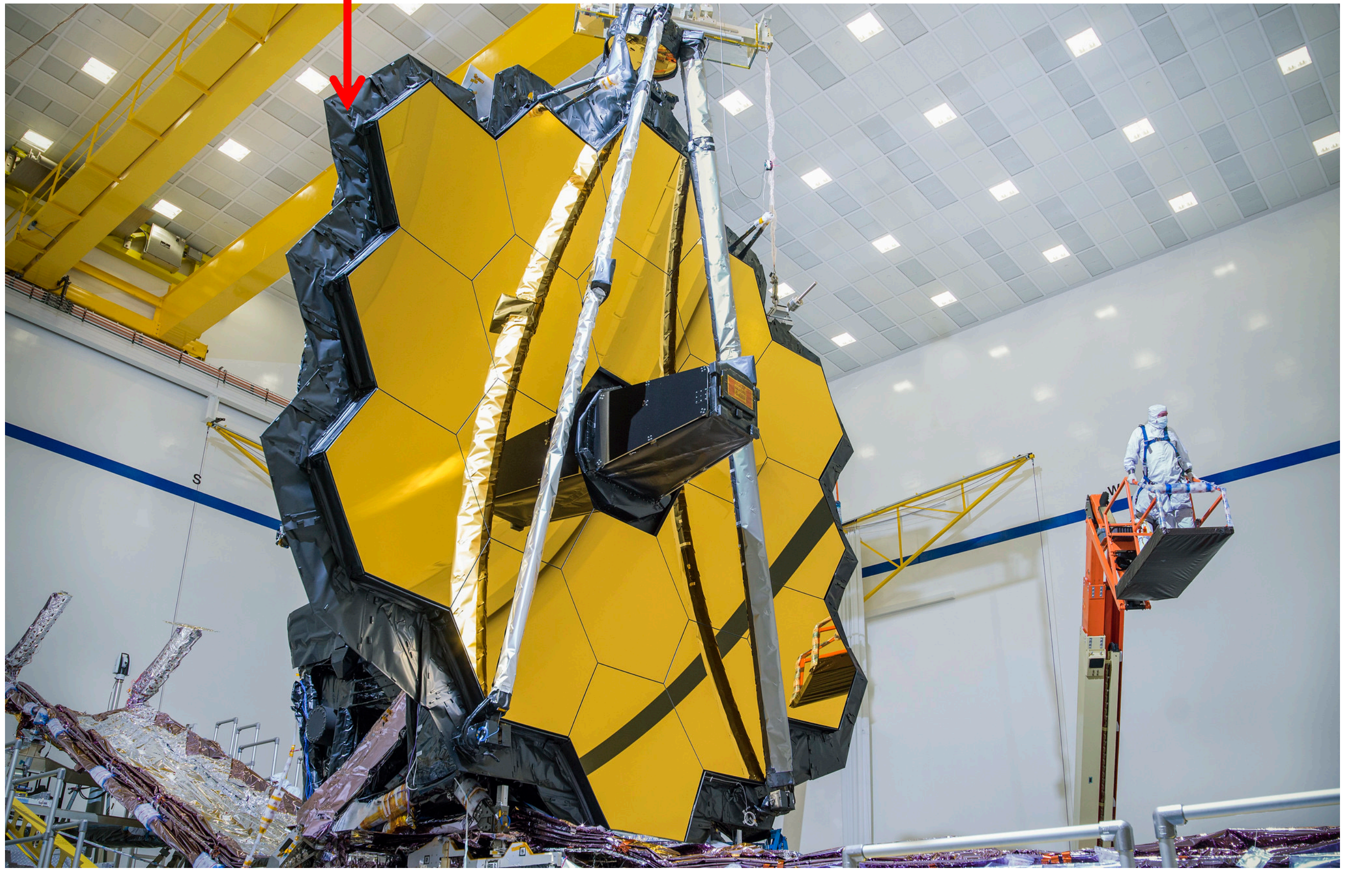


OTIS CV Figure Drift test vs. prediction validated models



Frill and PMSA Closeouts

Soft structure "frill" extends from the perimeter of the primary mirror to block unwanted stray light

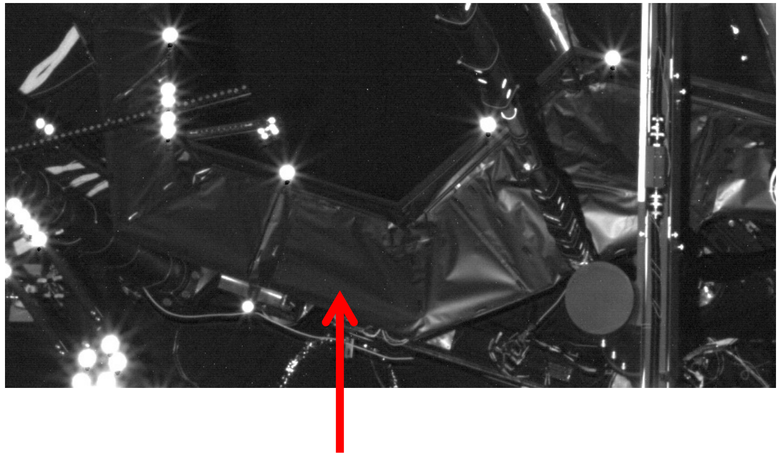


Primary mirror closeouts

Evidence of a Taut Frill during Cryo Testing

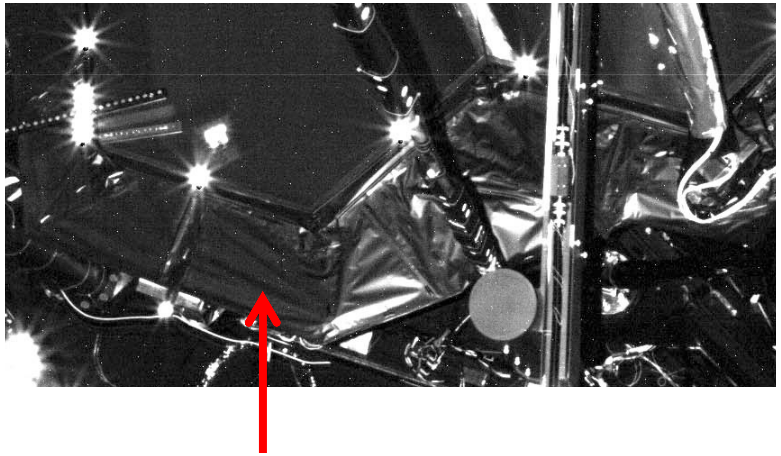
Ambient

125 K



tension folds apparent

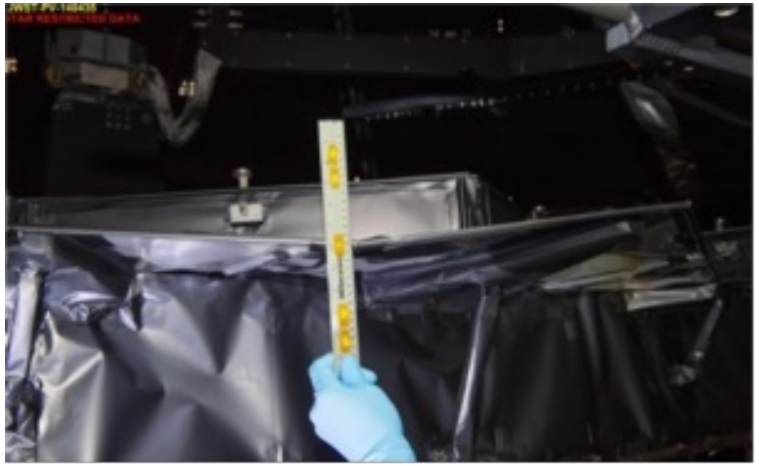
75 K



tension folds increased

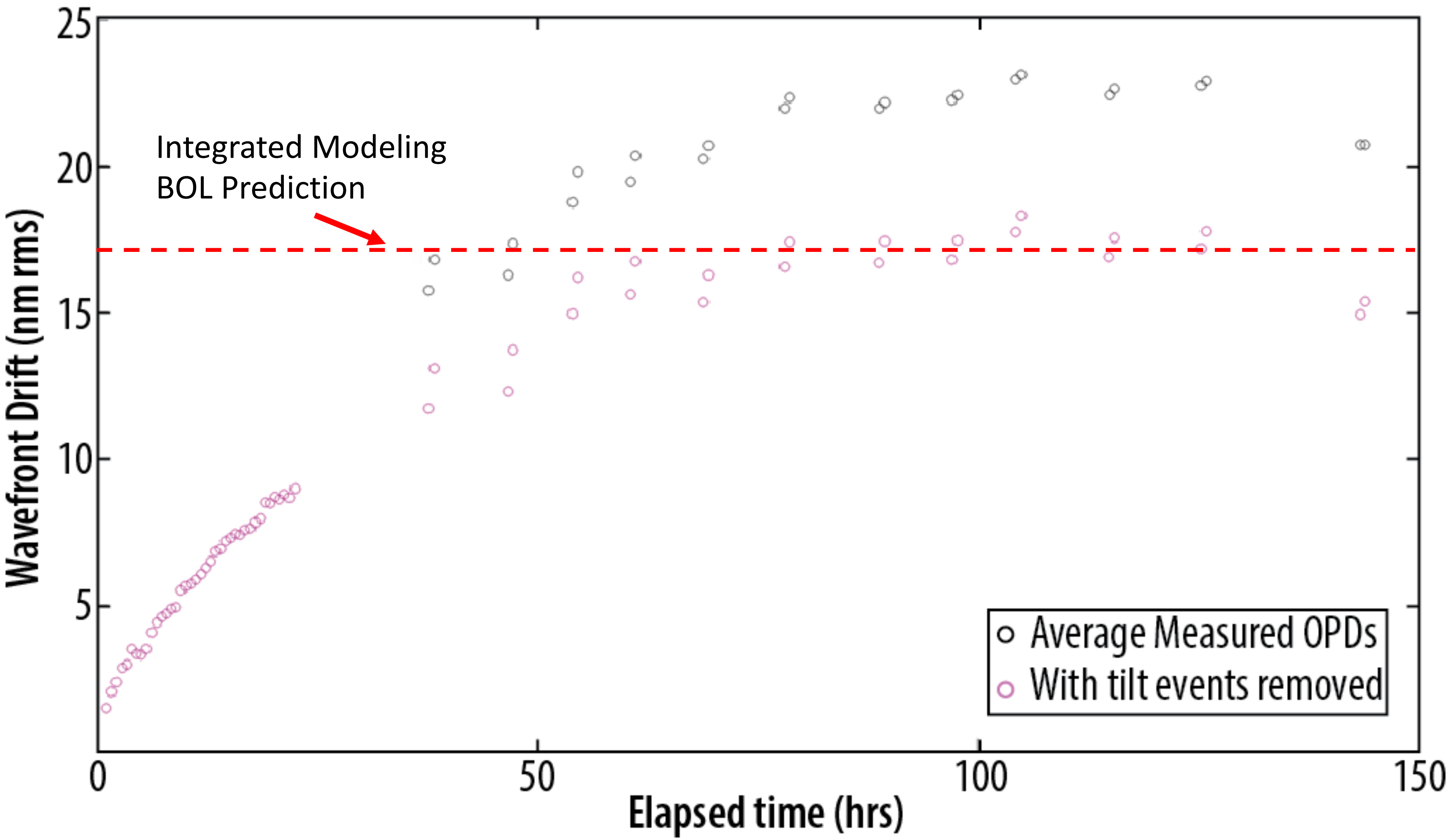
- Design intent was for frill and close-out to remain slack throughout operating temperature range.
- Evidence of tension fields in frill seen in photogrammetry system imagery

Frill Slack Measurements



- Following the test, direct inspections confirmed the design intent was not achieved
- Frill blanket inspections estimated the slack by measuring the available deflection when a gentle force was applied normal.
- Major effort was made to increase the slack but we didn’t do this in a few places near deployments and accepted there would be a few nm effect after a slew.
    - We were <u>*not*</u> able to re-test and verify the repaired performance.

On-orbit Thermal Distortion Measurement

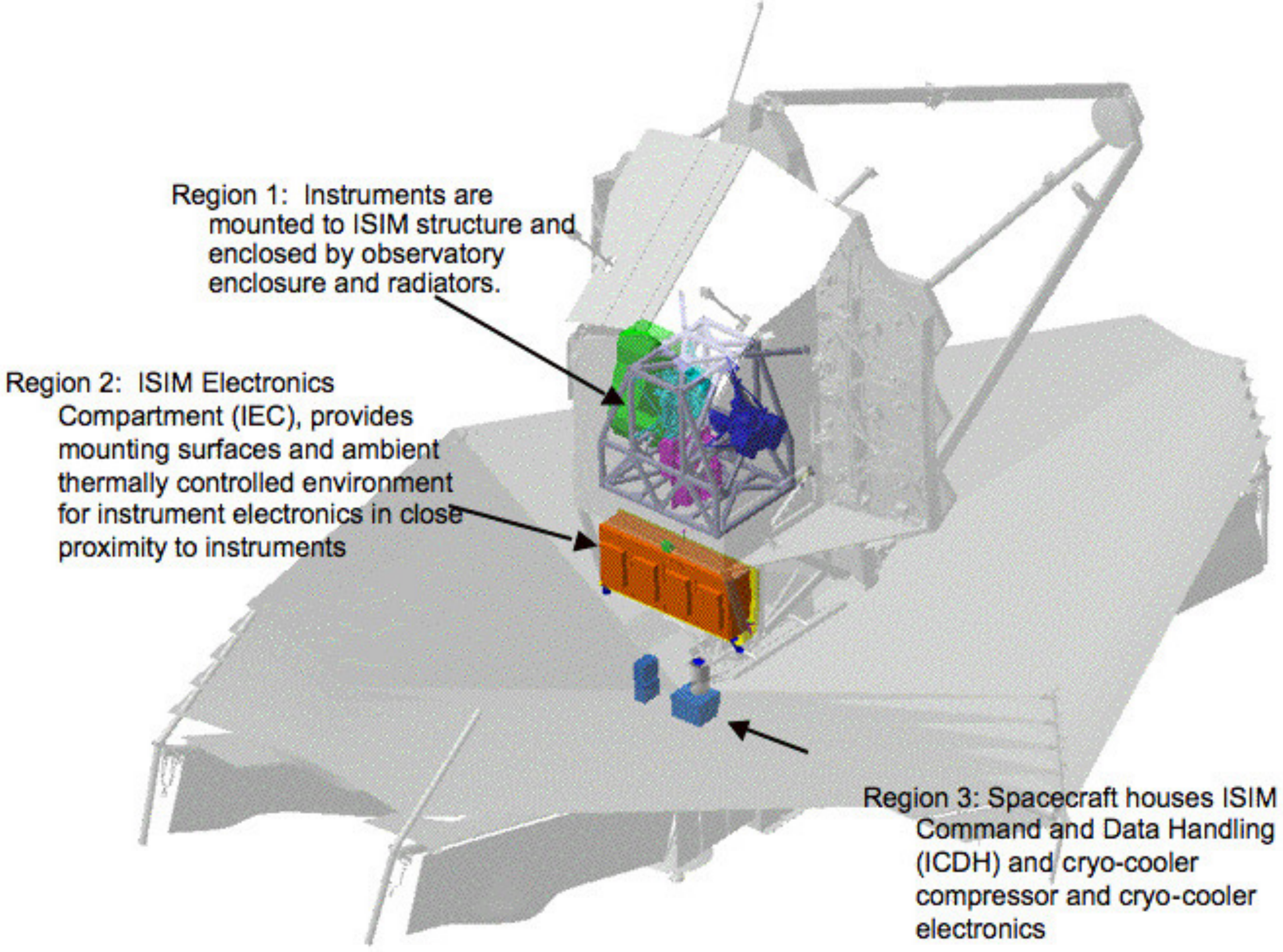


Feinberg, McElwain, Bowers, et al. 2023, JATIS (submitted)

IEC Cyclic Wavefront Drifts

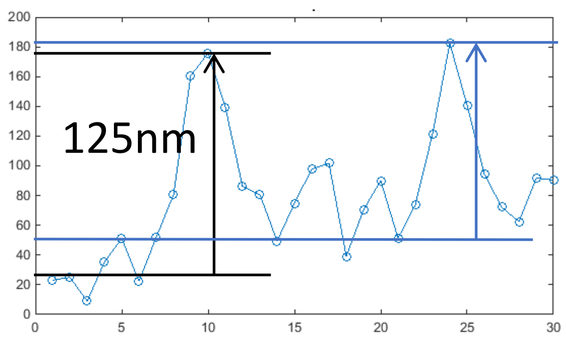
Instrument Electronics Compartment

- IEC electronics operate at ~280 K
- IEC electronics boxes use bang-bang heaters for thermal control
- IEC electronics boxes are connected via harnesses to the science instruments.

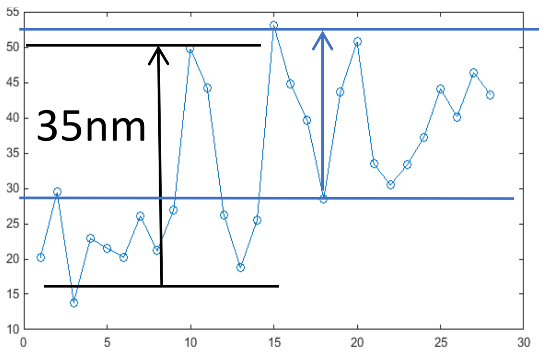


Cyclic Drift Instabilities Observed in OTIS cryotest)

- Large cyclic wavefront errors observed in test and correlated to IEC temperature control cycle
- During JSC there was a mechanical short between the IEC and Backplane from the GSE
- At the end of the test, the short was offloaded (using a large flexure) and showed the cyclic behavior greatly reduced
- Dead band was reduced from ± 1.0 K to ± 0.25 K, wavefront oscillations mitigated
- Analysis indicated not worth implementing pseudo PID control (complicated, late)
- Residual effect expected in flight; integrated modeling predicted 3.5 nm oscillations

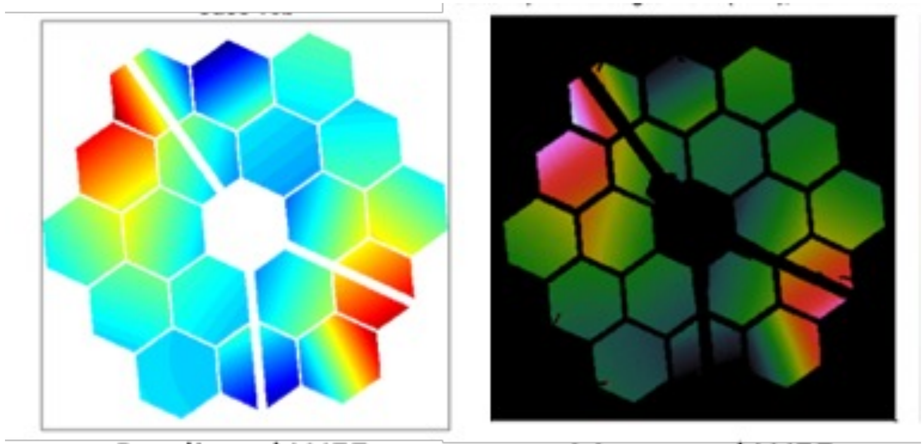


± 1.0 K
IEC heater dead band



± 0.25 K
IEC heater dead band

Harness Short Model Validation

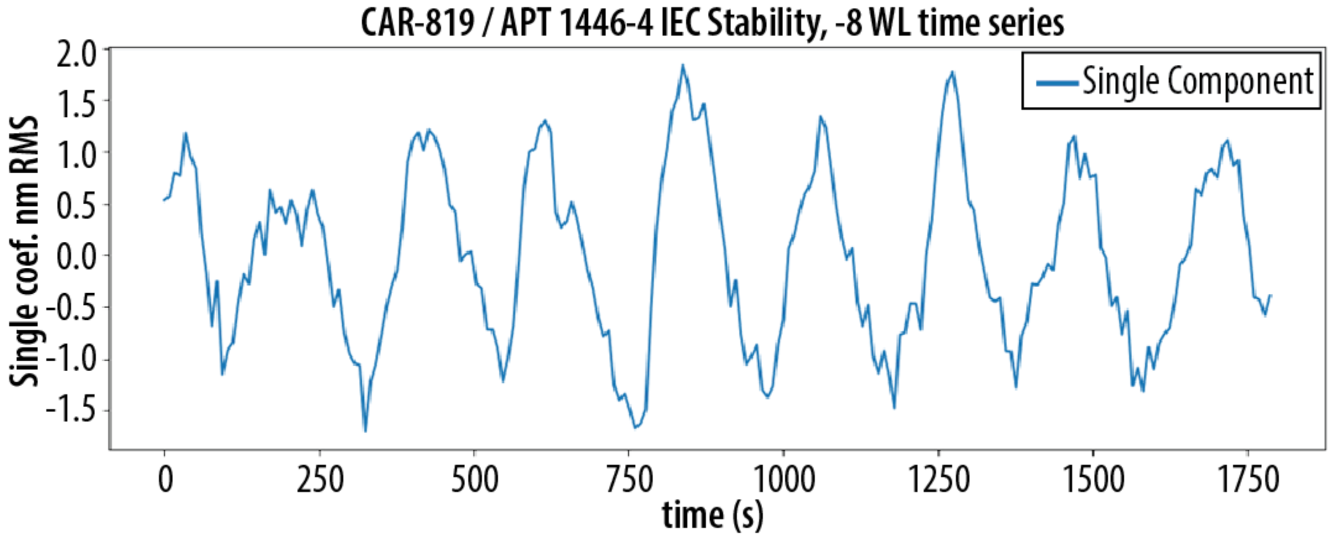


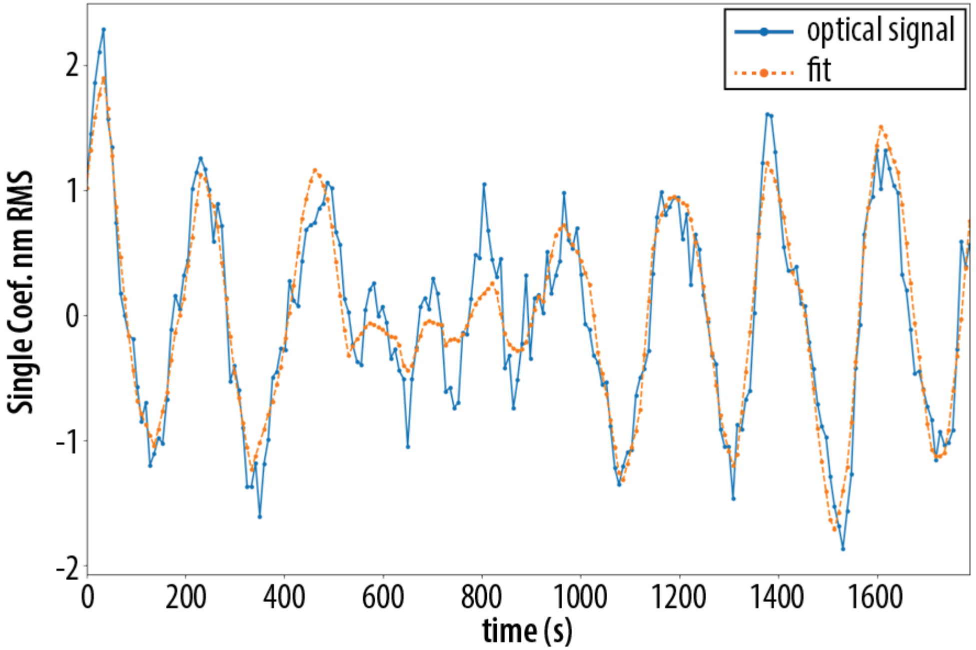
Predicted WFE
162nmRMS

Measured WFE
174nmRMS

IEC Cyclic Drifts Measured with 8.5 s sampling

- Cyclic drifts expected from IEC panel heater on-off cycle.
- Wavefront is primarily focus and astigmatism (single component model mixes focus and astigmatism).
- Delta WFE monitor achieved ~200pm resolution performance (analysis by Alden Jurling, GSFC).
- Transit spectroscopy measurements report correlated noise at timescales < 5 minutes, attributed to uncorrected noise from the IEC heater thermal cycling (Lustig-Yaeger et al., 2023).





Measured and Predicted Instabilities

Contributor	Predicted Amplitude (WFE nm rms)	Measured Amplitude (WFE nm rms)	Predicted Response	Measured Response
IEC Heater Cycling	3.5	2.5	240-480s period oscillation	224 s period oscillation
Frill & PMSA Closeout	9	4.45±0.19	8-10 hr time constant	0.77 hr time constant
Thermal Distortion	14.4	17.94±0.39	5-6 day time constant	1.41 day time constant

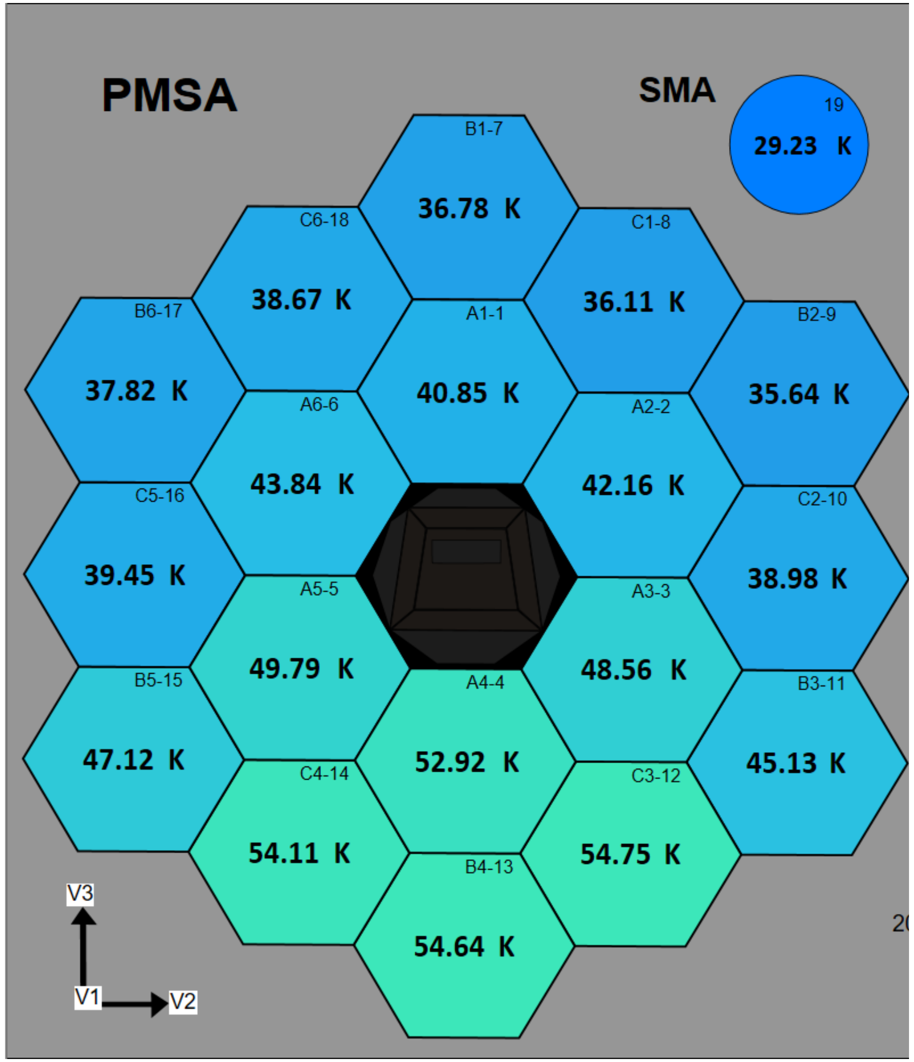
*The predicted values reported are for the beginning of life properties and including model uncertainty factors.

Feinberg, McElwain, Bowers, et al. 2023, JATIS (submitted)

Primary Mirror Segment Assembly Tilt Events (now infrequent)

Cooldown Created Mechanical Stress

- Passive cooling to its operational temperature by the 5 layer sunshield.
- Cooldown from room temperature to cryogenic temperatures created stress within the telescope materials and interfaces.
- Structural stress relief manifests itself as stick-slip releases, tilting the optical elements (called "tilt events").
- Tilt events were frequent early in the mission but have decreased in frequency as the structure equilibrates.



Tilt Events

- Frequency has reduced considerably as the OTE structure has equilibrated.
- Easily measured with wavefront sensing and corrected as needed.

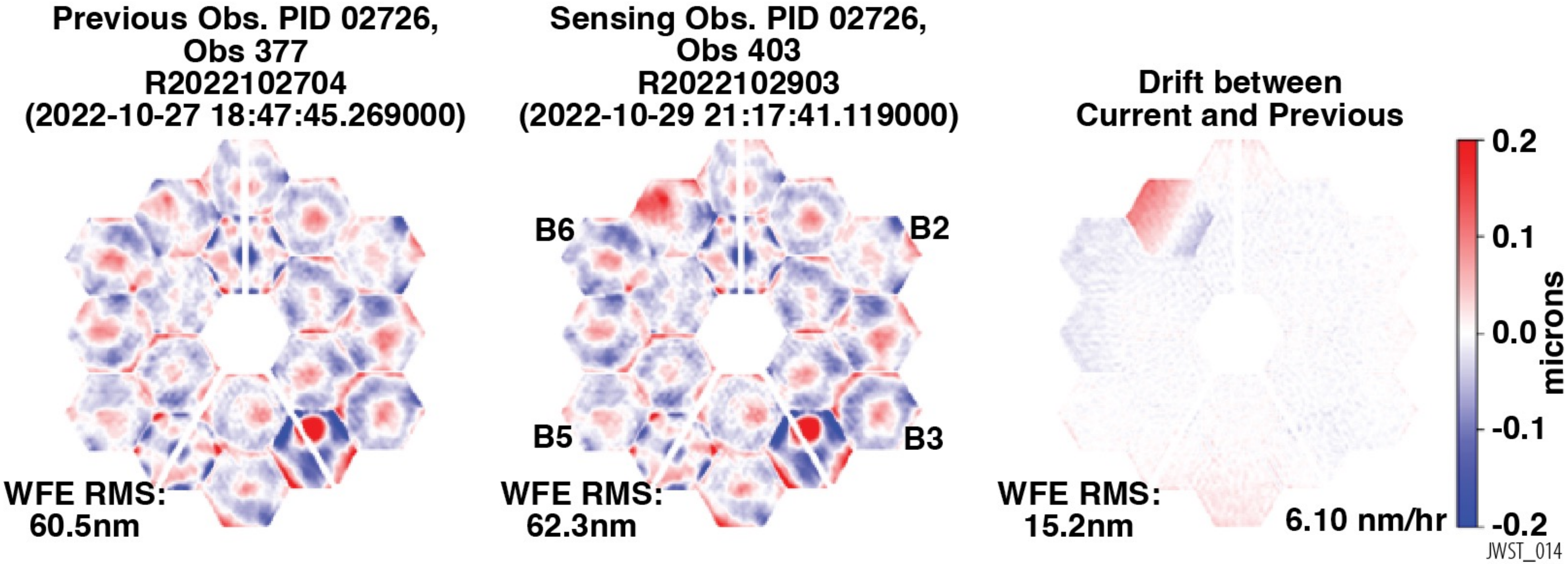
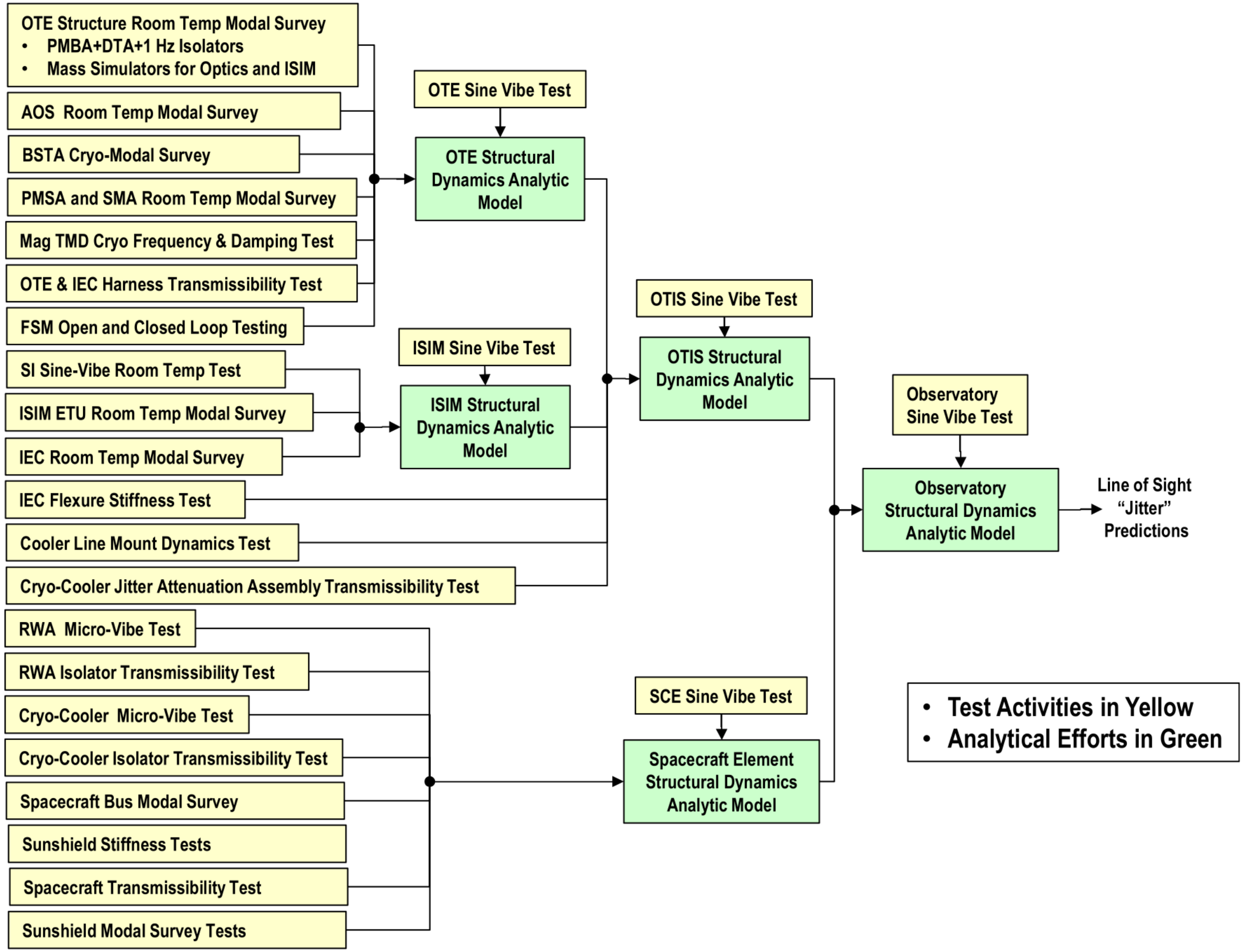


Image Motion

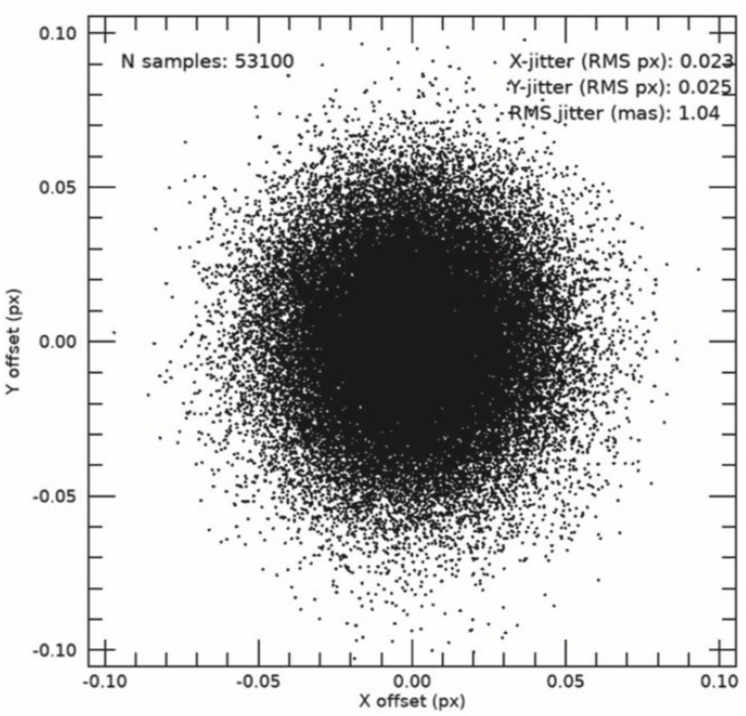
Jitter Verification by Analysis with Integrated Modeling



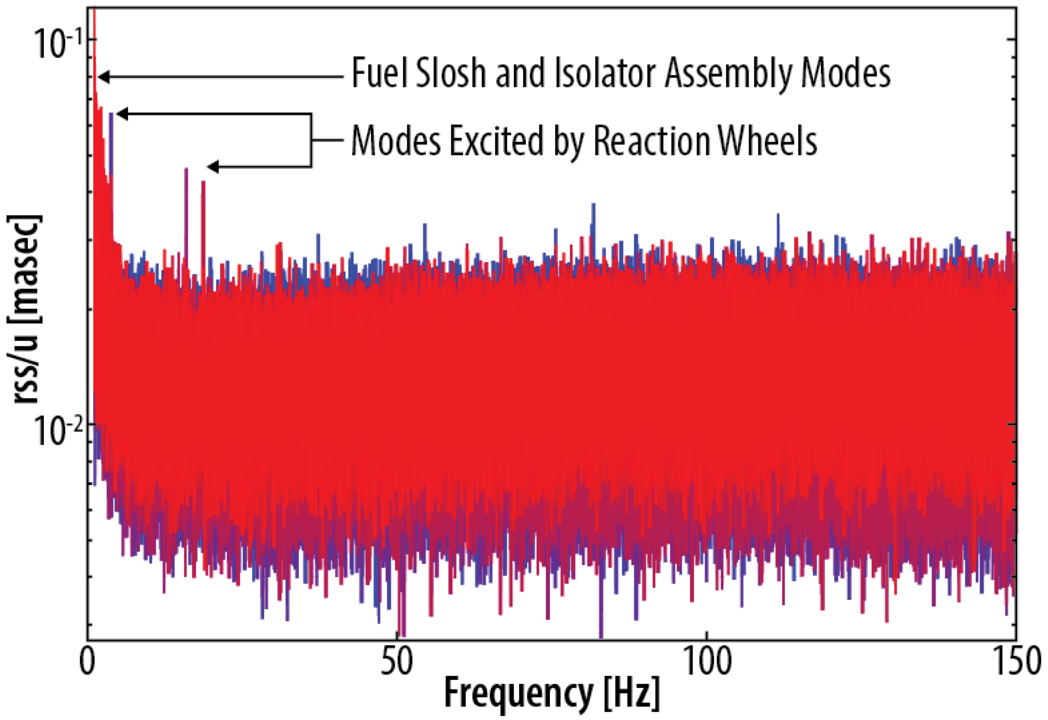
Menzel, Davis, Parrish et al., 2023, PASP Special Issue

Jitter Measurements

Typical Jitter Measurement



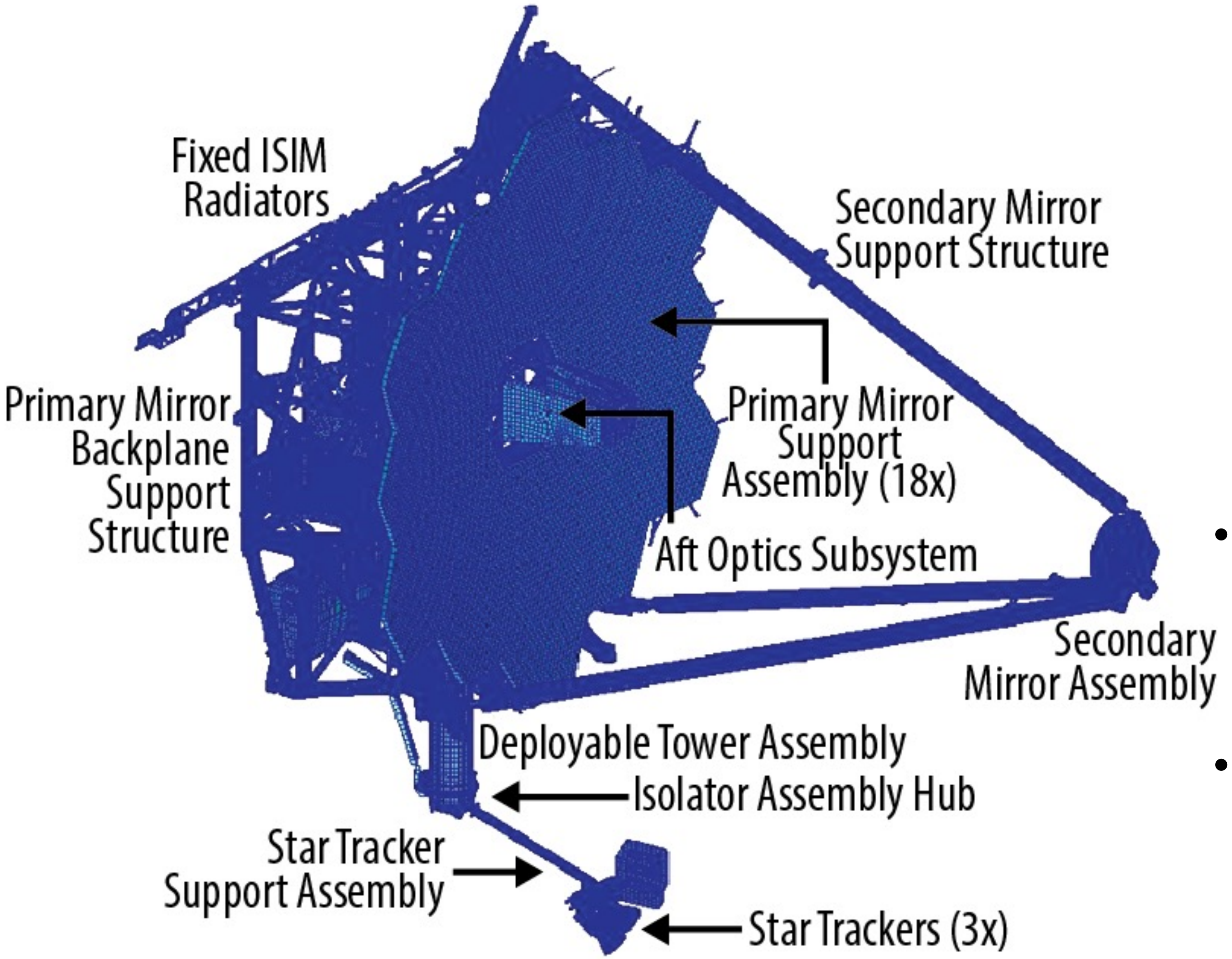
PSD Showing Excited Modes

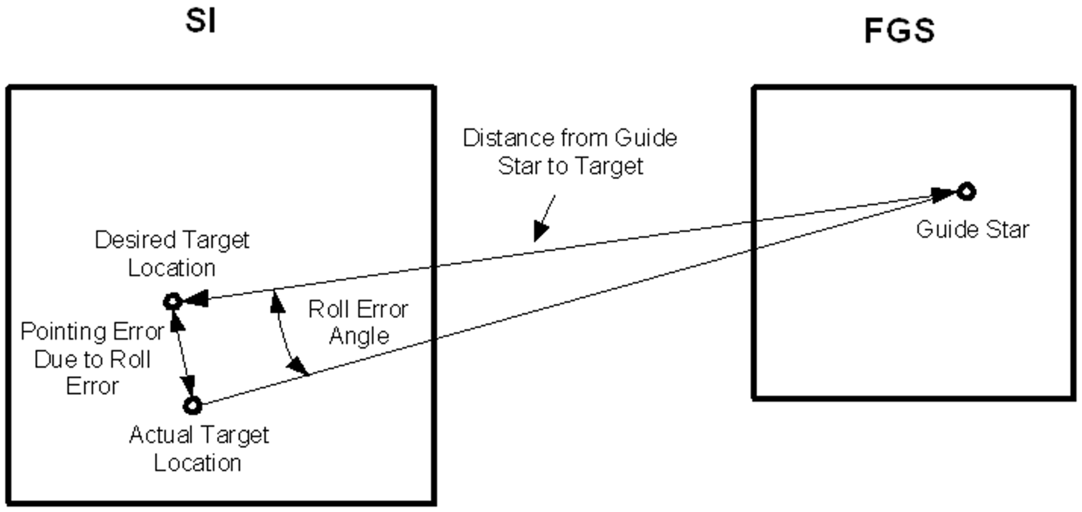


- Typical jitter rms is ~1 mas radial (cf. ~7 mas rms over 15 s requirement)
  - NIRCam 8x8 pix readout with 2.2 ms frame rate (=460 Hz = 230 Hz Nyquist frequency) for ~2 min
- Expected contributions from reaction wheels and cryocooler exported vibrations less than predicted (conservative modeling)
  - *Cryocooler tuning and Reaction Wheel push through algorithm (PTA) not needed!*
- Jitter measurements every 2 days as part of the routine wavefront sensing measurements.

Hartig & Lallo 2022, JWST-STScI-008271 Memo

Pointing Instability Overview

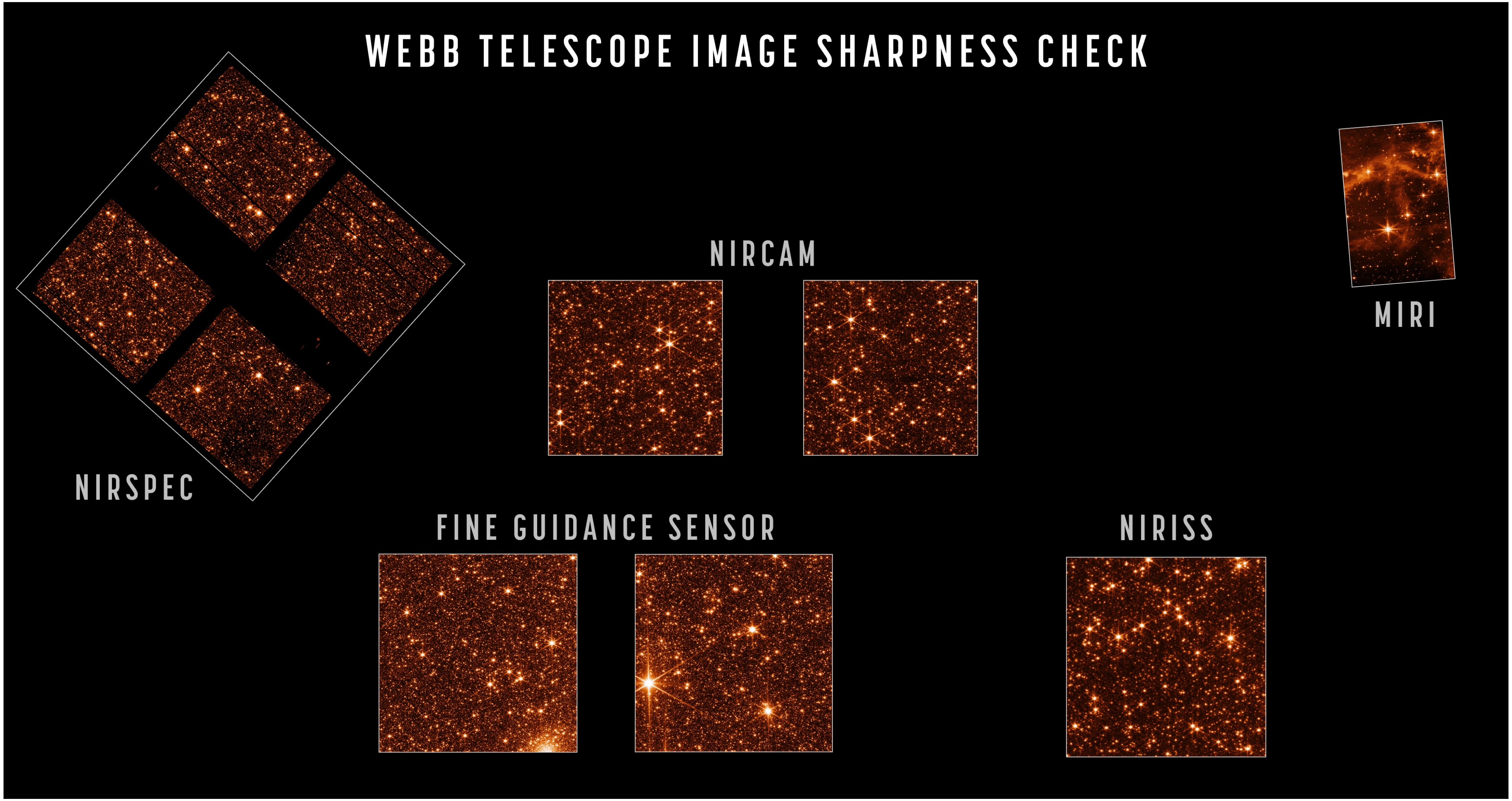




- Pointing instability following slews (τ~1 hr) can arise due to the different locations of the startracker (ST) in Thermal Region 3 on the spacecraft (hot) side of the Observatory and the fine guidance sensor (FGS) in Thermal Region 1 on the telescope (cold) side.
- Relative ST and FGS thermal drifts will cause inter-boresight motion that produces a guide star offset in FGS in the V2/V3 plane, which will be corrected through the ACS loop with offset loops and FGS to J-frame updates, and rotational drift about the V1 axis. The rotational drift is not sensed by the ACS system and not corrected.

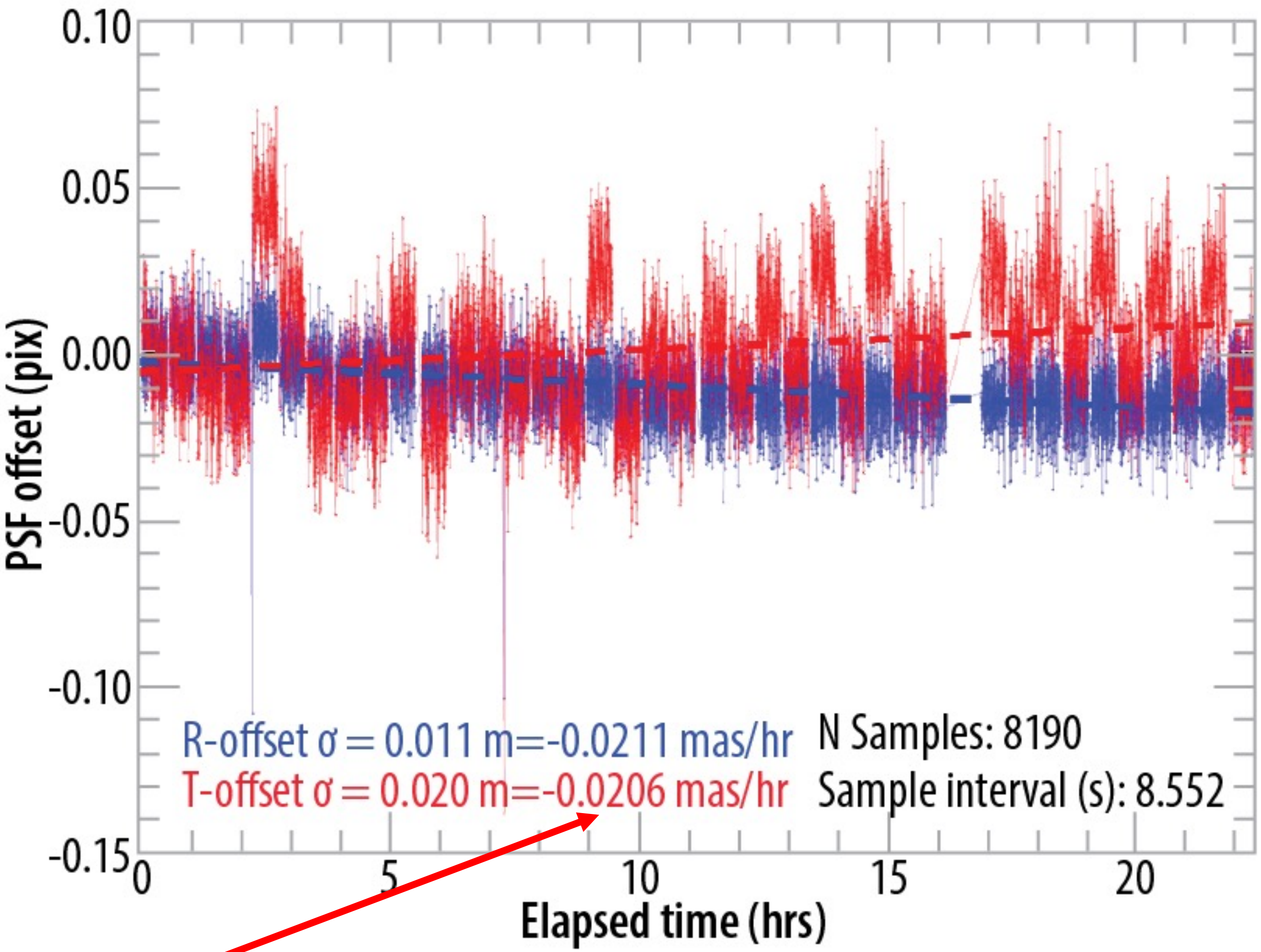
Feinberg, McElwain, Bowers et al. 2023, JATIS Submitted

Science Instrument Focal Plane Arrangement



On-orbit Pointing Stability Measurement using NIRCam

NIRCam shortwave platescale is 31.1 mas/pix



Predict 0.79 mas/hr

Hartig & Lallo 2022, JWST-STScI-008271 Memo

Environmental Factors: Micrometeoroids

See Menzel's talk at this conference

Lessons Learned

Some Stability Lessons Learned

- Piecewise verification by analysis works
- JWST wavefront sensing demonstrated in the sub-nm regime
- Soft structure is prone to workmanship issues and is difficult to verify
- Tilt event instabilities may be present for similar composite structures with wing latch interfaces
- Model uncertainties are required for requirements verification but can lead to conservatism. How you evaluate the model uncertainties should be revisited on a case by case basis. Day in the life at beginning of life performance should be emphasized too.
- Harness properties should be carefully included in thermal distortion models
- Avoid bang-bang heater control; include thermal control in integrated models
- Independent modeling and analysis is valuable throughout the development

Key References

JWST Topic	Reference
Telescope Development, Performance, Lessons Learned	McElwain, Feinberg, Perrin, et al., 2023, PASP, 135, 058001
Telescope Imaging Performance	Knight & Lightsey, 2022, SPIE, 12180, 121800V
Observatory Development & Performance	Menzel, Davis, Parrish, et al., 2023, PASP, 135, 058002
Line of Sight Measurements During Commissioning	Hartig & Lallo, 2022, JWST-STScI-008271
Science Performance	Rigby, Perrin, McElwain, et al., 2023, PASP, 135, 048001
Cycle 1 Wavefront Trending	Lajoie, Lallo, Meléndez, et al., arXiv: 2307.11179
Stability Lessons Learned	Feinberg, McElwain, Bowers, et al., 2023, JATIS (submitted)
Integrated Modeling Lessons Learned	Levine & Mosier, 2023, SPIE Optics + Photonics 2023