Centrum Badan Kosmicznych PAN

Webb Space Telescope
Mechanical Systems Challenges

Sandra Irish
NASA/GSFC
JWST Mechanical Systems
Structures Lead
sandra.m.irish@nasa.gov

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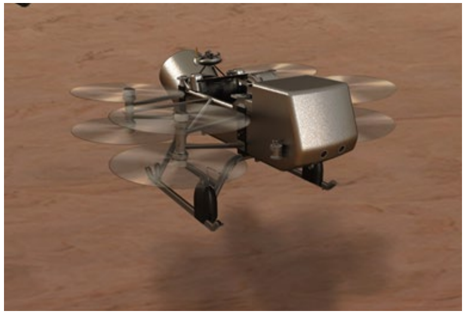
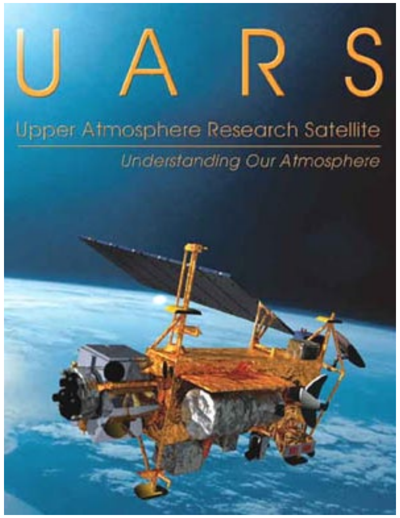
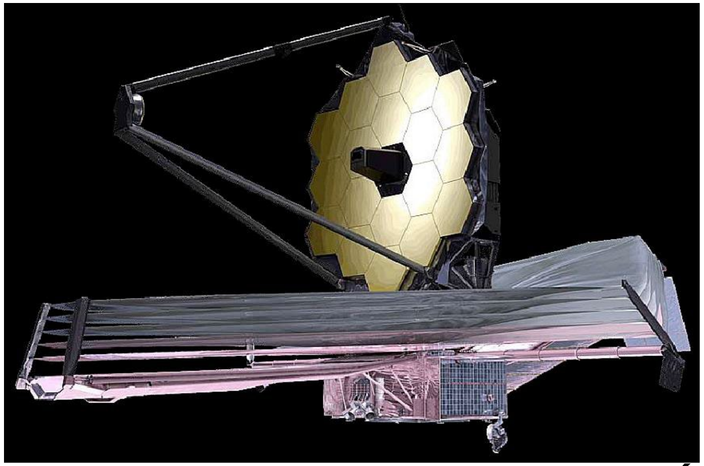
Introduction - Sandra Irish

- **BS Aerospace Engineering**
  - Aerodynamics focus
  - Worked in Glen L Martin wind tunnel
  - Boeing was my dream job!
- **NASA/GSFC**
  - 40 years in Mechanical Systems Analysis
  - Group Lead, Mechanical Systems Analysis and Simulation Branch, Code 542
- **Work Assignments**
  - Cosmic Background Explorer (COBE), First Light
  - UARS, BBXRT, ASTRO-E, ASTRO-E2
  - *James Webb Space Telescope (JWST) Mechanical Systems Structures Lead Engineer*
    - *Responsible for mechanical analysis and testing for launch and on-orbit mechanical performance*
- **Current position is Dragonfly Mass Spectrometer Structural Loads and Test Engineer**







Topics of Discussion

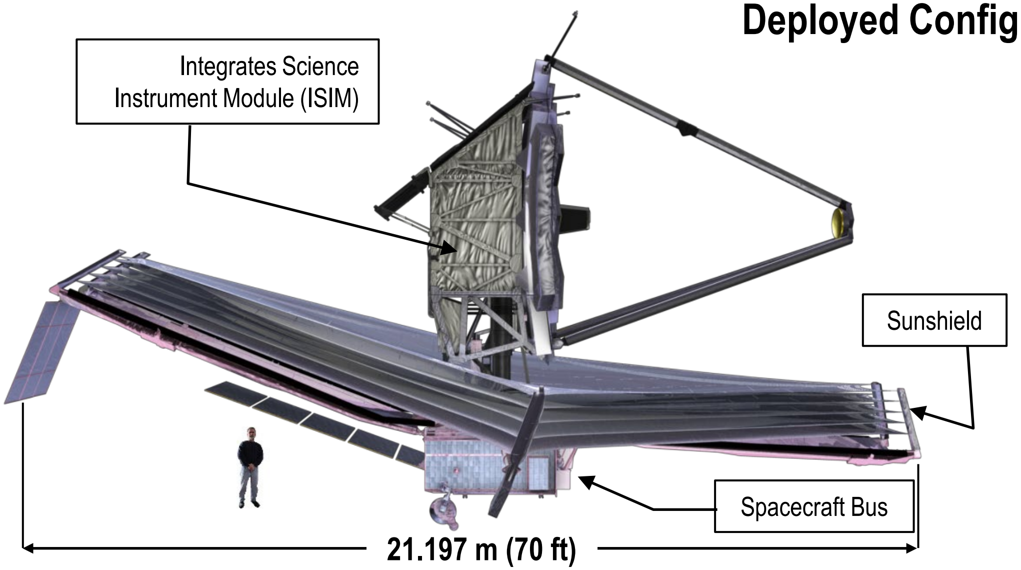
- **James Webb Space Telescope (JWST) Mission Overview and Engineering Design**
- **Mechanical Systems Challenges**
  - Focus on Structural Dynamics
- **Observatory Launch and On-Orbit Commissioning**

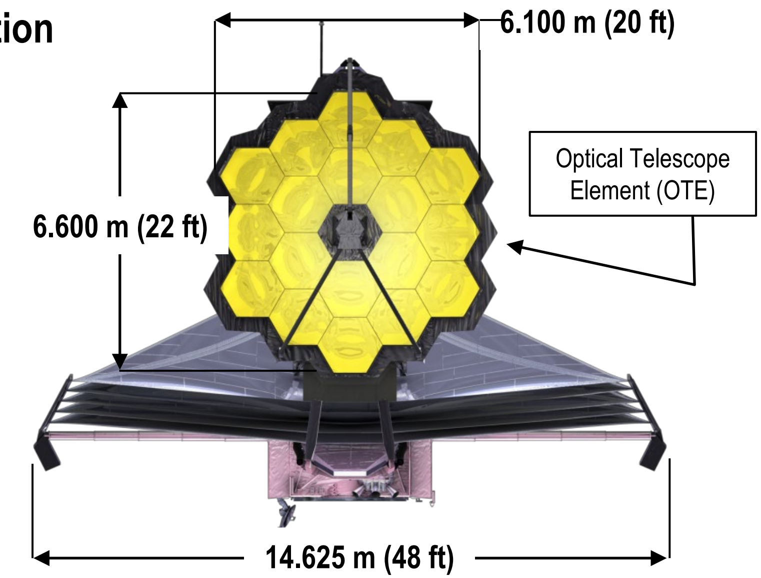
JWST Observatory Mission Overview

- **The James Webb Space Telescope (JWST) is a large infrared telescope with a 6.5-meter primary mirror (~6 times the size of the Hubble mirror).**
- **Webb is the premier observatory of the next decade studying First Light after the Big Bang, Galaxy Assembly, Birthplaces of Stars, and evolution of planetary systems.**
- **International collaboration: NASA, ESA, CSA**
- **Mass** JWST Observatory is 6310 kg (allocation)
- **Dimensions (stowed)** observatory is ~10m x 4.5mØ
- **Integrated and ambient tested Telescope at NASA/GSFC**
  - Integration, acoustics, sine vibration
- **Cryogenic tested Telescope at NASA/JSC**
- **Integrated and test Observatory at Northrop Grumman, CA**
  - Integration, acoustics, sine vibration
- **Shipped from Seal Beach, CA to Kourou, French Guiana**
- **Launch was on the Ariane 5 rocket, from Guiana Space Center in Kourou, French Guiana on Dec. 25, 2021.**

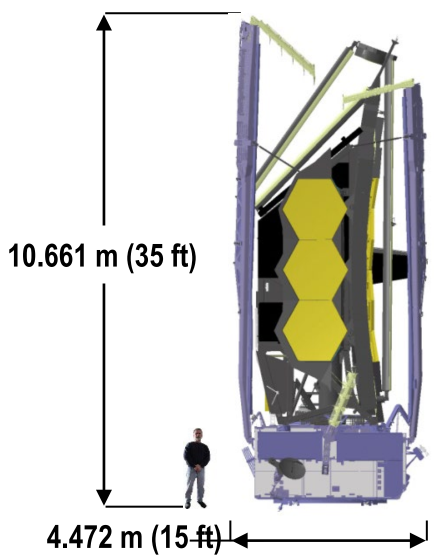
JWST Observatory Engineering Design

Deployed Configuration



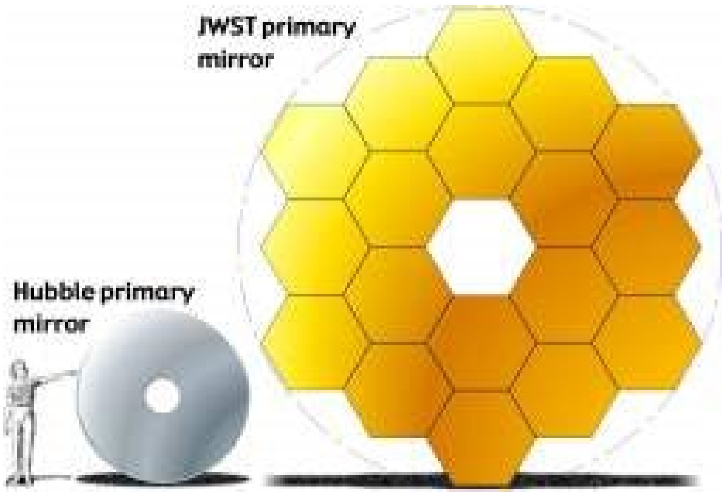


Stowed Configuration



- **Optical Telescope Element (OTE) diffraction limited at 2 micron wavelength.**
  - 25 m^2, 6.35 m (21 ft) average diameter aperture.
  - Deployable Primary Mirror (PM) and Secondary Mirror (SM).
  - 18 Segment PM with 7 Degree of Freedom (DOF) adjustability on each.
- **Integrated Science Instrument Module (ISIM) containing near and mid infrared cryogenic science instruments**
  - Cryogenic Instruments: MIRI, NIRCam, NIRSpec, FGS
- **Deployable sunshield for passive cooling of OTE and ISIM to below 50K (-370 F).**
- **OTE + ISIM referred to as OTIS or Telescope**
- **Mass: < 6310 kg (13910 lb) .**
- **Life: Designed for 10 years of operation.**

Comparison of JWST to HST Design Challenges



JWST Design Challenges

Performance Parameter	HST	JWST
OTE Diameter (meters)	2.4	6.1 by 6.6
Mass (kg)	11600	6310
Power (watts)	2400	2079
Light Collecting Aperture (Sq meters)	3.8	25
Overall Optical Transmission	45 to 25%	62% to 43%
OTE FOV (Arcmin)	14.6 (Radius)	~18 by 9
Wavelength of Diffraction Limit (Microns)	0.5	2
Rayliegh Radius (Arcsec)	0.043	0.069
OTE Strehl	80%	80%
Bulk Observatory Operating Temperatures	283K to 313K	40K to 400K
Pointing Accuracy (Arcsec)	22	7
Pointing Stability (Arcsec)	0.007	0.007
Total Pixels (mpixels)	56.8	66.1
Data Throughput (Gbits/day)	27	458
Observing Efficiency	50%	70%

JWST Deployments: Over 6m dia. Fit in a 5m LV Fairing

~½ the mass of HST

Over 6.5 times the light collecting area of HST

Order of magnitude colder than HST. Roughly 4000 kg needs to be cooled below 50K

Mechanical System Challenges

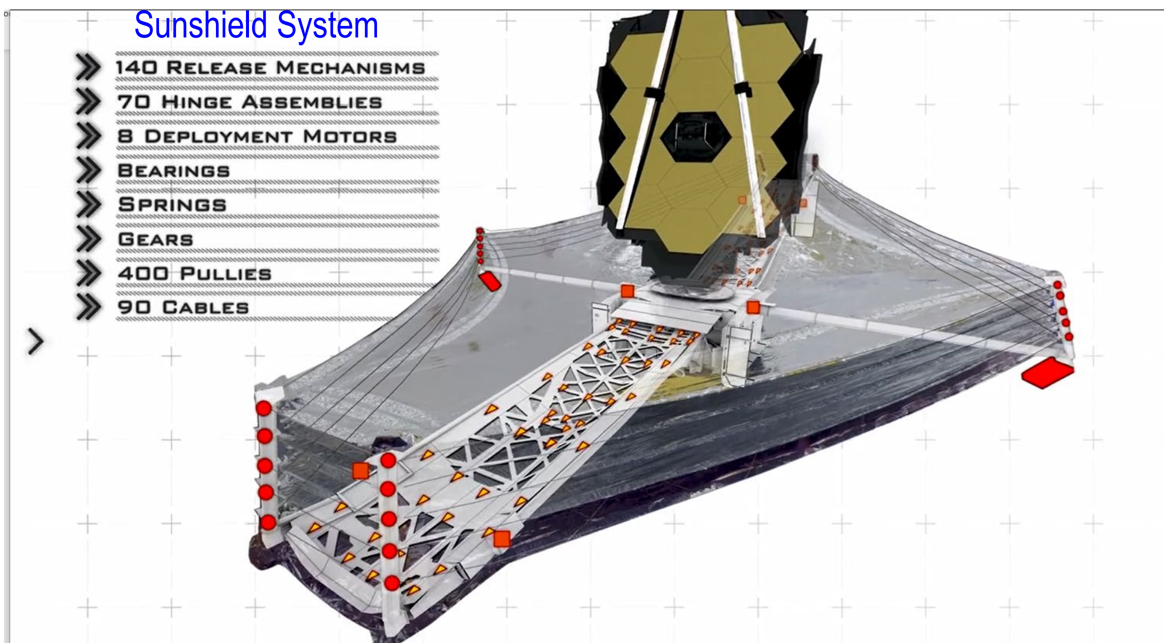
- **Unique Mechanical System challenges for JWST include:**
  - Deployments
  - Cryogenic Telescope
  - Verification
  - Ship Transport

Deployments

- Largest space telescope every built by NASA had to fold and fit into the A5 Rocket Fairing 5.4 m (17.7 ft) diameter
- *50 Major Deployments* to its deployed configuration
- *178 Release Mechanisms* all had to work!
  - Sunshield most complex deployment system
  - Redundant low shock devices
- Sunshield membranes and telescope thermal multi-layer insulation concerns with snagging, billowing, clearances
  - Hardware inspected after every I&T Operation

29 days on the Edge JWST (Deployments)

https://www.youtube.com/watch?v=uUAvXYW5bml

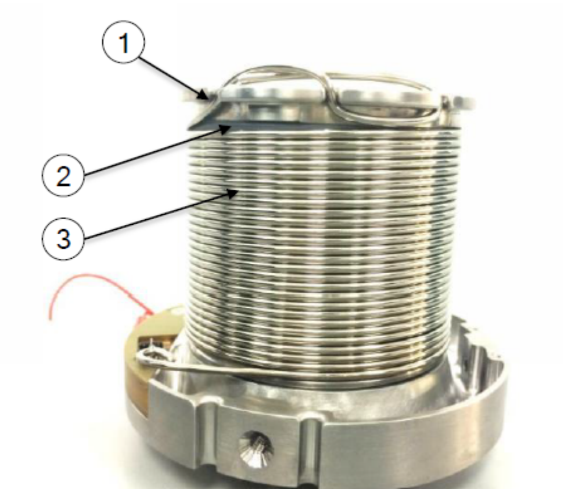


Non-Explosive Actuators (NEA) Concerns

- Custom ¾" NEA used for Telescope separation from Spacecraft.
- Found a concern with high shock load (> 2500 peakg SRS) when ambient release test performed
- Countless analyses and testing resulted in design changes to assure a reliable device for critical interface.
- Joint stiffness testing also performed.
- Recorded accelerometer data for all shock releases performed with the flight hardware to verify the updated design (max value recorded was less than 1800 peakg SRS requirement)
- Fatigue concern due to 14+ days ship voyage resulted in a MGSE joint design and Flight NEAs were installed in French Guiana.

The following key design features were changed or modified to resolve the issue of restraining wire fractures during actuation at max preload of 46,000 lbf

1. Spool Tie-off Slot
2. Dry Film Lubricant (DFL) on Spool
3. Restraining Wire

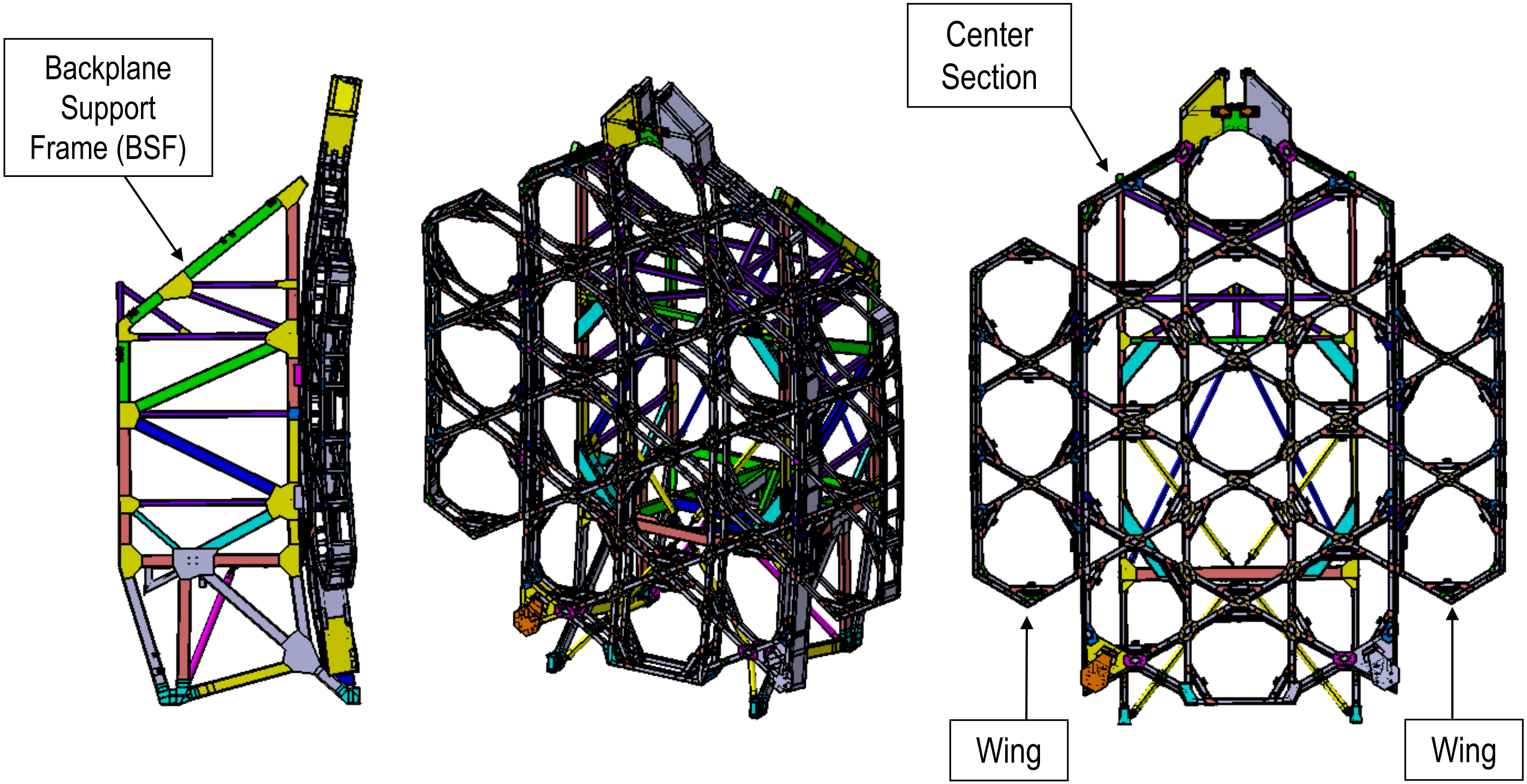


Extensive testing and design changes required to meet critical Spacecraft to Telescope Release low shock requirement.

Cryogenic Telescope

- Bonded joints/composite structure
- Cryo Temperatures (design for 25 – 323 K)
- Cryo Shock Load Environment

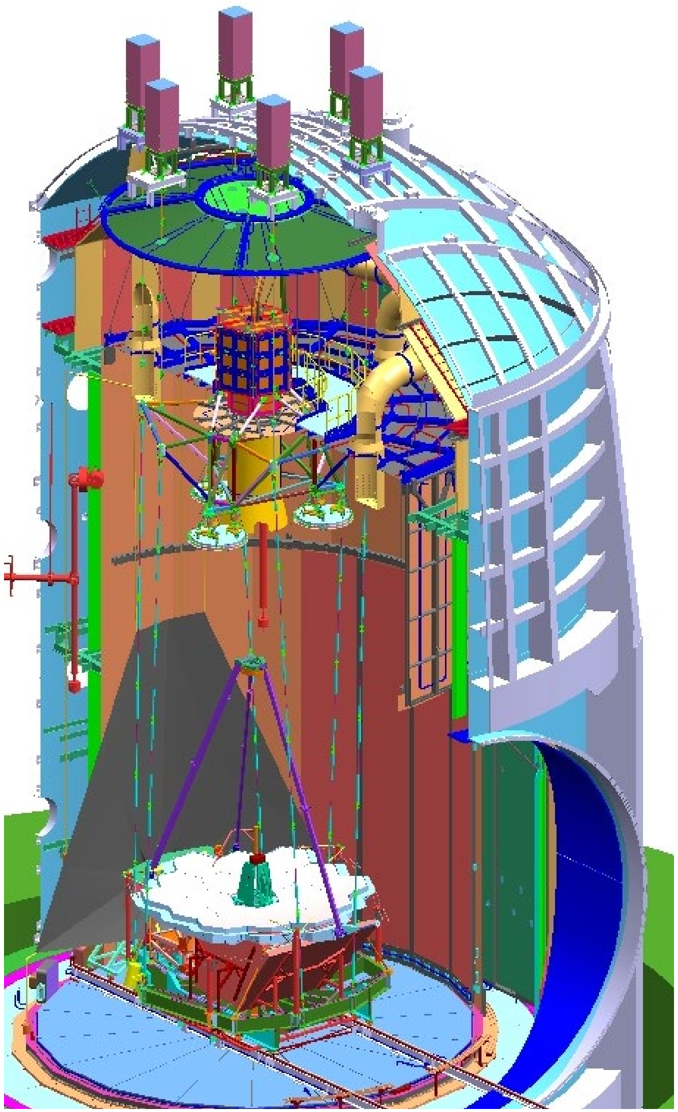
Telescope Backplane is a Tube Frame Composite Structure



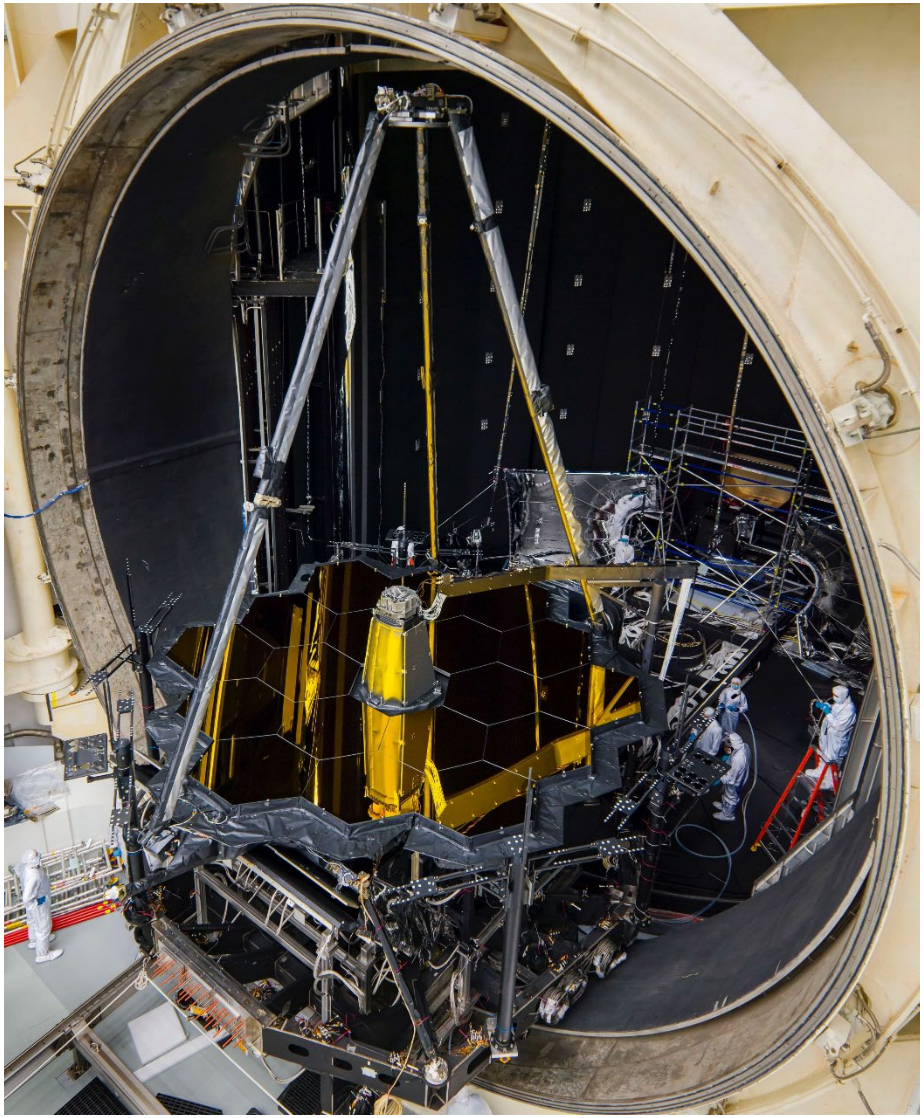
- Tube frame construction is a stiff, high load capable, low distortion design approach
- Open construction allows access to the many interfaces
- Composite tubes, metallic end fittings
- Maintain stability from 25 K to 323 K

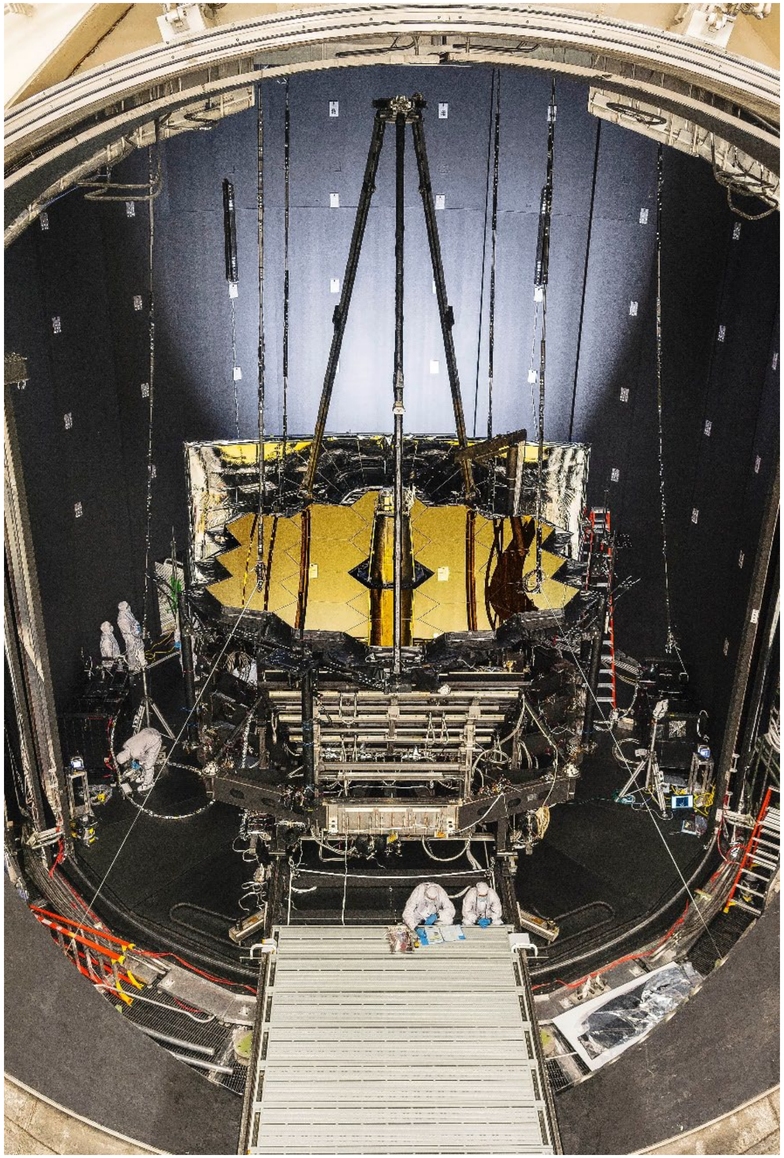
Cryo Environment

- **JWST Composite structures designed for large temperature range of 25 K (survival) to 323 K (launch ascent)**
- **Cryo-mechanical analyses performed to show positive margin with 1.5 safety factor**
- **Two cooldown tests performed to verify performance of GSE**
  - Required detailed modeling of isolation system and cryo test check-out
    - to reduce mirror distortions at cryo
    - To investigate damping at cryo and its affect to mirror tip/tilt modes
- **The Telescope CV test was a 3 month test of the flight telescope assembly under cryogenic temperature and vacuum environment.**
- **The test was conducted in the Chamber A facility at the Johnson Space Center (JSC).**
- **Perform optical test of the telescope assembly at cryo temperature.**



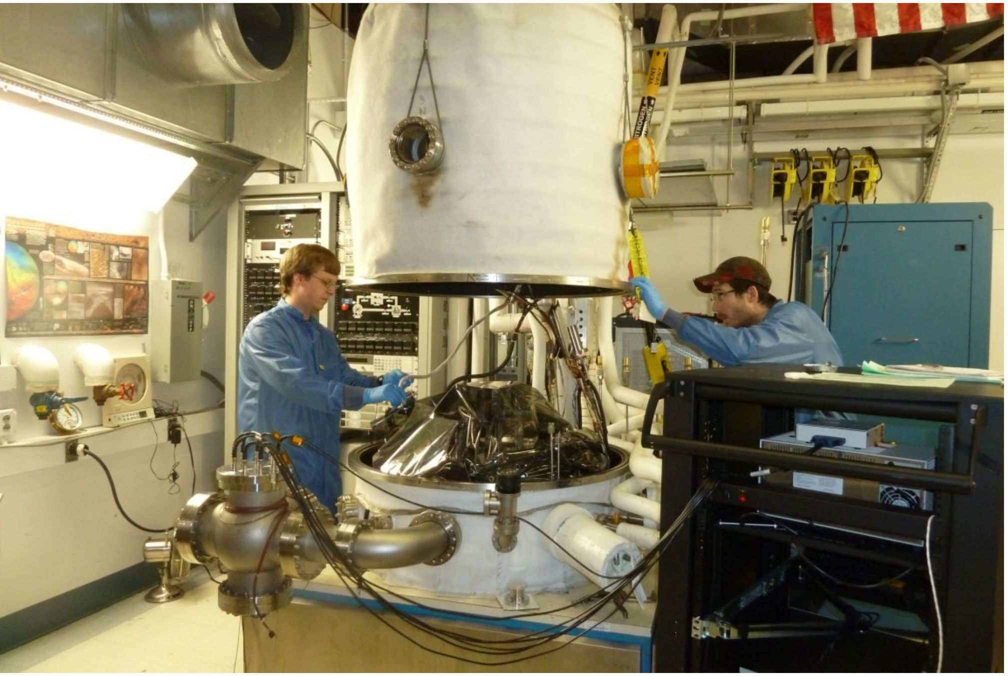
OTIS at JSC Chamber (before door close on July 12, 2017)

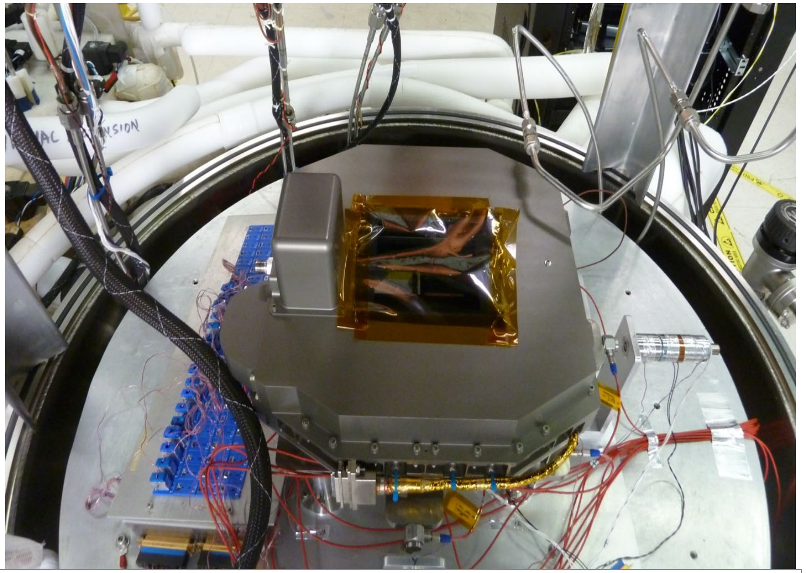


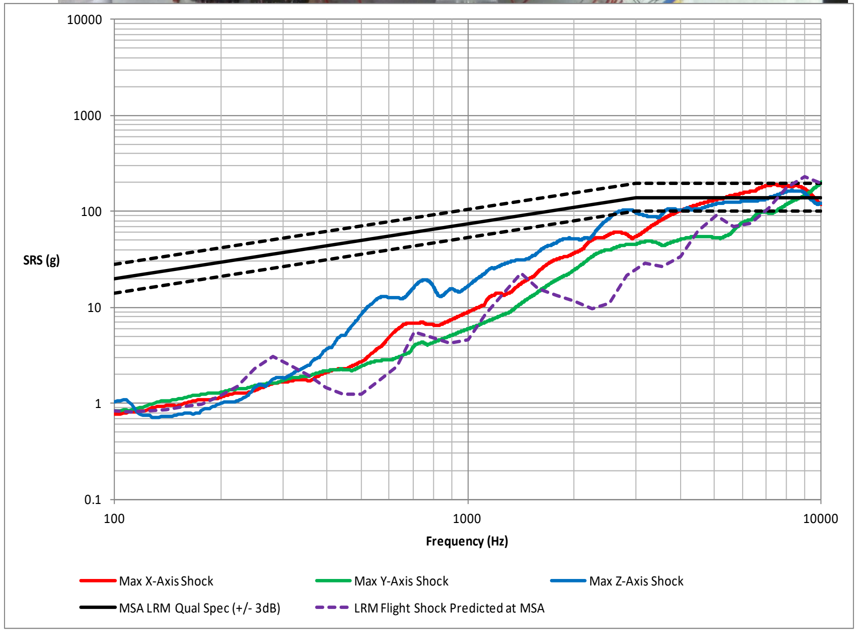


Component Cryo-shock Tests

- Shock attenuation increased for cryo composite hardware.
- Performed Cryo-shock tests on shock sensitive components: Applied high frequency shock level to ~100 gpeak at range of 85 – 160 K
- Tests performed at GSFC in Building 4 thermal chamber.
- Functional checking after test demonstrated success







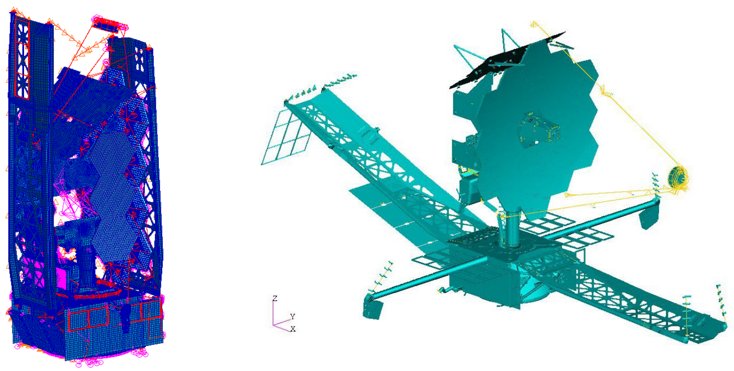
Verification

- Integrated System Modeling
- Specialized MGSE
  - Custom Shakers
  - Contamination Tent Frame
  - Earthquakes!
- A5 Requirements: Mechanical Testing
  - Multiple Coupled Loads Analysis (CLA) Cycles
  - Sine Vibration (Up to 100 Hz and Stay Above Floor Levels)
  - Acoustics (0 dB Tolerance and Homogeneity)

Verification Using Analytical Models

- **Verification of the stowed configuration and on-orbit performance involved analytical models which were correlated / anchored to "as-built" hardware by tests at lower levels of assembly.**
  - This proves that what is mathematically modeled is what was actually built.
- **Observatory system models were then assembled from these lower level models. The observatory level models were then correlated as practical to the as built observatory by system level tests.**
  - This proves the interfaces are modeled correctly.
- **The correlated models such as those shown on the right were used to predict and verify the on-orbit performance of:**
  - Thermal Performance
  - Optical Thermal Stability
  - Dynamics
  - Straylight

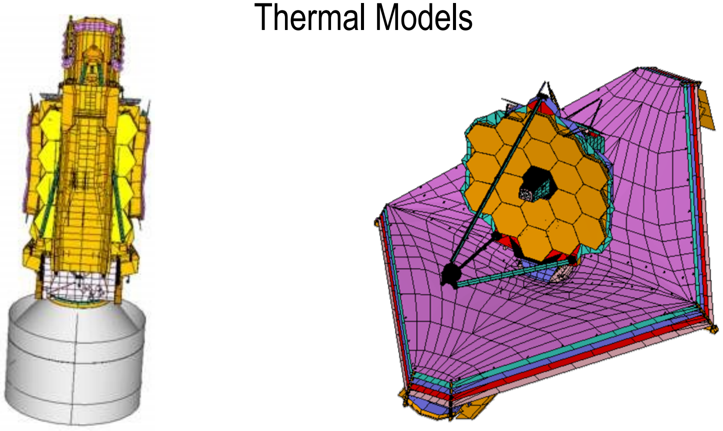
Structural Dynamics Models



Stowed

Deployed

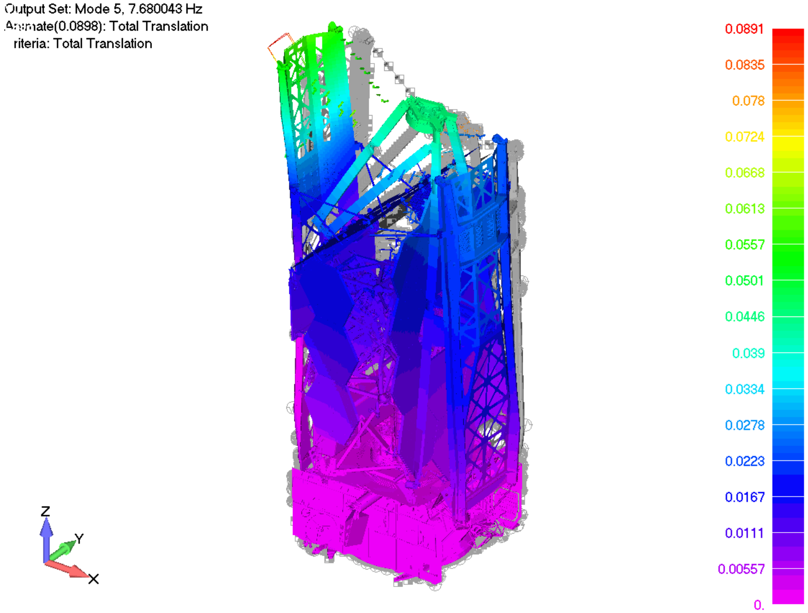
Thermal Models

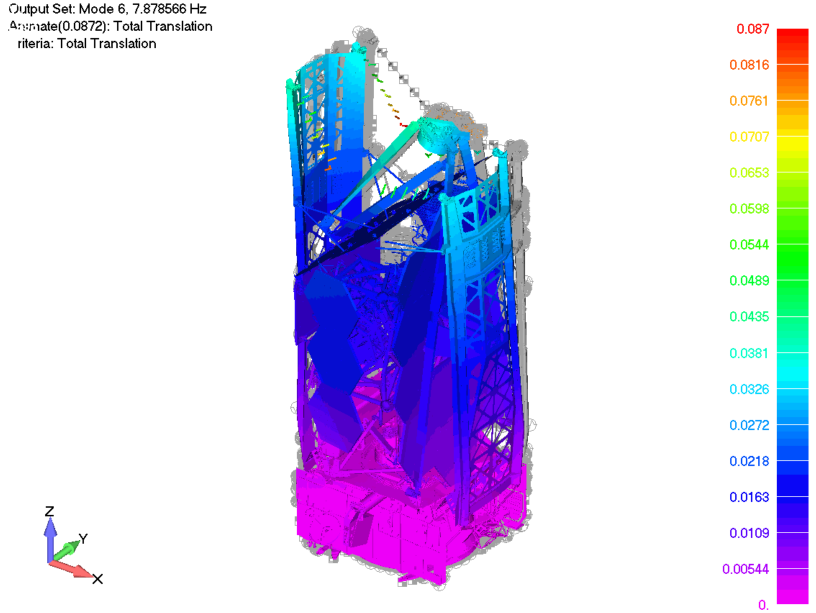


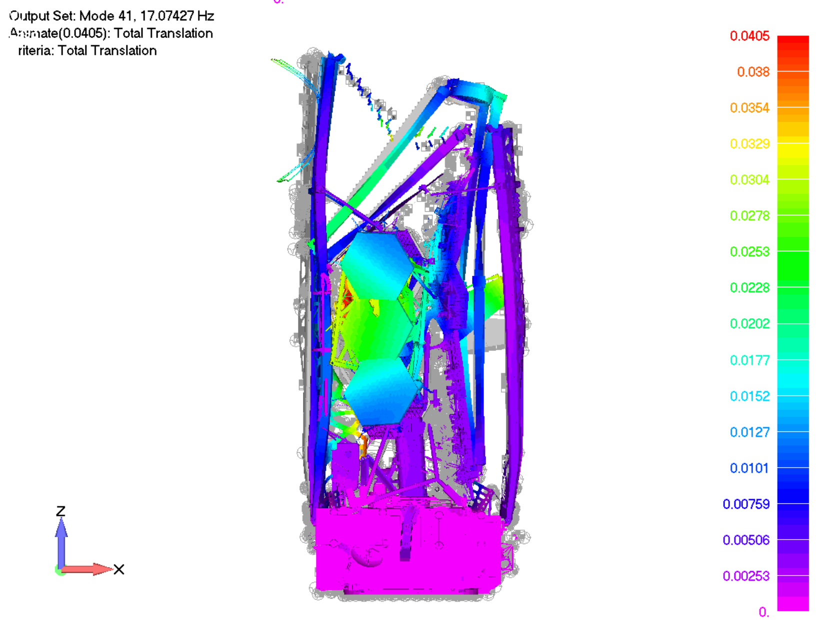
Stowed

Deployed

JWST Observatory Dynamics Analysis

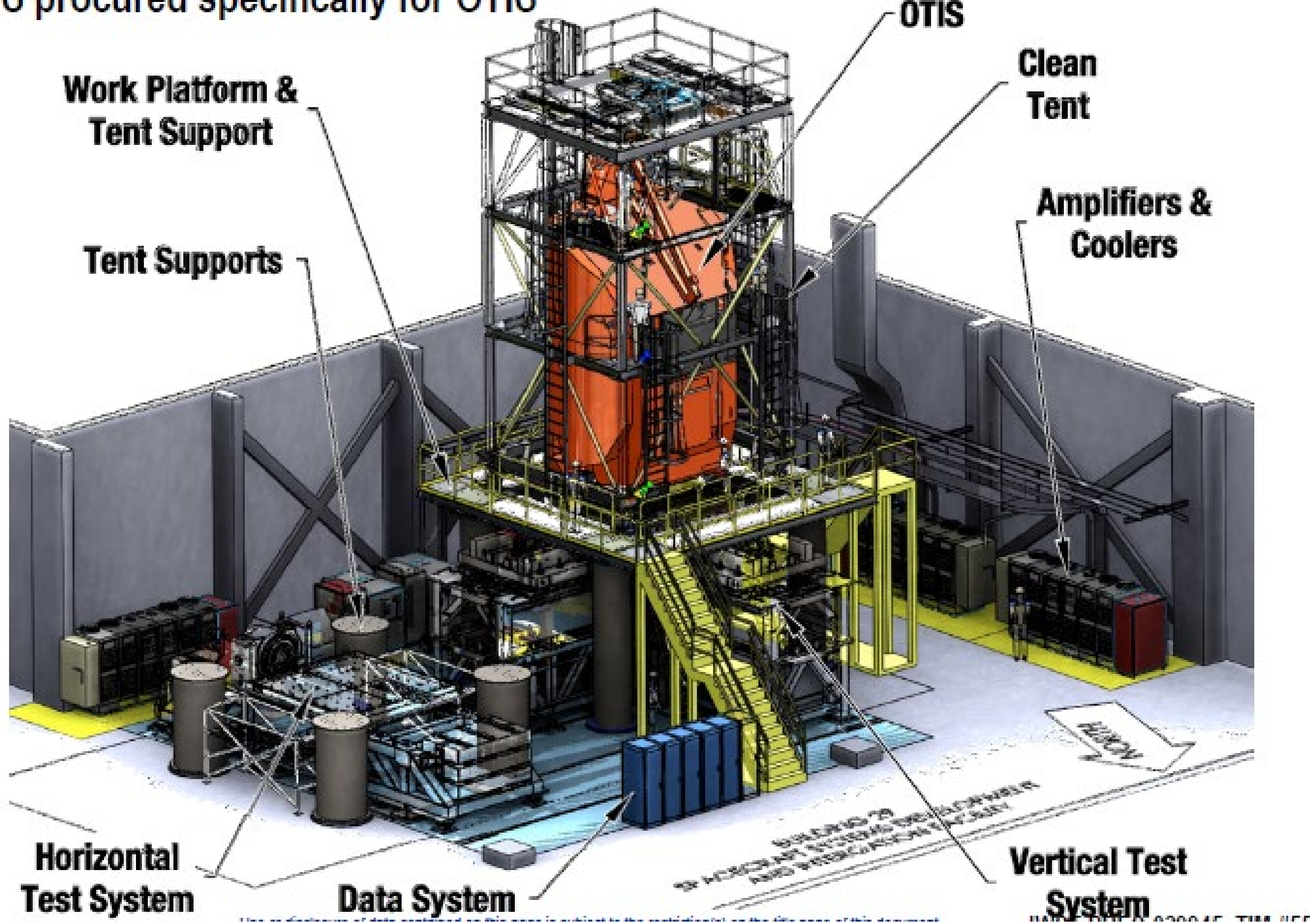






Specialized MGSE: Custom Shaker at NASA/GSFC JWST Vibration Test System (VTS)

- VTS procured specifically for OTIS



Key Facts of Custom Shakers at NASA/GSFC

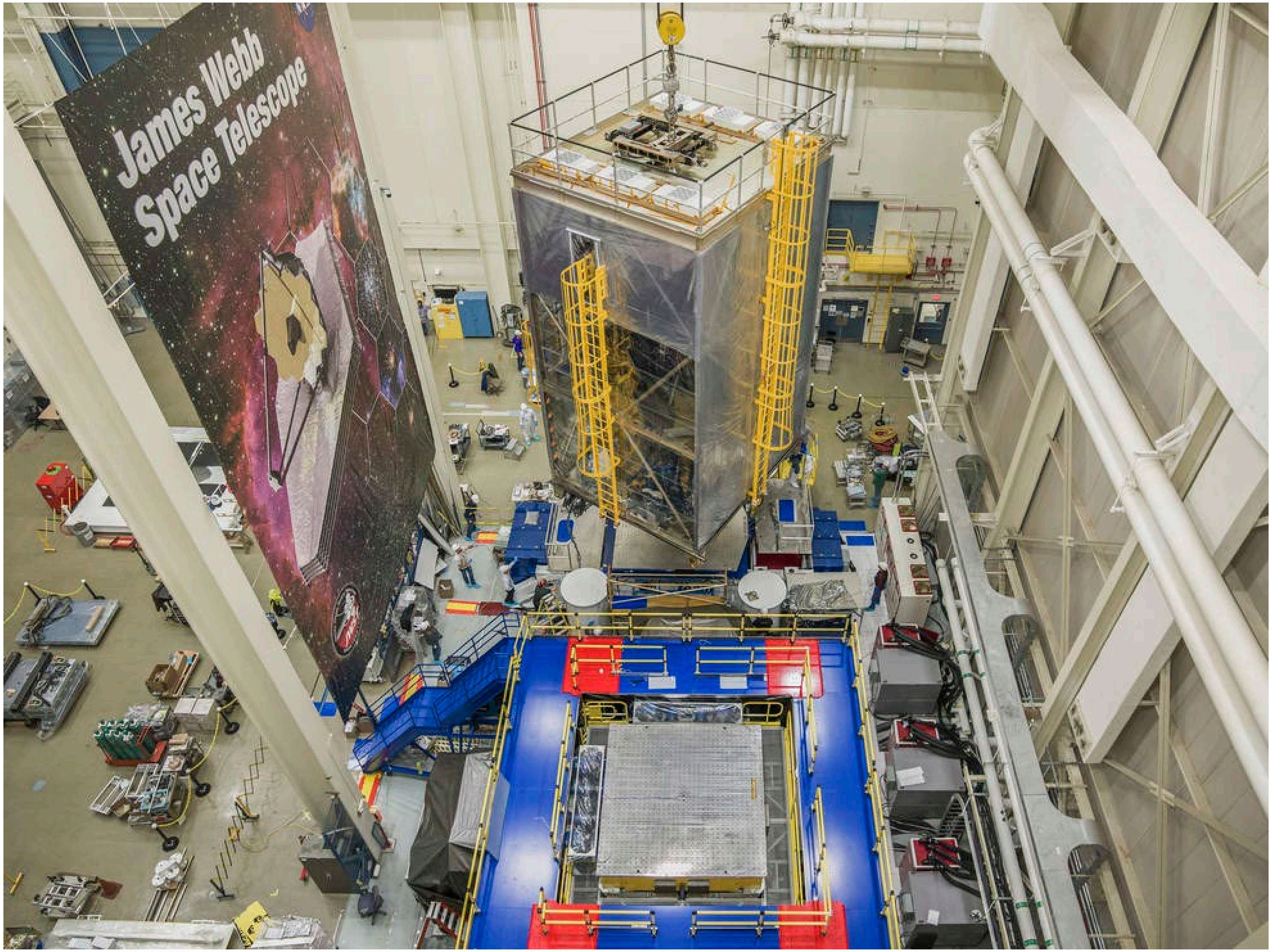
- **Fail-safe operation: system must shutdown “softly” to protect payload**
  - Performed analyses to determine safe shutdown duration for hardware
- **Clean environment provided by contamination tent—tent supports needed**
- **Large overturning moment due to offset CG (due to ISIM)**
  - Specify key requirements
    - Mass/force
    - Moments
    - Cross-axis response
- **Horizontal slip table configuration expected to provide full levels for 2 lateral axes**
- **Vertical facility requires guided head expander to react overturning moments**
  - Large mass of head expander
    - Design requires shaker to generate sufficient force to achieve specified levels
    - Design includes independent feedback loops/controls for shaker

Custom Shakers required early procurement and extensive checkout.

JWST Vibration Test System (VTS)

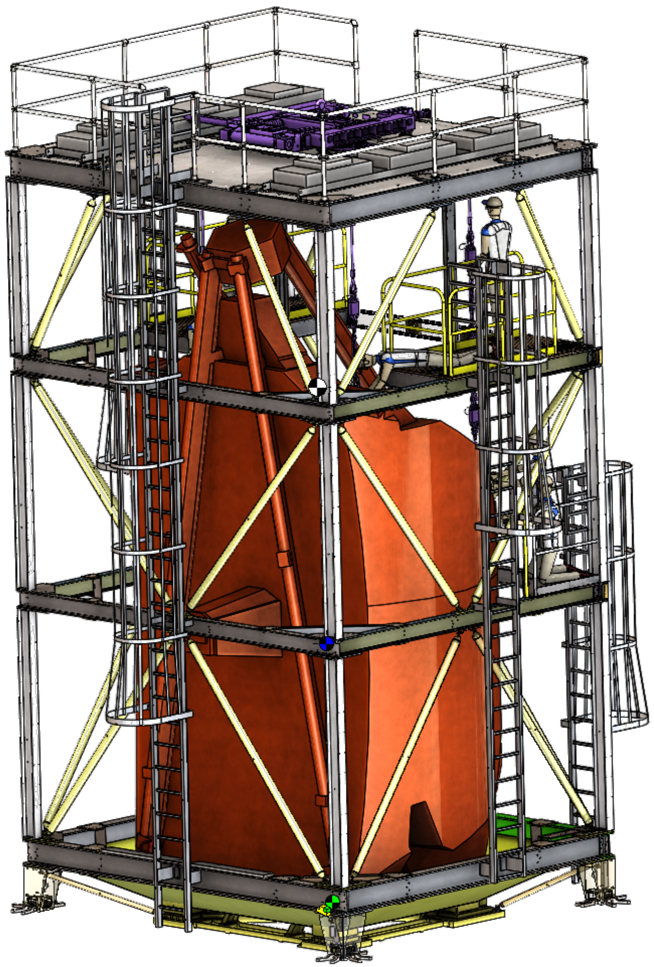
Telescope Sine Vibration Test: Horizontal and Vertical Tests

OTIS Sine Vibe Test: Changing Axes



Specialized GSE: Contamination Tent Frame

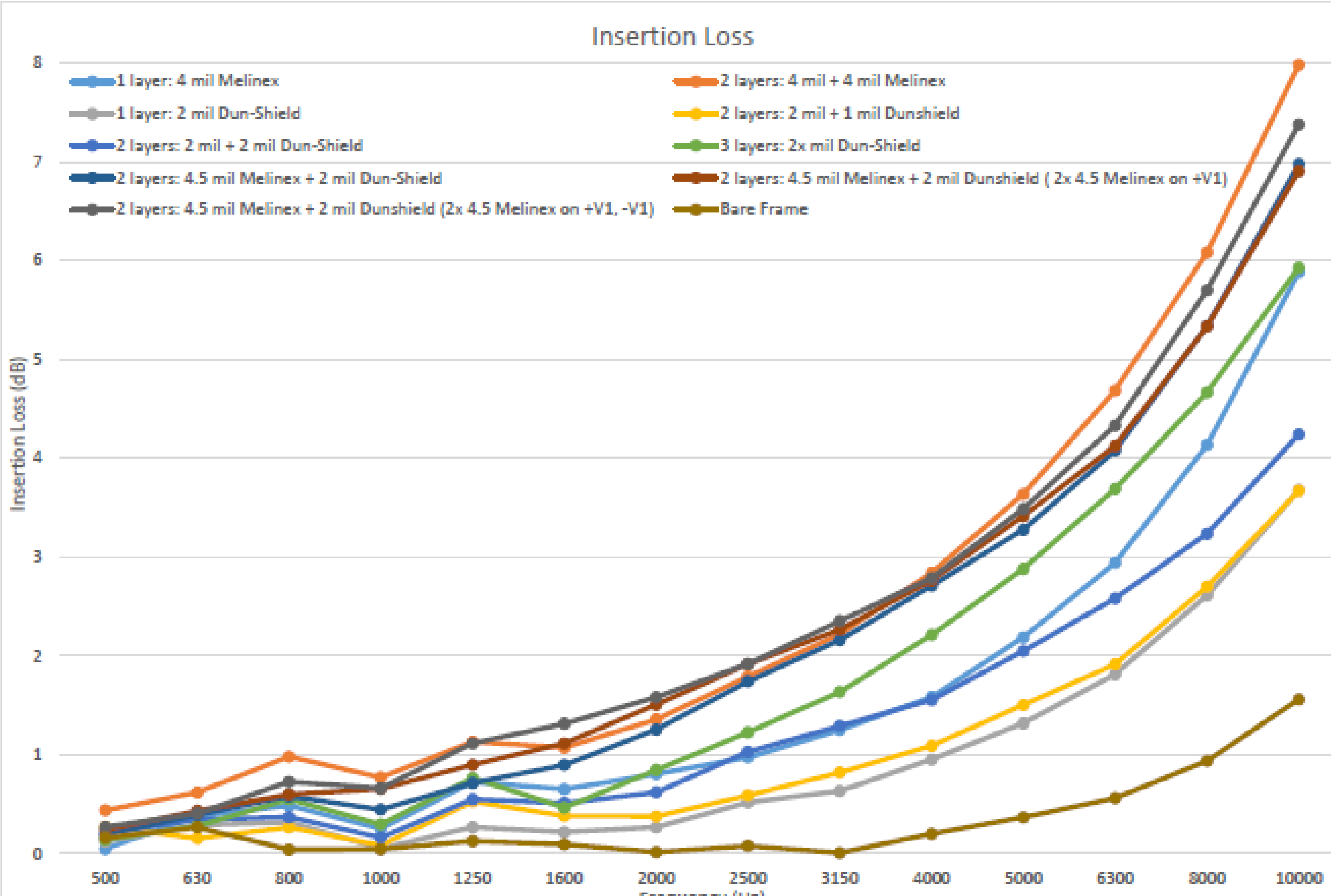
- **Attached to Test Supports for OTIS Sine Vibration Tests**
  - Not attached to OTIS during testing; stiffness does not affect OTIS hardware
- **Used with Dolly in OTIS Acoustic Test**
  - Tent Frame Design reviewed for Acoustic Environment
    - Acoustic loads factored into tent frame design
    - Tent material reviewed for acoustic attenuation
      - Two layers, 4.5 mil Melinex + 2 mil Dun-shield (final design)
      - Provides filter for high frequency load into microshutters
      - Maintain A5 acoustic spec to 2000 Hz
      - Visibility is considered for lifting over OTIS
  - Tent Frame Design Verified in Tent Frame Proof Test and Acoustic Check-out Test



Contamination Tent designed to withstand acoustic loading and limit high frequency loading to sensitive instrument microshutters.

Bagging Material for Telescope Tent

Insertion loss data was collected from acoustic runs with outside microphone control, nominal gas pressure, and the same controller references/tolerances as control.



Contamination tent materials chosen to obtain required A5 Acoustic Input but limit frequency input between 2500 – 30000 Hz.

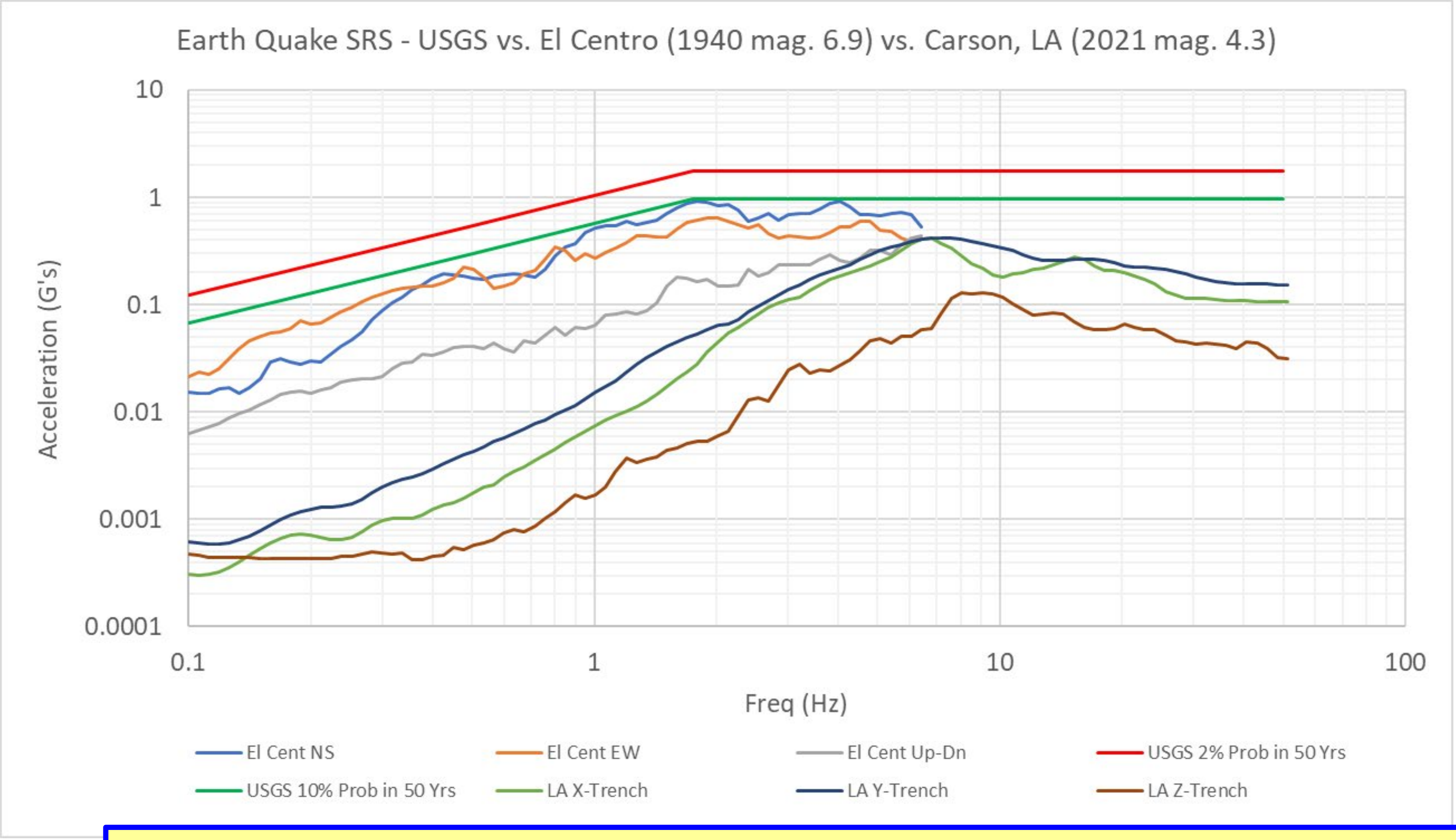
Earthquakes!

- **JWST observatory was assembled at Northrop Grumman in Redondo Beach, CA—quite active seismic loading environment!**
- **Extensive testing was performed of the observatory while it was in its deployed configuration.**
  - Sunshield, deployed tower assembly, secondary mirror, primary mirror wing deployments performed several times after mechanical testing
  - Concern for hardware to experience seismic loading while in deployed configuration.
- **Seismic analysis was performed to design MGSE for deployment testing and shipping configuration.**
  - Reviewed latest USGS seismic loading and applied to combined hardware and MGSE design.
  - Seismic accelerometers were mounted to the MGSE, building floor and ceiling and the flight hardware.
    - Data was continuously recorded during integration and testing. Safe limits set for all data.
    - Earthquake operation plan developed, and mechanical systems team alerted to data immediately from seismic event.
- **Many events occurred, the largest being when observatory was horizontal for shipping (Carson, CA EQ 4.3 mag, 9/17/21, 8pmPST)**

MGSE designed to limit seismic loading to flight hardware during I&T activities.

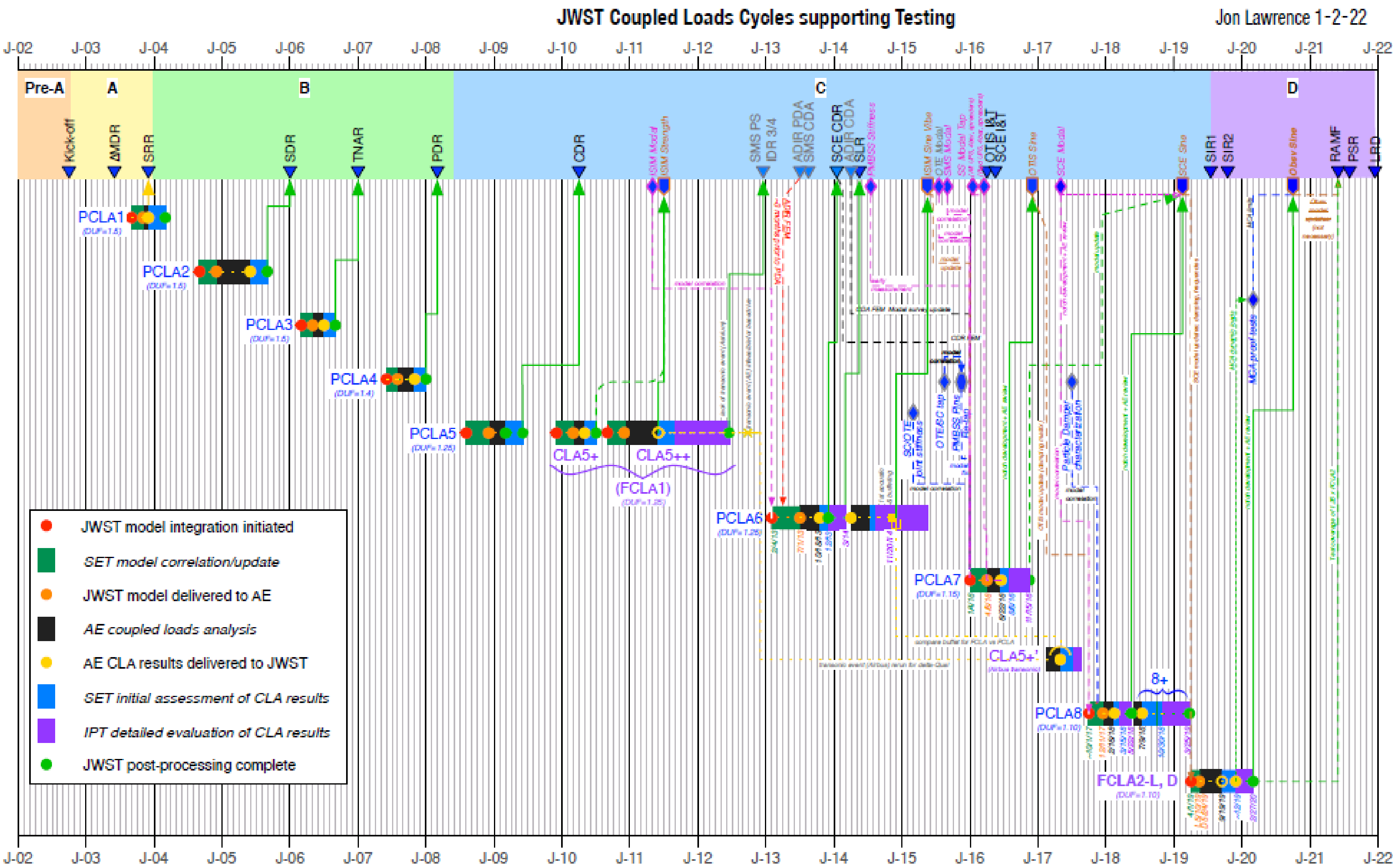
Seismic Assessment for JWST Observatory

- **USGS Seismic Inputs used for analysis compared to El Centro SRS data Circa 1940 magnitude 6.9 and Carson 09/17/21 magnitude 4.3**
- **Analyzed data:**
  - TRW SRS profile for 10% probability of exceedance in 20 years
  - USGS SRS profile for 10% probability of exceedance in 50 years



LA earthquake data compared to seismic analysis input data to verify hardware integrity.

A5 Requirements: Multiple CLAs



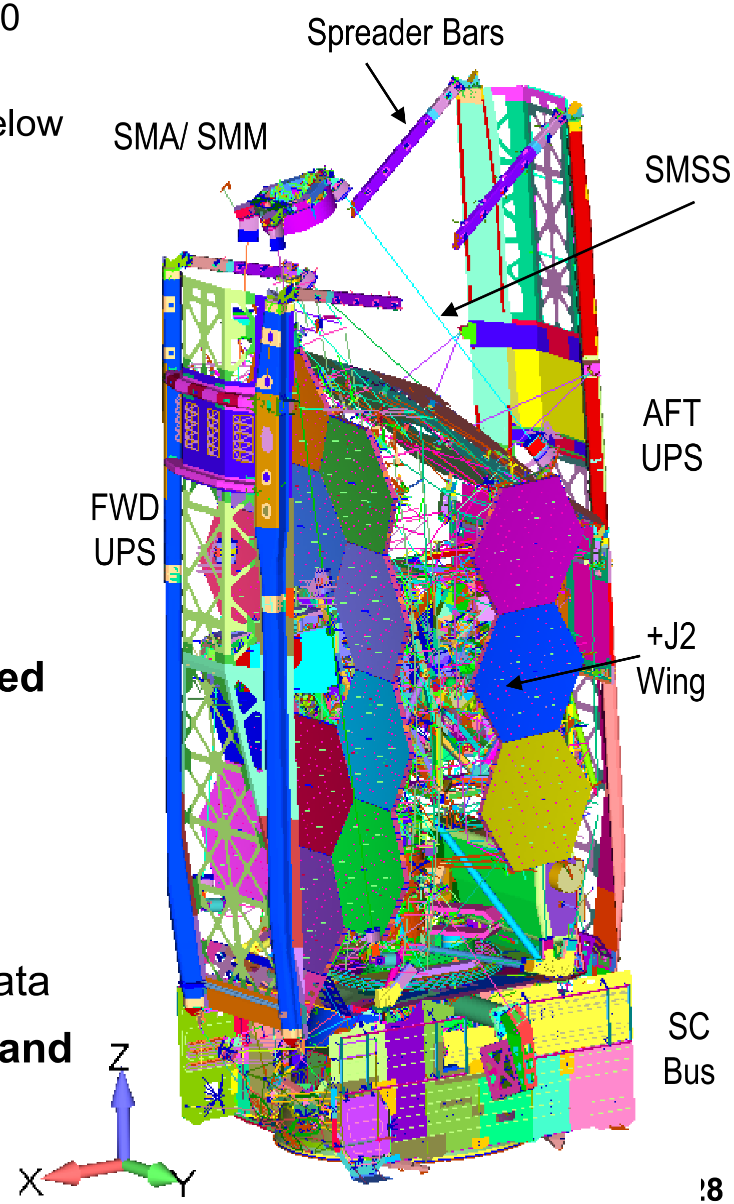
12 CLA performed! LTM Limitation required expansion for > 30000 OTM items!

A5 Requirement: Sine Vibration

- **Ariane 5 sine vibration specifications to 100 Hz.**
  - Required all modal surveys to correlate many modes out to 100 Hz.
  - Overall JWST stowed configuration FEM had ~1200 modes below 100 Hz---JWST was dynamically rich!
- **POGO analysis performed by Arianespace since observatory was not meeting the axial frequency requirement.**

Axis	Frequency (Hz)			
	Requirement	Test 0dB Sweep TF	Test Self-Check TF	Model TF
J3	≥ 15.0	19.50	19.44	19.50
J1	≥ 7.5	7.50	7.69	7.68
J2	≥ 7.5	8.08	8.38	8.35

- **Sine vibration input was required to be above specified floor level, 15-20 Hz range difficult to meet**
  - Particle dampers for telescope composite hardware needed to meet requirement
- **FEM Verification of frequency and damping**
  - Adjustments made to CLA if FEM did not match test data
- **Many deployment mechanisms, difficult to set limits and aborts**
- **605 accelerometers—Telescope accels survive cryo**



Observatory Sine Vibration Test at NGSS

Observatory Acceptance 3-axis sine vibration test:
8/24–10/2/2020 at NG M4

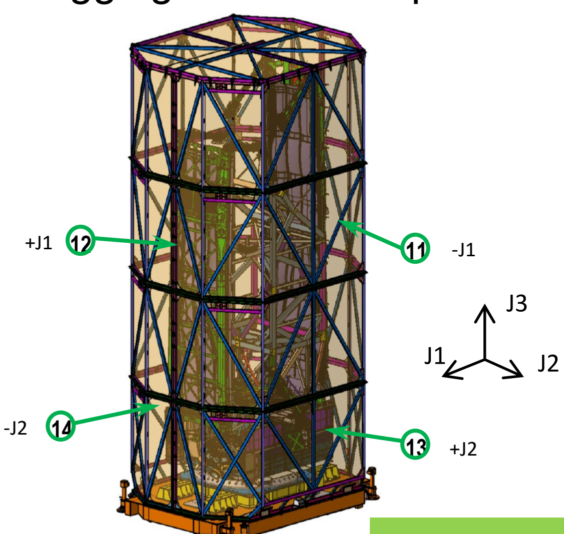
J3 Vertical Axis

Mounting to the J2 Lateral Axis

Observatory Vibration Test Team

A5 Requirements: Acoustics

- Arianespace requires S/C Test Plan level to be minimum level to be achieved by the average of the control microphones for the Acoustic Test (0 dB/+1 dB)
- Levels provided in full octave bands but ran in 1/3 octave
- Test Tolerances applies for the homogenity of the acoustic field in the chamber
  - Microphones internal to the test frame bagging measured up to 40 kHz



Control Microphones
All Inside the Bagging

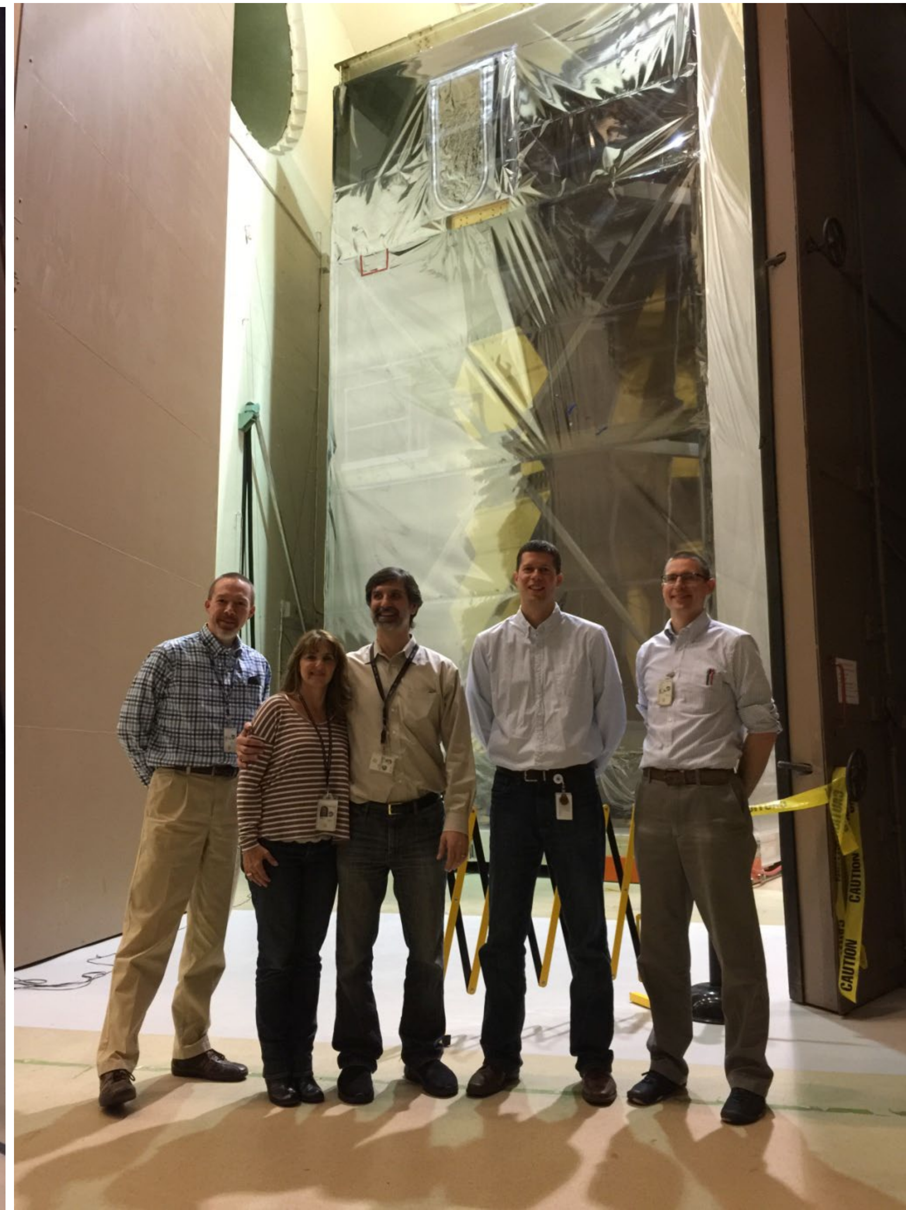
Table 4-2 Acceptance Acoustic Test Levels

F (1/3 Octave) (Hz)	Acceptance SPL (minimum) (dB)				
	S/C Test Plan (Fill factor <63%)		Test Results	MUA Iss. 5 rev.2 Oct 2016	Test Tolerances
25	123.4				
31.5	124.1	129	130.9	*(128+1) 129	-2,+4
40	125.0				
50	125.5				
63	126.6	131.5	132.2	*(131+0.5) 131.5	-1,+3
80	127.8				
100	130.8				
125	131.7	136	136.9	136	-1,+3
160	131.1				
200	129.4				
250	128.1	133	133.6	133	-1,+3
315	126.8				
400	125.6				
500	124.1	129	129.9	129	-1,+3
630	122.4				
800	120.0				
1000	118.1	123	124.5	123	-1,+3
1250	115.4				
1600	113.0				
2000	111.1	116	118.6	116	-1,+3
2500	108.4				
OPSL (dB)	139.6	**139.6**	**140.6**	**139.6**	-1,+3
Duration	1 minute		1 minute	1 minute	

* Third octave equivalents derived assuming a fill factor < 63%
Ref.: 0dB = $2x10^{-5}$ Pascal

Unique A5 Acoustic requirements were met.

Telescope Acoustic Test



Observatory Acoustic Testing

Observatory Acceptance Acoustic Test
(140.6 dB): 8/11–13/2020 at NG LATF

Ship Transport

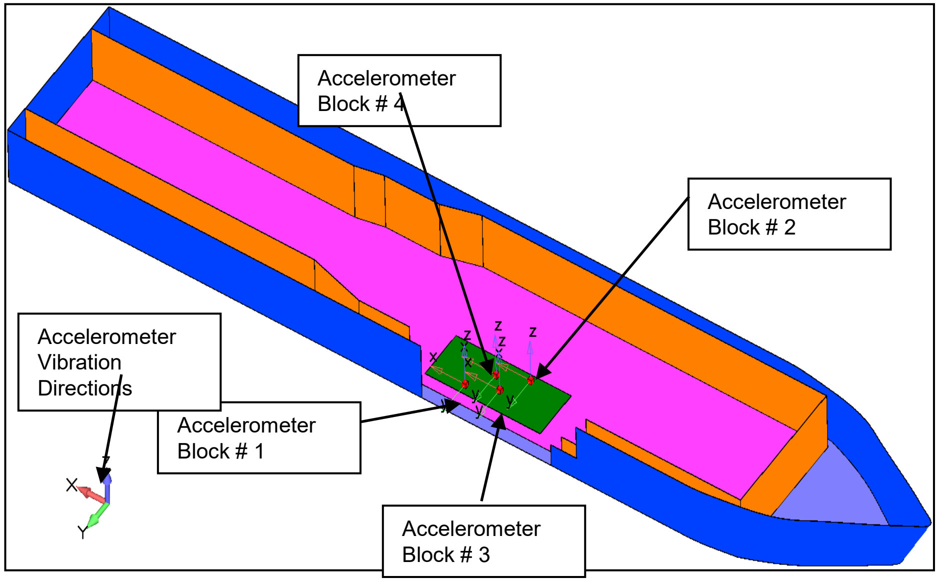
- Pathfinder Ocean Voyage to collect Acceleration vs Sea State Data

- Shipping container analysis and testing
  - Integrated Structural Model
  - Road Test
  - Proof Test

- Loads and Dynamic stiffness testing of Shipping Container Wire Rope Isolators

Ship Transport

- Due to high mass of Observatory transport exceeding structural limit of bridges in French Guiana and aircraft loads for observatory payload, ship was chosen to transport observatory to the launch site.
- Limited data available for ship transport, so arranged for data collection of ship voyage using MN Colibri.

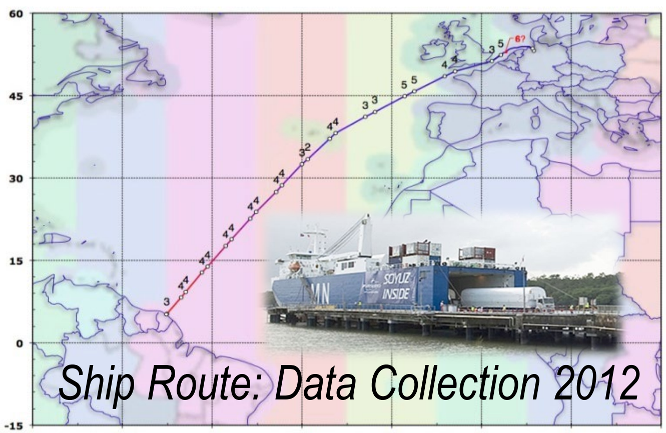


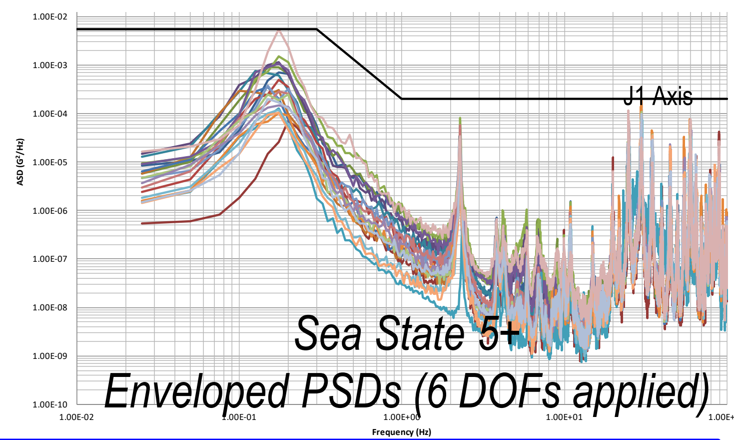
Ship Transport Loads

- **Ship transportation random inputs based on 10 day MN-Colibri voyage from Germany to Kourou across Atlantic Ocean, 3/2012**
  - Transient vibration data gathered from accelerometers mounted to cargo floor; reduced to PSDs by code 549 test group lead

Vertical (J1 axis)		Lateral (J2 axis)		Longitudinal (J3 axis)	
Frequency	**G²/Hz**	**Frequency**	**G²/Hz**	**Frequency**	**G²/Hz**
0.01	5.5E-3	0.01	1.5E-3	0.01	1.0E-4
0.3	5.5E-3	0.2	1.5E-3	0.3	1.0E-4
1.0	2.0E-4	1.0	1.5E-5	2.0	5.0E-7
100	2.0E-4	100	1.5E-5	10	5.0E-7
				20	3.5E-5
				100	3.5E-5

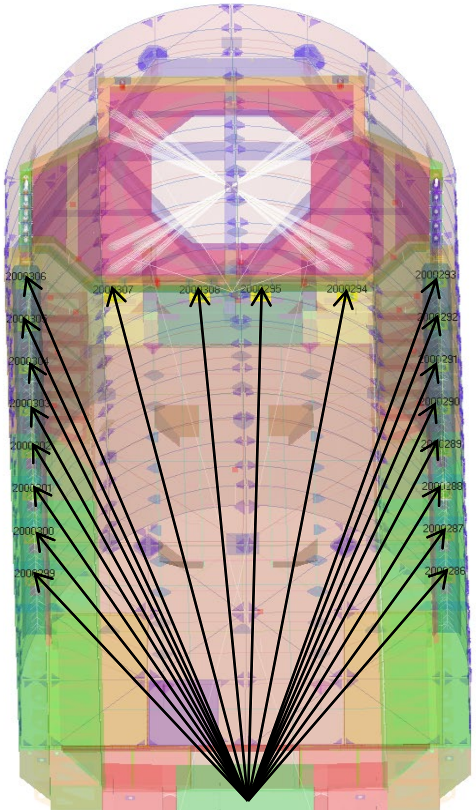
- **Ship random response analysis performed, and max sea state level chosen to limit key interface forces and relative motions**





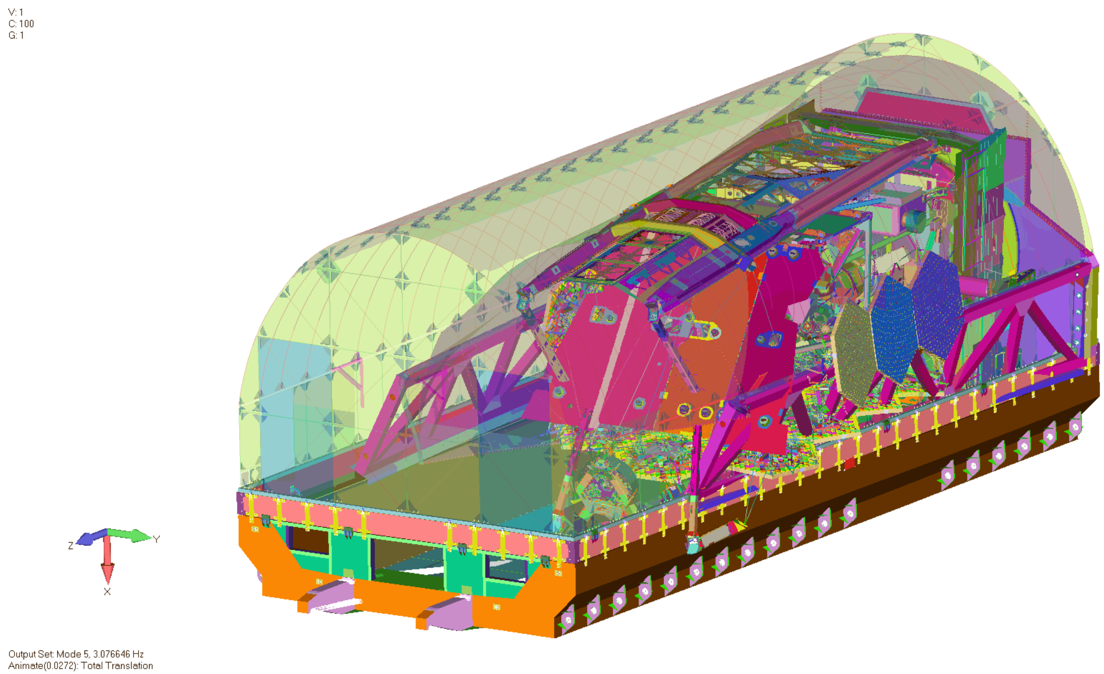
Ship Transport Loads developed for design and test of shipping container.

Observatory Shipping Container Road 1^{st} Mode Shape



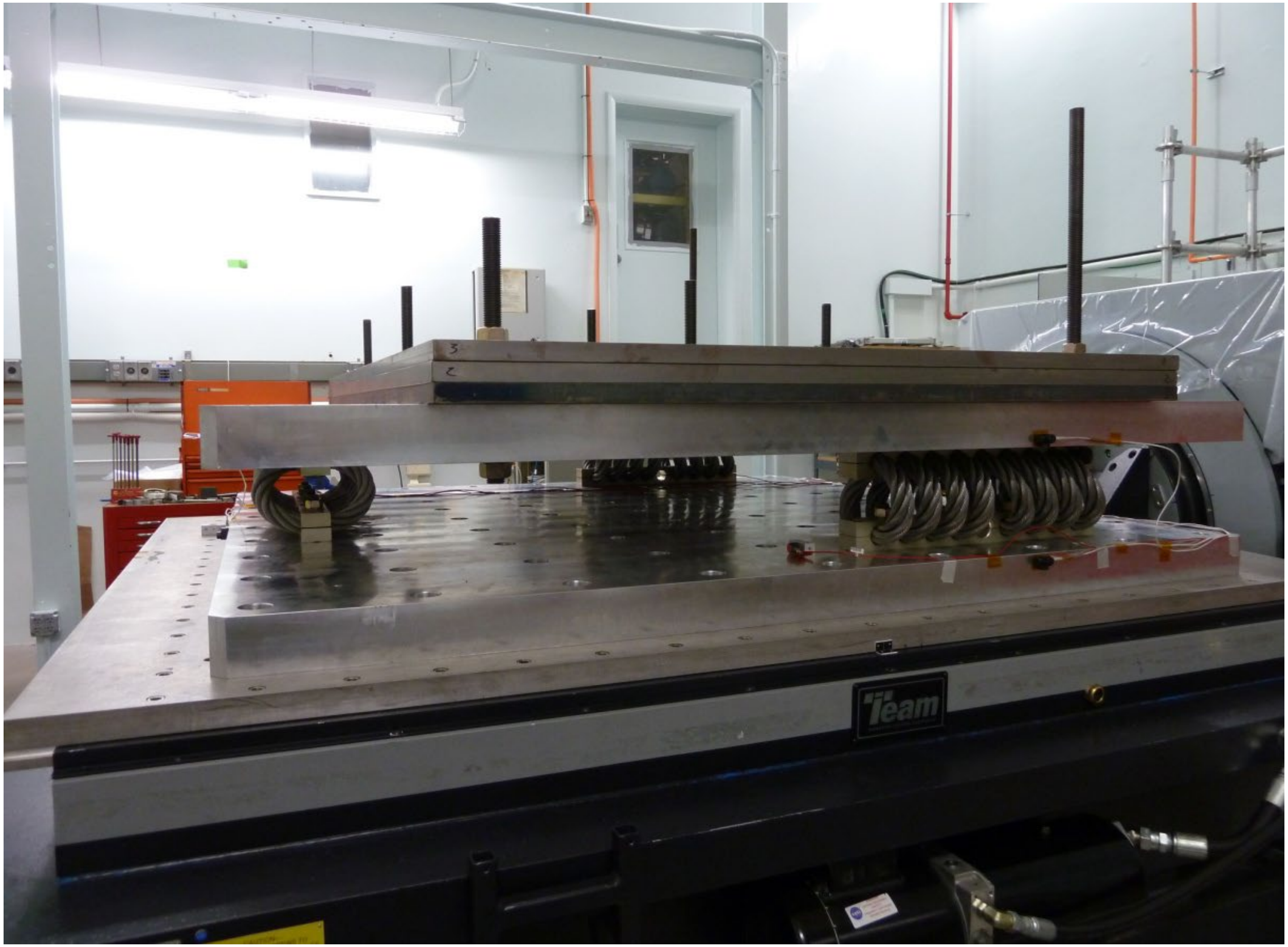
Baseline Isolator Configuration with 20 Locations on Pallet

OSTTARS/JWST on Isolators Lateral Frequency = 3.08 Hz



Lateral Isolation Mode of 3.1 Hz meets 2-5 Hz range per *JWST Pathfinder, OTIS and Launch Site Transportation Interface Requirement Control Document*

Wire Rope Isolator Dynamic Stiffness Test Set-up



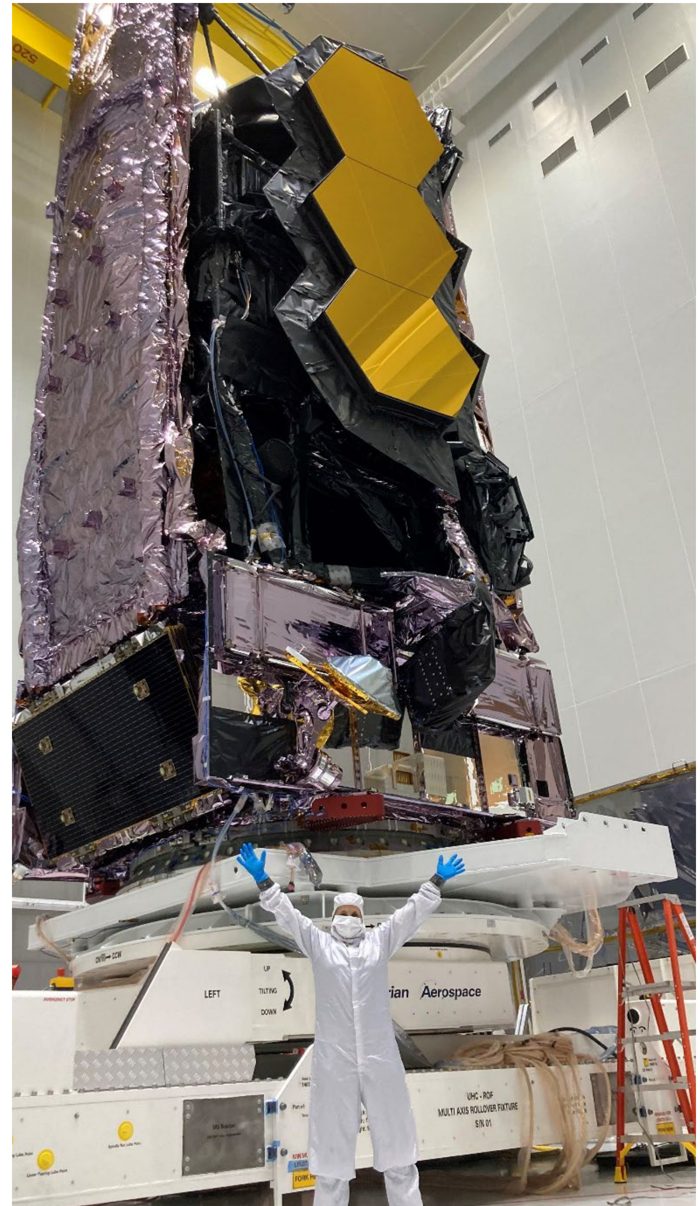
The CB2000-10 Isolator Test Set-Up in B7 Vibe Lab

MN Colibri Unloading in Kourou, French Guiana

Lessons Learned from Deployments

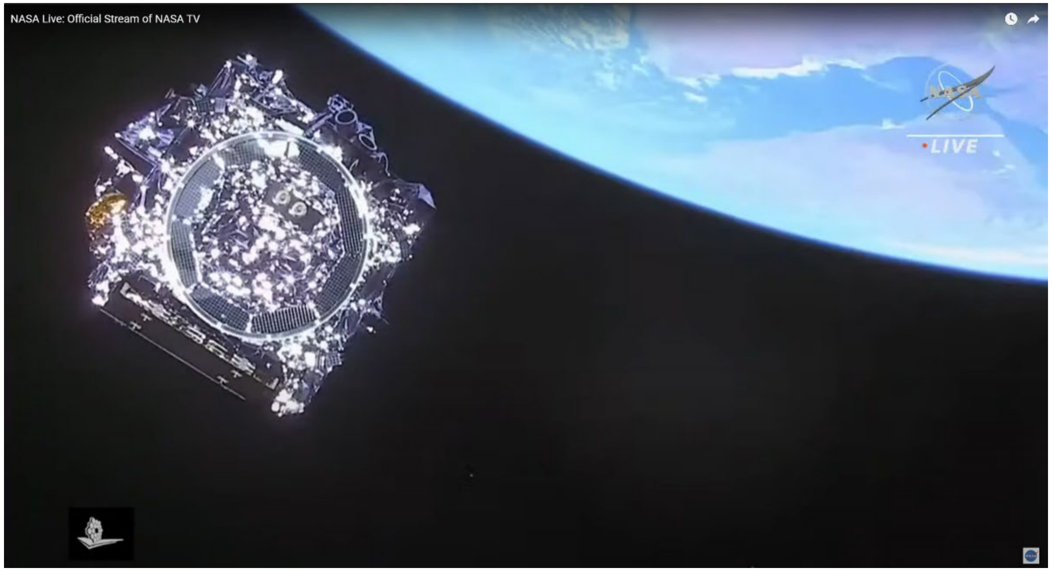
- **Deployments**
  - Fool-proof snag guards and cable/pulley guides were implemented
  - Testing deployment system design under temperature limits (utilize kinematic mounting where possible)
  - Consider leaving strain gage bolt wires in place to enable monitoring release mechanisms preload throughout testing (but this must be traded against having a non-disturbed deployment test)
- **Cryogenic Telescope**
  - Internal Mechanical shorts (cable stiffness, critical clearances, soft structure) need to be considered
    - 4 lbs of force made a difference
  - Huge value of the pathfinder tests
- **Verification**
  - Conservative damping (Q=40, minimum) should be assumed in the pre-test analysis when developing test limits for composite hardware
  - Redundant instrumentation
  - Design Change Process needs to be reviewed by all Engineering Disciplines
- **Ship Transport**
  - Pathfinder testing when possible (ship loads voyage)

S5C Highbay, CSG, French Guiana, Oct. 2021



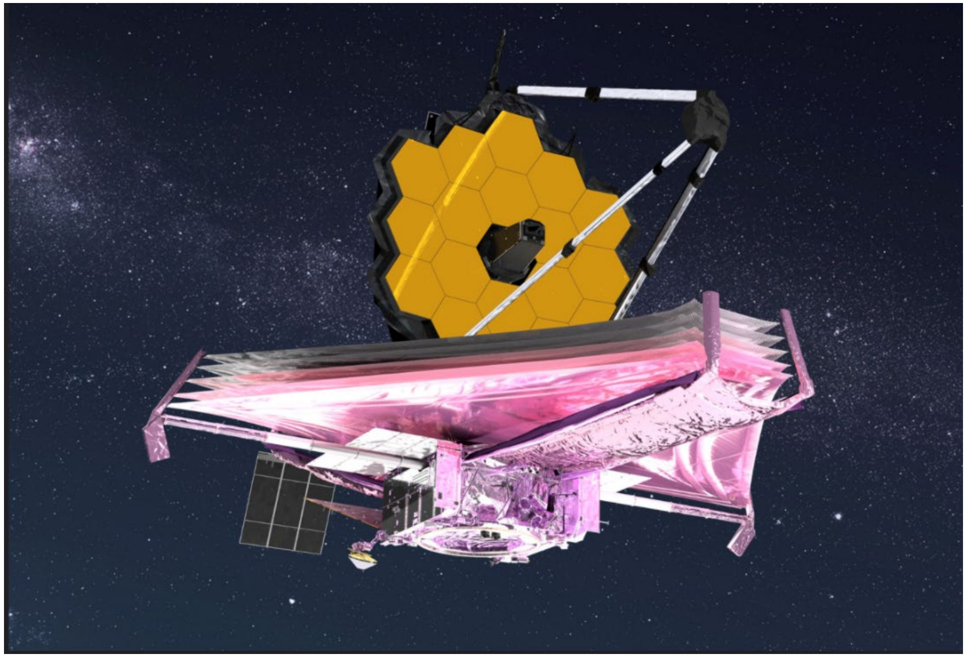
Launch December 25, 2021

Observatory Separation and Solar Array Deployment



Deployments Completed and Arrive Home-L2!

January 8, 2022 All Major Deployments Completed

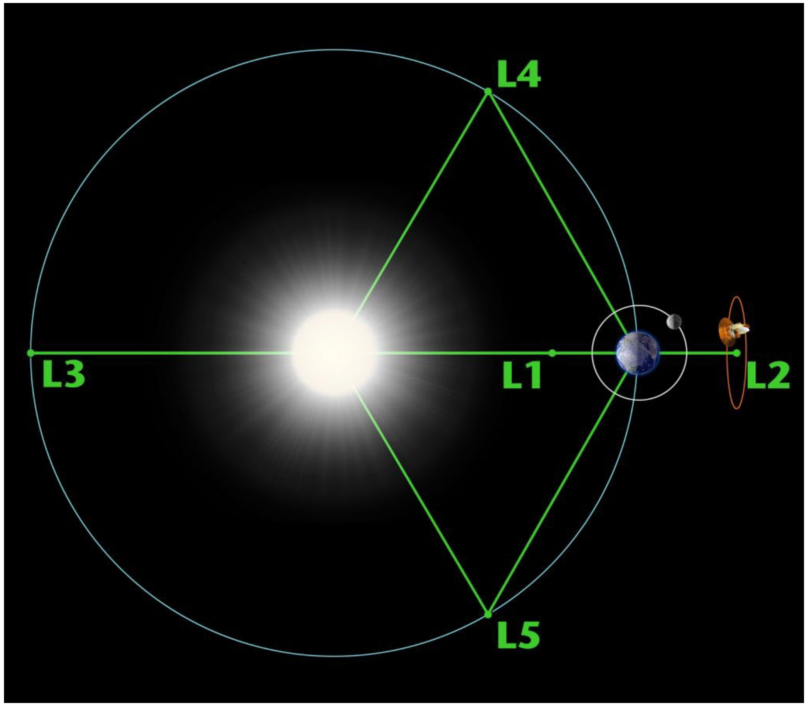


- 29 days on the Edge JWST (Deployments)
https://www.youtube.com/watch?v=uUAvXYW5bmI

Websites to follow Webb On-Orbit Commissioning

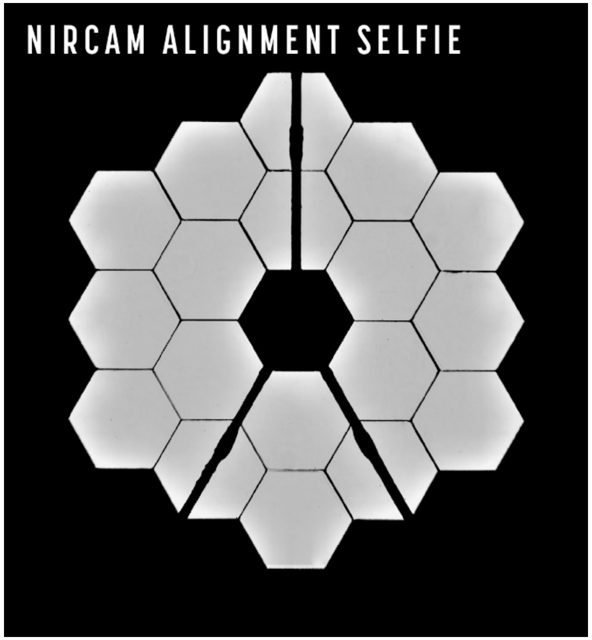
- Where is Webb?
  - https://webb.nasa.gov/content/webbLaunch/whereIsWebb.html
- JWST Blog
  - https://blogs.nasa.gov/webb/

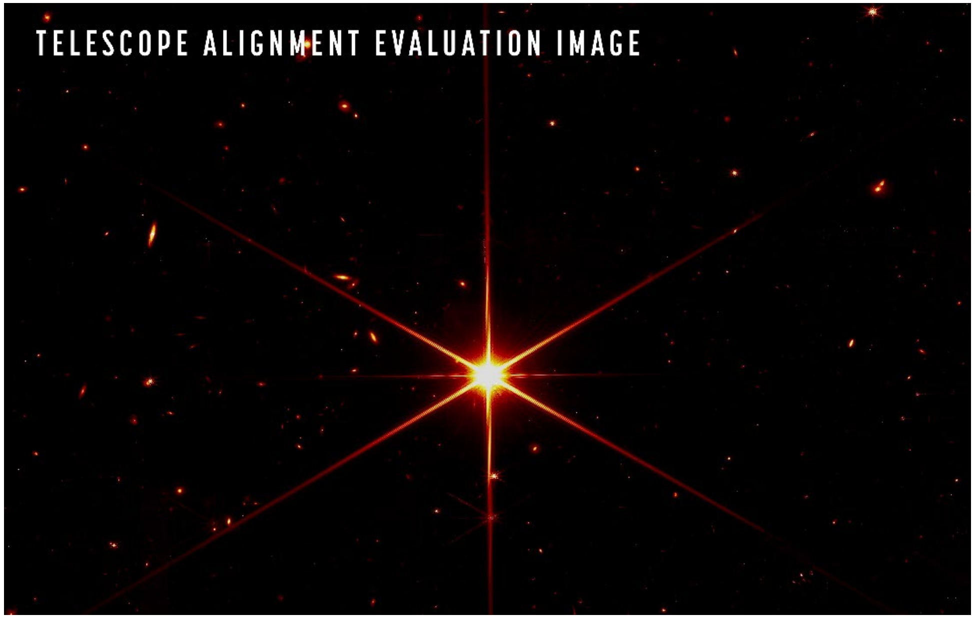
January 24, 2022 Arrive at L2 Orbit



PM Fine Phasing Completed March 16, 2022

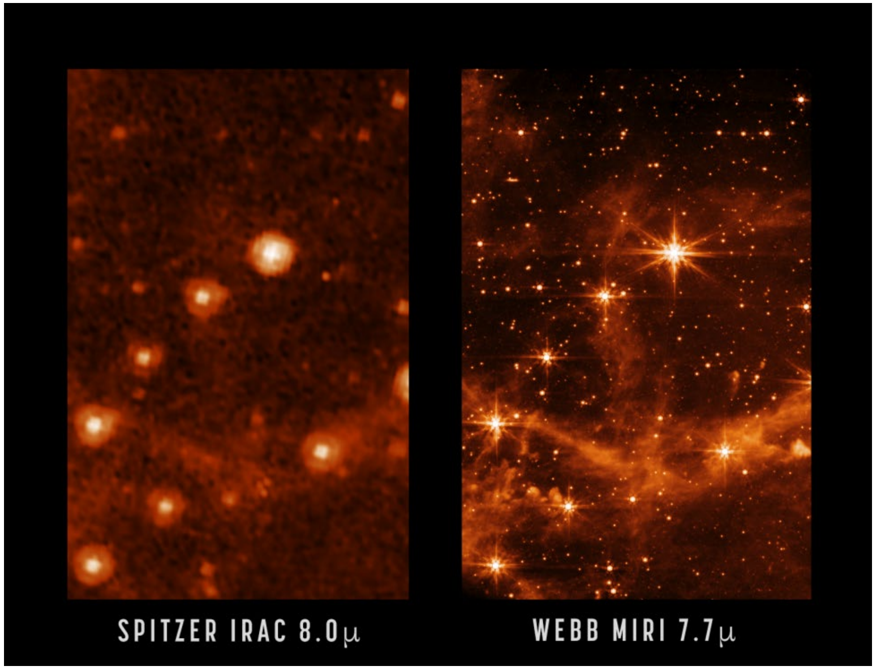
- **NASA Press Release**
- https://www.nasa.gov/press-release/nasa-s-webb-reaches-alignment-milestone-optics-working-successfully





Final Cooling of MIRI, April/May 2022

- NASA Press Release in April and JWST Blog post in May
- https://www.nasa.gov/feature/jpl/webb-telescope-s-coldest-instrument-reaches-operating-temperature



This shows a comparison between the Spitzer Space Telescope and the Webb Space Telescope of the Large Magellanic Cloud from the small satellite galaxy of the Milky Way.

- **Next Steps:**
  - Final Science Instruments tuning performed since the observatory was at steady state temperature
  - July 12, 2022 was "First Light" of the Webb Telescope

Webb Telescope Science!