National Aeronautics & Space Administration (NASA)/Goddard Space Flight Center (GSFC)

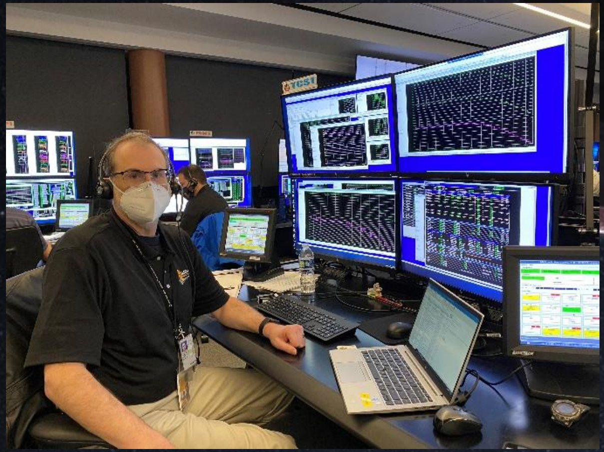
TFAWS 2023

JWST Thermal

(There and Back Again)

Shaun Thomson / GSFC

8/22/2023



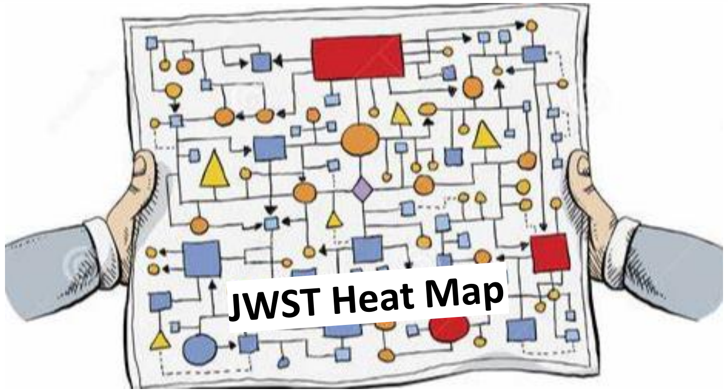
Unique Project Features

- NASA Class A – Flagship mission
  - 4th for Astrophysics Division
- Long development cycle – 25 year (approval-to-flight)
- Large expenditure - $8.8 billion for development
- Large & International Team
  - 3 Space Agencies (NASA, ESA, CSA)
  - 14 countries
  - 258 companies and universities
    - Northrup Grumman – Prime Contractor
- Only 3rd NASA mission to L2 (1.5 million km)
- Extensive oversight – Congress, GAO, IR committees
  - 1 descope
  - 2 cancellation threats
- Extensive media presence & public interest

Organization & Responsibilities

- Mission Lead: Goddard Space Flight Center
  - Mission Systems Engineering - GSFC
- International collaboration: ESA & CSA
- Prime Contractor: Northrop Grumman Aerospace Systems (Space Park, LA, CA)
  - OTE Structure
  - Sunshield element
  - Spacecraft Bus (& prop, commo, ACS, C&DH, PCS)
  - Deployments
  - OTE optics, ISIM radiators – Ball Aerospace
- Instruments:
  - Near Infrared Camera (NIRCam) – Univ. of Arizona
  - Near Infrared Spectrograph (NIRSpec) – ESA
  - Mid-Infrared Instrument (MIRI) – JPL/ESA
  - Fine Guidance Sensor (FGS) & Near IR Imaging Slitless Spectrometer – CSA
  - Cryocooler – JPL & GSFC
  - ISIM Structure, heat straps, IEC - GSFC
- Launch Vehicle: ESA & Arianespace
- Launch & Commissioning: All Teams. STScI with GSFC lead.
  - Science & Operations Center (S&OC) - JWST Mission Operations (MOC) Center – Baltimore, MD
- Post-commissioning Operations: Space Telescope Science Institute

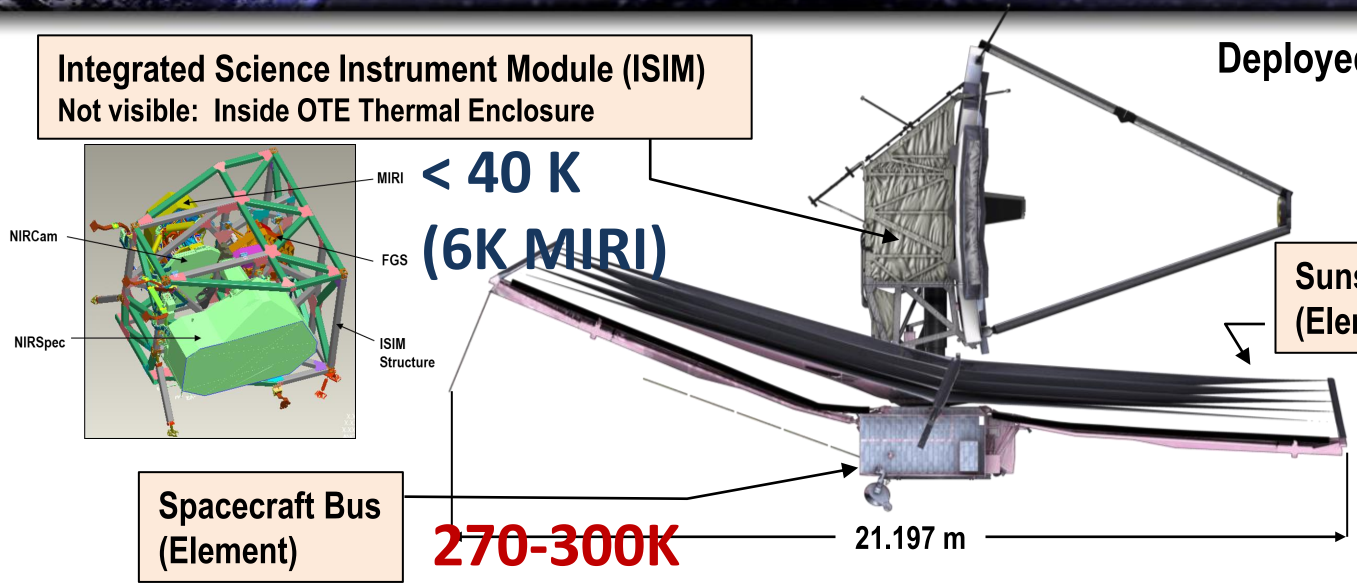
Challenging Thermal Subsystem

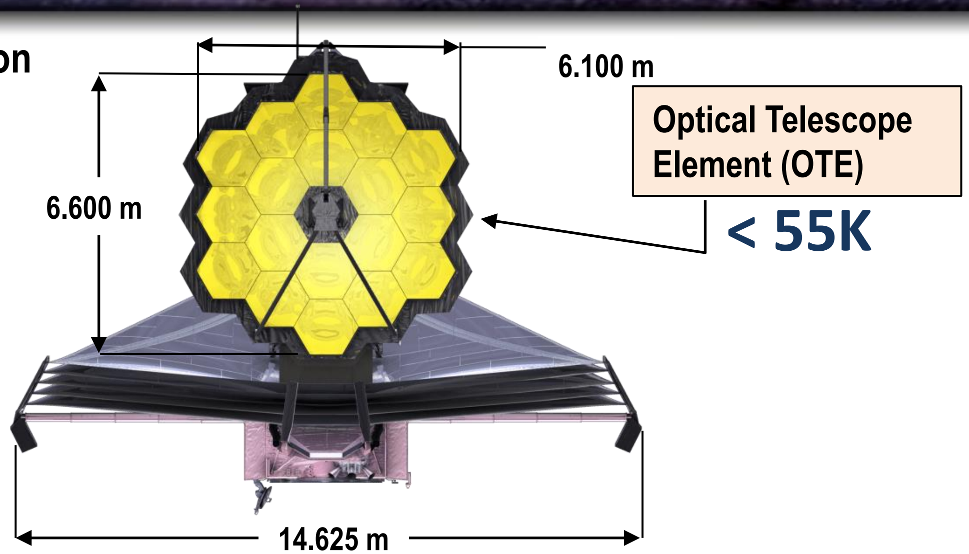


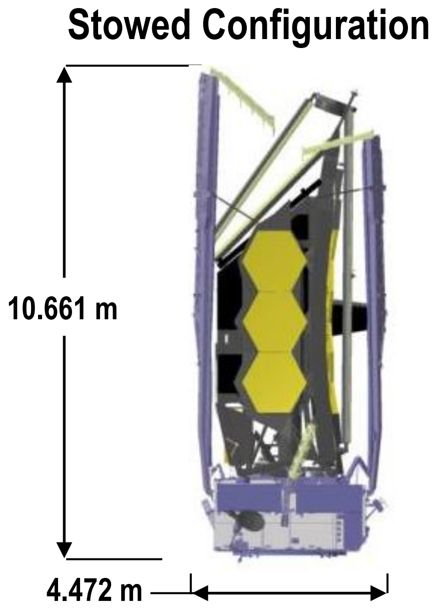
- Passive cryogenic cooling at an extremely large scale required for success
  - Active cooling to 6K for one instrument using new cryocooler design
- Controlling parasitic heat paths critical to achieving performance
  - Many very small and with complex paths (Radiative and Conductive)
- <u>No test-as-you-fly at the Observatory level</u>
  - [*Deployed Sunshield + Optical Telescope + Instruments + SC bus*] sees vacuum for the first time at flight
  - Thermal modeling intensive. Overall Observatory performance reliant on uncorrelated system-level models.
  - Two independent thermal models developed as part of risk reduction plan
- <u>344 Single points-of-failure</u> (launch locks, release devices, etc)
  - More than half associated directly with thermal success
- 1621 Thermal Requirements; 93 Operational limits/constraints
- Large number of long duration & complex cryogenic TVAC tests
- Complex 28-step deployment sequence with choreography of heater use
- Ariane 5 ECA launch vehicle – unique to NASA missions
- 6-month cooldown & commissioning plan with thermal supporting activities throughout

<u>Personal:</u>
- Began working on project in Aug 2001
- More than half my career
- 4x 30-day "TDYs" (TVAC tests & Flight Ops)
- More than half-million travel miles

Observatory Design Summary







- **Optical Telescope Element (OTE)**
  - 25 m^2 ,18 Segment PM
  - Passively cooled to <55K to minimize impact of thermal IR noise
- **Integrated Science Instrument Module (ISIM) containing 4 cryogenic science instruments (SIs)**
  - 3 instruments must be cooled passively to <40K (NIRCam, NIRSpec, and FGS/NIRISS)
  - 1 instrument (MIRI) must be actively cooled via a cryocooler to ~6K

  } *Minimize thermal IR noise*
- **Deployable sunshield**
  - 5-layer. 280 m^2 (~3,000 ft^2) Passive cooling of OTE and ISIM. 350^{o}C temperature differential, Layer 1 & 5.
- **Spacecraft Bus**
  - "Room Temperature"; Housing communication, power, ACS, propulsion, reaction wheels, computer)
  - Power dissipation: 2138 Watts Solar Array

Thermal Hardware (1 of 2)

Conductive Black Kapton XC used throughout OTE as outer layer of MLI or as film to control stray light

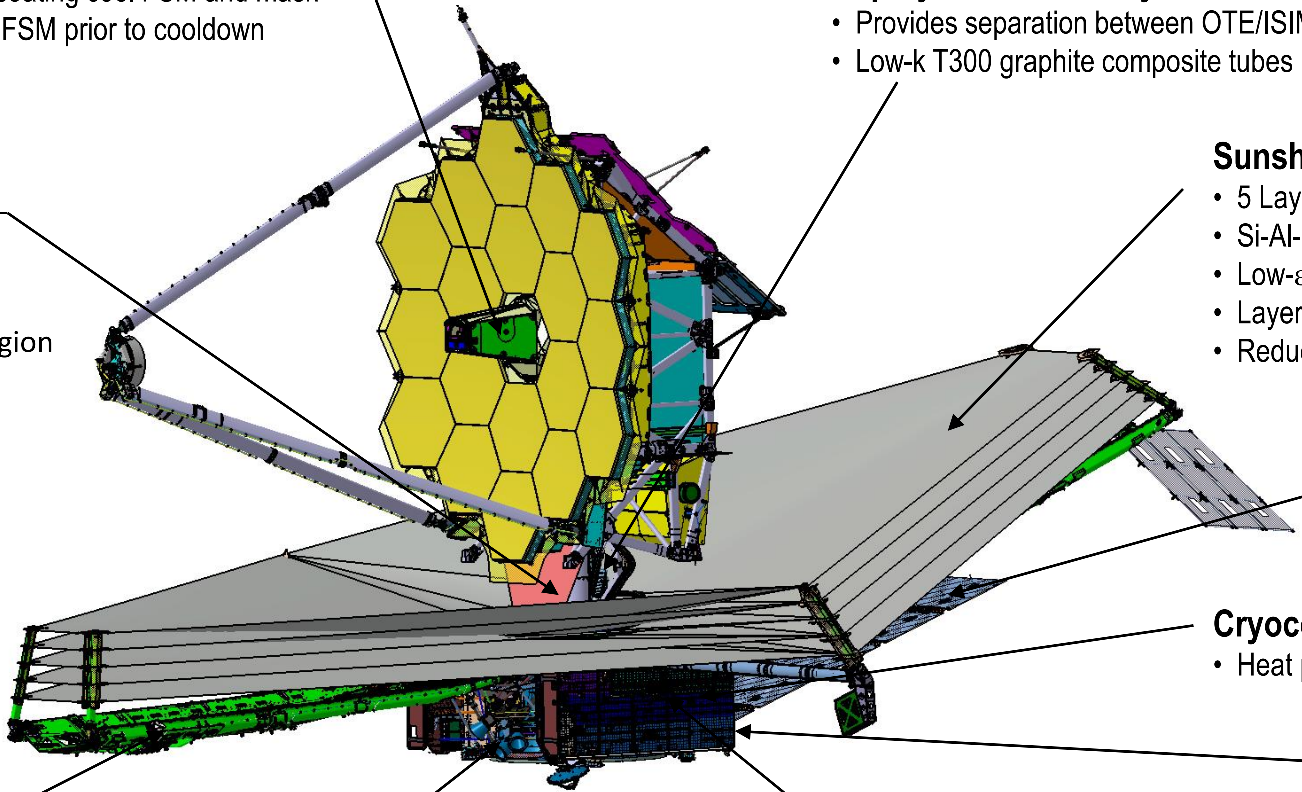
1009 Temp Sensors
150 prime heater circuits
3000+ pieces of MLI/SLI

Aft-Optics Subsystem
- Aluminum radiators with BIRB coating cool FSM and mask
- Heater prevents ice buildup on FSM prior to cooldown

Straylight Bib
- Rolls out
- Reduces MIR stray light reaching SM from “core” region

Deployed tower subsystem
- Provides separation between OTE/ISIM and SS
- Low-k T300 graphite composite tubes

Sunshield membranes
- 5 Layer “Hall of Mirrors”
- Si-Al-Kapton (low α_S / ε_H ; ~0.5 @RT) faces sun for layers 1 and 2
- Low-ε VDA provides radiative heat transfer barrier
- Layers fan out to help direct heat to space
- Reduces ~150,000 W of solar impingement to ~2 W into OTE



Single-wing solar array (fixed)
- Does not block radiators’ view to space
- Composite panel with Si-Kapton rear surface

Cryocooler compressors (not visible)
- Heat pipes carry dissipation to dedicated radiators on bus sides

Bus radiator panels (2 sides of bus)
- 1 for Avionics, 1 for cryocooler compressors, 1 for battery
- Aluminum honeycomb panels
- Embedded heat pipes
- Second surface mirrors

Sunshield UPS structure
- Houses membrane tensioning hardware
- Lattice construction
- Honeycomb with composite facesheets
- Si-Kapton faces sun (reduces T)
- Includes operational & survival heaters

Star Tracker / Inertial Reference Unit
- Exposed shade contained in radiant shield to minimize temp changes due to attitude
- Heat pipes carry heat to dedicated radiator

Deployed radiator shades
- Reduces IR heating from sunshield
- Reflects sunlight away from radiator

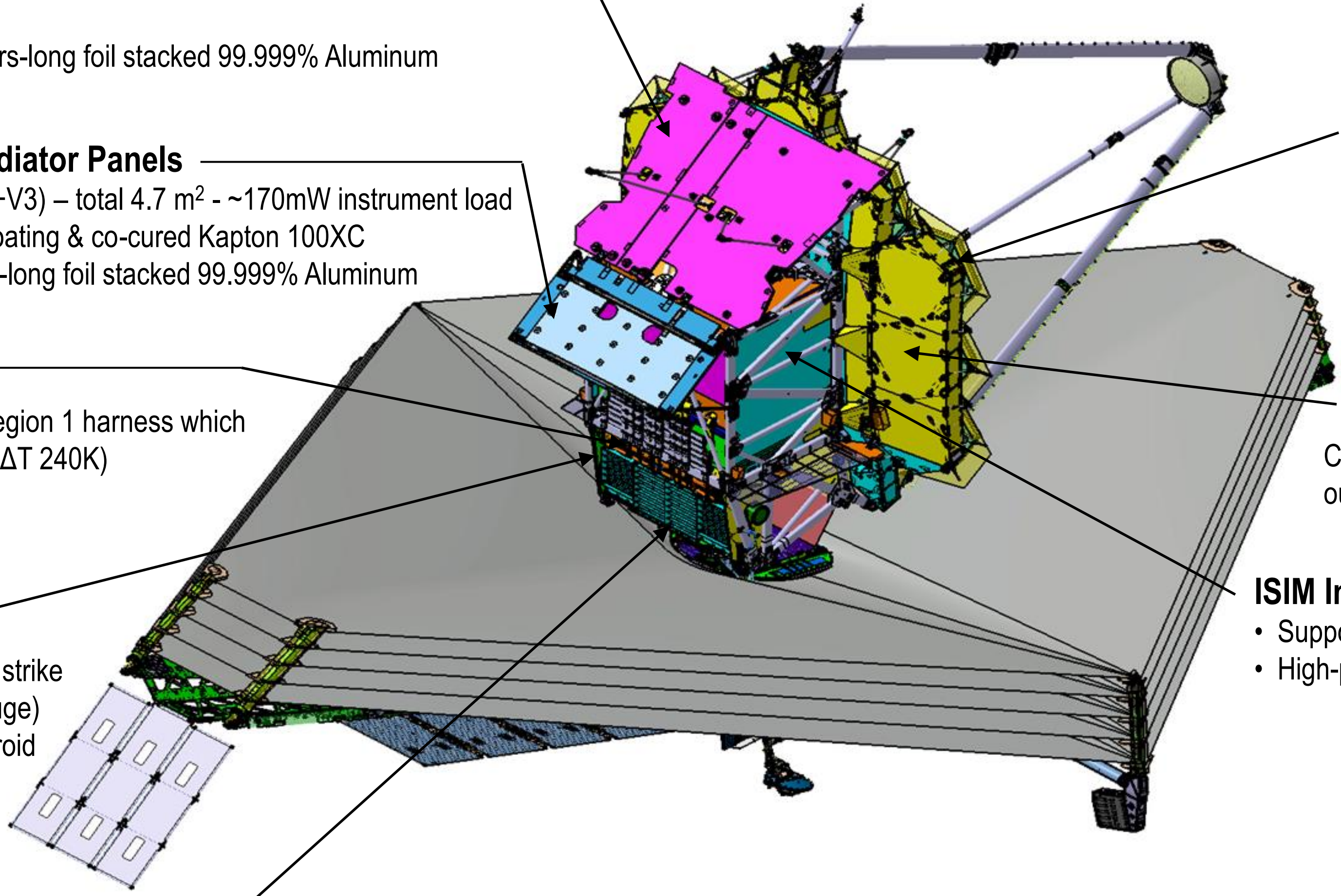
Thermal Hardware (2 of 2)

ISIM Fixed Instrument Radiator Panels (NIRCam, NIRSpec OA, NIRSpec FPA)
- Three independent aluminum panels (+V3) – total 9.2 m^2 - ~440mW instrument load
- Coated with high-ε BIRB paint
- Connected to Instruments via meters-long foil stacked 99.999% Aluminum

ISIM Deployable Instrument Radiator Panels
- Two independent aluminum panels (+V3) – total 4.7 m^2 - ~170mW instrument load
- Open faced honeycomb with Z307 coating & co-cured Kapton 100XC
- Connected to Instruments via meters-long foil stacked 99.999% Aluminum

Harness Radiator
- Radiatively cools the IEC-to-ISIM Region 1 harness which traverses 280K to 40K over 2 meters (ΔT 240K)
- 4 stage design, Z307 coating

IEC to ISIM Harnessing
- Signal: 38 gauge Stainless with Nickel strike
- Power: Phosphor Bronze (variable gauge)
- Wrapped with ceramic fabric for meteoroid protection

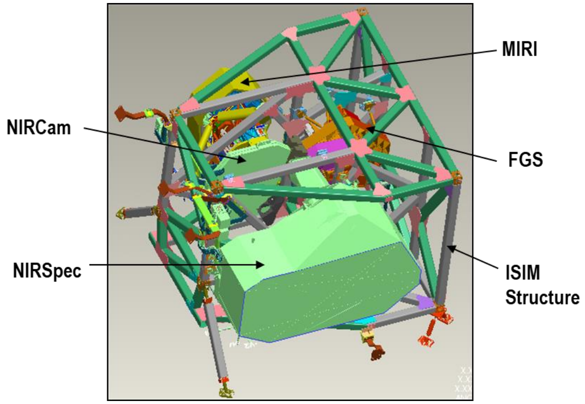


PMBA stray light shield
- mitigates stray light path

Cryogenic MLI and SLI used throughout

Conductive Black Kapton XC used throughout OTE as outer layer of MLI or as film to control stray light

ISIM Instruments (within enclosure, not visible)
- Supported via titanium flexures of graphite bench
- High-purity (99.999%) Al heat straps conduct heat to radiators



ISIM Electronics Compartment (IEC)
- Room temperature
- Accommodates 200 W of power @ 280 K
- Directional Baffles on –V1 side direct heat to space in ~50-60^o arc

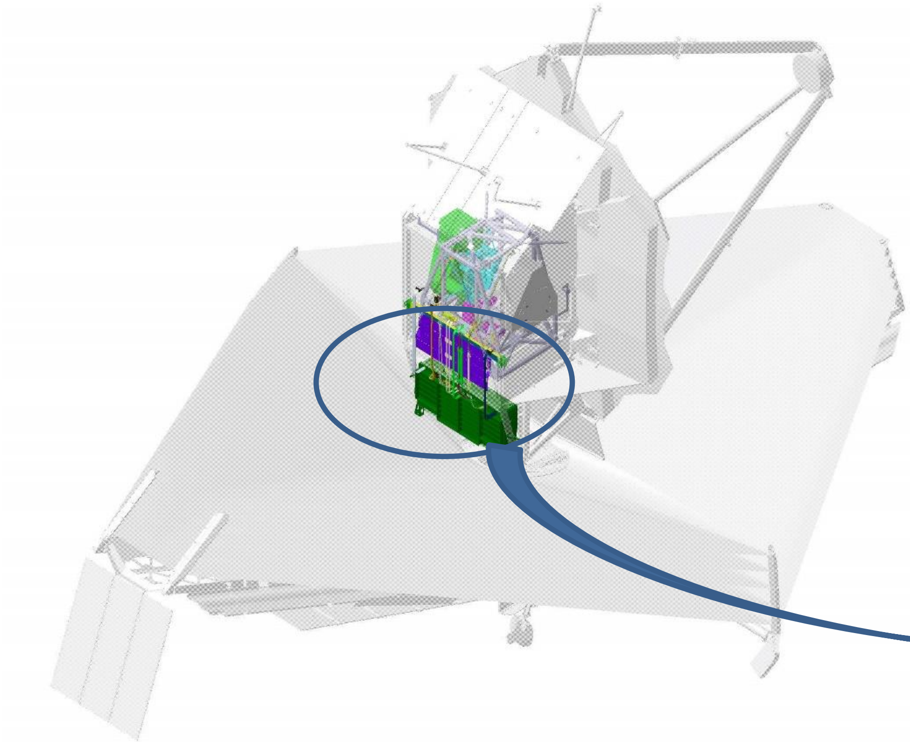
Cryocooler refrigerant lines (not visible)
- 10 meters (one-way) from compressors to 6K cold block
- Gold coated (Epner process)
- Specially designed line mounts along route (thermal and vibration isolation)

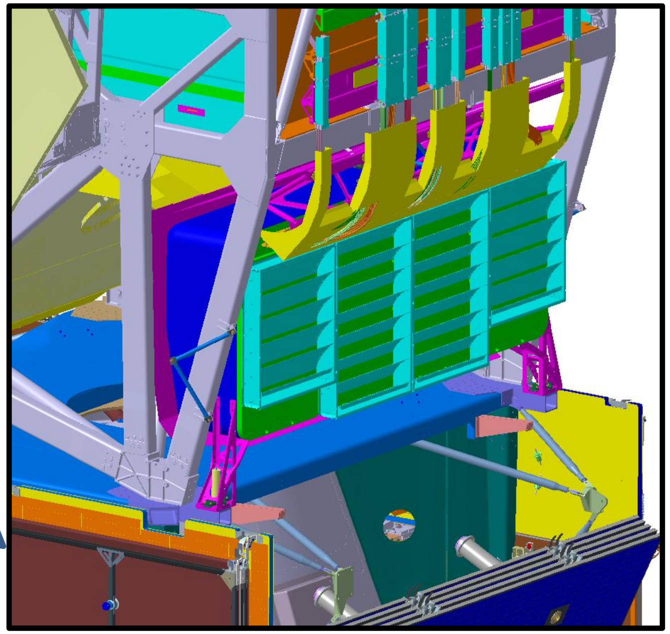
Example of Complicated Thermal Problem – ISIM Equipment Compartment (IEC)

- **Where is the Best place to put a hot, high-powered component?** <u>On the Cryo-side…Obviously!</u>

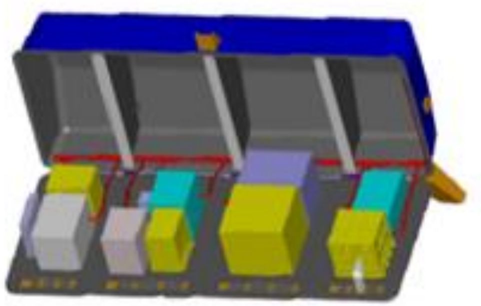
- *Requirement:* Instrument electronics required to be within 1.5 meters of instruments, to maintain signal integrity
- Boxes are warm (280K) sources, dissipating a sizable 200W. So, both a conducted and radiative heat source.
- Additionally, boxes needed to be vented which represents a significant long-term ice & contamination threat

- Thermal solution required a multi-prong effort utilizing all “tricks of the trade”

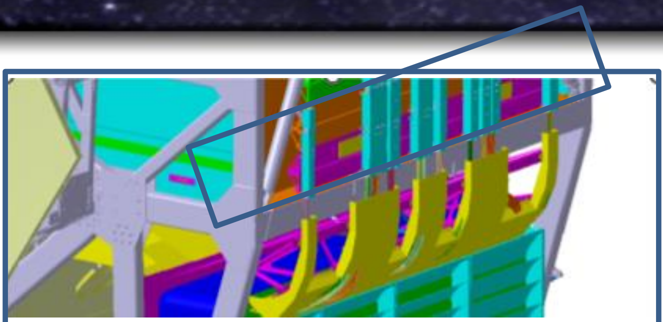




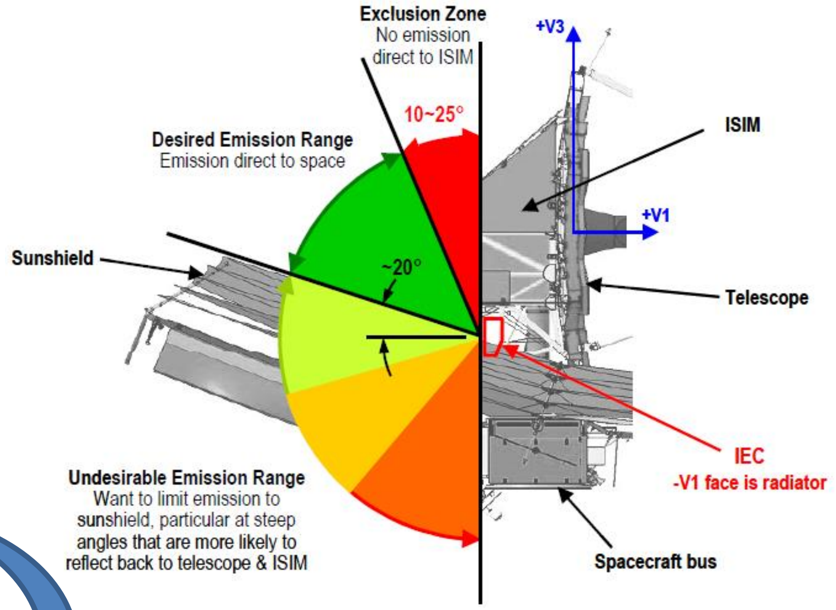
IEC “Kitchen Sink” Solution

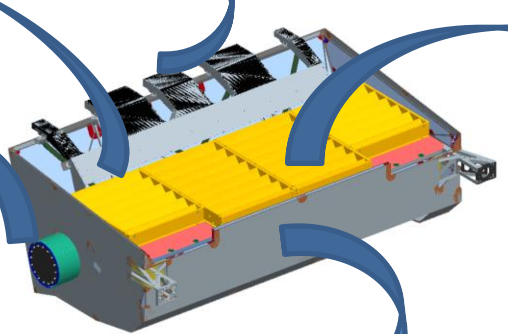


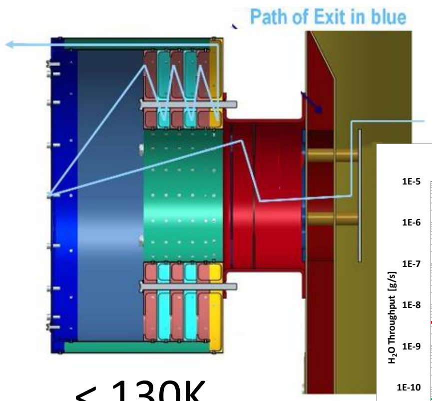
- Radiator panel with supported electronics boxes
- Radiators conductively isolated from enclosure
- Low conductivity enclosure
- High efficiency MLI built with offset seams on mandrel
- Enclosure suspended from OTE with low-conductivity
  T300 flexures once 3 LRMs are released



- 4-Stage Harness Radiator
- Low conductivity harnessing
  38ga Stainless Steel signal wires
  32ga Phosphor Bronze power wires

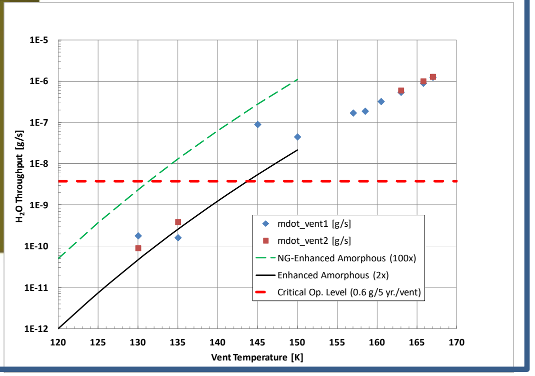


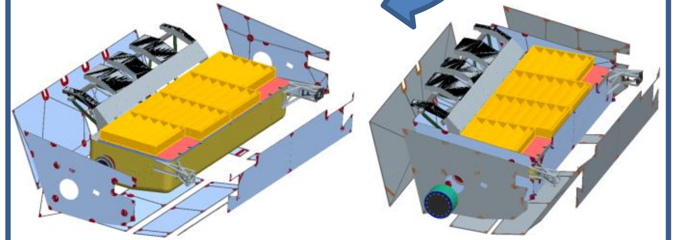




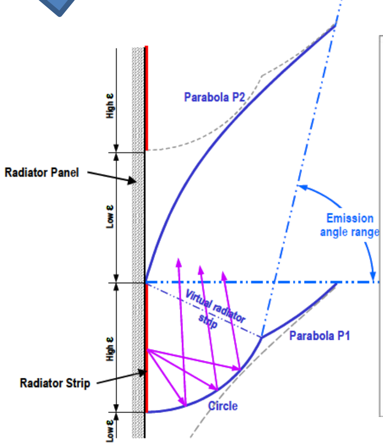
< 130K

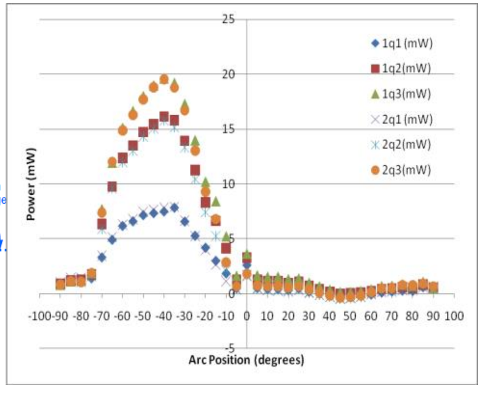
Multi-bounce passively cooled vent traps water while allowing depressurization of electronics compartment





Dual Nested Specular shields

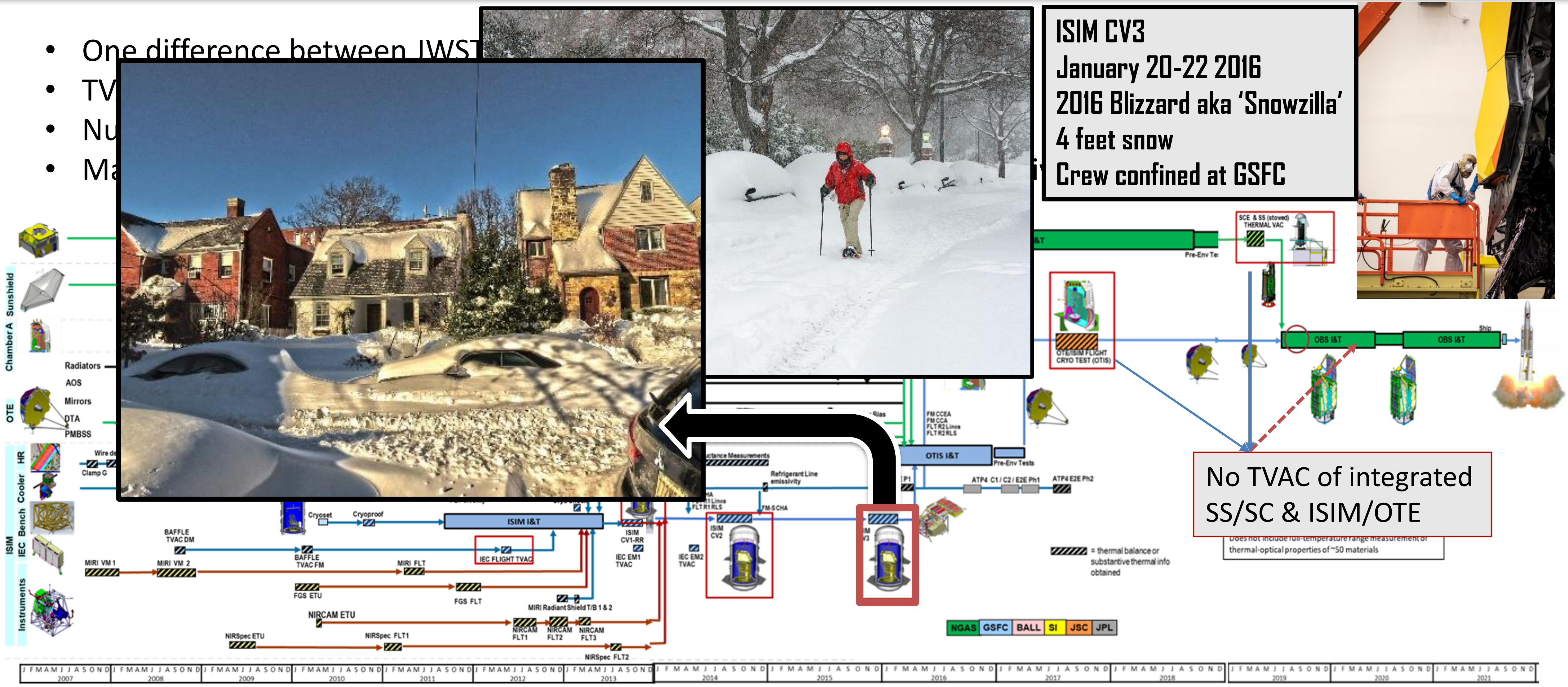




Directional Baffles based on Compound Parabolic Concentrators control Radiant Emission

Verification/Validation Testing was not without drama

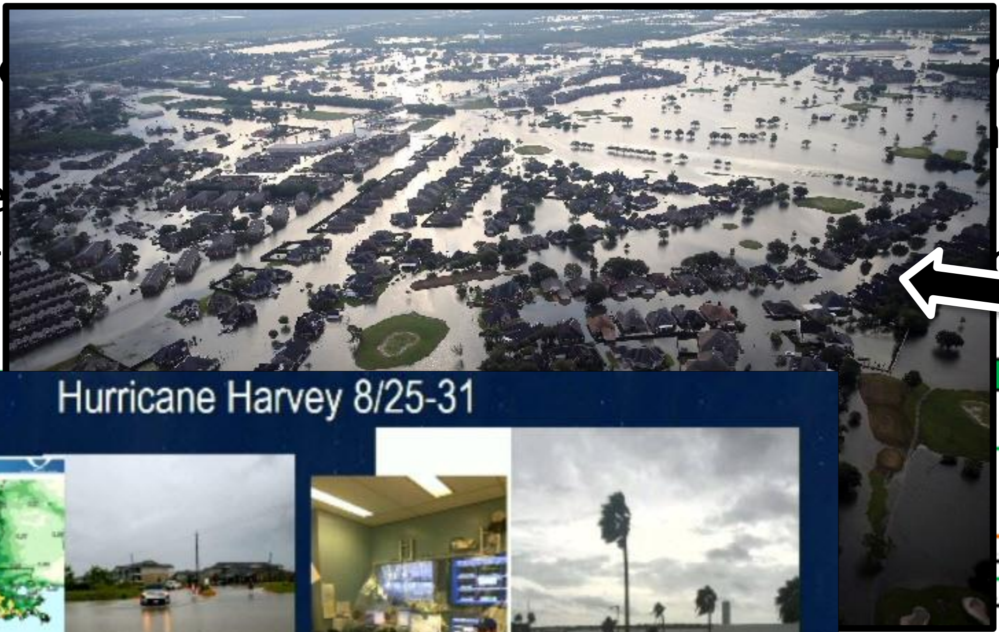
- One difference between JWST
- TV
- Nu
- Ma

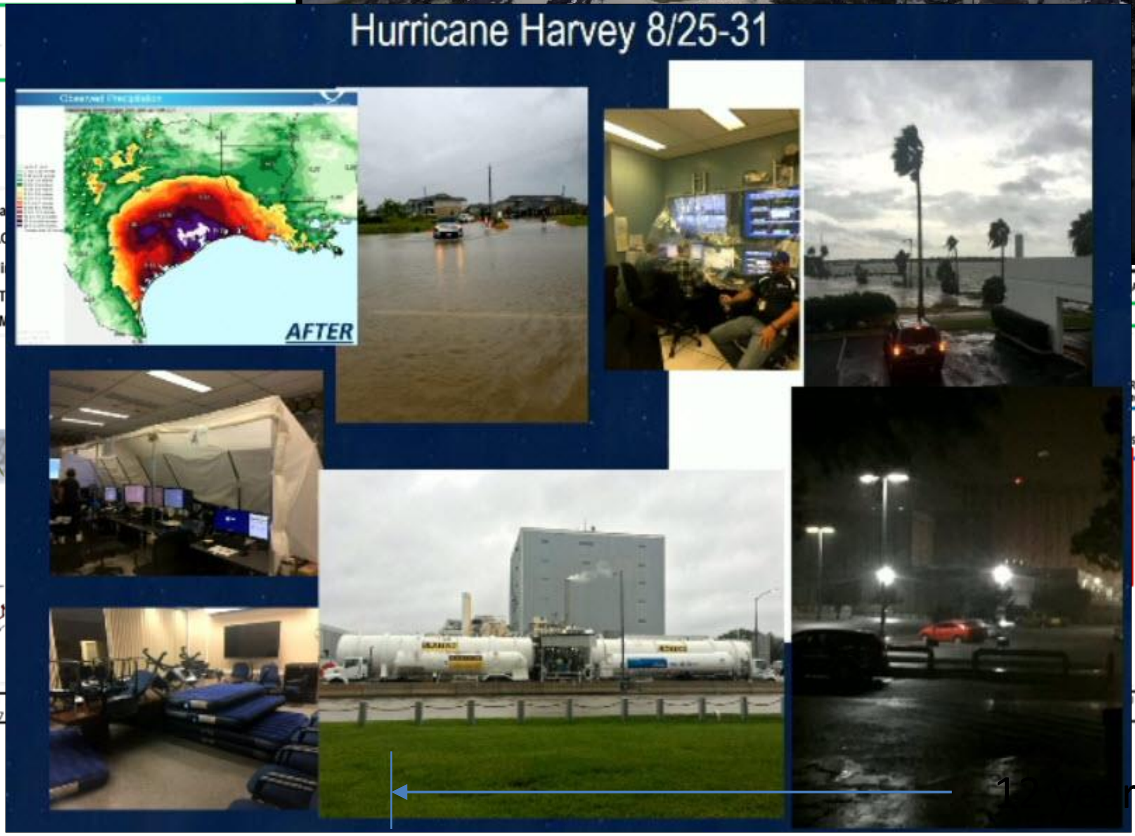


12 years of I&T

Verification/Validation Testing was not without drama

- One differen… as very long
- TVAC GSE eq… rdware
- Numerous te…
- Major tests r… onnel intensive

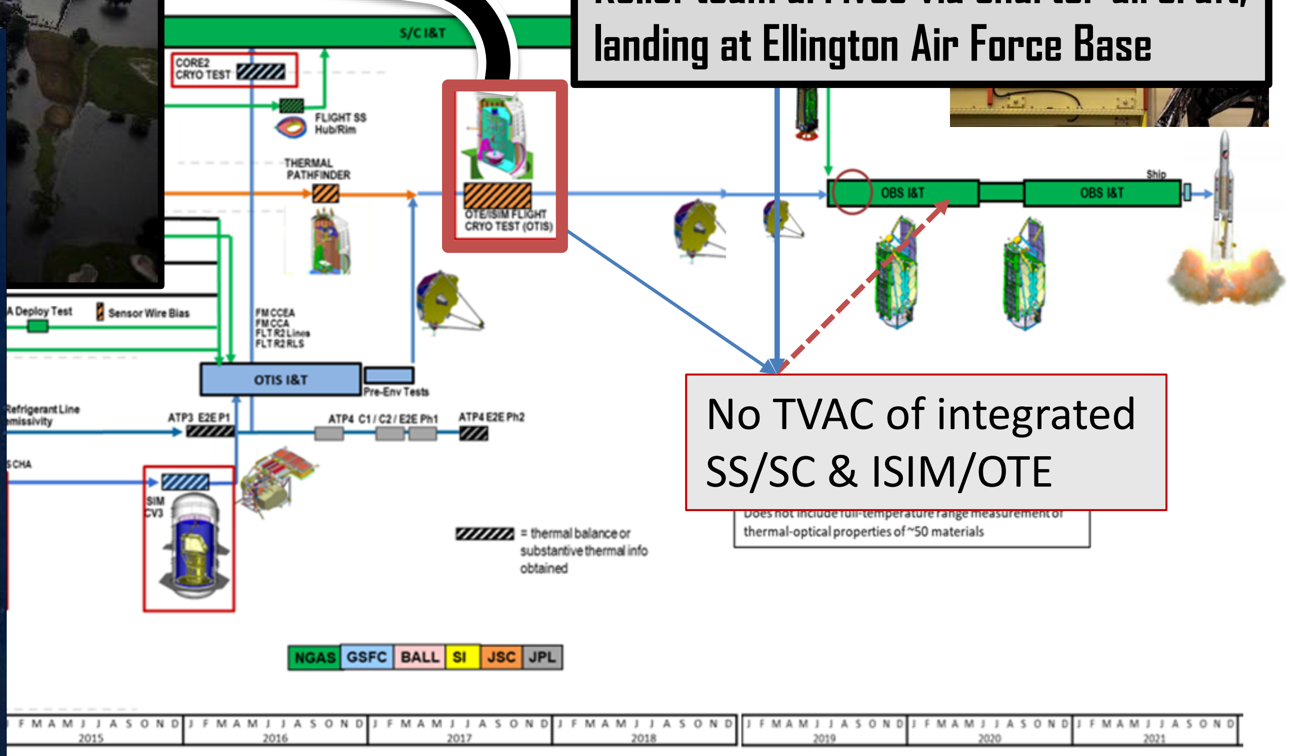




August 25-29 2017
Hurricane Harvey, 50" rain

Crew confined at MSFC for several days as OTIS reaching cryostable state

Relief team arrives via charter aircraft, landing at Ellington Air Force Base



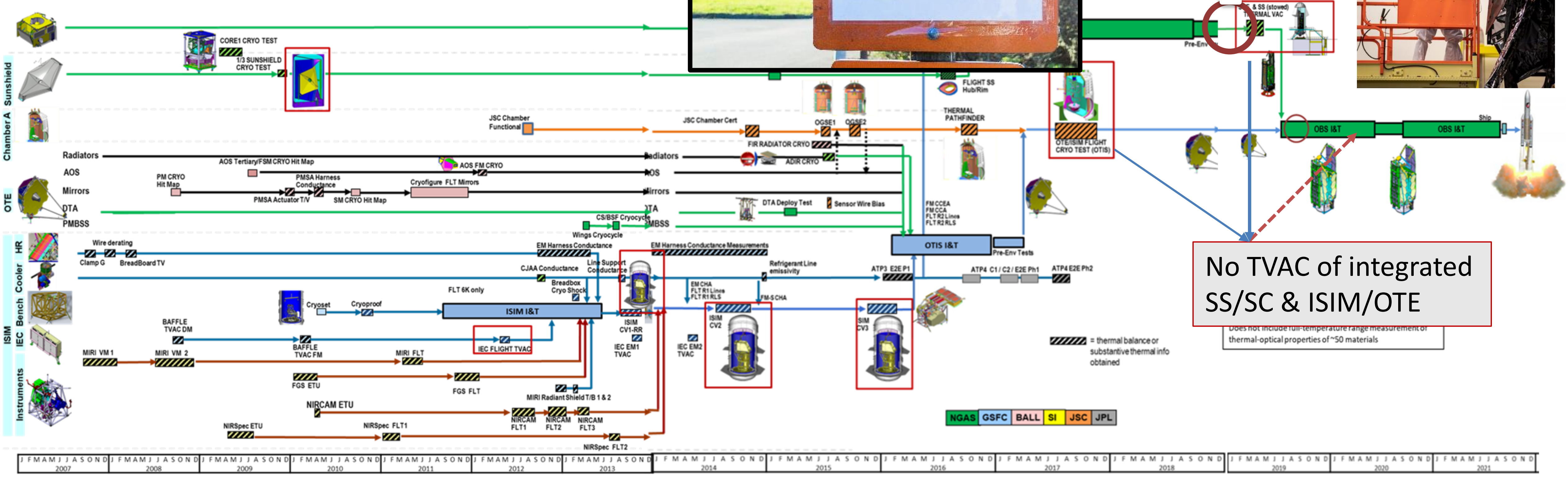
No TVAC of integrated SS/SC & ISIM/OTE

1… rs of I&T

Verification/Validation Testing was not without drama

- One difference between JWST and other prog
- TVAC GSE equipment was often as complex as
- Numerous tests/measurements with flight-lik
- Major tests required months under vacuum a

22 Dec 2018 to 25 Jan 2019
35-day Federal Shutdown
Complicates prep for SC TVAC

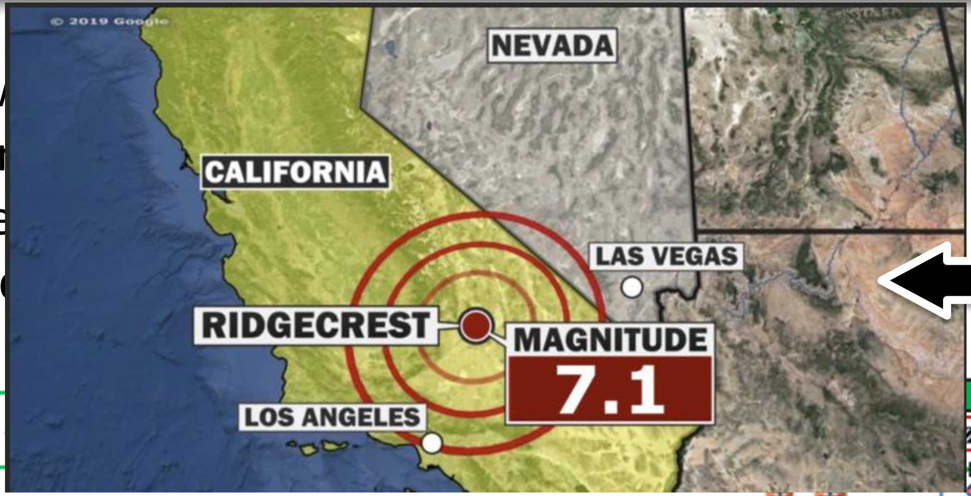


No TVAC of integrated SS/SC & ISIM/OTE

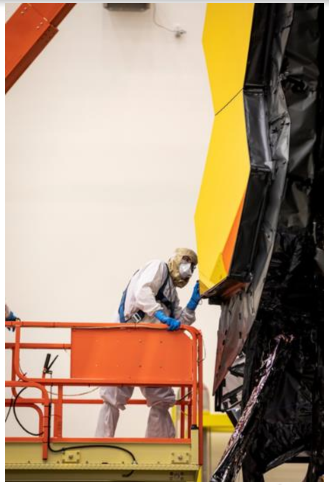
12 years of I&T

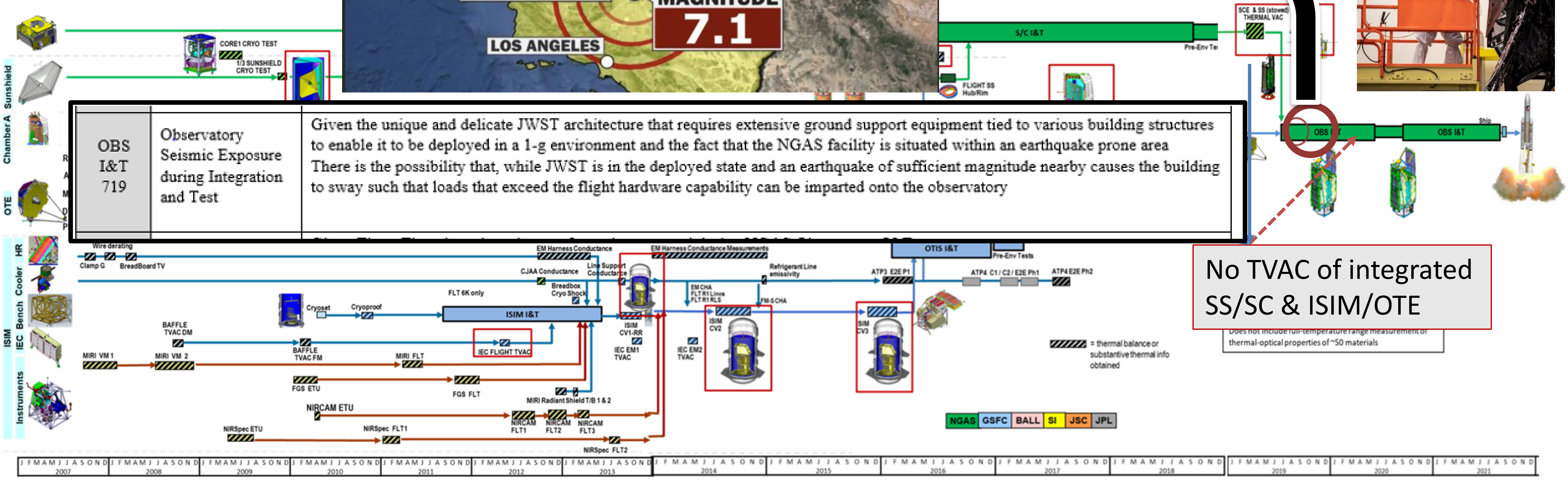
Verification/Validation Testing was not without drama

- One difference betw
- TVAC GSE equipmen
- Numerous tests/me
- Major tests require



July 4-6 2019
Ridgecrest earthquakes
Magnitudes 6.4, 5.4, 7.1
OTIS on stand





OBS I&T 719	Observatory Seismic Exposure during Integration and Test	Given the unique and delicate JWST architecture that requires extensive ground support equipment tied to various building structures to enable it to be deployed in a 1-g environment and the fact that the NGAS facility is situated within an earthquake prone area There is the possibility that, while JWST is in the deployed state and an earthquake of sufficient magnitude nearby causes the building to sway such that loads that exceed the flight hardware capability can be imparted onto the observatory

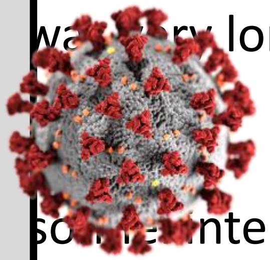
No TVAC of integrated SS/SC & ISIM/OTE

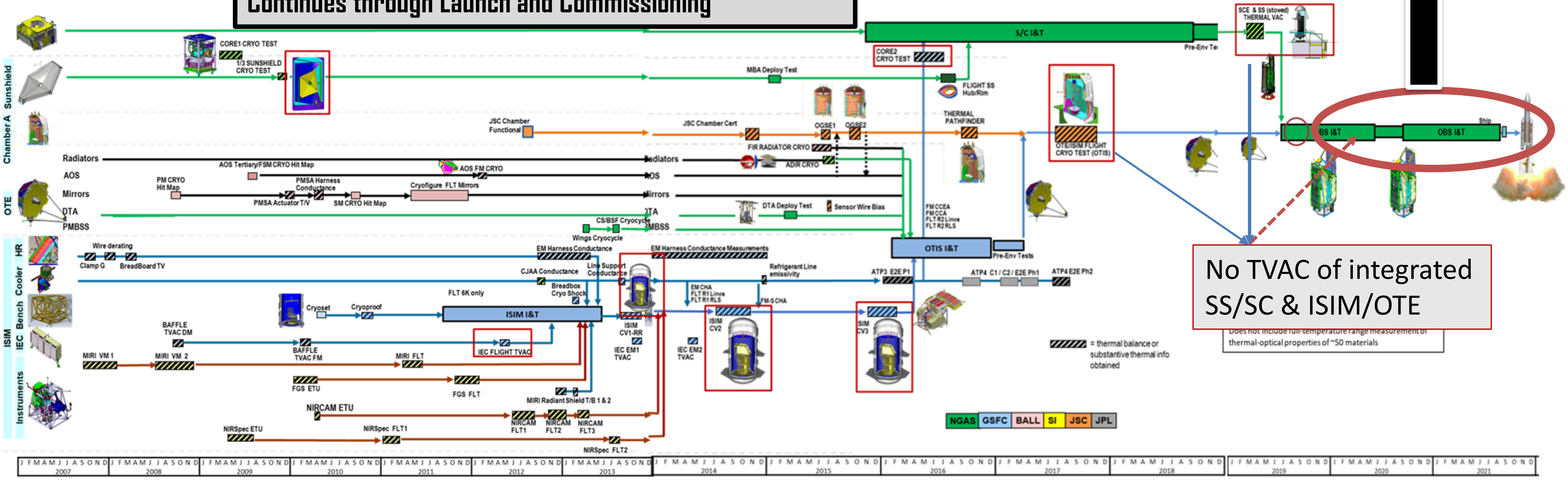
12 years of I&T

Verification/Validation Testing was not without drama

- One differe ... wa ... ry long
- TVAC GSE e
- Numerous t
- Major tests ... so ... ntensive

March 16, 2020 - Launch
COVID-19 pandemic
Slows final integration, delays launch 6-months
Complicates launch site operations and launch rehearsals
Travel restricted, requires additional authorization
Continues through Launch and Commissioning





12 years of I&T

Thermal Analysis

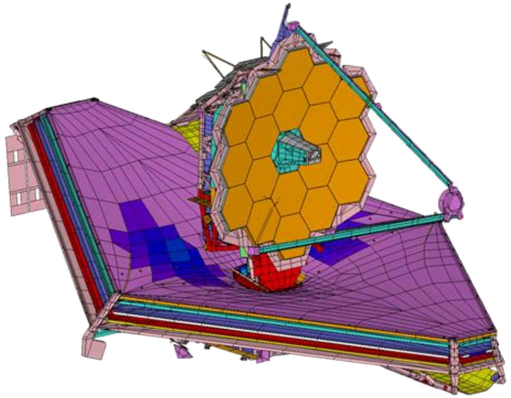
- Significant analysis effort was required in order to generate and validate thermal design & mission operations
  - Launch & Ascent phase. When in stowed configuration, cryogenic-optimized regions are very sensitive to solar exposure. Required clocking and roll profile development
  - Many deployment configurations. Most involved thermal preconditioning (ex. Motor and hinge heating)
  - Cooldown (180 days). Develop a thermal timeline as many activities required to negotiate 97 Limits & Constraints
  - Commissioning. Achieving final science thermal state.
  - Thermal Vac testing. GSE was often as thermally complicated as the test article.

- For the cryogenic regions, models required a lot of detail in order to ensure no heat paths were missed. Even a “negligible” path can be significant in a cryo environment where sizable temp, stray light, and stability impacts are measured in milliwatts.
  - Non-grey effects have impacts
  - Large number of ray casts; low extinction.

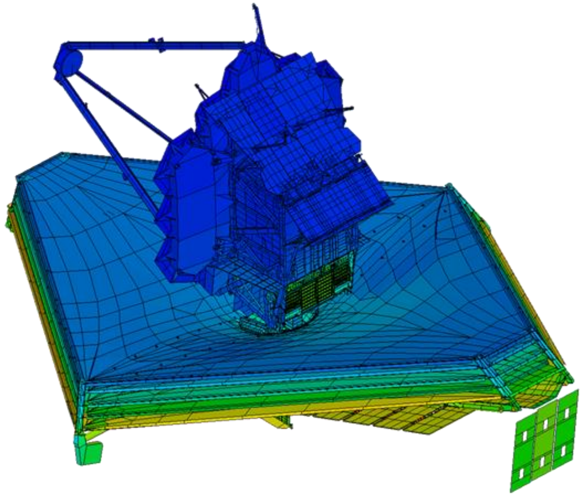
- Even for the room-temperature spacecraft bus, attention to detail was important. Bus runs hot when Observatory deployed.
  - One hemisphere is a view to a hot Layer 1 sunshield layer (~400K, e=0.75)
  - Solar energy is reflected off Layer 1 onto the bus (50% solar reflectance)

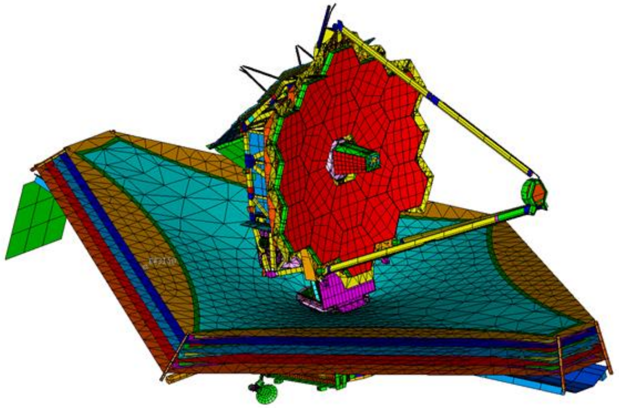
Thermal Models

- JWST/Thermal employed two independent thermal models for nearly all major efforts. One managed by NGAS, GSFC the other.
    - Little historical experience with such a large and passive cryogenic spacecraft. Failed performance was identified as a Project high-Risk
    - Increases confidence in model results. Greatly lowers risk of a “gotcha”.
    - No thermal-vacuum test of entire Observatory. Either stowed or deployed. A large amount of design verification cannot progress beyond “analysis only”.
    - <u>Represented a major component of the thermal verification process.</u>

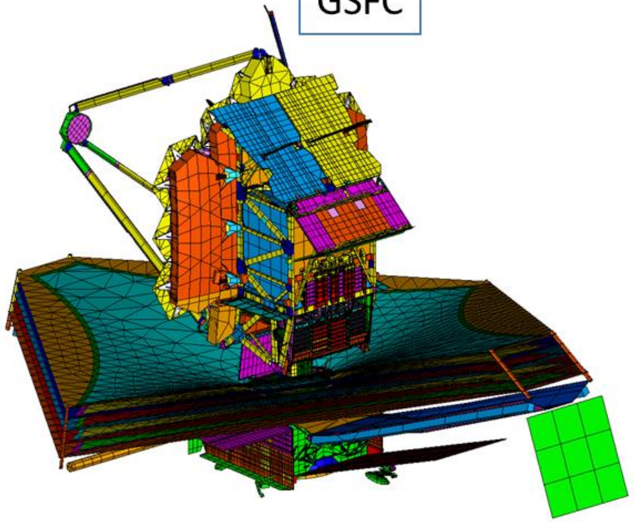


NGAS





GSFC



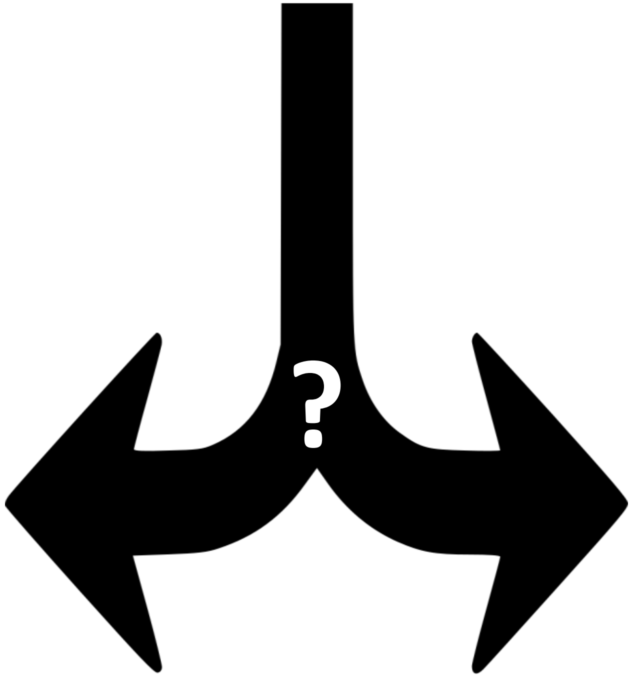
	NGAS	GSFC
Geometry	TSS	NX-IDEAS
Solver	SINDA-G	TMG
Nodes	312,000	901,900
Couplings	25,600,000	130,000,000*

Solution times vary depending on case type:
4 hours for SS rerun to 2 weeks for 180d commissioning transient run

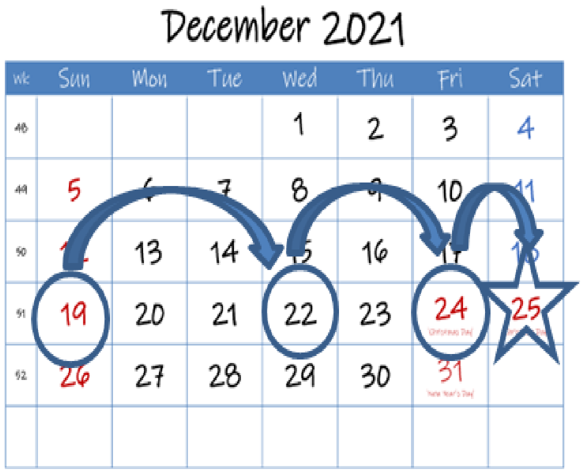
So….How did we do?

Project Risk

530	Cryo Temperature Performance	GIVEN THAT 1.) material and coating properties have higher uncertainty and variability at temperature than margined and/or 2) MLI performance and variability at temperature exceeds margins and/or 3) sunshield shape and irregularities at temperature exceed margins and/or 4) cable harness bundles, shape, and properties uncertainty at temperature exceed margins and/or 5) deployment particulate or ice contamination from I&T, launch vibration shedding, esp. on sunshield exceed margins and/or 6) IEC back loading on ISIM via the sunshield is higher than predicted THERE IS THE POSSIBILITY THAT the observatory is unable to achieve OTE & ISIM temperature requirements WITH THE RESULT THAT the science performance will be degraded

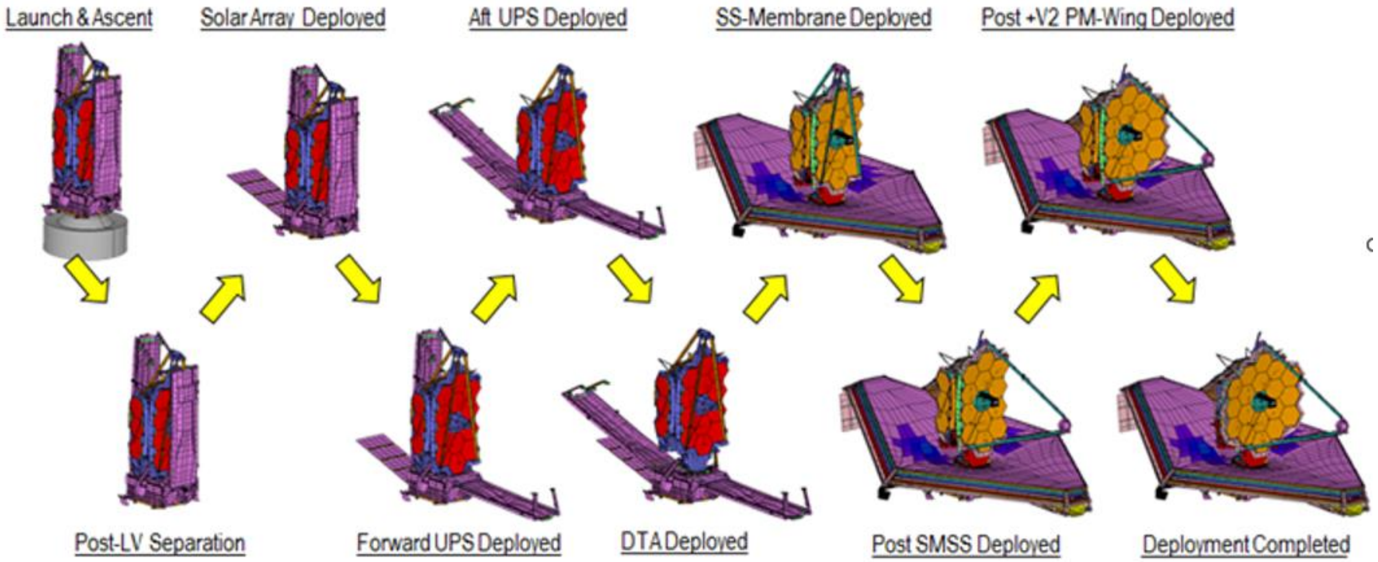


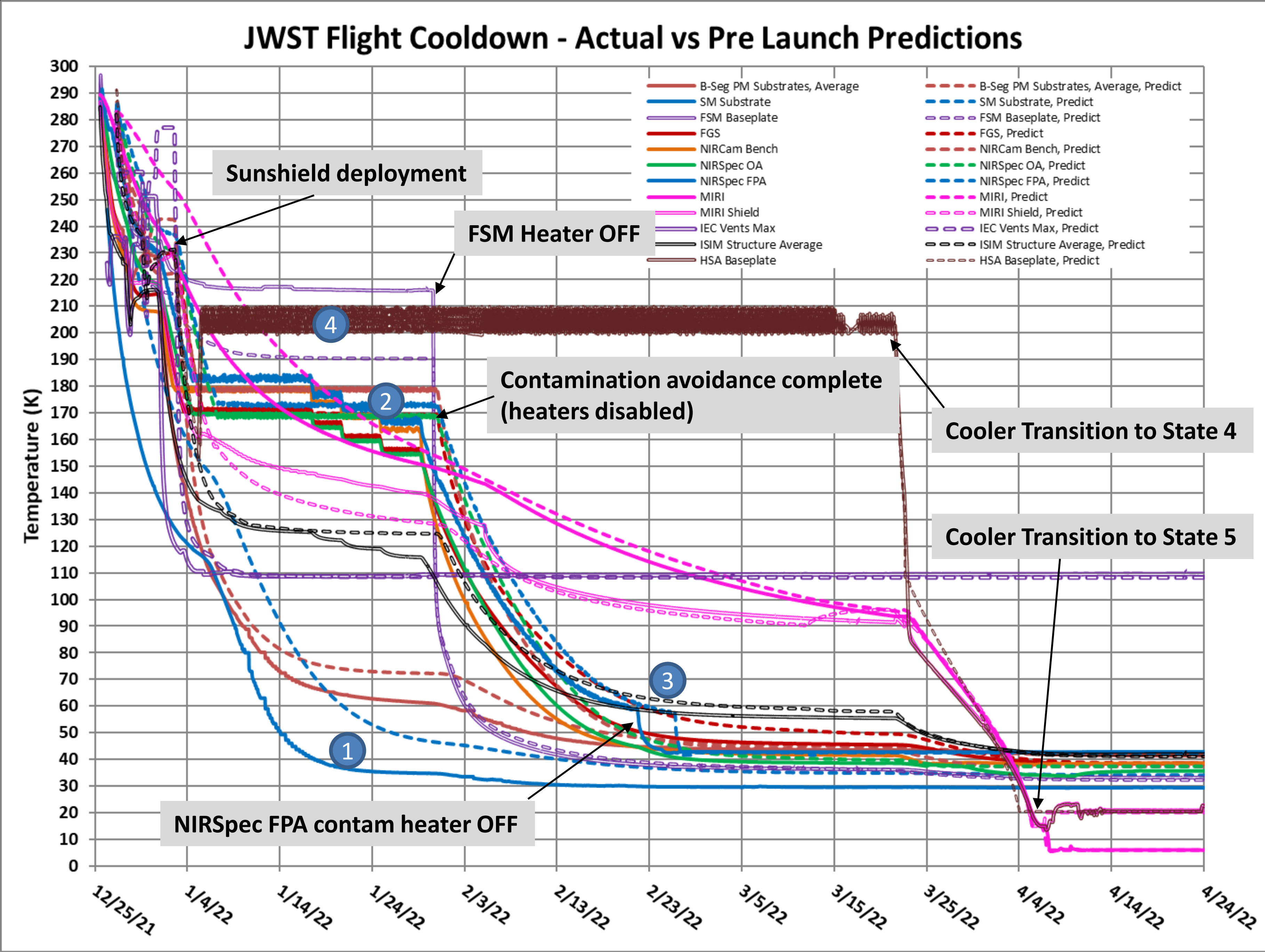
Launch – 25 December 2021 12:20 UTC (0720 EST)



Deployments

- Overall, deployments and early operations (first 2 weeks) went extremely smooth.
- Issues/Anomalies involving Thermal Team:
  - Following Sunshield Mid Boom deployment, Forward and Aft sunshield deployment hardware used for tensioning was projected to exceed pre-launch predictions. This was a concern because the tensioning motors will increase in temperature by 15-20K during operation. This could threaten Operational limits.
    - Thermal team identified a better Sun-Pitch orientation for tensioning. Reducing temperature by ~10K
    - Deployment team and Motor manufacturer reviewed testing and heritage and determined that Op limit could be raised by 10K.
    - Combination of these two paths returned margin to permit continuing safely with sunshield tensioning.





Most differences occurred prior to sunshield deployment and converged with predictions afterwards. Conservatism was much larger early as high temperatures were concern

1. Secondary Mirror Assembly cooled faster and approx. 5K lower at SS
2. MSE opted for a step-down plan not in pre-launch baseline
3. NS FPA heater released earlier at higher temp. 5d early
4. Conductance of heat strap connecting FSM to AOS radiator proved to be less than predicted

Actual cooldown time only 1.8 days longer than predicted (122d vs 120d)

Sensors vs Predictions at SS:
85% within 2K
96% within 5K

Final Instrument Temperatures & Margins

- Final instrument trim heater settings matched prediction

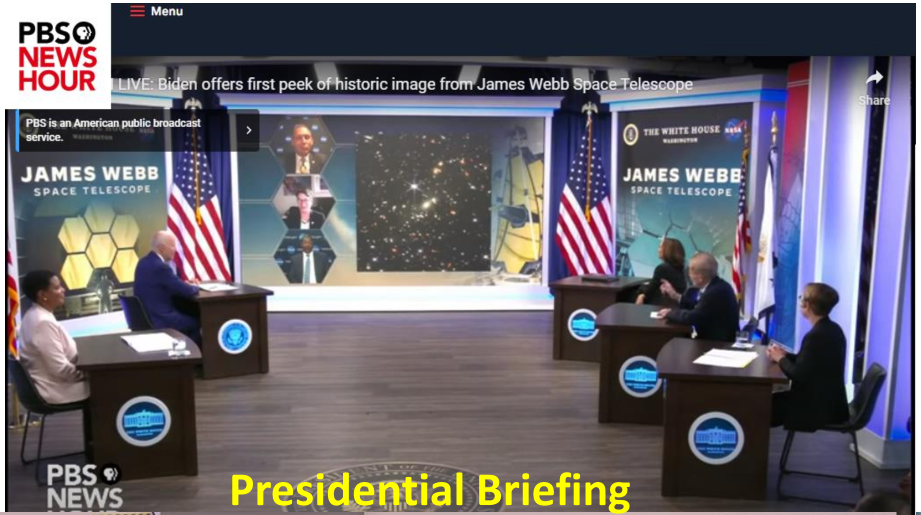
Instrument Interface	Flight (K)	Target (K)	Trim Settings
NIRSpec OA	35.57	35.5	10
NIRSpec FPA	42.80	42.8	8 (trim), 30 (CCH)
FGS	38.48	38.5	4
NIRCam	38.52	38.5	14

MIRI mounting feet 35.48K vs < 40K target

- Measured parasitic heat loads on the cryocooler are close to predictions at end of Commissioning
  - 118.6 mW (Flight) vs 117.6mW (predicted)

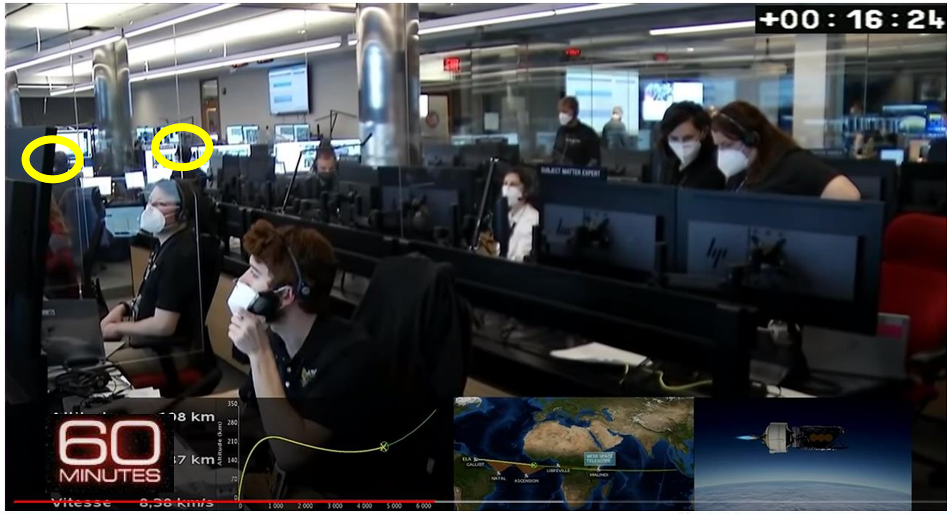
This confirms that the Observatory is demonstrating margins to parasitics very similar to predictions (>75% against future growth)

“Celebrity” – Project members get 15 minutes of Fame

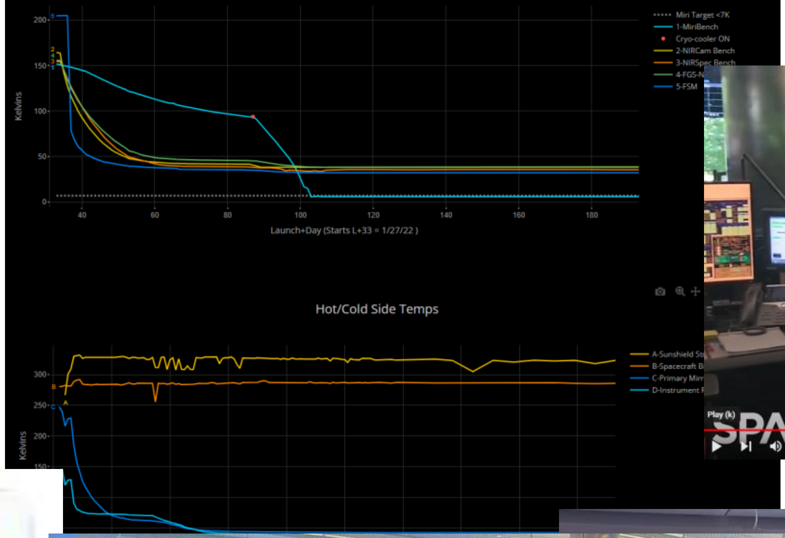


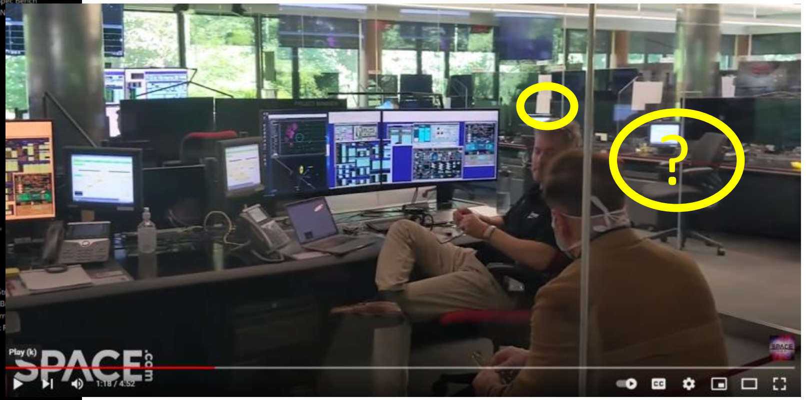
Milky J (center) poses with members of the Webb team. From left to right: Phil Driggers, Katie Lilly, Milky J, Mike Menzel, Amber Straughn, Ray Lundquist. Mike is demonstrating his "JW" hand sign. (Image credit: NASA/Chris Gunn)

Thermal?...well...15-milliseconds of Fame

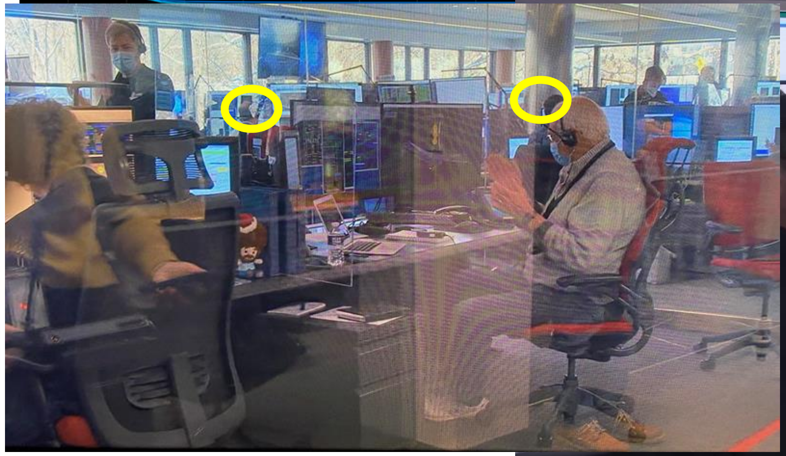


Where is Webb? Public Outreach

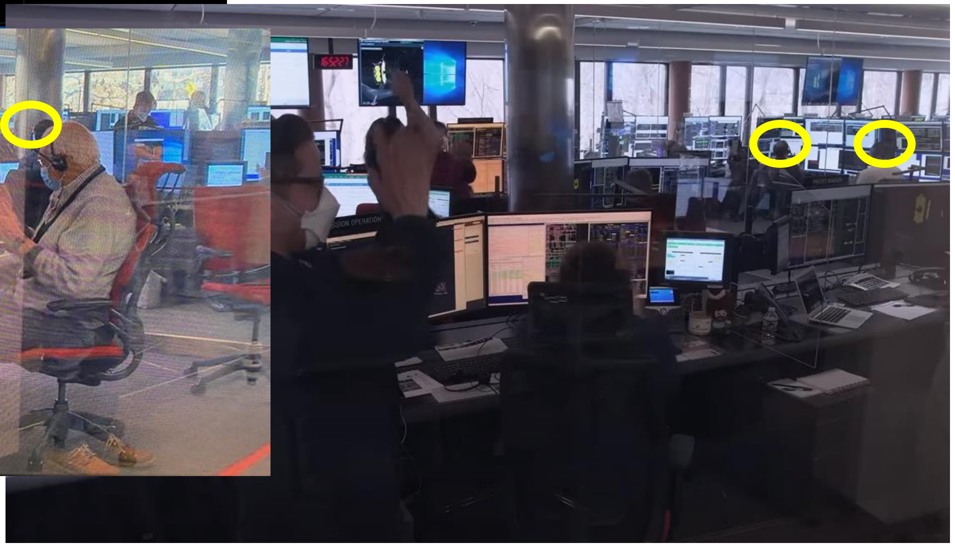




NASA TV deployment coverage



Netflix 'Unknown: Cosmic Time Machine'



NOVA “Ultimate Space Telescope: Making the James Webb Space Telescope”

Handoff after 180-day Cooldown & Commissioning Campaign

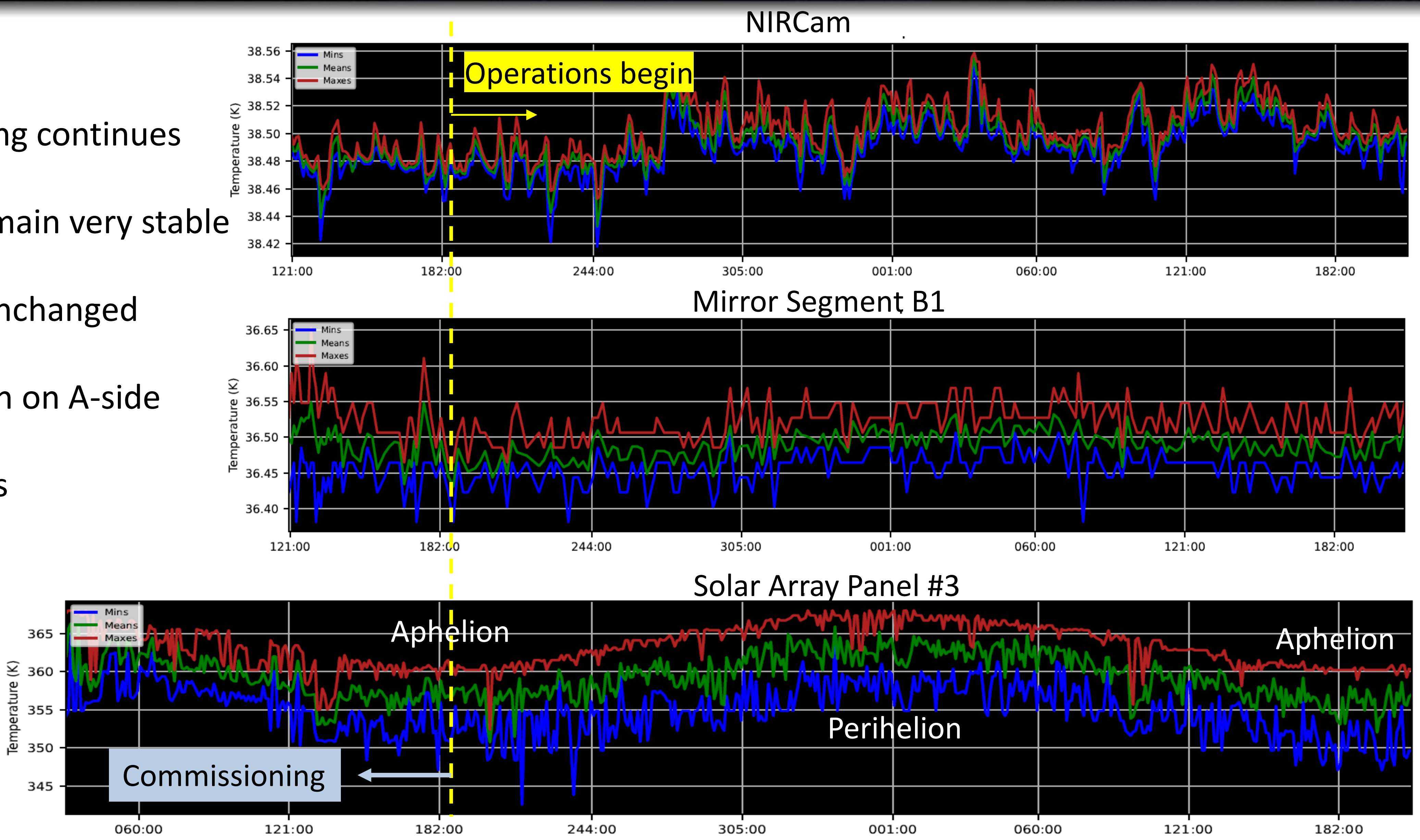
- Commissioning ended 10 July 2022 with official handover to STScI FOT personnel.

- **Tale of the Tape:**
- Thermal team participated 24/7 in monitoring JWST from the MOC for 83 days (12hr/shift). Then another 52 days at 8hr/shift for first and second shift. Then on-call/remote.
  - Total of 532 personnel shifts completed (> 2800 person-hours)
  - *Personal*: 19 COVID-19 rapid antigen tests taken

- **Status at handoff:**
  - All 150 Heaters circuits nominal on A-side (redundancy preserved)
  - 1 failed sensor (out of 1048). Used for hinge temperature.
    - Failed after deployments during cooldown.
  - No Red alarms for violation of limits throughout 180 days
  - No violations of the 93 Limits & Constraints during cooldown
  - Cooldown required only 2 days more than predicted (120 days predicted)
  - 3 Mission-level Anomalies encountered. 2 resolved (SCAT Valves on Pad, MTS motor). 1 minor and tracking (Catbed temp sensor)

1-year Later

- Long term trending continues
- Temperatures remain very stable
- Duty cycles are unchanged
- All heaters remain on A-side
- No loss of sensors



Thanks to <u>Everyone</u> over the years for making this Successful

Shaun	Thomson**	GSFC
Paul	Cleveland	GSFC
Brian	Comber	GSFC
Christine	Cottingham	GSFC
Angel	Davis	GSFC
Amy	Delisa	GSFC
Matt	Garrison	GSFC
Stuart	Glazer	GSFC
Chris	May	GSFC
Dan	Nguyen	GSFC
Tak	Or	GSFC
Wes	Ousley	GSFC
Keith	Parrish	GSFC
Jignasha	Patel	GSFC
Hume	Peabody	GSFC
Jeremy	Samuels	GSFC
Chad	Sheng	GSFC
Jim	Tuttle	GSFC
Kan	Yang	GSFC
Michelle	Elie	STSCI
Bill	Bast	STSCI

Perry	Knollenberg*	NGSS
Josh	Adamson	NGSS
Andre	Aroyan	NGSS
Katherine	Booth	NGSS
Bill	Burt	NGSS
Dorothy	Foreman	NGSS
Catherine	Gaydosh	NGSS
John	Guildalian	NGSS
George	Harpole	NGSS
Stanley	James	NGSS
Peter	Munther	NGSS
John	Pohner	NGSS
James	Stanley	NGSS
Pam	Brinckerhoff	Ball
Ben	Drillick	Ball
Randy	Franck	Ball
Rusty	Sweigart	Ball
Dennis	Teusch	Ball
Sang	Park	Smithsonian

Additionally,

Our partner thermal engineers for instruments and launch vehicle
- Marc Maschmann (Airbus)
- Bryan Shaughnessy (STFC UKRI)
- Liz Osborne (LMCO)
- Dave Aldridge (Honeywell)
- Arianespace Thermal team

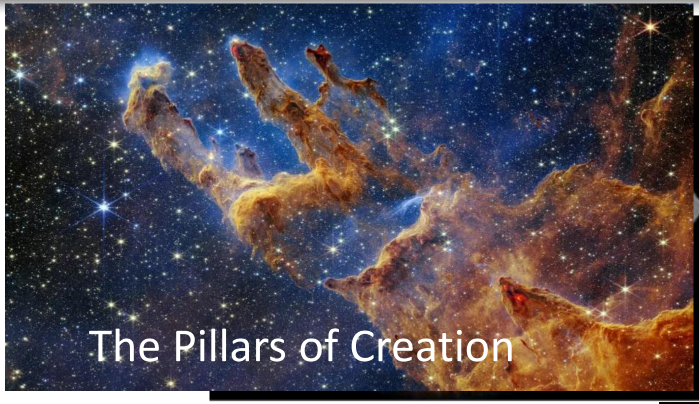
The numerous people who helped staff (very long) TVAC tests:
- ISIM CV Tests
- OTIS CryoVac Test
- SCE Thermal Vac Test

And extra NGSS members who filled in so the MOC team would not be stretched too thin.

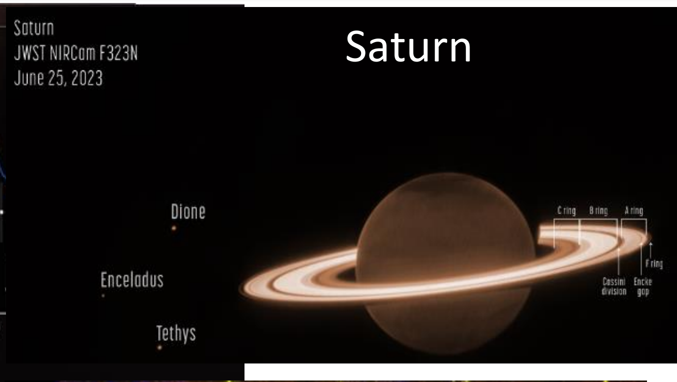
*NGSS Lead
** GSFC Lead

In Conclusion. Leave you with some of JWST's Observations…


Tarantula nebula


The Pillars of Creation

Water vapor on Wasp-96b

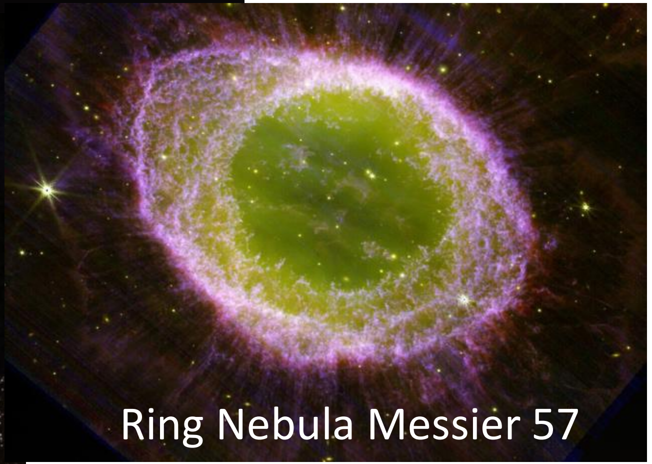


Saturn


Southern Ring nebula

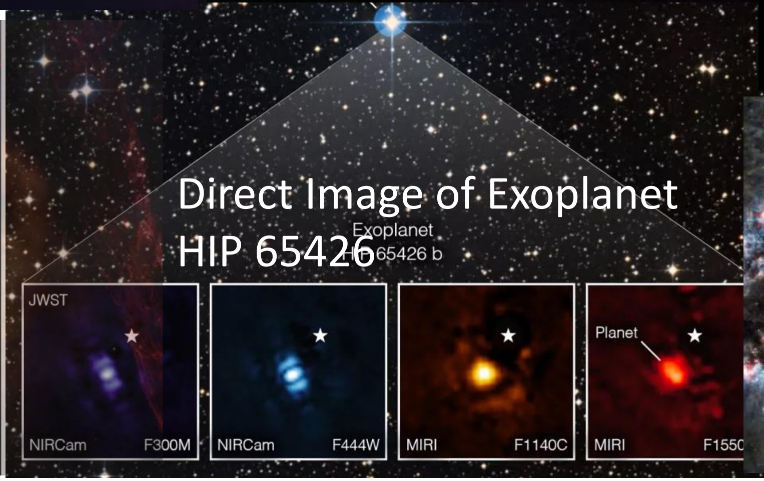

Star in constellation Taurus


Neptune


Ring Nebula Messier 57


Spiral galaxy NGC 7496


Rho Ophiuchi



Direct Image of Exoplanet HIP 65426


Galaxy M74 "Phantom"

...and some apparently not getting much attention

It's All A Simulation! Webb Telescope SHOCKS The Entire Space Industry!
12K views • 1 month ago
Voyager
The James Webb telescope has made an astonishing revelation that suggests a mind-boggling possibility: we might all be ...

James Webb Telescope Just Detected Alien-Like Structure In Space!
47K views • 3 weeks ago
Voyager
The **James Webb space telescope** has made headlines across the world because it is capturing some of the most exquisitely ...

James Webb Telescope Just Detected 755 Unidentified Objects Arriving From Another Solar System
33K views • 1 day ago
Future Space

James Webb Just Detected A Huge Structure Older Than The Universe!
235K views • 1 month ago
EYES 200M
Welcome to EYES 200M, where we explore the fascinating world of science, technology, and the universe! From the inner ...