James Webb Space Telescope
Optical Telescope Element / Integrated Science Instrument Module (OTIS) Cryogenic Vacuum Test

Part I: Thermal Architecture

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Introduction to the JWST OTIS CV Test Lecture Series

- This lecture series discusses the cryogenic vacuum (CV) testing of the James Webb Space Telescope (JWST) Optical Telescope Element / Integrated Science Instrument Module (OTIS)[1,2] from July – October, 2017 at NASA Johnson Space Center

- There are four parts to this series:
  - Part I: Thermal Architecture
  - Part II: Thermal Analysis
  - Part III: Preparations for Off-Nominal Events
  - Part IV: Lessons Learned

- Objectives of this lecture series:
  - Familiarize the audience with the James Webb Space Telescope architecture
  - Understand the thermal challenges to executing the most complex cryogenic vacuum test ever undertaken by NASA
  - Act as a guideline for planning future system-level thermal vacuum tests for large cryogenic missions

The James Webb Space Telescope: Introduction

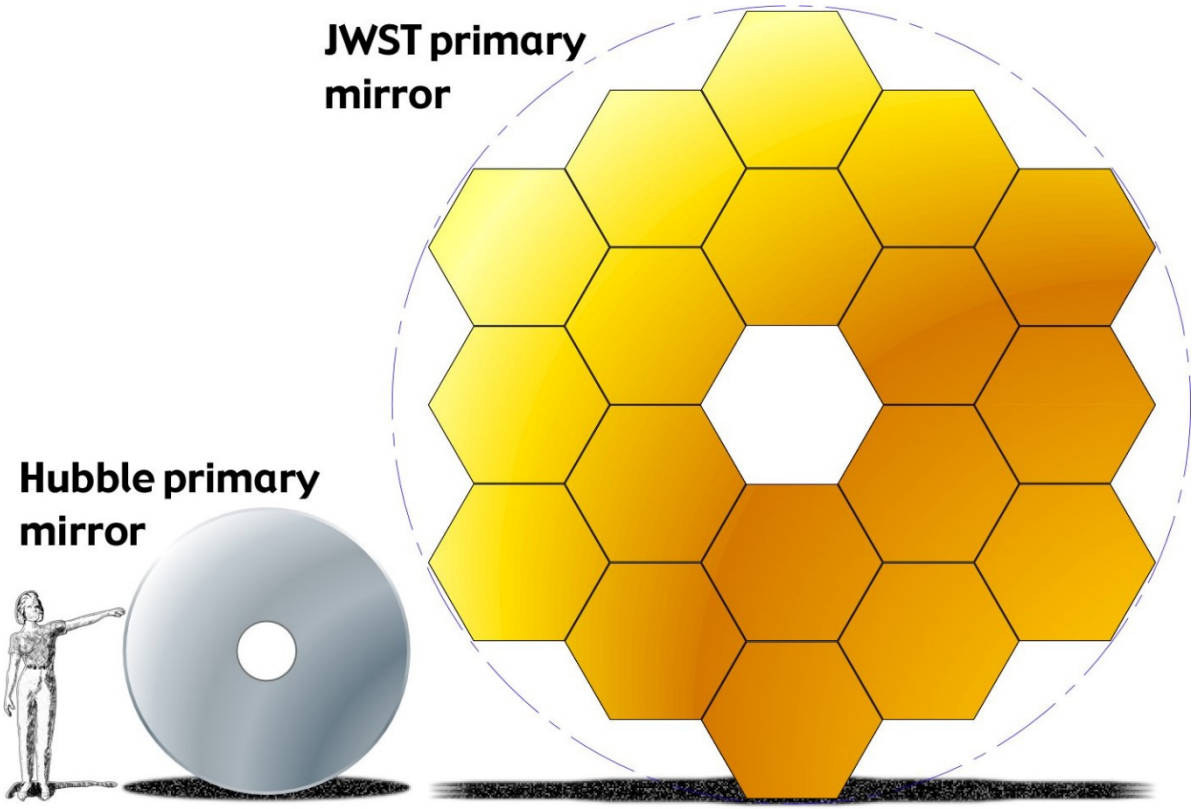
- Upon launch in 2021, the James Webb Space Telescope will become the world's most powerful general-purpose space observatory
  - Scientific successor to the Hubble Space Telescope
  - Optimized to observe in near-to-mid infrared wavelengths (0.6 – 28 μm)



JWST Full-scale model at SXSW in Austin, TX, 2013. Image source: NASA/JWST

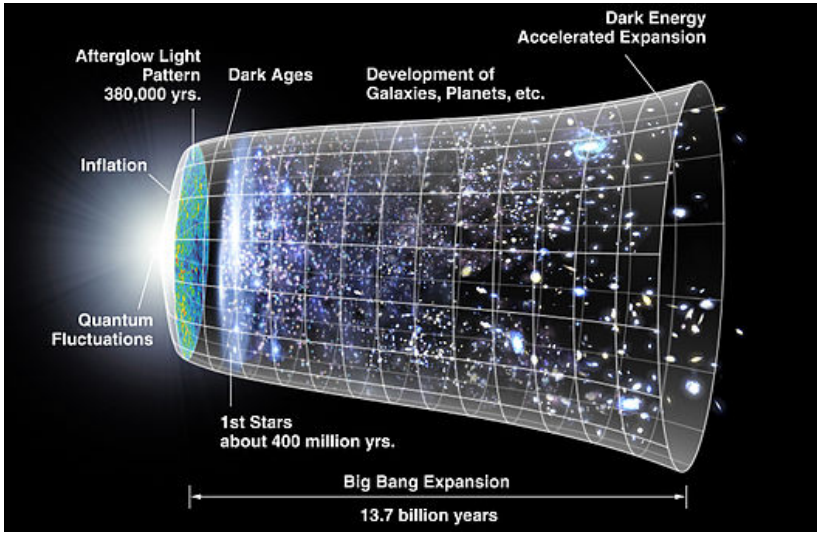
JWST vs. Hubble Primary Mirror Comparison

- JWST's primary mirror is 6.5 m in diameter and has 25 m^2 of light-collecting area
  - This is powerful enough to see the heat of a bumblebee on the moon from Earth!
- By comparison, the Hubble Space Telescope's primary mirror is 2.4 m in diameter with 4.5 m^2 of light-collecting area



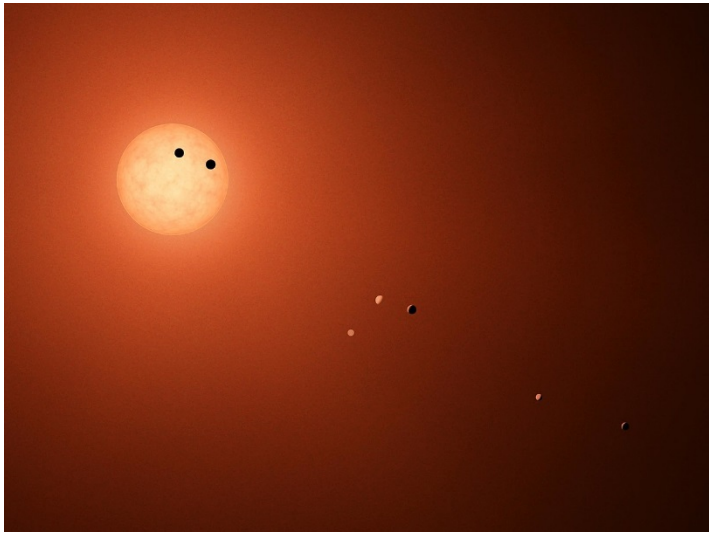
Source: NASA/JWST

JWST Science [3]



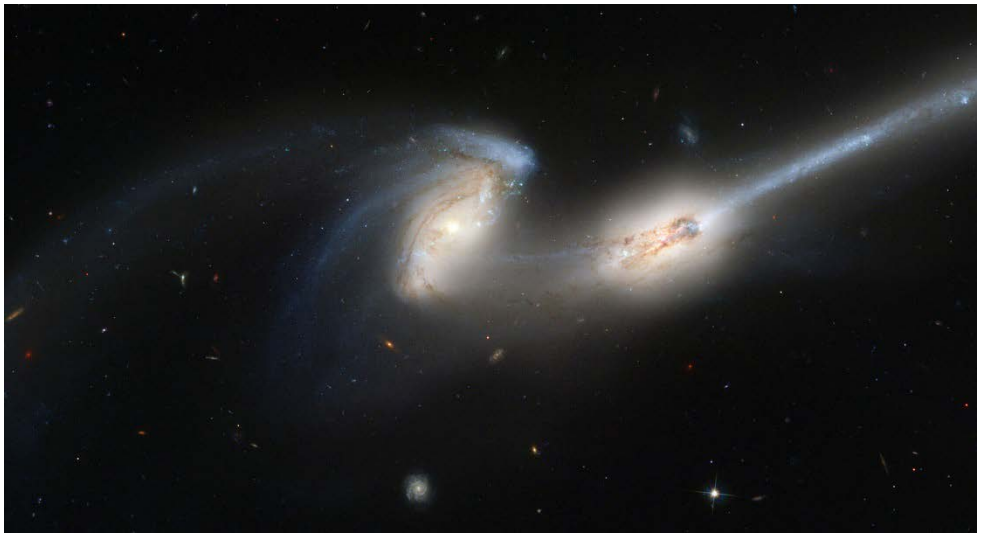
Source: NASA/WMAP

First Light and Reionization



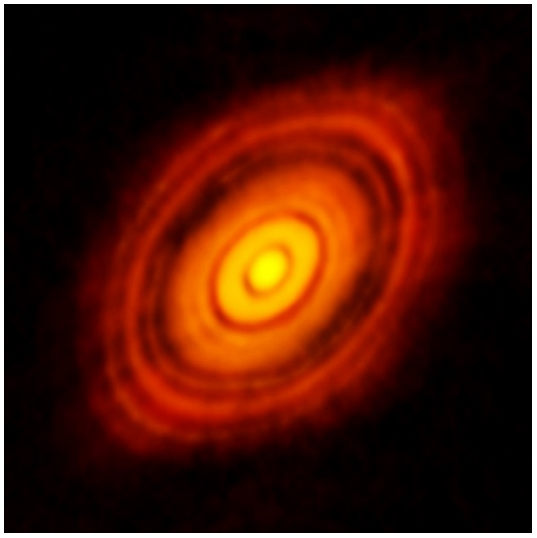
Source: NASA/JPL-Caltech

Planetary Systems and the Origins of Life



Source: NASA/ESA

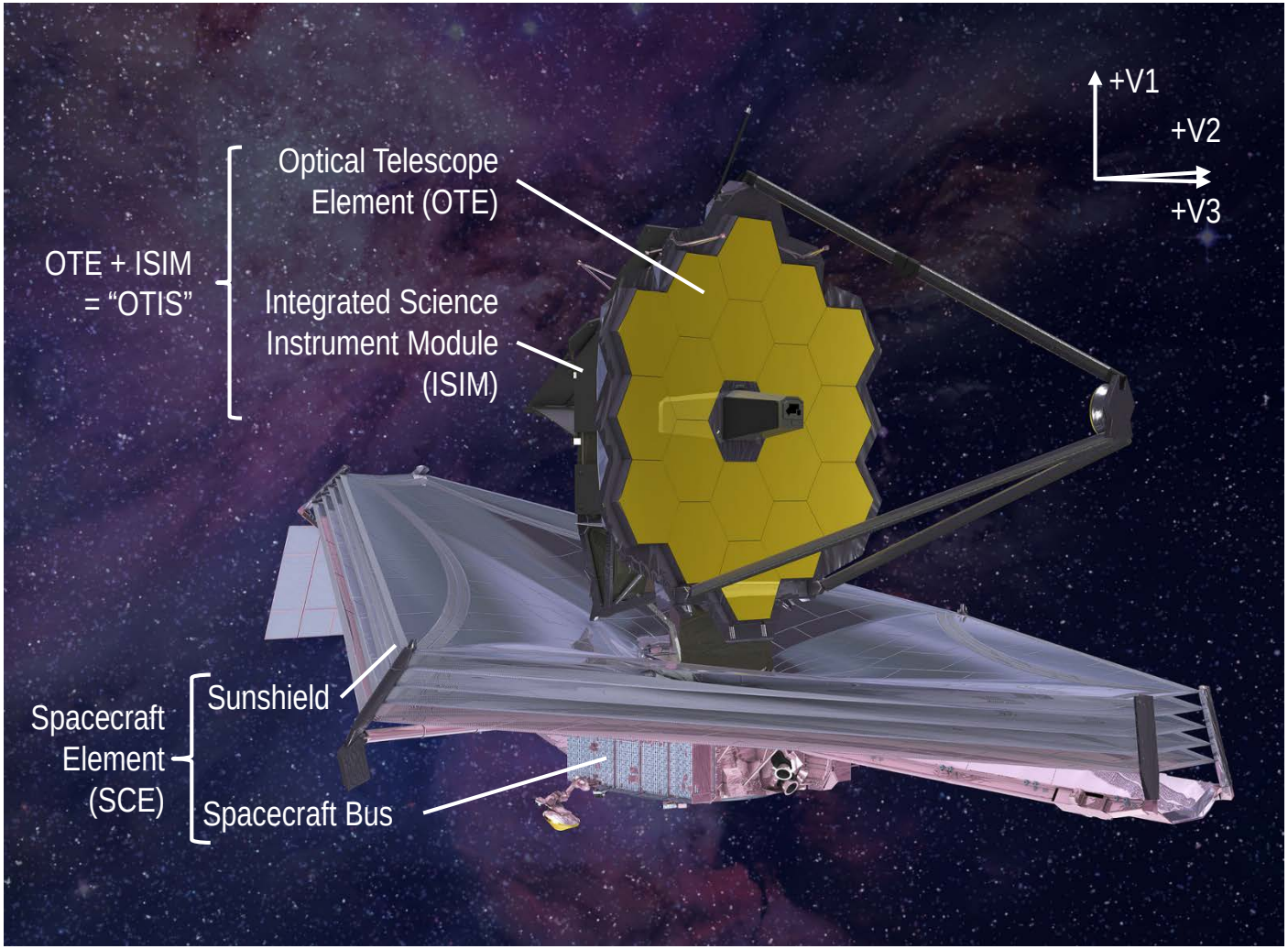
Assembly of Galaxies



Source: ALMA Observatory

Birth of Stars and
Protoplanetary Systems

Major System-Level Assemblies of the James Webb Space Telescope



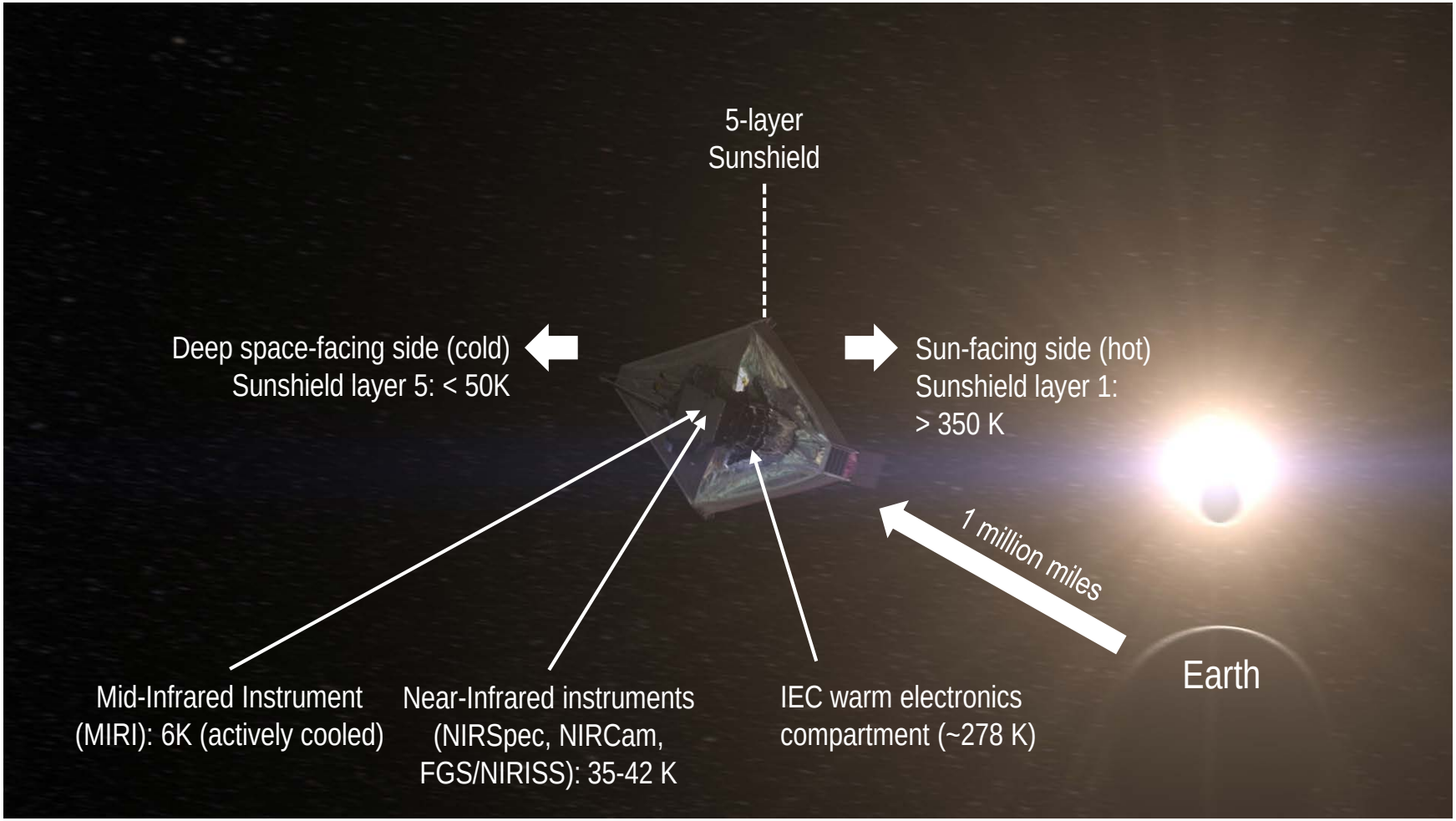
Source: NASA/JWST

Completed "OTIS" Element at NASA Goddard Space Flight Center SSDIF Clean Room



Source: NASA/JWST

Thermal Environment in Flight



Source: svs.gsfc.nasa.gov

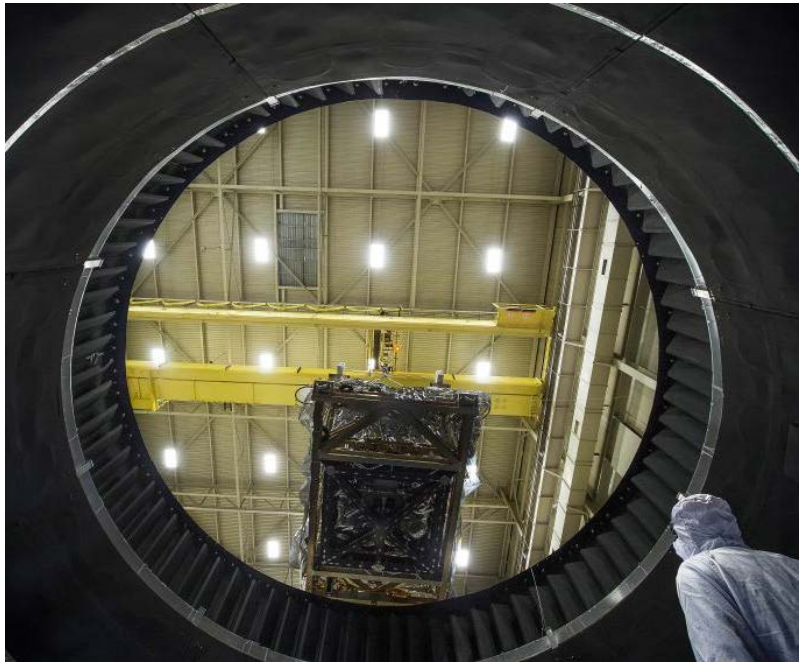
OTIS CV Thermal Test Objectives [4]

- Preserve hardware integrity upon transition to cryogenic thermal balance (cryo-balance) conditions and transition back to ambient temperatures by respecting all imposed limits and constraints (L&Cs)
- Achieve the simulated on-orbit payload temperature levels and stability for optical, mechanical, and instrument tests
- Predict and measure thermal balance test data for model crosscheck, both on ISIM and OTE components
- Achieve a workmanship thermal conductance assessment of the flight instrument heat straps which for the first time would be connecting all the payload flight instruments and radiators
- Achieve test timeline optimization by executing the OTIS CV cooldown and warmup in a time-efficient manner

What's the Importance of Thermal Vacuum Testing?

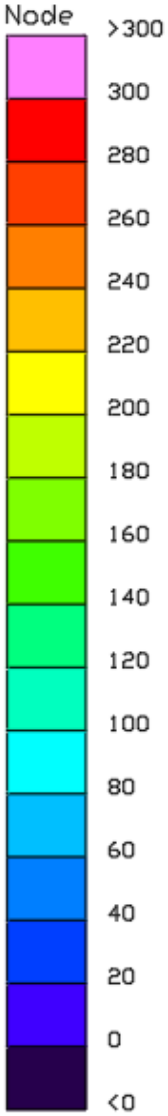
Thermal testing is done in a vacuum chamber at *margined* temperature extremes and is designed to verify workmanship, demonstrate performance, and collect data to be used in correlating thermal models

Two types of testing are performed:
Thermal balance plateaus: thermal environment is set, and spacecraft must achieve energy balance with environment. Balance criteria met from achieving temp. rate-of-change requirement on components. Thermal data collected is used to verify predictive accuracy of thermal models
Thermal vacuum cycles: Quality assurance test to take hardware beyond its operational temperatures and ensure it will survive temperature extremes: used to verify workmanship on components

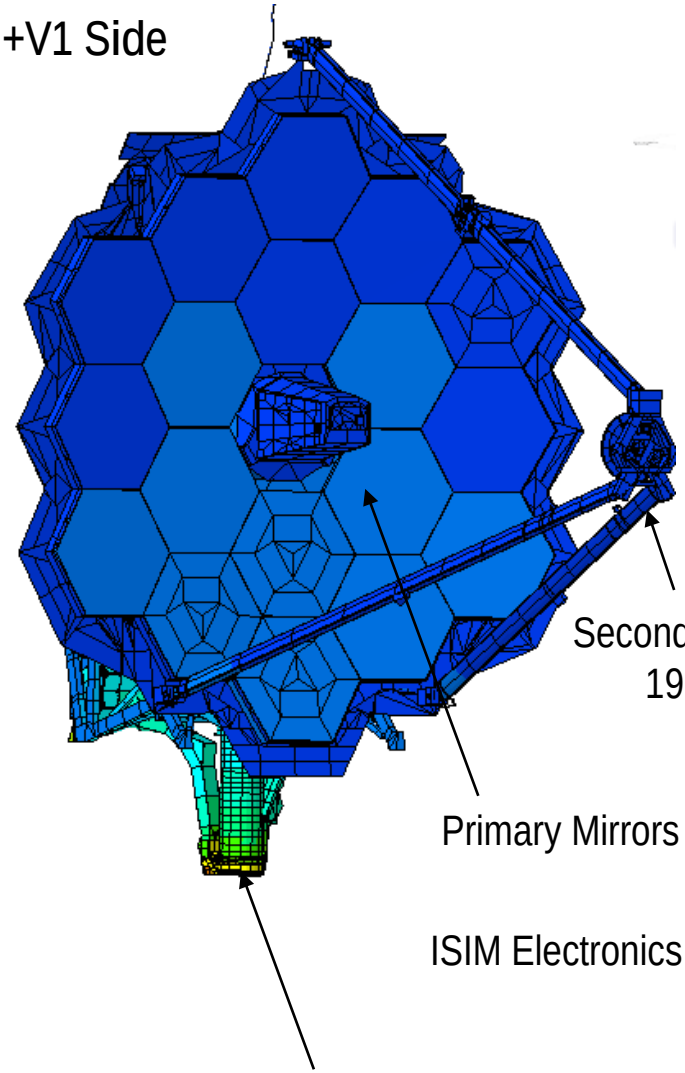


Cryo-vacuum testing of ISIM at NASA Goddard Space Flight Center's Space Environment Simulator Chamber
Source: NASA/Chris Gunn

What Are Our Temperature Goals on OTIS?



+V1 Side



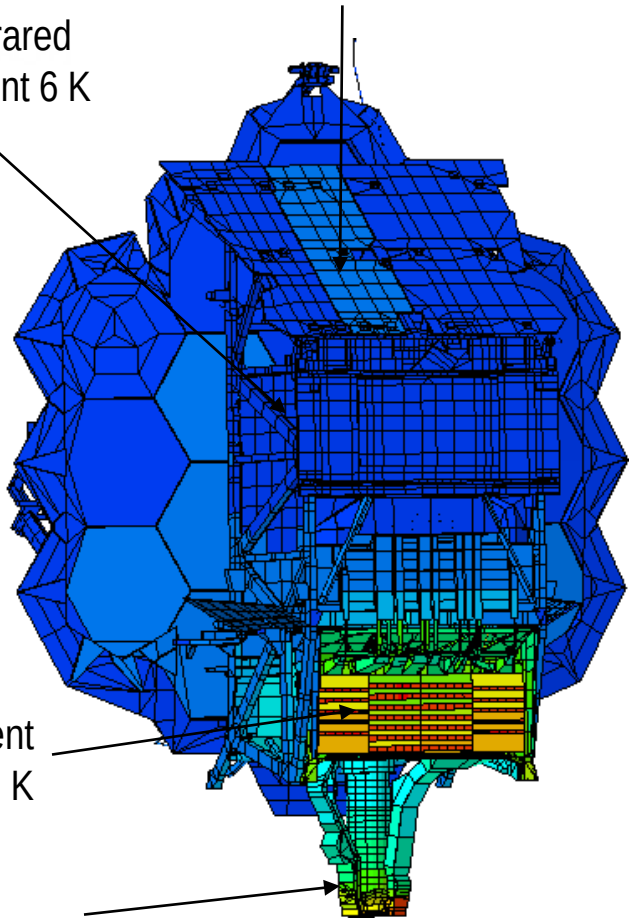
Secondary Mirror
19-54 K

Primary Mirrors 32-59 K

Interface with Spacecraft Bus 295 K
(Plus surfaces to simulate backloading from the sunshield)

Near-Infrared Instruments
and Instrument Radiators
35 K – 42 K

Mid-Infrared
Instrument 6 K

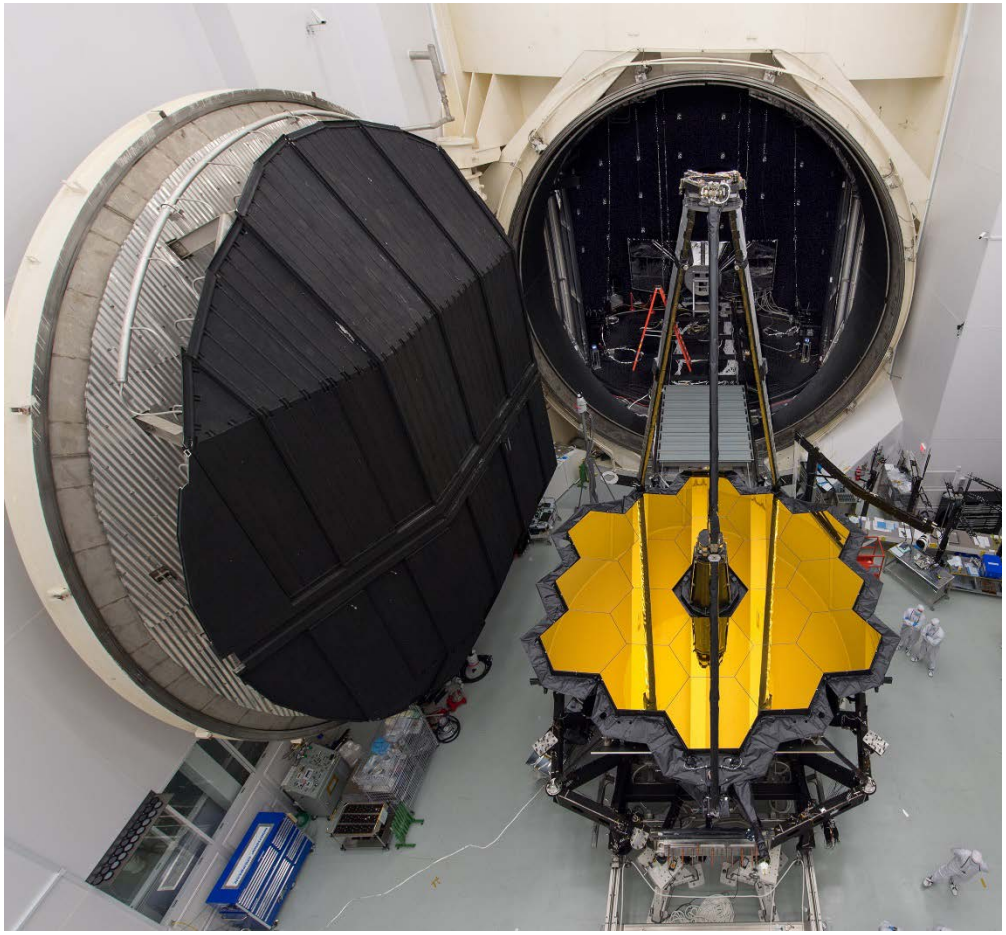


ISIM Electronics Compartment
278 K - 288 K

-V1 Side

Image sources: NASA/JWST

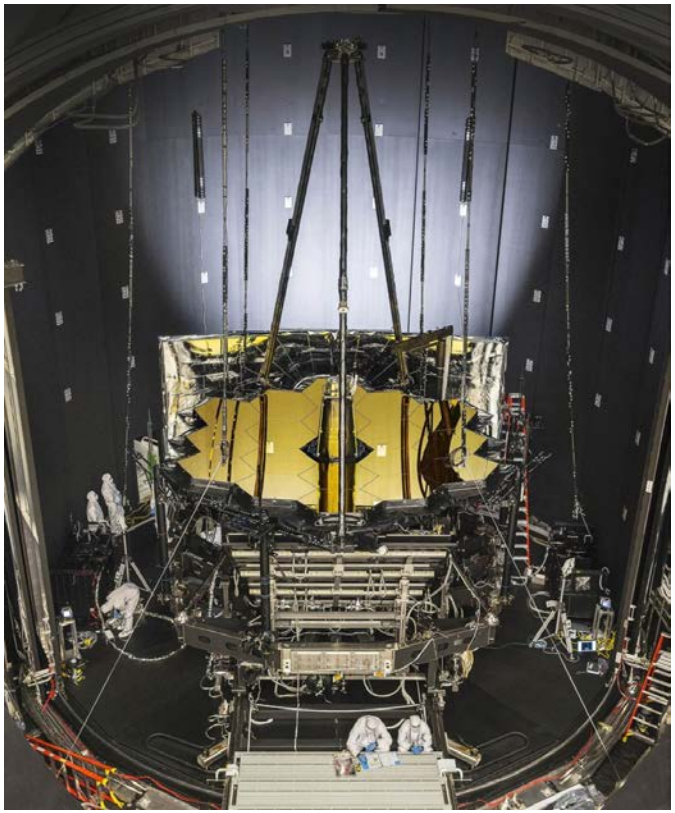
How Do We Replicate JWST's Flight Thermal Environment in Test ?



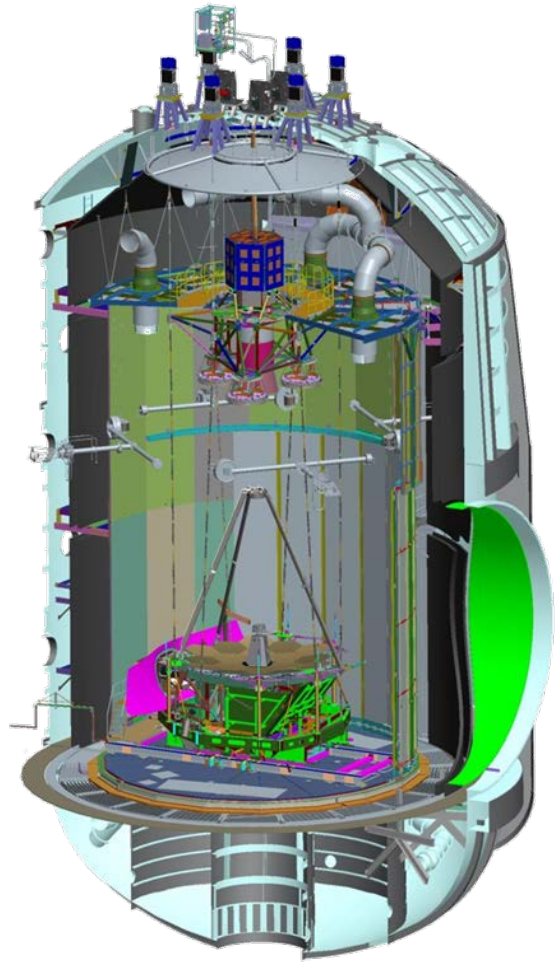
Source: NASA/JWST

- Use one of the largest thermal vacuum chambers in the world (NASA Johnson Space Center's Chamber A)
  - Unfortunately, even this chamber is not large enough to fit all of JWST, so we need to test in separate system-level assemblies (OTIS being the major cryogenic test)
- Install a gaseous helium shroud to lower the payload temperatures to 20K, and an LN2 shroud to lower the overall environmental loads on the helium shroud/refrigerator [5]
- Install GSE to simulate heat from the flight spacecraft bus

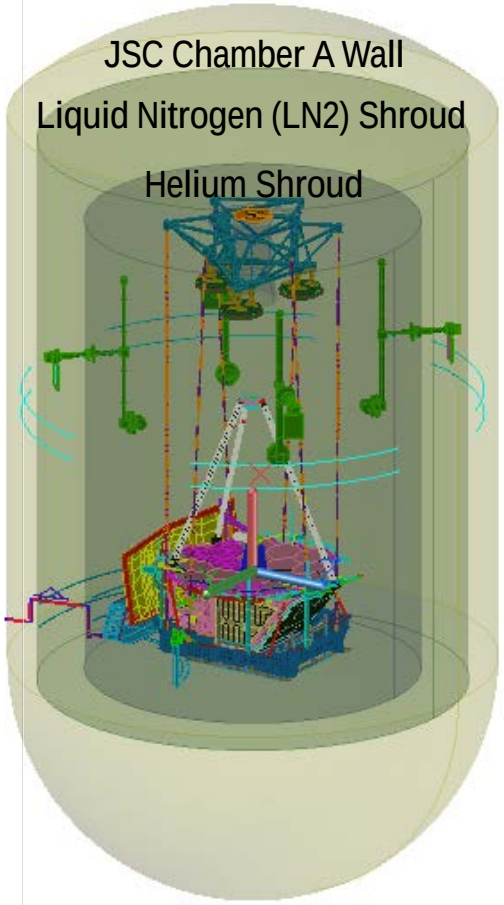
OTIS CV Test Setup Inside Chamber A: Three Different System-Level Representations



Physical Hardware



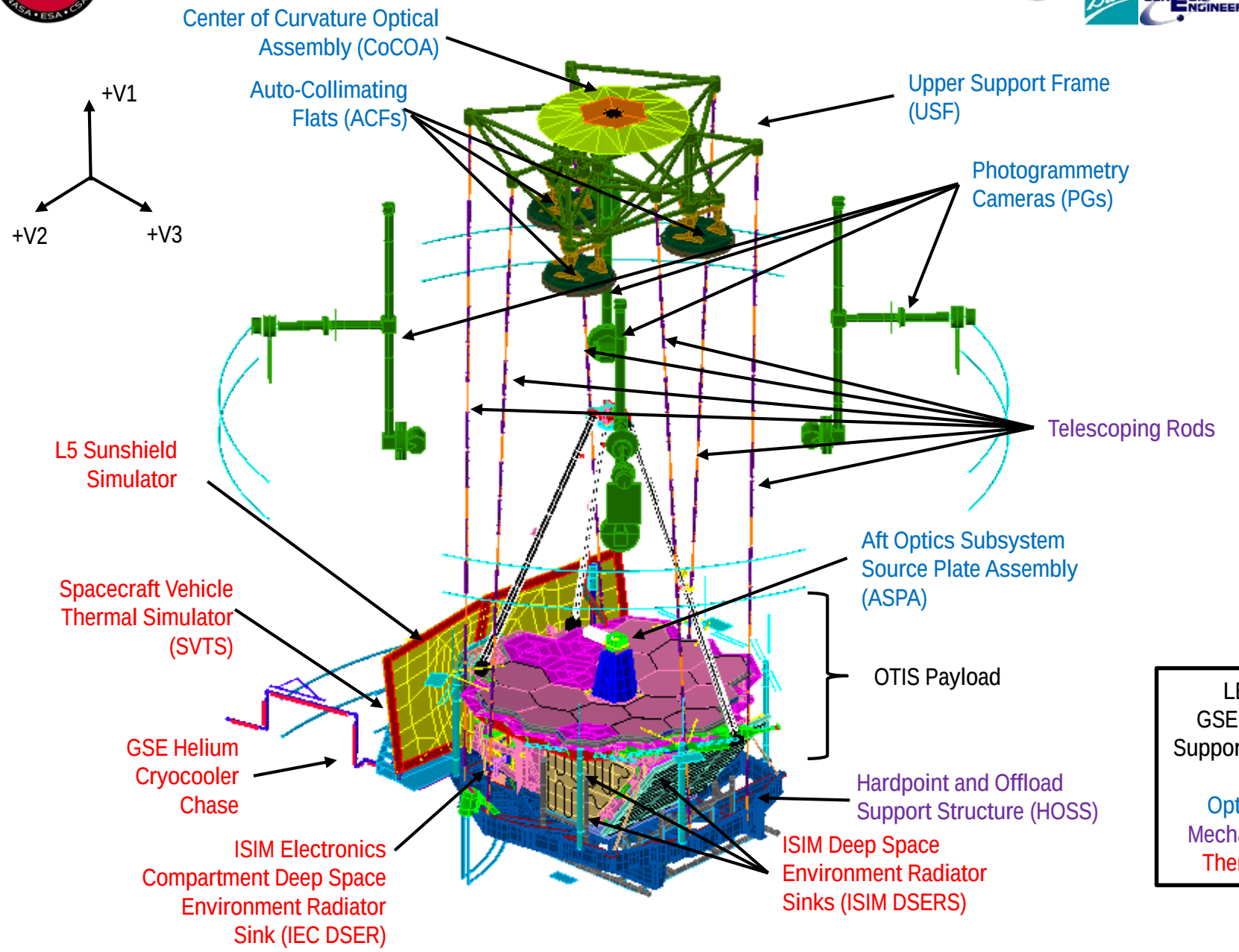
CAD Model



Thermal Model

Image sources: NASA/JWST

JWST OTIS CV Test Setup: Inside the Helium Shroud

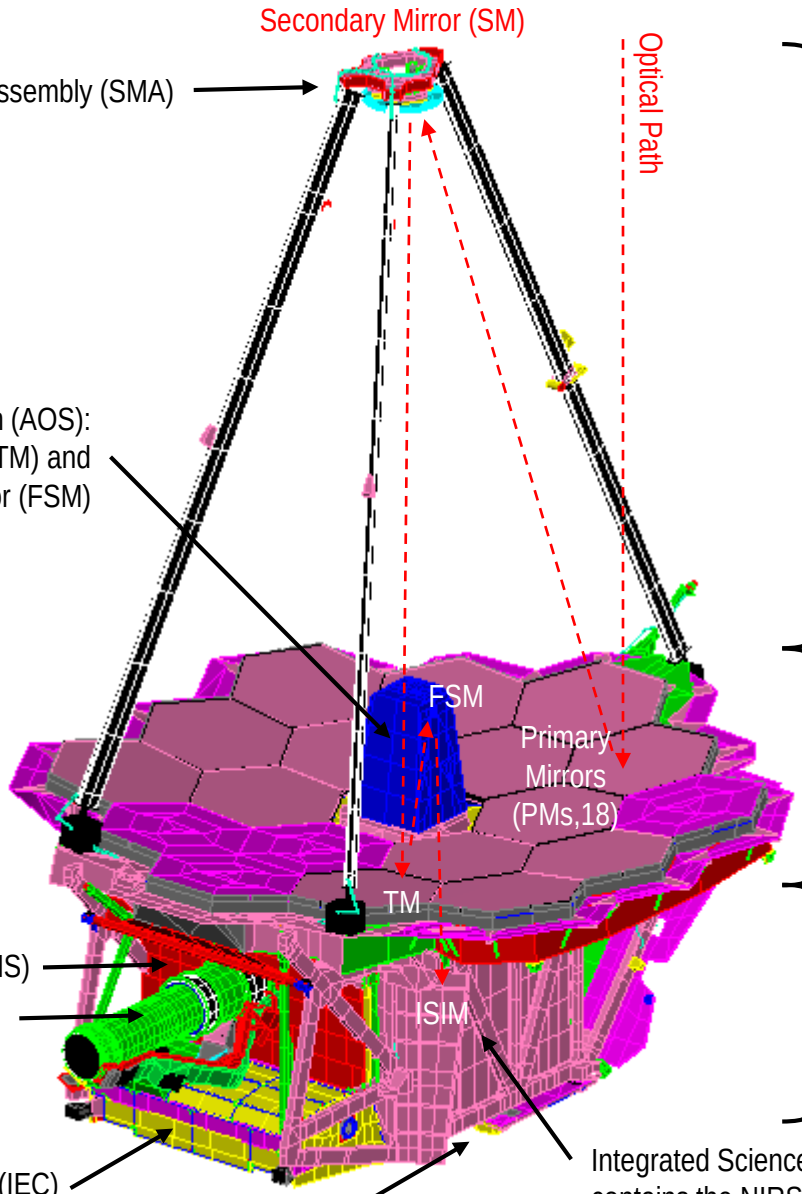


Source: NASA/JWST

LEGEND
GSE = Ground Support Equipment

Optical GSE
Mechanical GSE
Thermal GSE

JWST OTIS CV Test Setup: Payload Configuration

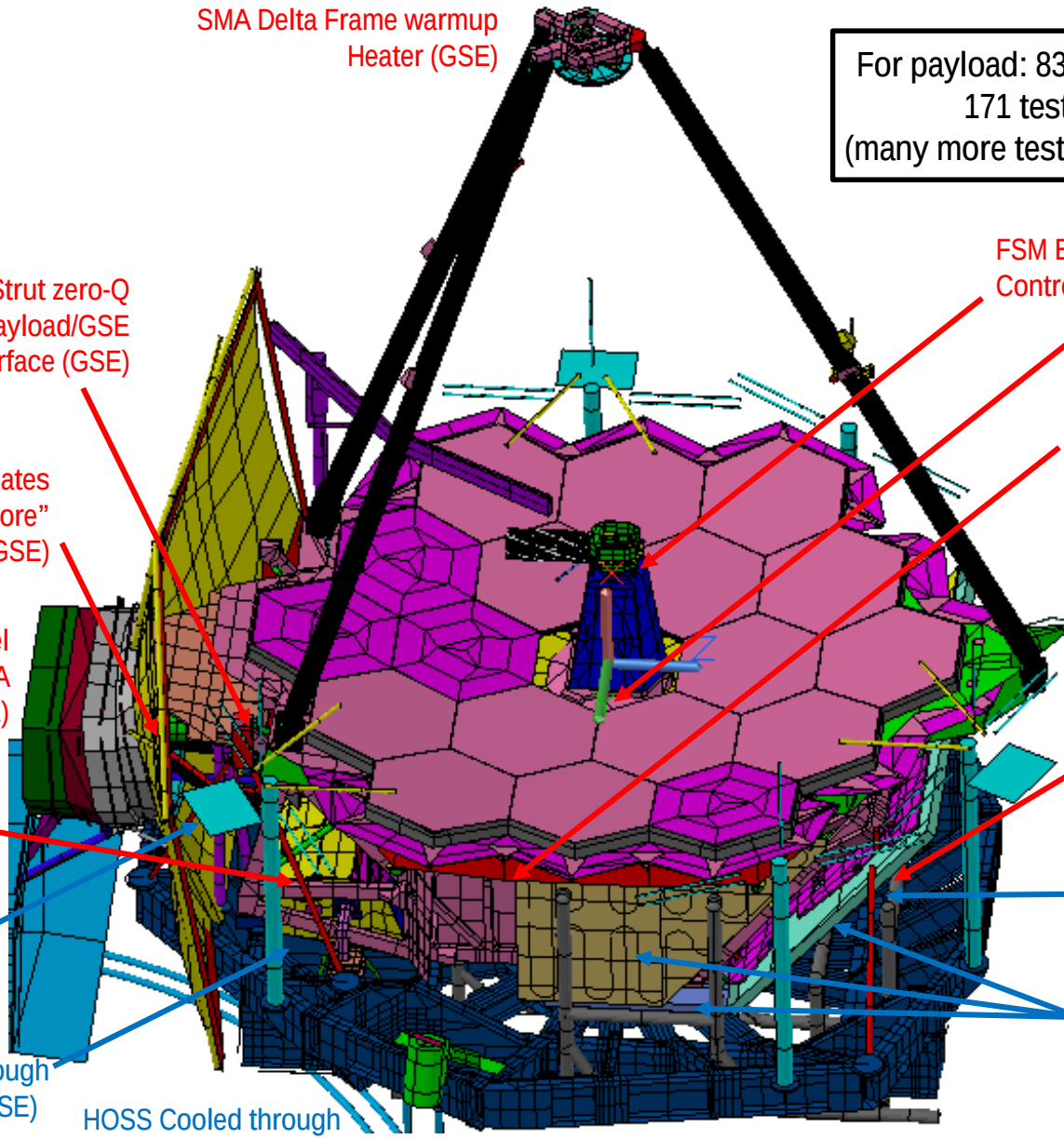


Source: NASA/JWST

OTIS Thermal Control Hardware [6]

Red: Heater Controlled
Blue: Helium Controlled

For payload: 836 flight sensors,
171 test sensors
(many more test sensors for GSE)



SMA Delta Frame warmup Heater (GSE)

BSF Hardpoint Strut zero-Q heaters control Payload/GSE interface (GSE)

SVTS Heater Plates control "Core" Environment (GSE)

DTA Wagon Wheel Heaters maintain DTA base at 295K (GSE)

IEC contains suite of control heaters for the instrument electronics boxes (flight)

MIRI GSE Cryocooler to provide cold sink

IEC DSER controllable through individual helium zone (GSE)

HOSS Cooled through helium line (GSE)

FSM Baseplate Contamination Control Heater (flight)

TM Sub-bench Warmup Heater (GSE)

ISIM contains multiple instrument bench and trim heaters (flight): NIRSpec OA, NIRSpec FPA, NIRCam, FGS, MIRI

ISIM Precool Strap zero-Q heaters for cryo-balance (GSE)

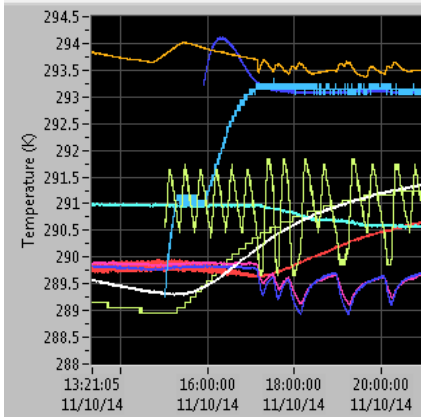
ISIM Precool Straps controllable through individual helium zone (GSE)

ISIM DSERS (+V2, -V2, +V3, -V1, HR) in one Helium zone (GSE)

Source: NASA/JWST

GSE Considerations for the Cryogenic Test Environment [7]

- A robust thermal instrumentation plan was developed with multiple systems to rigorously interpret cryogenic test results
  - Calibrated diodes, precise data acquisition units for accuracy/resolution through range of test temperatures
  - Radiometers to measure localized heat sources
  - Calorimeters for understanding radiative boundaries and icing
- Thermal balance test required precise control of boundary heat leaks on the mW scale, and optical / instrument tests required management of stray light entering optical path
  - Stationary penetrations on Helium shroud closed out with single layer insulation (SLI) or multi-layer insulation (MLI)
  - Specialized systems of light-tight baffles, shell structures, and MLI used for shroud penetrations which moved due to cryo-shift (e.g. Down / Telescoping Rods) or mechanism operations (e.g. photogrammetry cameras)
  - Harnessing from external environment was anchored to increasingly colder thermal sinks to reduce stray light into chamber



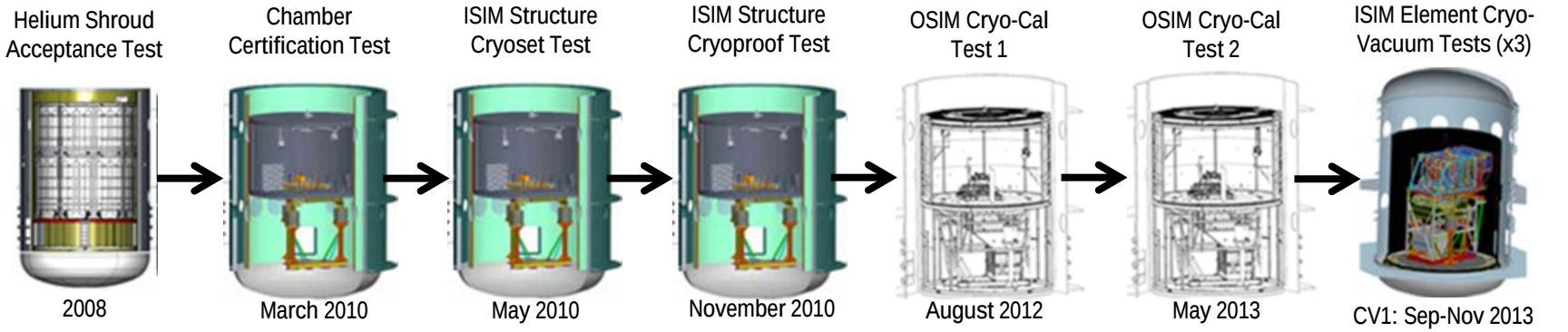
Screenshot of Harris TTS Data Acquisition System
Source: Harris Corp.



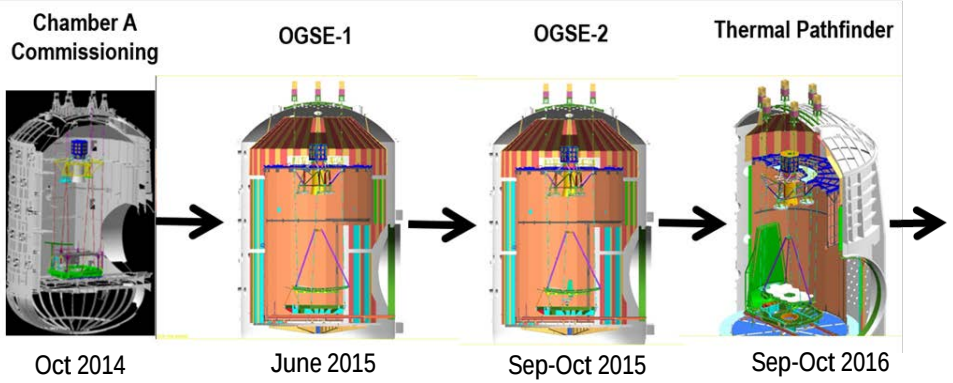
Closeout of Down Rods
Source: Harris Corp.

How Did We Prepare for OTIS?

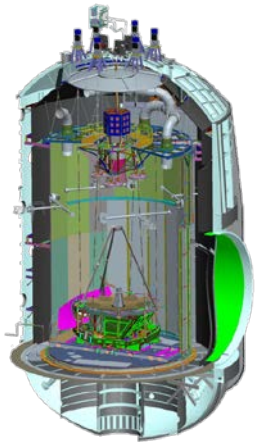
Major ISIM Element Thermal Vacuum/Thermal Balance Tests (SES Chamber, NASA GSFC) [8]



Major OTE Thermal Vacuum/Thermal Balance Tests (Chamber A, NASA JSC) [9-12]



OTIS



Jul-Oct 2017

OTIS Analytical Models:

- Contamination
- Cryocooler
- Mechanical / Dynamics
- Optical / Stray Light
- Spacecraft Sim / Software
- Thermal
- Thermal Distortion

Multi-year Development / Iterative Process

Image Sources: NASA/JWST

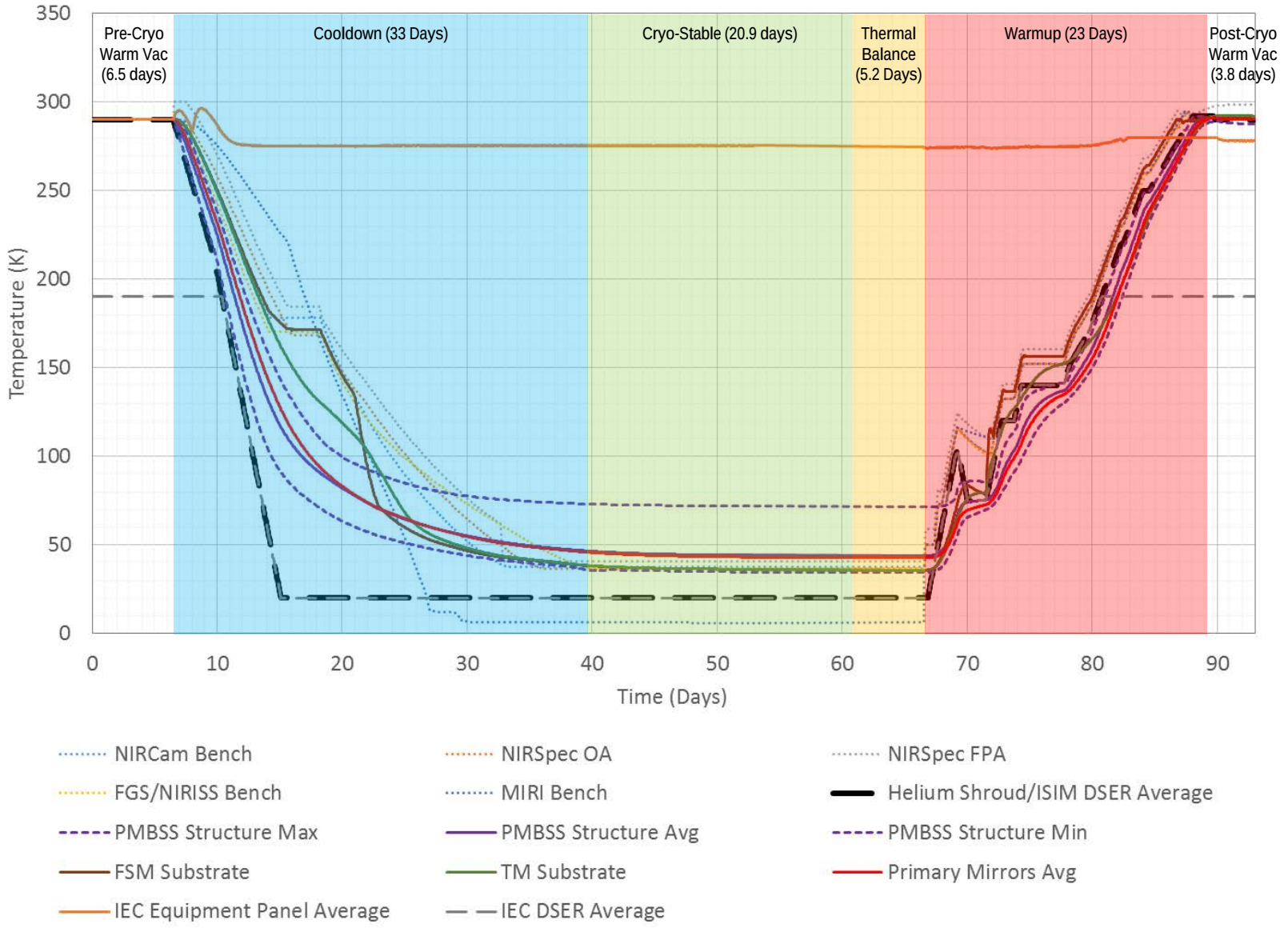
What Are Our Requirements?

Constraints are put in place to avoid actions, conditions, or events, which if realized, will result in damage to flight hardware.

Limitations are put in place to avoid actions, conditions, or events, which have the potential for temporarily impacting performance or resulting in loss of test time.

- For the Thermal Subsystem, there were 84 constraints and 8 limitations out of more than 1,000 total for the OTIS test
  - Most thermal constraints and limitations were designed to avoid contamination, overstressing of structural elements and instruments. They defined absolute temperature limits, rates of change, gradients within structures, instruments, and temperature relationships between instruments, optics, thermal boundaries, usage of heaters
- The OTIS thermal team installed alarms to monitor and prevent any exceedances of L&Cs
  - Separate monitoring systems were used for flight and GSE sensors
  - FUSION, an in-house system developed at NASA GSFC, was employed to visualize both flight and GSE sensor data as it pertained to thermal-specific L&Cs
  - An alarm limit philosophy was developed to provide margin and time to respond on components which had L&Cs levied against them, but which did have sensors to directly measure their temperature against L&Cs

Full OTIS Predicted Profile



Source: NASA/JWST

Part I Summary

- In this lecture, we reviewed the mission of James Webb Space Telescope's OTIS element and its thermal architecture
  - Science objectives for OTIS
  - Constituent components (flight and GSE)
  - Justification for and method of thermal vacuum testing
  - Thermal test objectives and requirements

- In the next lecture, we will focus on the development of the thermal test methodology via thermal analysis
  - Assembly of OTIS system-level model
  - Test profile generation via limit and constraint "feedback loop"
  - Accommodations for contamination and structural concerns

Reference: Acronyms (Page 1)

Acronym	Definition	Acronym	Definition
AOS	Aft Optical System	*ESA*	European Space Agency
ACF	Auto-Collimating Flat	*FGS*	Fine Guidance Sensor
ADIR	Aft Deployable ISIM Radiator	*FIR*	Fixed ISIM Radiator
ASPA	Aft Optical System Source Plate Assembly	*FPA*	Focal Plane Arrays
BP	Back Plane	*FSM*	Fine Steering Mirror
BSF	Backplane Support Fixture	*GSE*	Ground Support Equipment
CoCOA	Center of Curvature Optical Assembly	*GSFC*	NASA Goddard Space Flight Center
CPP	Cryo-Pumping Panels, cold panels between the Helium and LN2 shrouds at NASA JSC	*HOSS*	Hardpoint and Offload Support Structure
CSA	Canadian Space Agency	*IEC*	ISIM Electronics Compartment
CTE	Coefficient of thermal expansion	*IR*	Infrared
CV	Cryogenic Vacuum	*ISIM*	Integrated Science Instrument Module, which contains the Science Instruments (SIs)
ΔT, Δt	Change in temperature; change in time	*JSC*	NASA Johnson Space Center
DTA	Deployable Tower Assembly	*JWST*	James Webb Space Telescope
DSERS	Deep Space Environment Radiative Sink	*K*	Kelvin
EC	European Consortium	*L&Cs*	Limits and Constraints

Reference: Acronyms (Page 2)

Acronym	Definition	Acronym	Definition
L5	Layer 5 Sunshield simulator	*POM*	Instrument Pick-Off Mirror
LN2, N2	Liquid Nitrogen; Gaseous Nitrogen	*PM*	Primary Mirror(s)
LRM	Launch Release Mechanism	*PMSA*	Primary Mirror Segment Assembly
MIRI	Mid-Infrared Instrument	*PMBSS*	Primary Mirror Backplane Support Structure (BSF + BP)
MLI	Multi-Layer Insulation	*Q*	Heat
NASA	National Aeronautics and Space Administration	*SI*	Science Instrument
NGAS	Northrop Grumman Aerospace Systems	*SINDA*	Systems Improved Numerical Differential Analyzer modeling tool
NIRCam	Near-Infrared Camera Instrument	*SM*	Secondary Mirror
NIRSpec	Near-Infrared Spectrograph Instrument	*SMA*	Secondary Mirror Assembly
OA	Optical Assembly	*SMSS*	Secondary Mirror Support Structure
OGSE	Optical Ground Support Equipment, a series of pre-OTIS Optical pathfinder tests	*SVTS*	Space Vehicle thermal Simulator
OTE	Optical Telescope Element	*TM*	Tertiary Mirror
OTIS	Optical Telescope Element plus Integrated Science Instrument Module (OTE + ISIM)	*TPF*	Thermal Pathfinder test
PG	PhotoGrammetry cameras	*W*	Watt(s)

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