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

Part I: Thermal Architecture

Kan Yang
NASA Goddard Space Flight Center

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

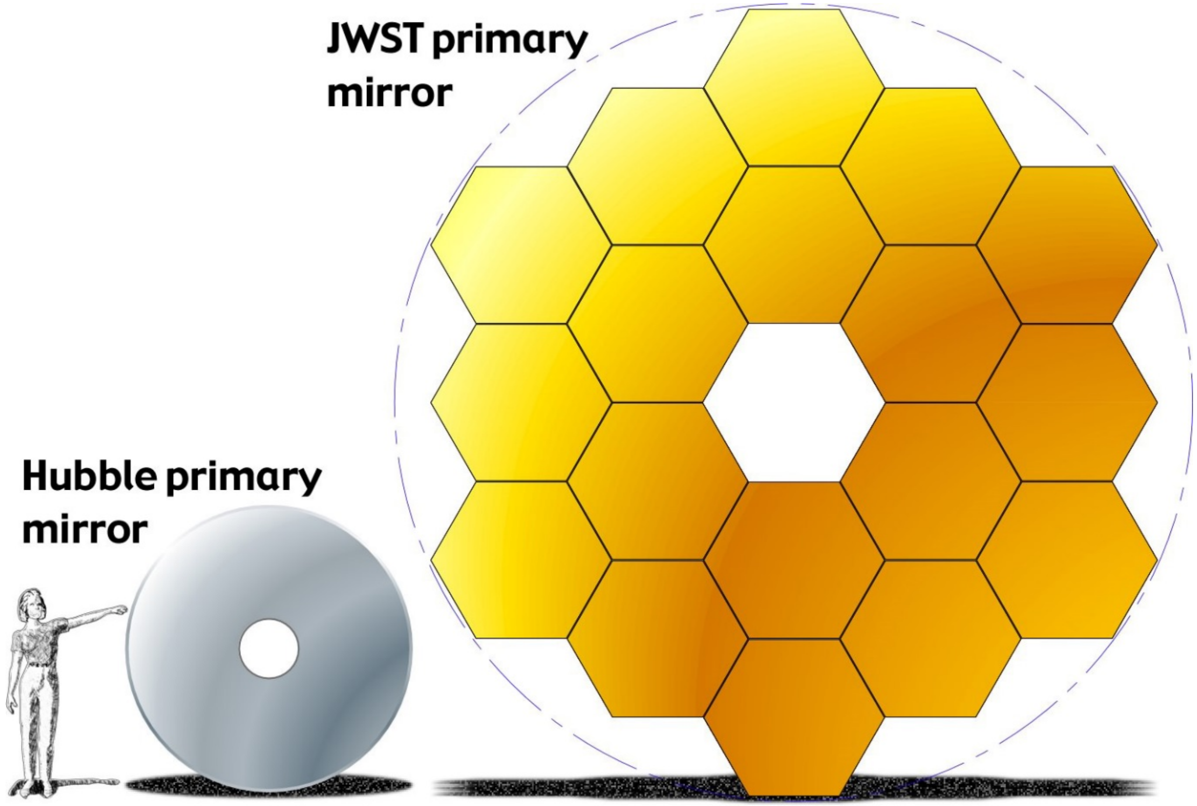
The James Webb Space Telescope: Introduction

- 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

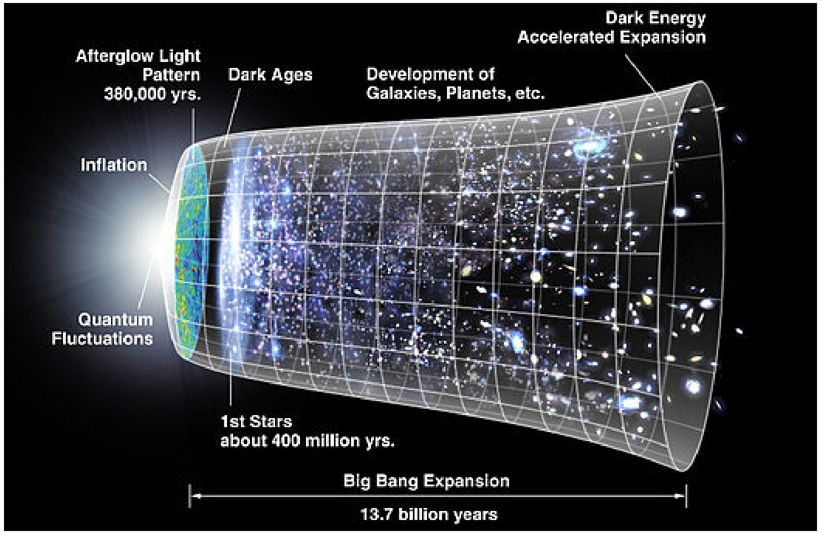
JWST vs. Hubble Primary Mirror Comparison

- 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



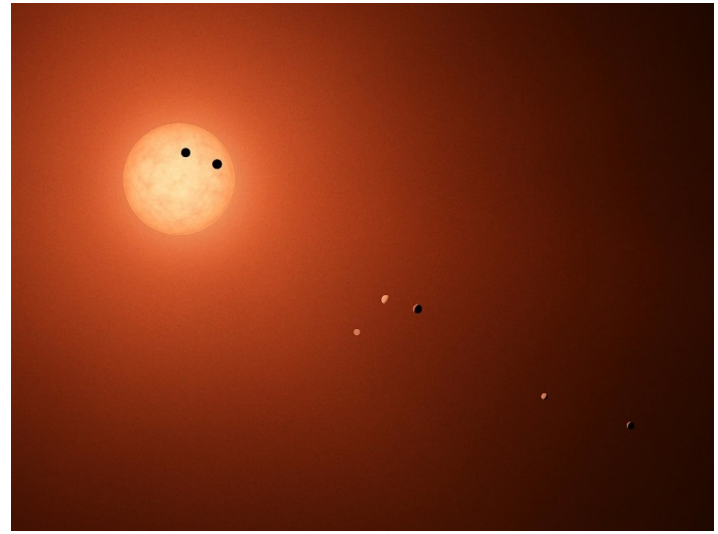
Source: NASA/JWST

JWST Science [3]



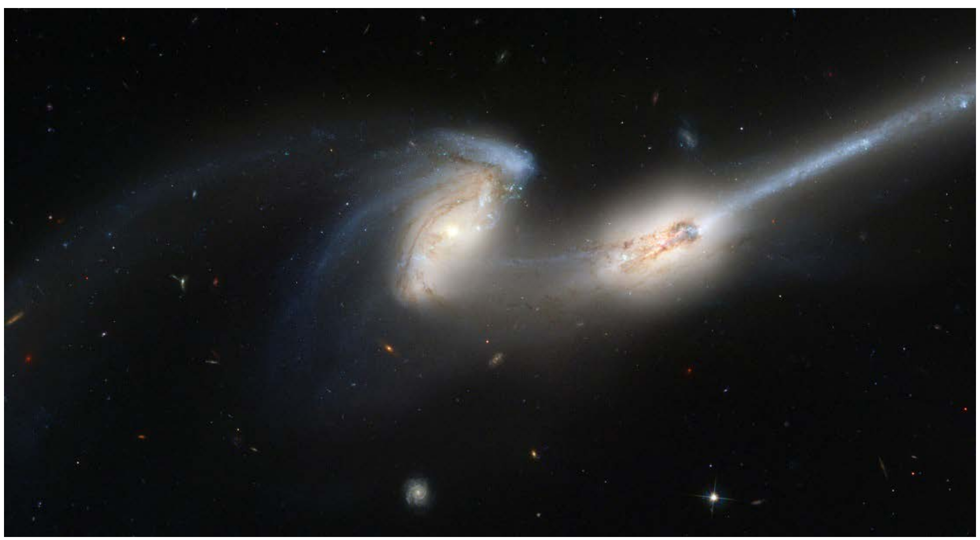
Source: NASA/WMAP

First Light and Reionization



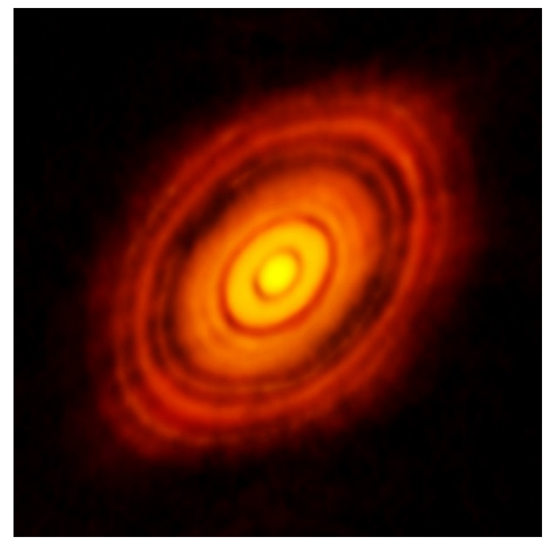
Source: NASA/JPL-Caltech

Planetary Systems and the Origins of Life



Source: NASA/ESA

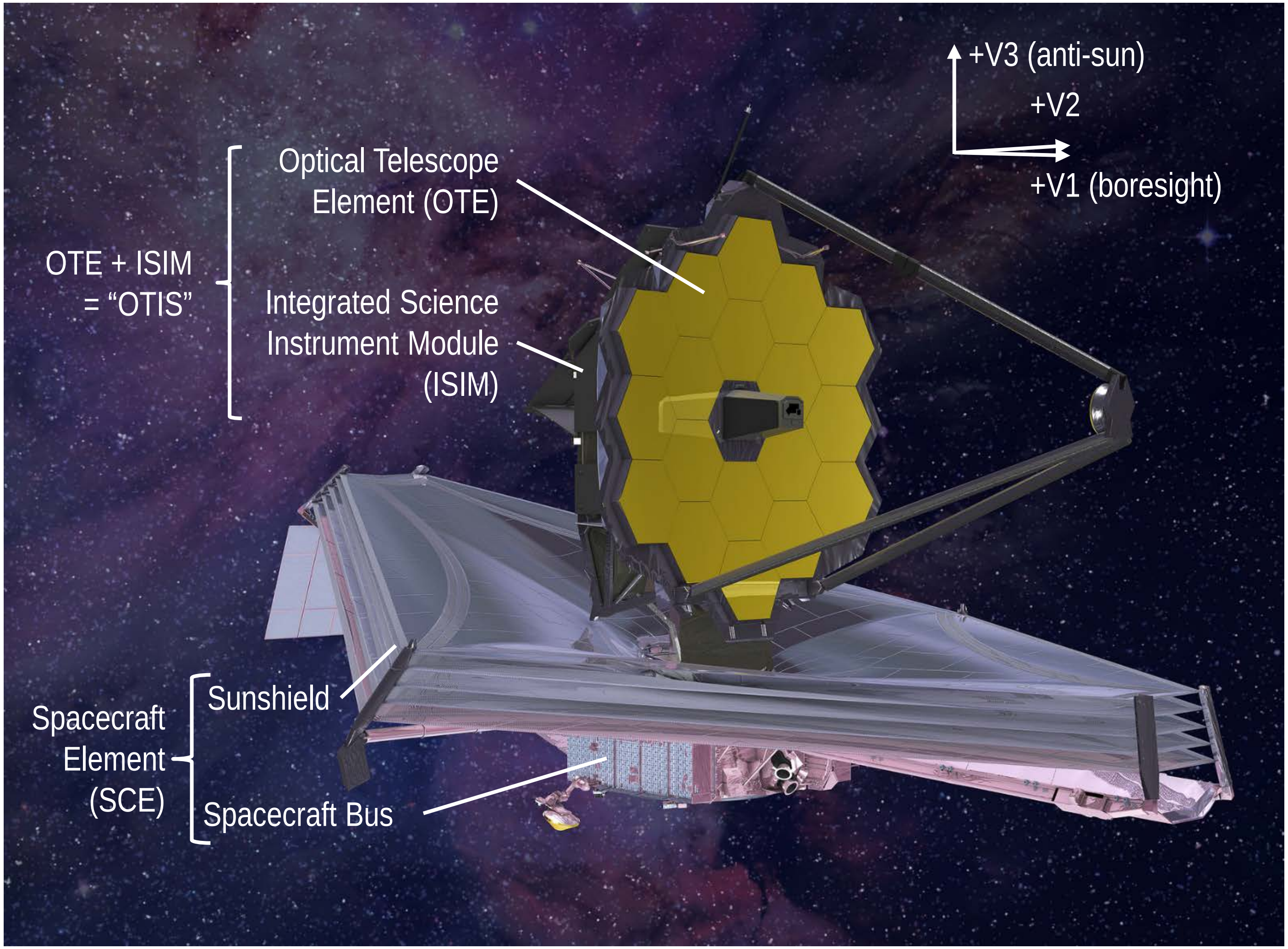
Assembly of Galaxies



Source: ALMA Observatory

Birth of Stars and Protoplanetary Systems

Major System-Level Assemblies of the James Webb Space Telescope

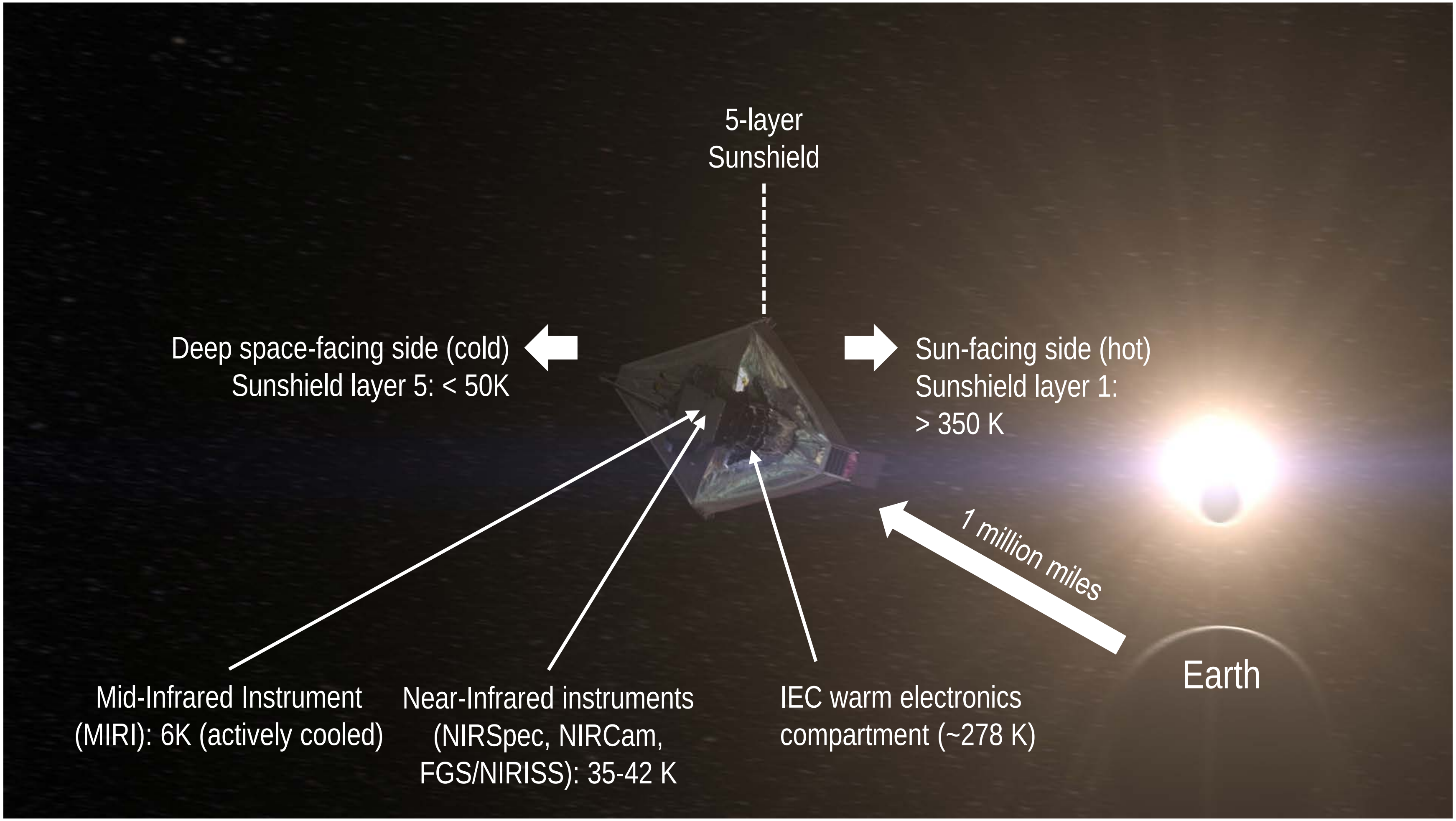


Source: NASA/JWST

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

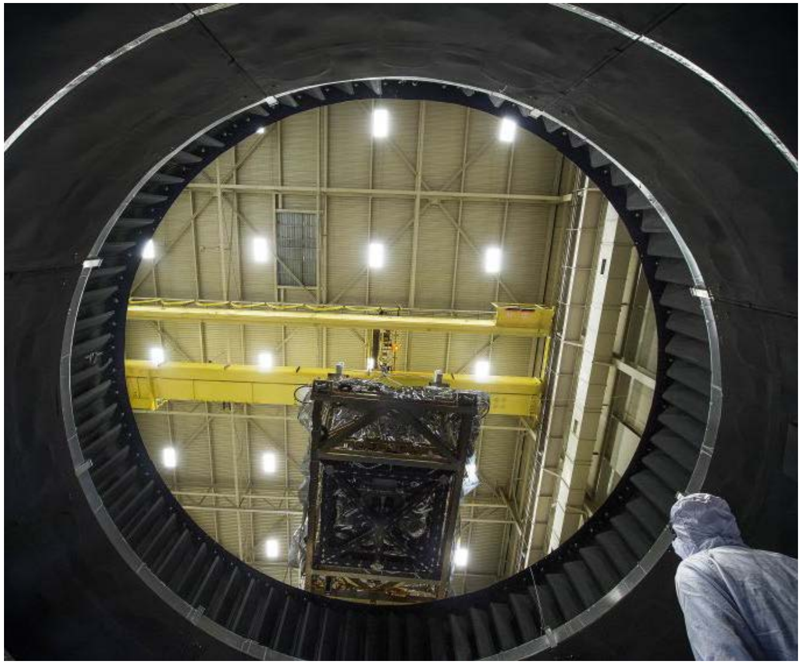
What’s the Importance of Thermal Vacuum Testing?

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:

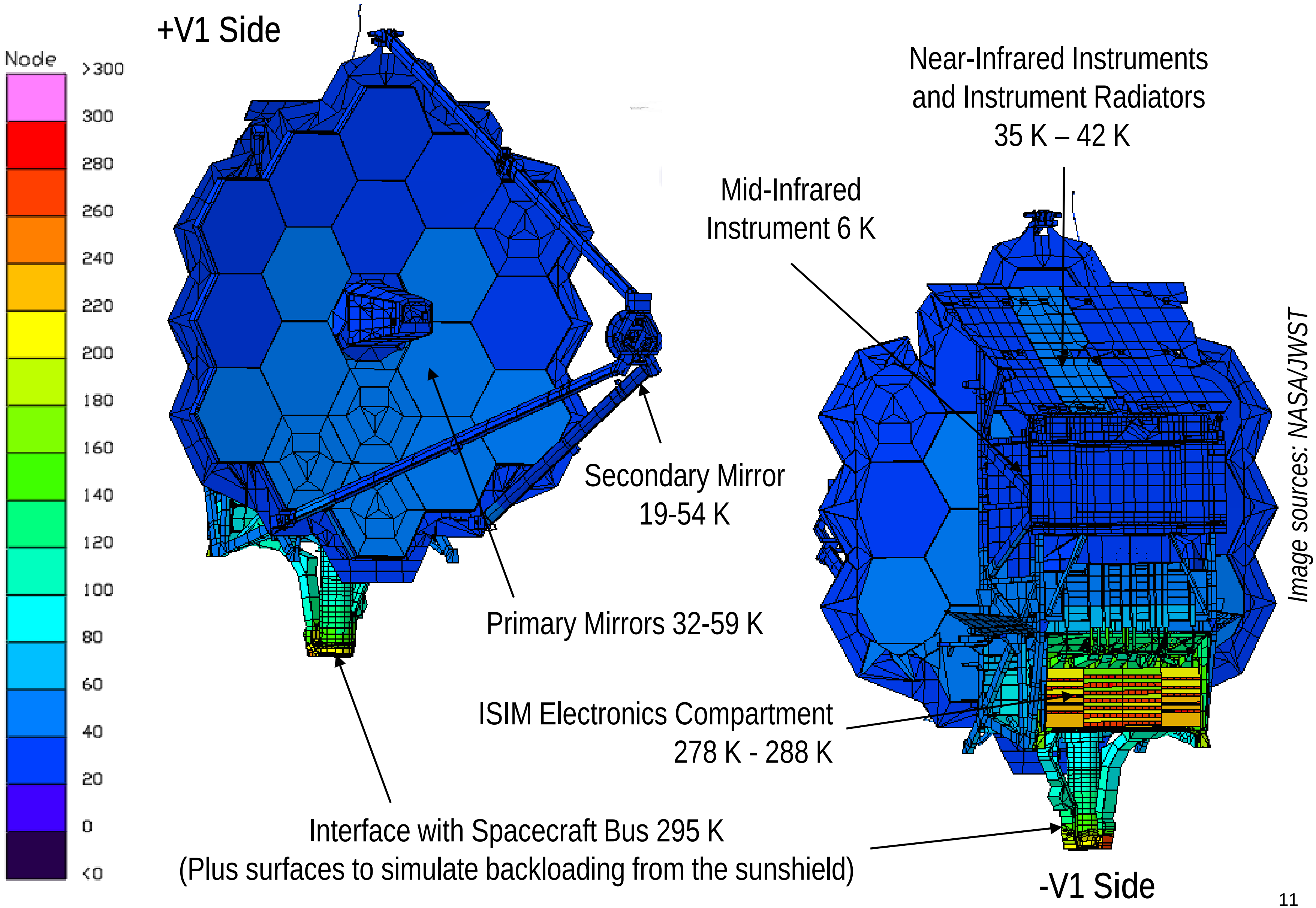
Thermal balance plateaus: thermal environment is set, and spacecraft must achieve energy balance with environment. Balance criteria met from achieving temp. rate-of-change requirement on components. Thermal data collected is used to verify predictive accuracy of thermal models

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

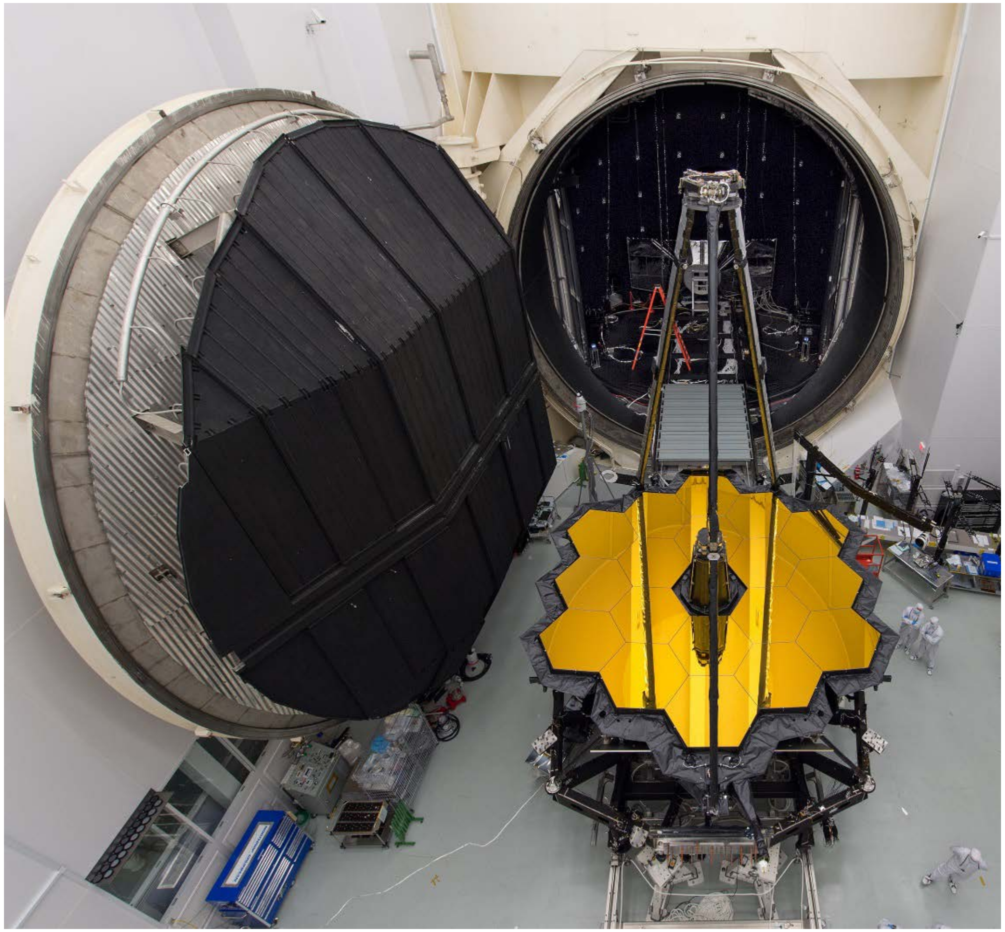


Cryo-vacuum testing of ISIM at NASA Goddard Space Flight Center’s Space Environment Simulator Chamber Source: NASA/Chris Gunn

What Are Our Temperature Goals on OTIS?



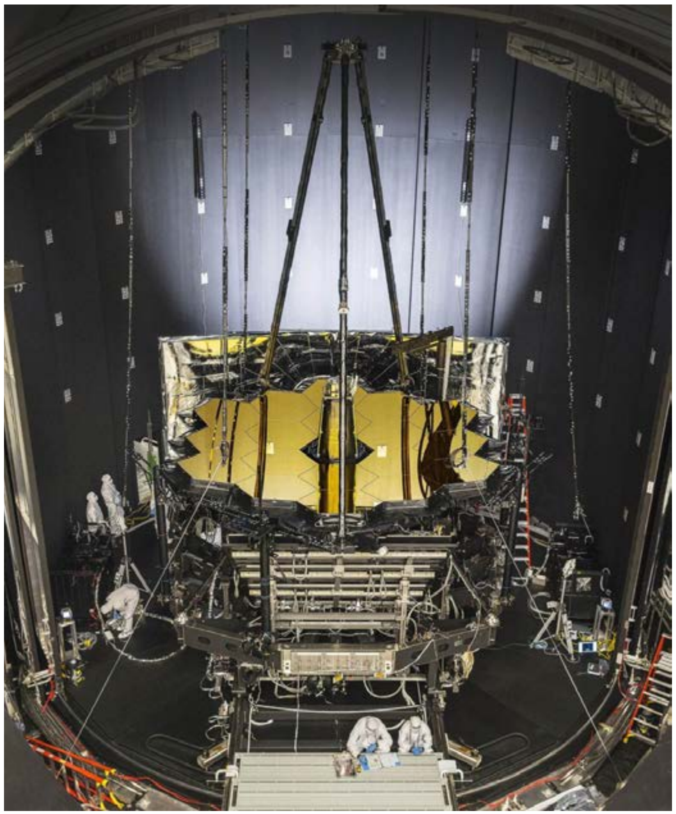
How Do We Replicate JWST's Flight Thermal Environment in Test ?



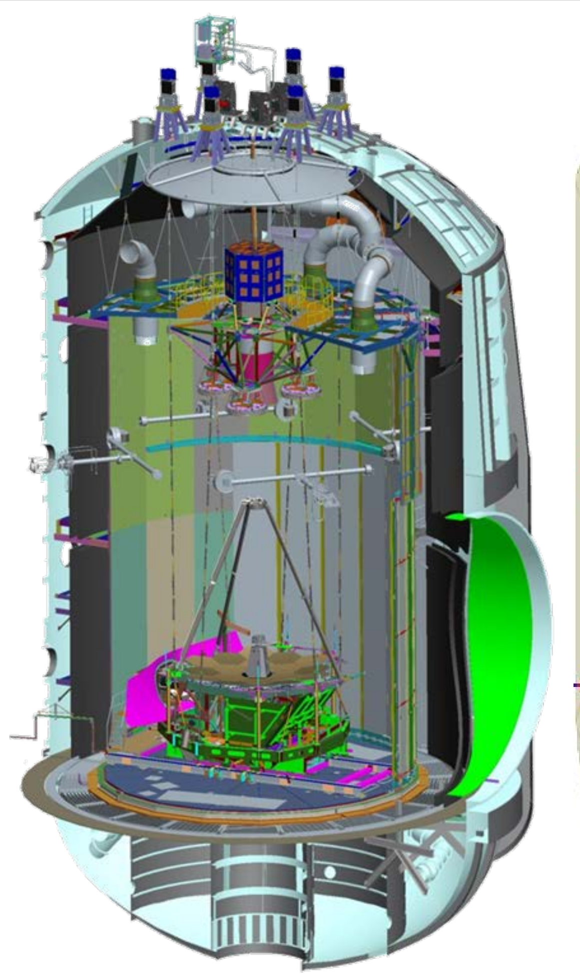
Source: NASA/JWST

- 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

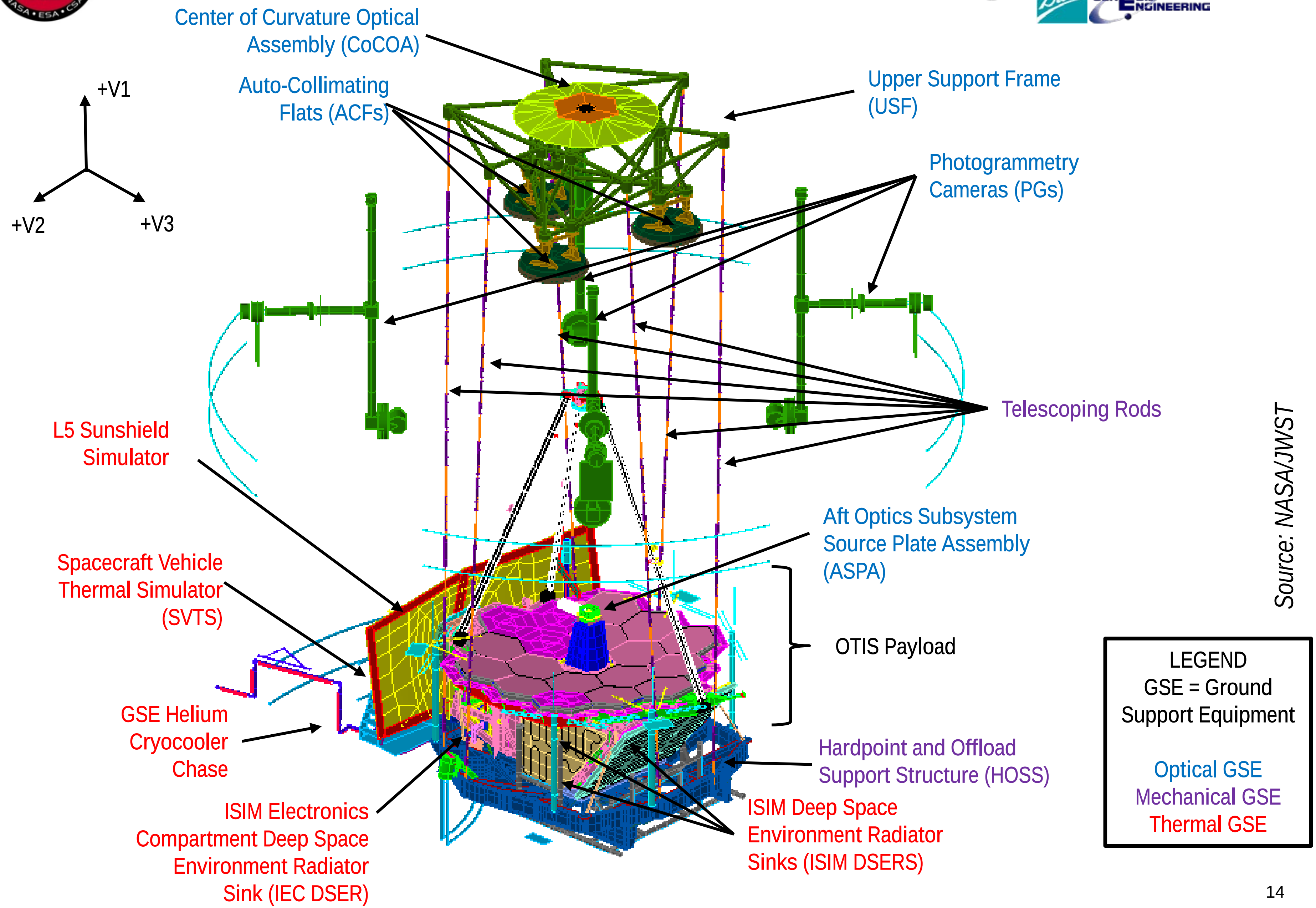


CAD Model

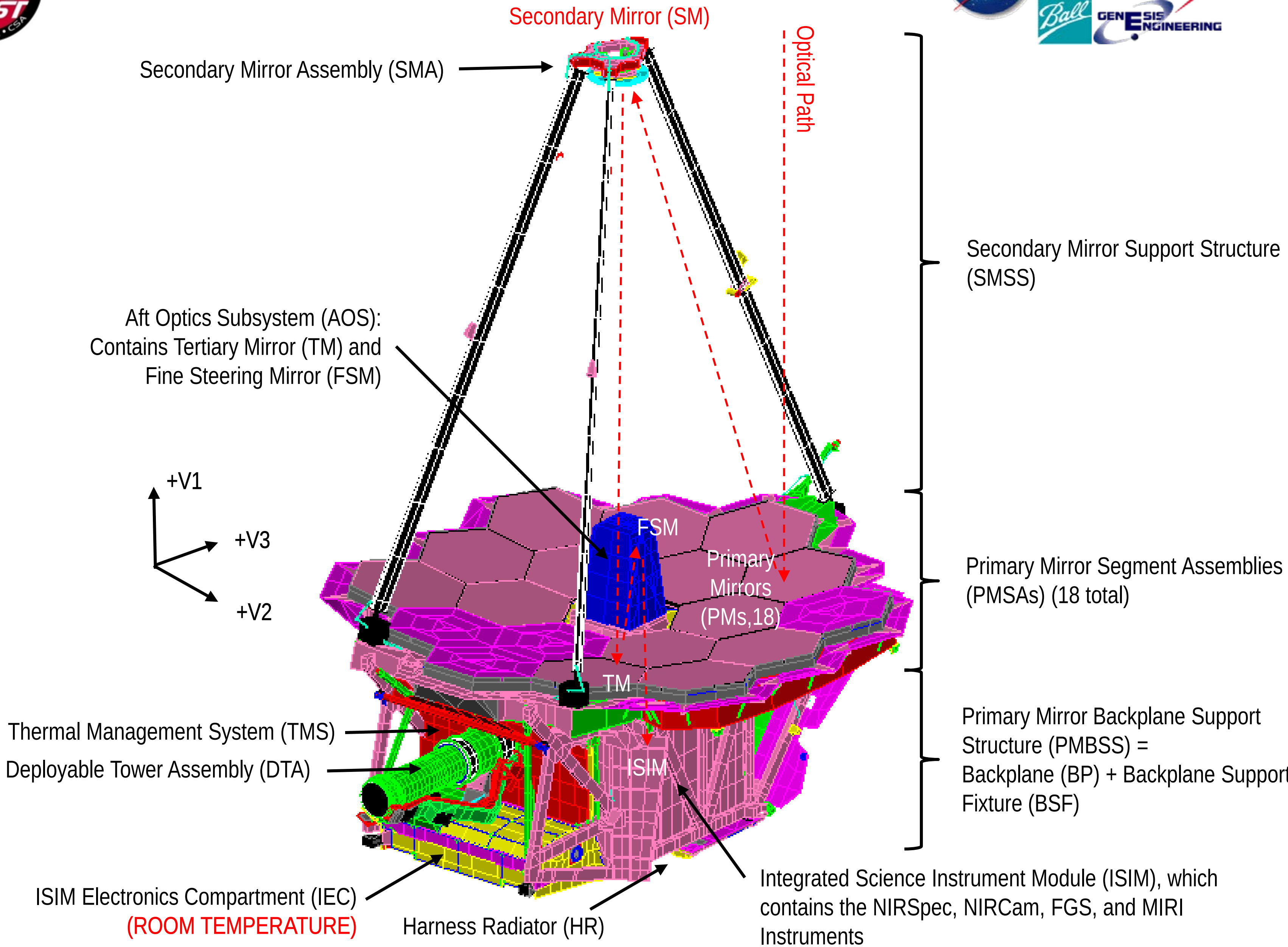
Thermal Model

Image sources: NASA/JWST

JWST OTIS CV Test Setup: Inside the Helium Shroud



JWST OTIS CV Test Setup: Payload Configuration

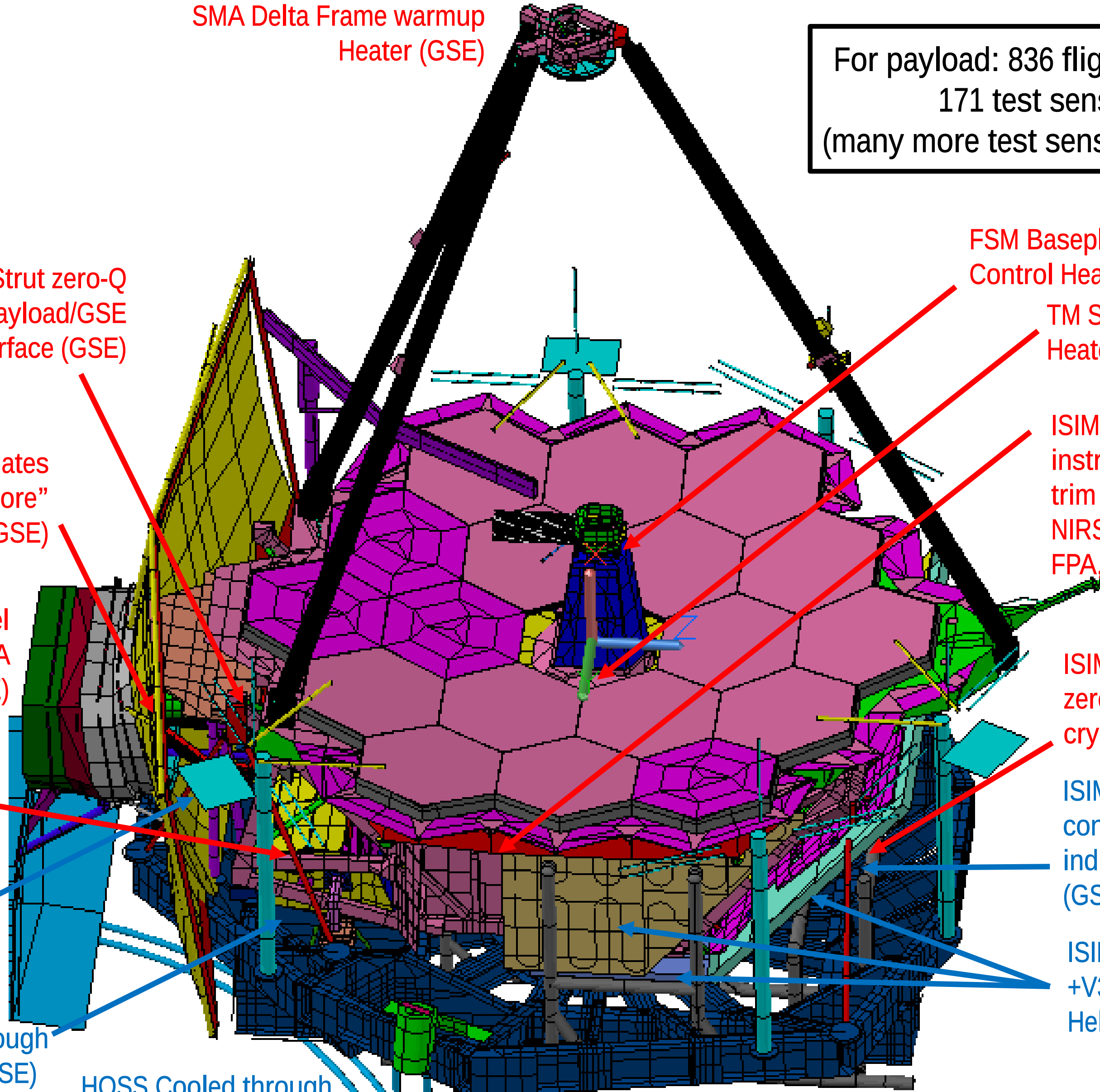


Source: NASA/JWST

OTIS Thermal Control Hardware [6]

Red: Heater Controlled
Blue: Helium Controlled

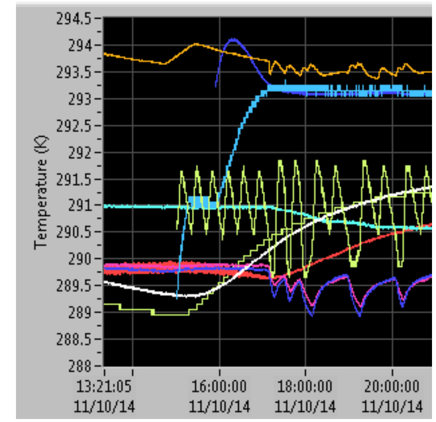
For payload: 836 flight sensors,
171 test sensors
(many more test sensors for GSE)



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



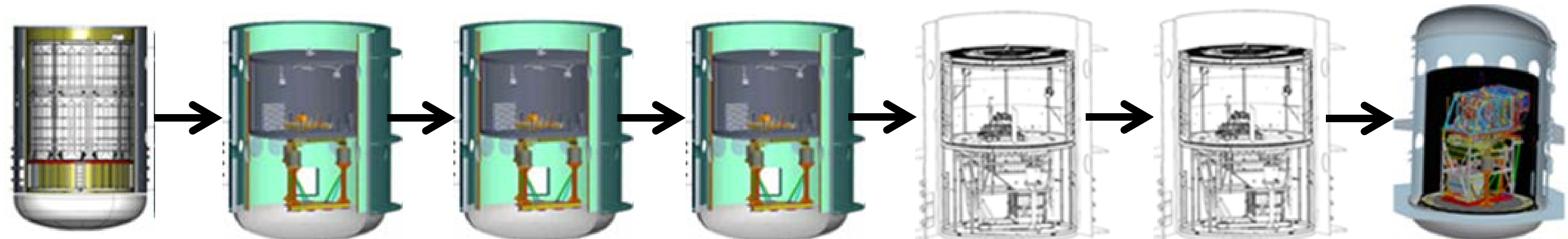
Screenshot of Harris TTS Data Acquisition System Source: Harris Corp.

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]

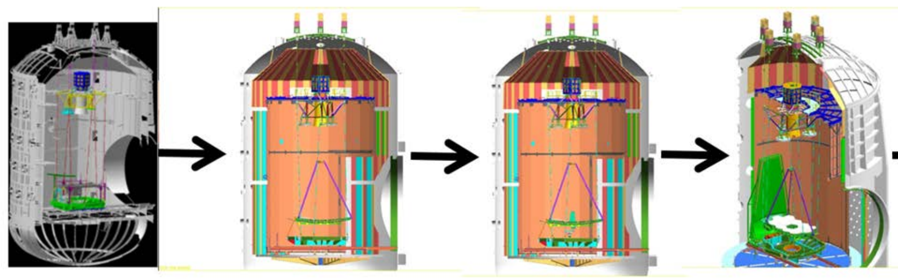
Helium Shroud Acceptance Test → Chamber Certification Test → ISIM Structure Cryoset Test → ISIM Structure Cryoproof Test → OSIM Cryo-Cal Test 1 → OSIM Cryo-Cal Test 2 → ISIM Element Cryo-Vacuum Tests (x3)



2008 | March 2010 | May 2010 | November 2010 | August 2012 | May 2013 | CV1: Sep-Nov 2013, CV2: Jun-Oct 2014, CV3: Nov 2015 - Feb 2016

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

Chamber A Commissioning → OGSE-1 → OGSE-2 → Thermal Pathfinder →



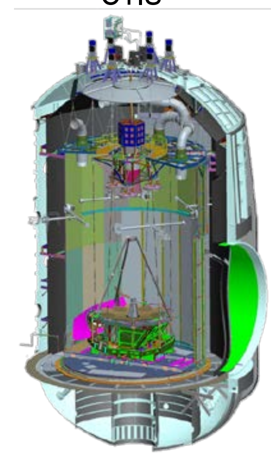
Oct 2014 | June 2015 | Sep-Oct 2015 | Sep-Oct 2016

OTIS Analytical Models:

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

Multi-year Development / Iterative Process

OTIS



Jul-Oct 2017

Image Sources: NASA/JWST

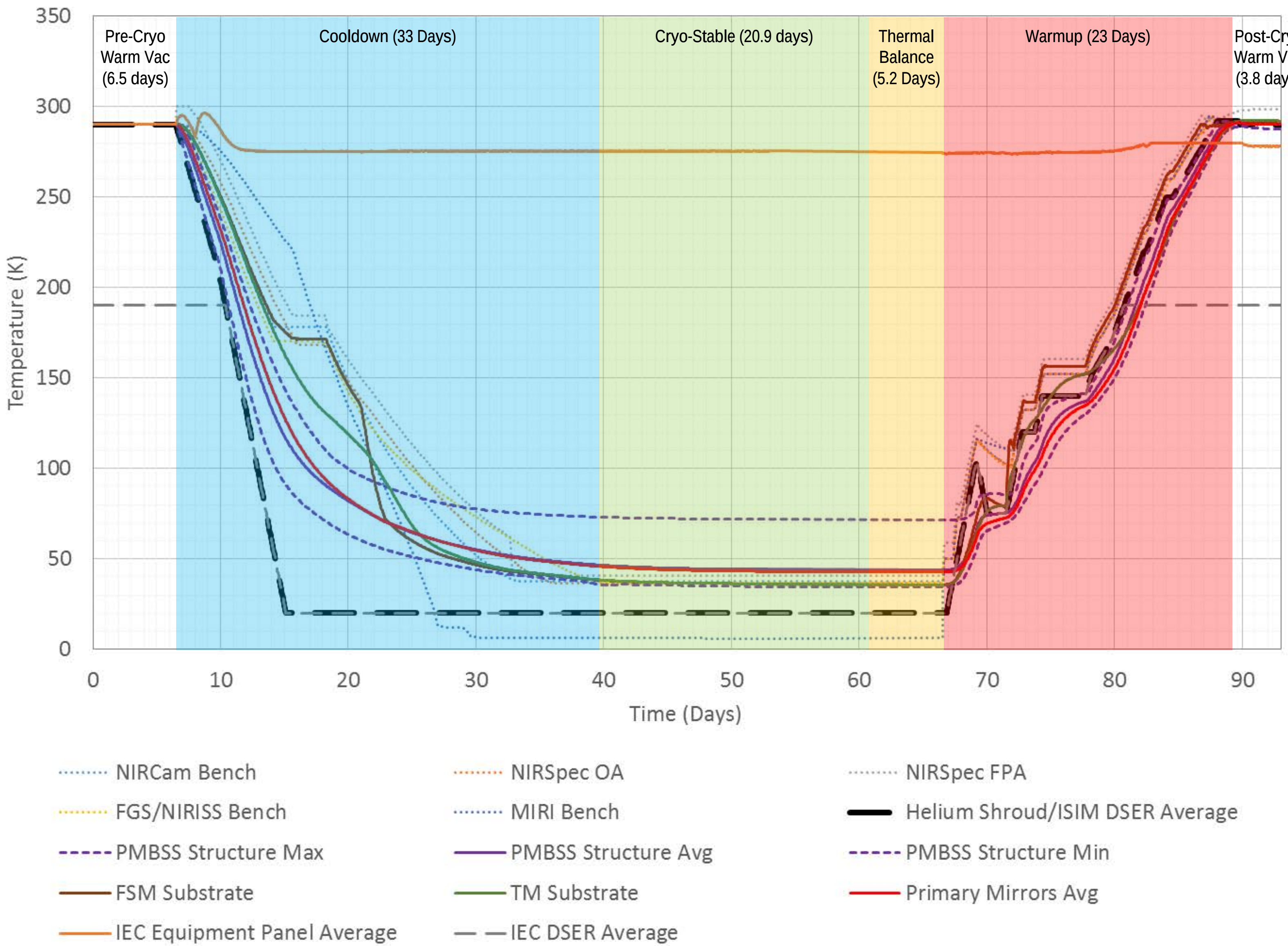
What Are Our Requirements?

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

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

- 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)

References (Page 1)

1. Feinberg, L., Voyton, M., Lander, J., Keski-Kuha, R., and Matthews, G. “James Webb Space Telescope Optical Telescope Element/Integrated Science Instrument Module (OTIS) Status.” *Proceedings of the SPIE.* Volume 9904, id. 990407. 2016.
2. Kimble, R., Apollo, P., Feinberg, L., Glazer, S., Hanley, J., Keski-Kuha, R., Kirk, J., Knight, S., Lambros, S., Lander, J., McGuffey, D., Mehalick, K., Ohl, R., Ousley, W., Reis, C., Reynolds, P., Begoña Vila, M.; Voyton, M., Waldman, M., Whitman, T. “Cryo-Vacuum Testing of JWST’s Integrated Telescope & Scientific Instrument Suite.” *American Astronomical Society.* AAS Meeting 229, id. 238.14. 2016.
3. Kimble, R. “Cryo-Vacuum Testing the James Webb Space Telescope.” Presented at the NASA Goddard Space Flight Center Engineering Colloquium. March 26, 2018.
4. Yang, K., et al. “Thermal Model Performance for the James Webb Space Telescope OTIS Cryo-Vacuum Test .” *48th International Conference on Environmental Systems.* Albuquerque, NM, July 8-12, 2018
5. Homan, J. Cerimele, M., and Montz, M. “Creating the Deep Space Environment for Testing the James Webb Space Telescope at NASA Johnson Space Center's Chamber A.” *43rd International Conference on Environmental Systems.* Vail, CO, July 14-18, 2013.
6. Havey, K., Cooke, D., Huguet, J., and Day, R. “Thermal Management of JWST Cryo-Vacuum Test Support Equipment.” *48th International Conference on Environmental Systems.* Albuquerque, NM, July 8-12, 2018
7. Huguet, J., Day, R., Havey, K., and Cooke, D. “Thermal Control of Boundaries for JWST Infrared Tests in Cryogenic Vacuum Configuration.” *48th International Conference on Environmental Systems.* Albuquerque, NM, July 8-12, 2018

References (Page 2)

8. Glazer, S., and Comber, B. “James Webb Space Telescope Integrated Science Instrument Module Thermal Vacuum/Thermal Balance Test Campaign at NASA's Goddard Space Flight Center.” *46th International Conference on Environmental Systems.* Vienna, Austria, July 13-17, 2016
9. Park, S., Brinckerhoff, P., Franck, R., Schweickart, R., Thomson, S., Burt, W., and Ousley, W. “Successful Completion of the JWST OGSE2 Cryogenic Test at JSC Chamber-A while Managing Numerous Challenges.” *46th International Conference on Environmental Systems.* Vienna, Austria, July 13-17, 2016.
10. Ousley, W., Burt, W., and Davis, A. “James Webb Space Telescope Cryogenic Thermal Pathfinder Test” *44th International Conference on Environmental Systems.* Tucson, AZ, July 13-17, 2014.
11. Davis, A., Ousley, W., Burt, W., and Cottingham, C. “James Webb Space Telescope Thermal Pathfinder Test Development.” *46th International Conference on Environmental Systems.* Vienna, Austria, July 13-17, 2016.
12. Davis, A., Ousley, W., and Burt, W. “James Webb Space Telescope Thermal Pathfinder Test Results.” *47th International Conference on Environmental Systems.* Charleston, SC, July 17-20, 2017.