Thermal Model Performance for the James Webb Space Telescope

OTIS Cryo-Vacuum Test

ICES Paper 2018-35

Kan Yang – NASA GSFC
Stuart Glazer – NASA GSFC
Shaun Thomson – NASA GSFC
Lee Feinberg – NASA GSFC
William Burt – Genesis Engineering Solutions, Inc.
Brian Comber – Genesis Engineering Solutions, Inc.
Wes Ousley – Genesis Engineering Solutions, Inc.
Randy Franck – Ball Aerospace
Upon launch, the James Webb Space Telescope (JWST) 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)
Major System-Level Assemblies of JWST

Image source: www.jwst.nasa.gov
JWST OTIS Payload Major Components

- Primary Mirror Segment Assemblies (PMSAs) (18 total)
- Primary Mirror Backplane Support Structure (PMBSS)
- Integrated Science Instrument Module (ISIM), which contains the NIRSpec, NIRCam, FGS, and MIRI Instruments
- ISIM Electronics Compartment (IEC) (ROOM TEMPERATURE)
- Secondary Mirror Support Structure (SMSS)
- Secondary Mirror Assembly (SMA)
- Aft Optics Subsystem (AOS): Contains Tertiary Mirror (TM) and Fine Steering Mirror (FSM)
- Deployable Tower Assembly (DTA)
- Secondary Mirror (SM)
- Primary Mirrors (PMs, 18)
- Optical Path

Thermal Management System (TMS)
OTIS CV Thermal Test Objectives

1. To 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, 92 total)

2. To achieve the simulated on-orbit payload temperature levels and stability for optical, mechanical, and instrument tests

3. To predict and measure thermal balance test data for model crosscheck, both on ISIM and OTE components

4. To 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

5. To achieve test timeline optimization by executing the OTIS CV cooldown and warmup in a time-efficient manner
OTIS CV Test Configuration

Without Chamber and Shrouds

Center of Curvature Optical Assembly (CoCOA)
Auto-Collimating Flats (ACFs)
Upper Support Frame (USF)
Photogrammetry Cameras (PGs)
Telescoping Rods
Aft Optics Subsystem Source Plate Assembly (ASPA)
OTIS Payload
Hardpoint and Offload Support Structure (HOSS)
ISIM Deep Space Environment Radiator Sinks (ISIM DSERS)
IEC Deep Space Environment Radiator Sink (IEC DSER)
GSE Helium Cryocooler Chase
Spacecraft Vehicle Thermal Simulator (SVTS)
L5 Sunshield Simulator

With Chamber and Shrouds

JSC Chamber A Wall LN2 Shroud
Helium Shroud

48th International Conference on Environmental Systems
July 2018, Albuquerque, NM
Photo of OTIS CV Test Configuration inside NASA JSC Chamber A

Image source: www.jwst.nasa.gov
Pre-Test Predictions (shown at ICES 2017 Conference)

Cooldown (33 Days)
- MIRI cryocooler turn-on
- Contamination avoidance hold for ISIM
- ISIM heater step-down through water contamination band
- Helium shroud reaches 20K at day 16

Cryo-Stable (20.9 days)
- ISIM pre-cool strap “zero-Q”
- MIRI cryocooler “pinch point”

Thermal Balance (5.2 Days)
- End of molecular contamination band
- Start of molecular contamination band
- Start of water contamination band
- End of water contamination band

Warmup (23 Days)
- Start of Alignment Drift Test

Post-Cryo Warm Vac (3.8 days)

Temperature (K)
- Time (Days)
- Pre-Cryo Warm Vac (6.5 days)
- Cryo-Stable (20.9 days)
- Warmup (23 Days)
- Post-Cryo Warm Vac (3.8 days)

Contamination avoidance hold for ISIM
- MIRI cryocooler turn-on
- ISIM heater step-down through water contamination band
- Helium shroud reaches 20K at day 16

Start of Alignment Drift Test
- Latch and Hinge Deployment Tests
- End of water contamination band
- Start of molecular contamination band
- End of molecular contamination band

Legend:
- NIRCam Bench
- FGS/NIRISS Bench
- PMBSS Structure Max
- FSM Substrate
- IEC Equipment Panel Average
- NIRSpec OA
- MIRI Bench
- PMBSS Structure Avg
- TM Substrate
- IEC DSER Average
- NIRSpec FPA
- Helium Shroud/ISIM DSER Average
- PMBSS Structure Min
- Primary Mirrors Avg
As-Tested Full OTIS CV Profile

- Cooling from scavenger plates at ambient temperatures
- Unexpected maximum temperature achieved on PMBSS structure at LRM interface
- Faster warmup than expected due to schedule conservatism in pre-test model
- Shorter thermal balance duration: quicker stability to thermal balance requirements than pre-test predictions

Hurricane Harvey

Nitrogen “burp” off CPPs
OTIS CV Pre-Test Model Predictions vs. Test Measurements: ISIM Cooldown

Note: Dashed Lines are Predictions, Solid Lines are Measurements

- Start of ISIM Decontamination Hold
- ISIM Structure Max $\Delta T$ predicted up to 10 K lower in this range: anticipated earlier end to Decontamination phase
- Instrument step-down through water contamination band at end of ISIM Decontamination Hold
- Predicted MIRI cryocooler Pinch-Point
- Measured MIRI cryocooler Pinch-Point in test
OTIS CV Pre-Test Model Predictions vs. Test Measurements: OTE Cooldown

Note: Dashed Lines are Predictions, Solid Lines are Measurements

- Divergence of SM (up to 20K) and PM (up to 15K) between pre-test predictions and measured data due to emissivity simplifications in transition regime. Specifically for SM, divergence was also due to activation of SM heater for L&C control.

- TM predictions track within 5K of test data through entire cooldown.

- Divergence of predicted PMBSS structure max up to 22K due to model discrepancy at LRM interface between BSF and IEC.
Vast majority of temperatures were within 3K of predictions.

OTIS CV Pre-Test Model Predictions vs. Test Measurements: Thermal Balance

PMSA mechanisms predicting colder in OTIS model than test.

Discrepancy at BSF/IEC LRM Interface.

DTA and IEC predict warmer than test due to configuration differences in model / some incorrect model assumptions.
OTIS CV Pre-Test Model Predictions vs. Test Measurements: ISIM Warmup

Note: Dashed Lines are Predictions, Solid Lines are Measurements

Discrepancy between model predictions and test measurements in warmup rate due to model bias towards schedule conservatism, as well as changing of contamination requirements in-test

End of molecular contamination band

Start of molecular contamination band

End of water contamination band

Start of water contamination band

Legend:
- FSM Substrate
- NIRCam OA
- NIRSpec Bench
- NIRSpec FPA
- FGS Bench
- MIRI Bench
- Helium Shroud
OTIS CV Pre-Test Model Predictions vs. Test Measurements: OTE Warmup

Note: Dashed Lines are Predictions, Solid Lines are Measurements

Thermal Distortion Alignment Drift Test: test-predicted peak for driving PMBSS and SMSS was 105K on the Helium shroud. Actual payload response only required shroud to be driven to 95K

Large N2 “burp” event
Discussion of Discrepancies between Model and Test: Cooldown

At Thermal Balance:

- IEC and DTA region predicted warmer in model than test
  - Blanket high $\epsilon^*$ assumption resulted in more heat escaping from IEC warm electronics components via MLI: background sink temperature of modeled test environment was warmer than observed
  - Conservatively high copper conductance through harnesses caused more heat to flow into the IEC than assumed
- For faster runtimes in transient analysis, only two discrete emissivity sets (room temperature and cryogenic) were used, with an abrupt transition between emissivity sets when PMBSS average reaches 90K
  - However, temperature-dependent emissivity is a large driver of model accuracy in the transition regime between 60K and 170K
  - Generally, assumption of room temperature emissivities when PMBSS Avg > 90K cause model predictions to cool more rapidly than test, while assumption of cryogenic emissivities after PMBSS Avg < 90K cause predictions to transition slower than test (shown in plot on next page)
In-Depth Look at Emissivity Effects on OTIS CV Predictions

Using room temp emissivities caused model to predict max ISIM structure sensor cooldown faster than test: pre-test model expected ISIM decontamination phase to end sooner (i.e. ISIM structure max < 140K) than actually observed in test.

Coldest PM predictions show significant divergence from test data due to emissivity assumption.

Dashed lines denote predictions, solid lines denote measurements.
Discussion of Discrepancies between Model and Test: Thermal Balance and Warmup

At Thermal Balance:

- Max PMBSS temperatures diverged from as-predicted results due to LRM interface between BSF and IEC
  - Since IEC was 270K and BSF at interface was 80-90K, even small differences in conductance/material properties between model and actual hardware were enough to cause large temperature differences between model predictions and test measurements
  - The resultant model discrepancy was attributed to errors in assumed conductances across LRM joints and conservatively high composite conductance in BSF

On Warmup:

- Payload response was faster on hardware than in model predictions
  - Original pre-test analysis stacked worst-case conditions for schedule conservatism, and placed large margins on performance with respect to structural and contamination constraints to ensure hardware safety
  - In test, it was observed that components could maintain faster rate without violating constraints: overall warmup rate was accelerated
Conclusions and Recommendations from OTIS CV Modeling

• The extensive thermal modeling effort ensured that schedule was met and the payload was kept safe during the 100-day OTIS CV test
  • The model gave OTIS thermal engineers insight into payload behavior during transitions between ambient and cryogenic temperatures and understanding as to the driving L&Cs for each phase of test
  • Most of the discrepancies between model and test were due to conservative modeling assumptions and simplifications in the interest of runtime and test schedule
• From this effort, the following recommendations are made improving future system-level accuracy of test cryogenic thermal models:
  • For large-scale cryogenic systems, a modeling and analysis plan which trades analysis speed and geometric fidelity against accuracy should be developed
  • Use of more temperature-dependent emissivity sets between 60K and 170K greatly increases prediction accuracy this transition regime
  • Conservatism built into payload models consistently results in longer predicted transition times than observed
  • For interfaces with large gradients or temperature change vs. time, a greater number of test sensors is critical to understanding physical phenomena in case trends observed do not match pre-test predictions
Acknowledgments

The authors would like to thank

The OTIS CV Test Thermal Team

for their invaluable contributions to this work and to the success of the JWST OTIS CV Test

The authors would also like to recognize the following organizations for their extensive efforts: ATA Aerospace, Ball Aerospace, Edge Space Systems, Energy Solutions International L.L.C., Genesis Engineering Solutions, Harris Corporation, the NASA JSC Chamber A Facilities Team, Northrop Grumman Corporation, Smithsonian Astrophysical Observatory, Stinger Ghaffarian Technologies Inc., and the JWST management team at NASA GSFC.