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

JAMES WEBB SPACE TELESCOPE (JWST)

Off-Nominal Planning for the Cryogenic Vacuum Test of the JWST Optical Telescope Element/Integrated Science Instrument Module at JSC

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Agenda

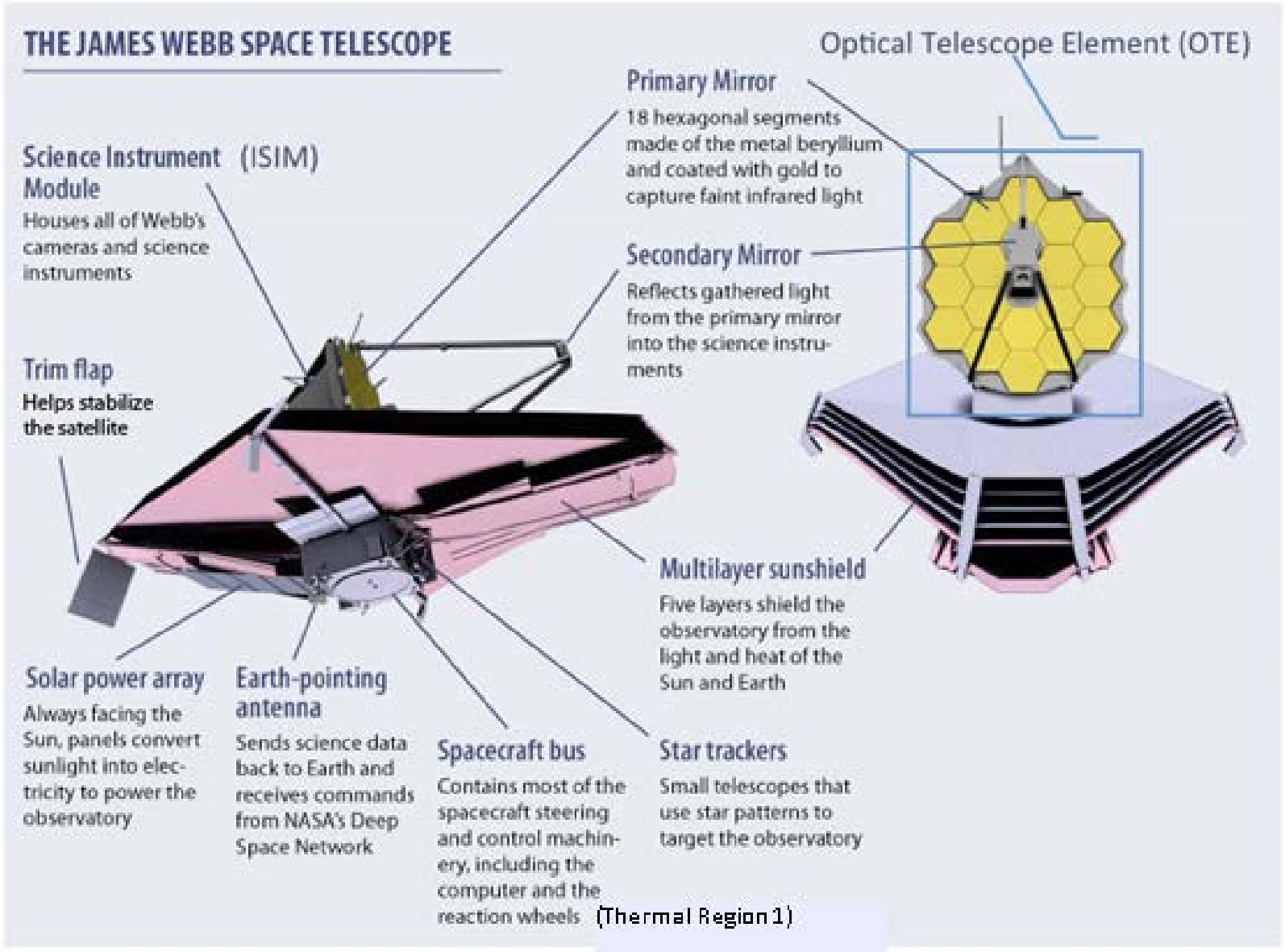
- Description of Flight Observatory, ISIM Element, OTE Element
- JWST ISIM, OTE Thermal Test Program
- Principal OTIS Test Thermal Objectives
- Constraints and Limitations
- Pre-test Prediction vs. Actual As Run Profile
- Off-Nominal Planning, Events Considered, Mitigations Developed
- Hurricane Harvey Consequences
- Conclusions, Recommendations for Off-Nominal Testing Planning for other Projects

Murphy's Law

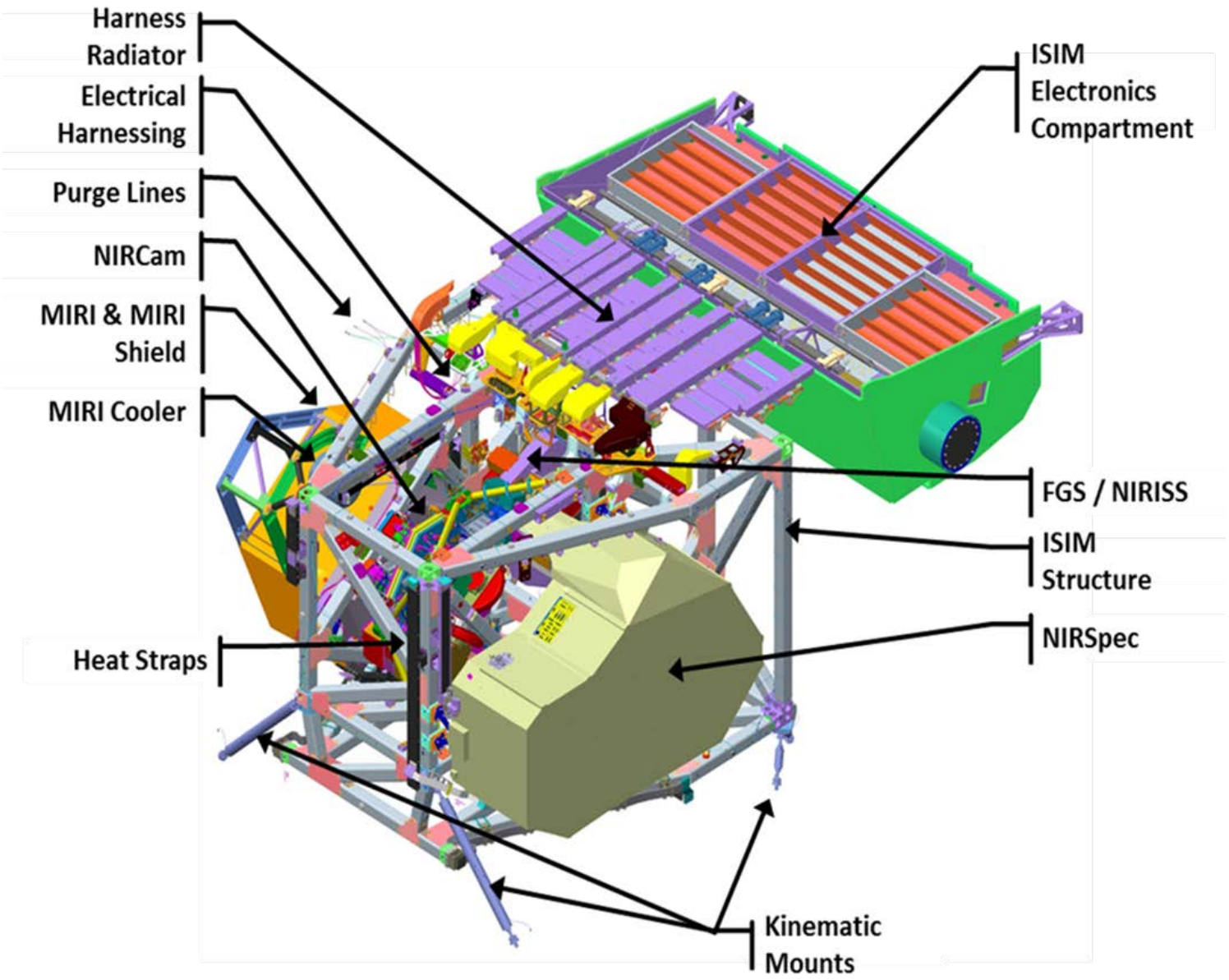
"Anything that can go wrong will go wrong."

-Edward A. Murphy, Aerospace Engineer at Edwards AFB, 1949

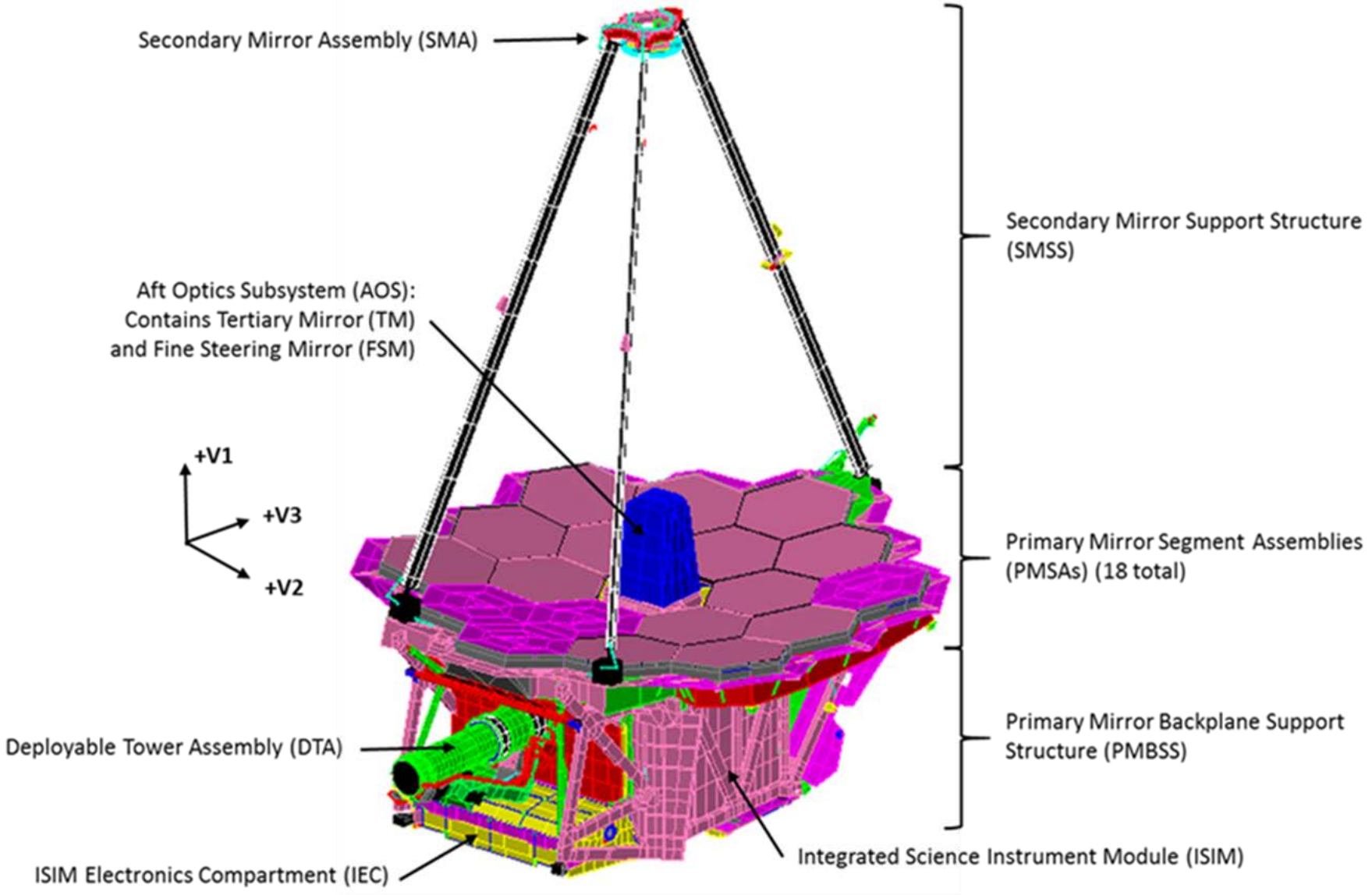
Major Components of JWST Observatory



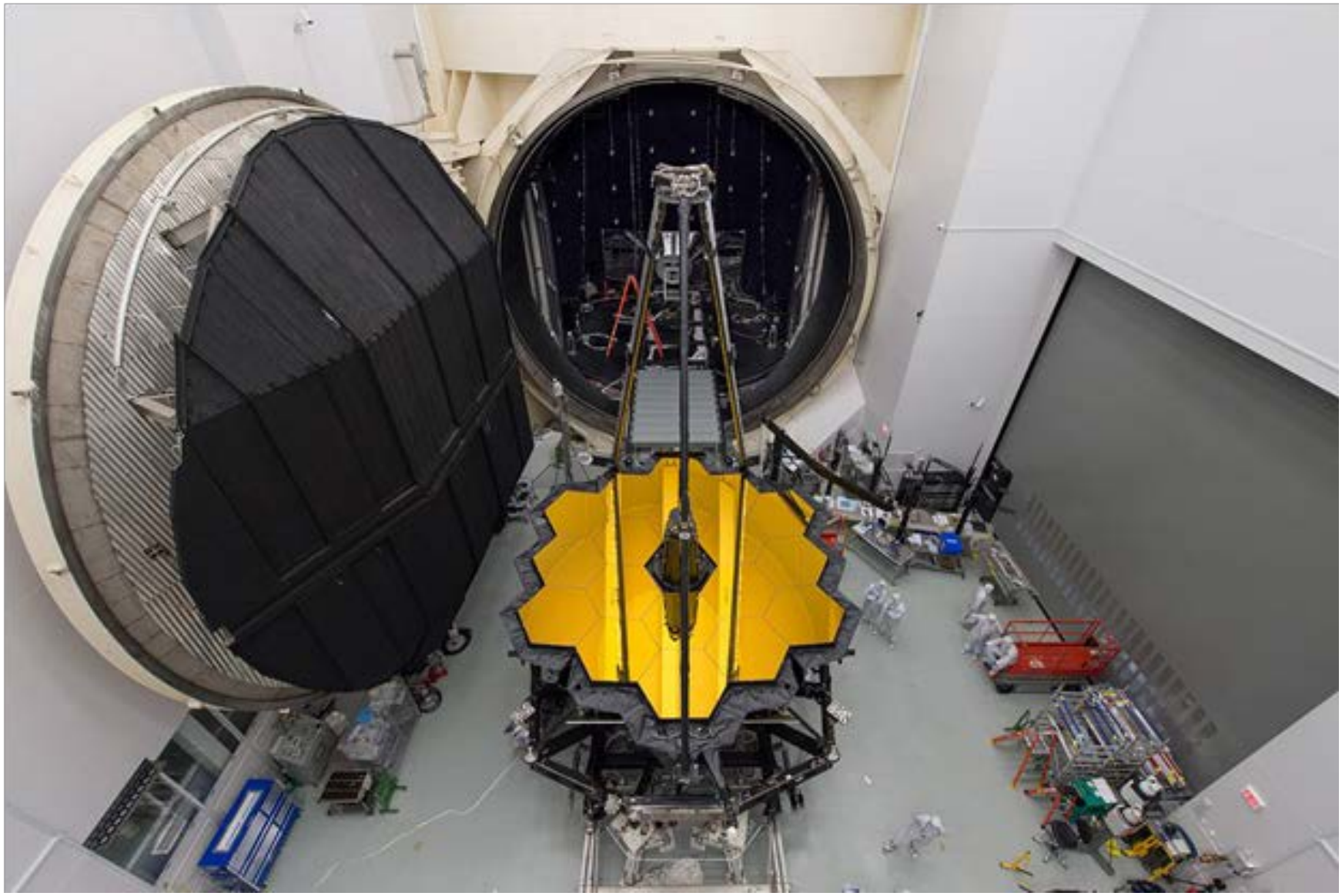
Integrated Science Instrument Module (ISIM), Flight Configuration



Optical Telescope Element + ISIM Element (OTIS) Test Configuration

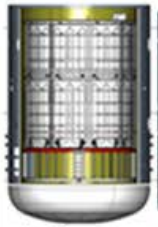
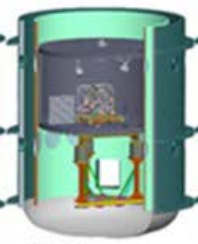
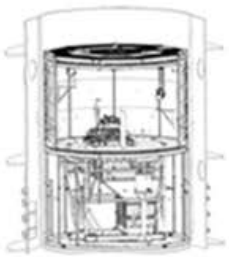


OTIS Being Readied for Test, Prior to Entry into JSC Chamber A



Major ISIM Element TV/TB Tests in SES Facility at GSFC

Test Items – Test Exposure of Items in SES Testing

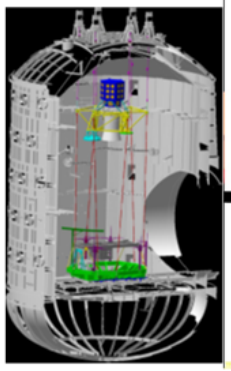
Tests	 He Shroud Acceptance Test (-03) **COMPLETE 2008**	 Chamber Certification Test (-01) **COMPLETE March 2010**	 ISIM Structure Cryoset Test **COMPLETE May 2010**	 ISIM Structure Cryo-Proof Test **COMPLETE Nov 2010**	 OSIM Cryo-Cal Test 1 **COMPLETE Aug 2012**	 OSIM Cryo-Cal Test 2 **COMPLETE May 2013**	 ISIM Element Cryo-Vacuum Tests (3 tests completed) **CV1: Nov 2013, CV2 Nov 2014 CV3 Feb 2016**
Items in Test	He Shroud (-03)	He Shroud (-01) Lower GESHA Upper GESHA GIS ITP Photogrammetry Fabreeka VIS* MIRI MLI Expmnt Bolometers	He Shroud (-01) Lower GESHA Upper GESHA GIS ITP / MATF Photogrammetry Fabreeka VIS* MIRI MLI Expmnt Bolometers Flight Structure IATF	He Shroud (-01) Lower GESHA Upper GESHA GIS ITP Photogrammetry Fabreeka VIS* Radiometer Flight Structure IATF	He Shroud (-01) Lower GESHA Upper GESHA GIS ITP / MATF Photogrammetry Fabreeka VIS OSIM Baffle OSIM OSIM Shroud BIA SIF/Shroud Support Frame		He Shroud (-01) Lower/Upper GESHA, GIS ITP/ MATF Fabreeka VIS* Flight Structure IATF OSIM OSIM Shroud SIF/Shroud Support Frame Science Instruments (SI) Flight Harness Flight Heat Straps MIRI Cryo-Cooler MCA SIF & Interfaces to Frame Surrogate TMS IEC w/ Shroud /LN2 Panel Harness Radiator HR Shroud
Cycles	1 cycle to 15K B/O to 70C	1 cycle to 15K 1 cycle to 30K B/O to 50C	1 cycle to 39K 1 cycle to 28K B/O to 40C	1 cycle to 28K	1 cycle to 30K (BIA) 1 cycle of OSIM to 100K		CV1: 1 cycle to 43K CV2: 1 cycle to 37K + 43K CV3: 1 cycle to 37K + 43K

* - caveat; Fabreeka's were not energized in these tests

- caveat; NIRSpec, NIRCam are not in CV1, and Cryo Cooler CHA ETU used in CV 1 & 2 tests.

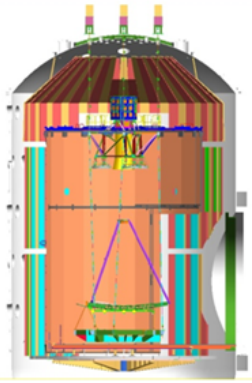
Major OTE/OTIS TV/TB Tests in Chamber A at JSC

Chamber A Commissioning



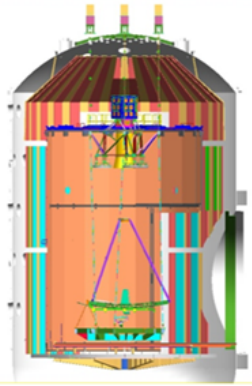
- Cryo load and stress test of suspension system with payload mass simulator
- Chamber verification
- OGSE vacuum integrity
- OGSE functional testing and thermal characterization
- Cryo shift measurements

OGSE-1



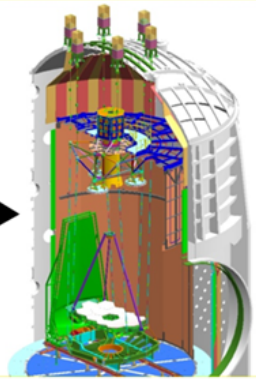
- Pathfinder cryo-vac exposure
- Cryo proof AOS interfaces
- Operated OGSE (CoCOA, PG, DMI) in OTIS-like config
- Checked out BIA in Chamber A
- Thermal Distortion and Dynamics testing
- Vacuum portion of cooldown to check SM model characteristics

OGSE-2



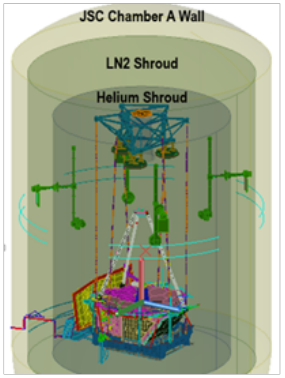
- Added flight AOS and GSE AOS Source Plate.
- Checked out Half-pass and Pass-and-a-half tests
- Used BIA camera as SI simulator
- Thermal Distortion and Dynamics testing

Thermal Pathfinder



- Thermal GSE Checkout (including SVTS, DSERS)
- Dry run cooldown, practiced warmup tests
- Backplane Thermal Balance (design validation off critical path)
- Thermal Distortion and Dynamics testing

OTIS



- **Complete Flight ISIM plus OTE (OTIS)**
- **Previously Checked GSE**
- **Independently controlled IEC DSERS**

Principal OTIS Thermal Test Objectives

Primary Objective of OTIS TV/TB test was considered verification of optical requirements, but included many other tests. Only one thermal balance point was planned. The five principal thermal objectives defined were:

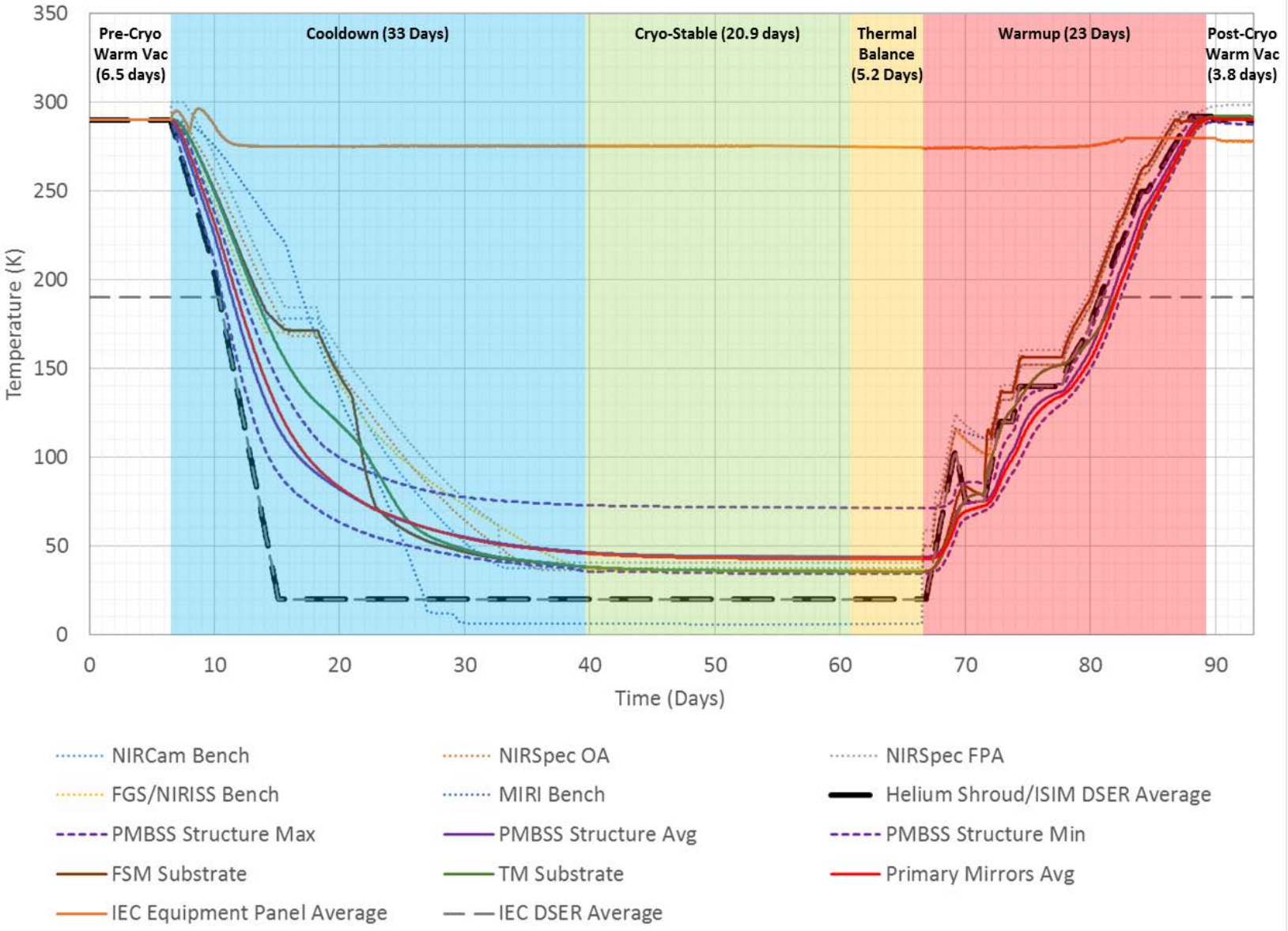
- OTIS Temperature Limits and Constraints - The OTIS temperature limits and constraints shall conform to the requirements found in OTIS Limitations and Constraints Implementation Plan.
- Boundary and Influence temperatures - The test shall verify at thermal balance the element-to-element and key subsystem boundary temperatures and interface temperatures and/or rates as specified in OTIS Thermal Operation Document
- Thermal Model Validation - The test shall verify OTIS system thermal workmanship, and provide thermal balance test data to validate the OTIS thermal model.
- Model Validation Tolerances - The data collected shall be sufficient to validate the models consistent with the numerical requirements found in JWST Systems Analysis and Model Validation Plan
- OTIS Heat Strap Workmanship Test - The test shall perform a workmanship thermal conductance assessment of the flight SI heat straps in the OTIS test configuration at operating temperatures.

Thermal-Applicable Limitations and Constraints

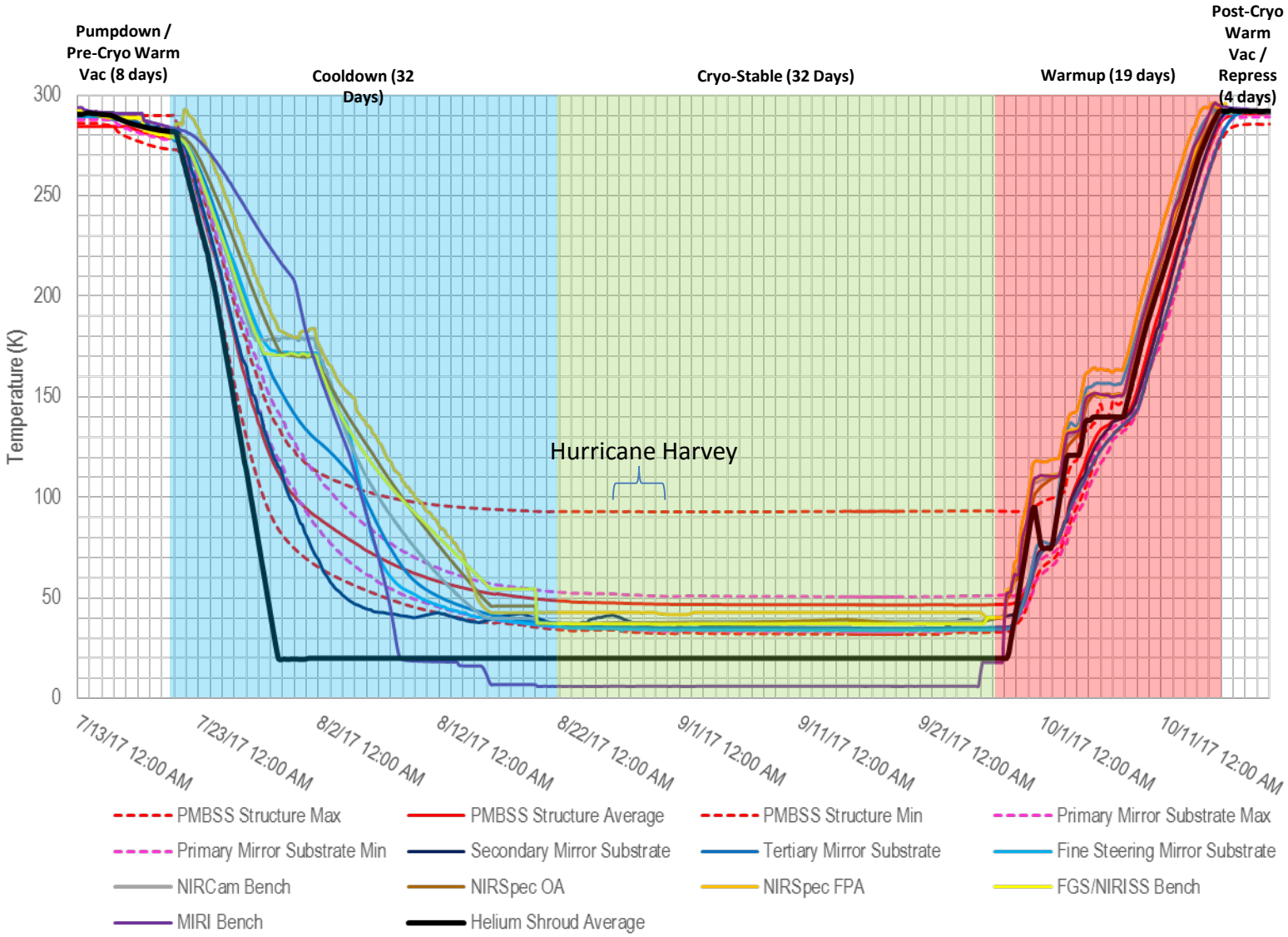
Source Document: "OTIS JSC Constraints & Limitations Implementation Plan"

- 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.
- Several Hundred L&C's divided into two groups
  - Thermal Applicable – Monitored and alarmed by OTIS Thermal Team (92 total)
    - 84 Constraints
    - 8 Limitations
  - Non Applicable - Not monitored by OTIS Thermal Team
- 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

Pre-Test OTIS Profile Prediction



As-Run OTIS Test Profile



OTIS Susceptibility to Off-Nominal Events (1 of 2)

- Large temperature range of components
  - Electrical boxes in IEC: 278K
  - Near IR instruments, instrument detectors: 36.5K - 42.8K, Mid Infrared Instr.: 6.2K
  - Flight radiators: 30K-40K;
  - Telescope optics generally in the 40K-60K range.
  - GHe shroud, other thermal boundaries: 20K, LN2 shroud: 80K
- Complexity of GSE
  - 16 individually controlled GHe flow valves: 7 for shroud, 9 for individual DSER's & thermal boundaries plus supplemental heater circuits for precise temp. control
- Nominal cooldown from ambient to steady state cold planned over 3 weeks
  - To control stress in mechanical components (rate limitations, gradient restrictions).
- Nominal warmup planned over 3 weeks
  - Nominal warmup carefully choreographed, reliant on precise thermal control of shroud, multiple thermal boundaries, instruments. N2 frozen on He shrouds released at ~27K - 34K, caused pressure increase which changed heat transfer mechanism to FMHT, causing rapid temperature and gradient changes, with possible effect on structural component integrity. Large number of rate, gradient C&L's identified.

OTIS Susceptibility to Off-Nominal Events (2 of 2)

- Contamination from water moisture, particulates, molecular contaminants a major concern
  - Sensitive optics in telescope and instruments must be warmer than surroundings during warmup, cooldown to avoid water and molecular contaminants collecting on critical surfaces. Key instrument, optical temperatures kept close to each other during critical parts of transitions to avoid cross-contamination.
- Extremely high value flight payload
- Long test duration 93 days, very high test cost

Pre-Test Preparations for Off-Nominal Events (1 of 2)

- Extensive preparations made during test planning and development:
  - Critical power supplies, test data, control systems on UPS, diesel generator circuits;
  - spare power supplies/temperature measurement equipment available;
  - redundant flight/test sensors identified, added to control heater circuits;
  - Pre-test checkout of JSC facilities (N2 system, He compressors, control software).
  - Test GSE checked to assure proper operation and safety of payload during off-nominal conditions.
  - Roof repairs made to Building 32 (Chamber A, cleanroom, control room)
  - Alternate control room in Building 30 prepared and checked.
- Critical test control equipment covered with plastic sheeting to protect from potential water damage if it rained heavily.
- Potential for hurricanes was identified early on
  - Volunteer Hurricane Rideout Team and Recovery Team members identified and took required FEMA training. Rideout team members also took physical exams.

Pre-Test Preparations for Off-Nominal Events (2 of 2)

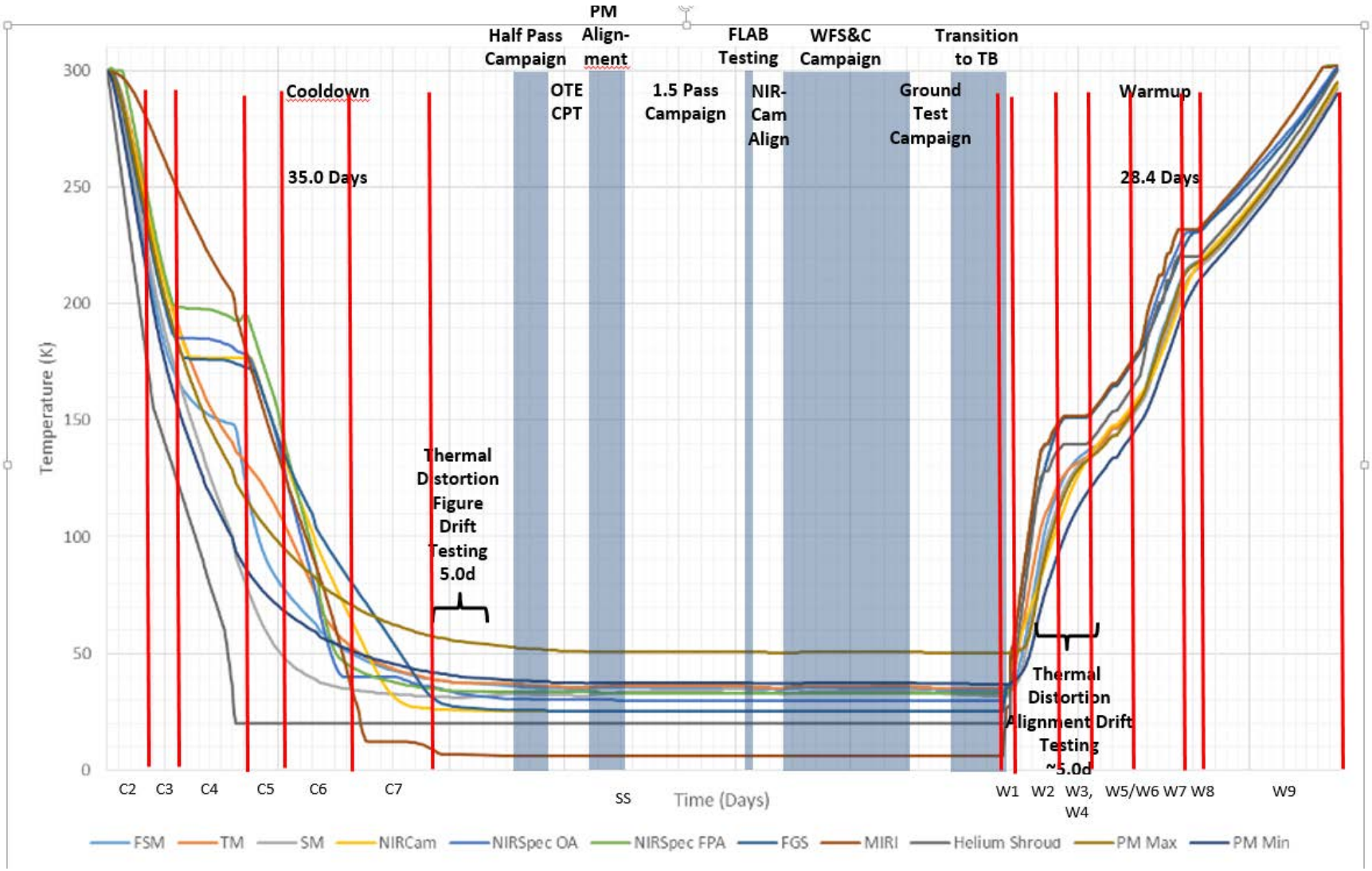
- Thermal staffing shift schedule
  - Established for entire anticipated test period prior to test start.
  - Multiple thermal engineers on shift 24/7 throughout test, with “floaters” (experienced senior thermal engineers with background in JWST) always present in Houston area, ready to assist and replace scheduled shift support if necessary.
  - Thermal support personnel undertook test support and safety training.

Additional OTIS Off-Nominal Planning

- Subsystems directed to perform extensive planning for off-nominal events, to assure safety of personnel and flight hardware.
- Payload thermal developed OTIS Off-Nominal Thermal Consequences and Mitigations Workbook.
  - Excel spreadsheet, reviewed/approved by GSE thermal, facilities, Flight systems teams, identified the following 10 major events, and developed mitigation actions to be taken by Payload thermal, GSE thermal, facilities, test director, depending on test thermal state (see next page):
    - Partial Loss of Vacuum pumps;
    - Loss of LN2 System;
    - Loss of He system-Train 1 – CPP;
    - Loss of He system – Train 3-Shroud, DSERs;
    - Loss of SC Simulator;
    - Loss of IRSU;
    - Loss of Eclipse;
    - Loss of the Thermal Test Set (TTS) data system;
    - Loss of the Fusion data system;
    - Loss of Facility Electrical Power (Loss of both Helium refrigerators. partial loss of vacuum pumps);
- An Emergency Safing Procedure, and a Safing procedure if 48 hours available (in preparation for hurricane or other natural disaster) were also developed.

OTIS Off-Nominal Planning – Mitigations during Specific Test Periods

Note: These predicted test periods were based on an earlier version of the pre-test thermal model



Major Off-Nominal Events during ISIM, OTE, OTIS Tests

Test	Date	Event	Consequences
OSIM Cryo-Cal 1	6/12/2013	Derecho (high wind storm) – extended power loss in area	Impacts to personnel availability
ISIM CV1	10/1/2013-10/17/2013	17-day US Government shutdown	Test placed on "hold" – no progress
ISIM CV2	7/3/2014	Emergency light in test control room caught fire	Control room evacuated, test on hold until smoke cleared
ISIM CV2	7/8/2014	Thunderstorm – Power outage at facility	Emergency generator did not start automatically. He compressor off for ~ 30 minutes. Shroud warmed, test time lost.
ISIM CV2	7/9/2014	Thunderstorm – Lightning strike at GSFC	Lost cooling water for He compressor. Facility electrician was not on shift to restore power to cooling water. Shroud warmed, test time lost.
ISIM CV2	7/10/2014	Continue from above event	He compressor turned off without cooling water.
ISIM CV2	10/3/2014	Fire alarm in B10 basement (part of GSFC thermal test complex)	Thermal engineers, control personnel briefly evacuated (<30 minutes), test resumed without incident
ISIM CV3	1/22/2016 through 1/25/2016	Extreme blizzard ~2 to 3 feet snow in area	Extremely hazardous travel conditions. Test personnel either sheltered at GSFC or if staying within 1 mile of GSFC, were transported to/from GSFC by persons with heavy trucks. Test continued without loss of any facilities.
OTE Pathfinder		Water pipe break in basement of test complex at JSC	Primary He compressor Train 3 unavailable during event, had to switch to alternate Train 3 use.
OTIS	8/26/2017 through 8/30/2017	Hurricane Harvey hits Houston area. Weather conditions during the hurricane JSC included thunderstorms, tornado watches, flood warnings, and periods of severe rainfall (Houston received ~1270 mm (50 inches) of rain in 4 days).	Extreme care had to be used in transit between hotels and JSC for test personnel. Shifts were extended to 12 hours to minimize travel, some people slept at JSC for a few nights, and active optical testing was curtailed for a time. JSC center was closed for ~9 days to regular JSC employees from the start of the hurricane until facilities could be verified as safe for return. Meanwhile, roof of Building 32 (test building) leaked, resulting in substantial use of plastic sheeting to keep critical electronic equipment in the building and the control center dry and safe. Principal concerns included potential loss of electrical power, and inability to refill LN2 tanks. Loss of power would have resulted in loss of He Train 3, and would have required warming to LN2 temperature. Loss of LN2 would have eventually resulted in full warmup We were fortunate that neither occurred during the Hurricane, as they would have had week(s) of impact to test time. Since we had just entered Cryo-stable phase of test, most test objectives had not yet been met.

Dealing with ISIM CV3 Blizzard

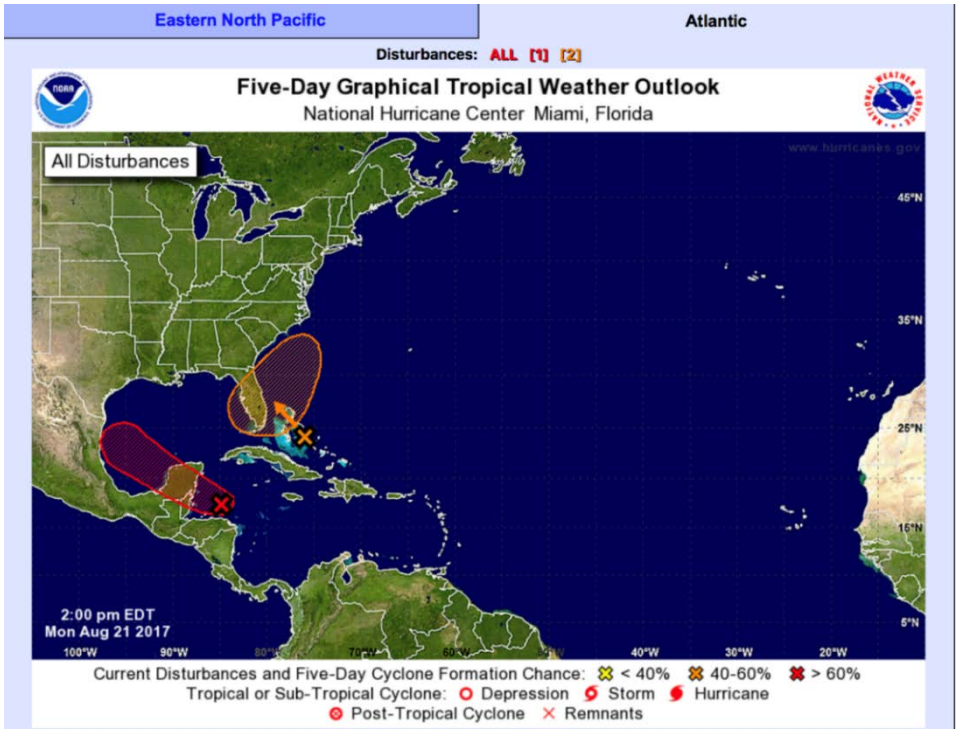
Snowed in at NASA, Keeping Watch Over a Space Colossus

Time is running out on the agency's most ambitious science mission in generations, and that means no stopping for anything—not even a historic blizzard.

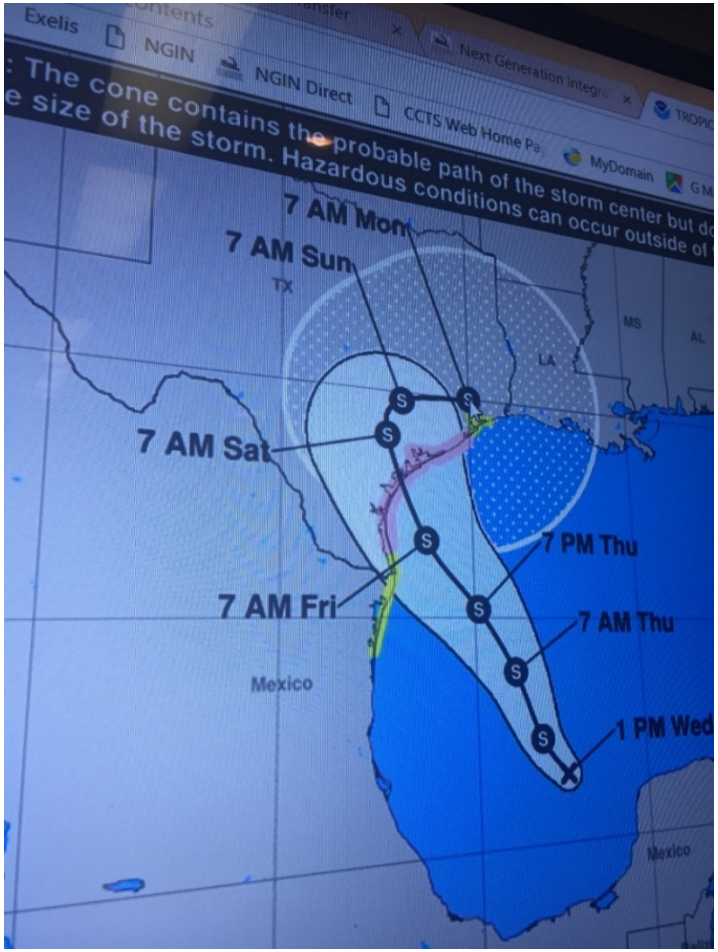
- Massive blizzard warnings (for Greenbelt MD) at least 4 days before blizzard arrival (January 21, 2016)
- Preparations made for locals to shelter at GSFC for several days, arrangements made to ferry non-local test participants to/from local hotels in privately owned trucks
- 21-34 inches snow in Washington DC area (NASA/GSFC received ~21 inches)
- Test progress not impacted!

OTIS Test: Hurricane Harvey Storm Warnings

Hurricane forecasts were monitored daily throughout OTIS test. Initial warnings of possible Hurricane Harvey impacting Houston area ~5 days before landfall



Monday, August 21



Wednesday, August 23

(Photos Credit: L. Feinberg)

Initial Preparations for Harvey

(Photo Credit: L. Feinberg)

- By Friday, August 25, Project had purchased 40 air mattresses, set up in conference rooms
- Project had stockpiled food rations for several days

- Potential effect on personnel more severe than blizzard during ISIM CV3 test, since most test participants were non-resident in Houston area and had to fly in from around the US and world to staff test.
- Plans made to extend shifts to 12 hours to minimize travel to/from hotels
- Hurricane Ride-out team members were identified, prepared to stay at JSC
- Hurricane safing procedures reviewed, plans to deal with individual system failures printed (on laminated paper)

Dealing with Harvey: Initial impacts - Saturday *night* into Sunday morning, August 26/27

Weather conditions

- ~20 inches of rain *overnight* at JSC, 45-50 inches total in Houston area (over 4 days)
- Flash flooding, storm, and tornado warnings all night

Impacts to personnel, JSC

- Extremely hazardous travel, several experienced test support personnel called in to JSC prior to landfall in case Center access became impossible
- Only JSC entrance was closed for several hours due to flooding

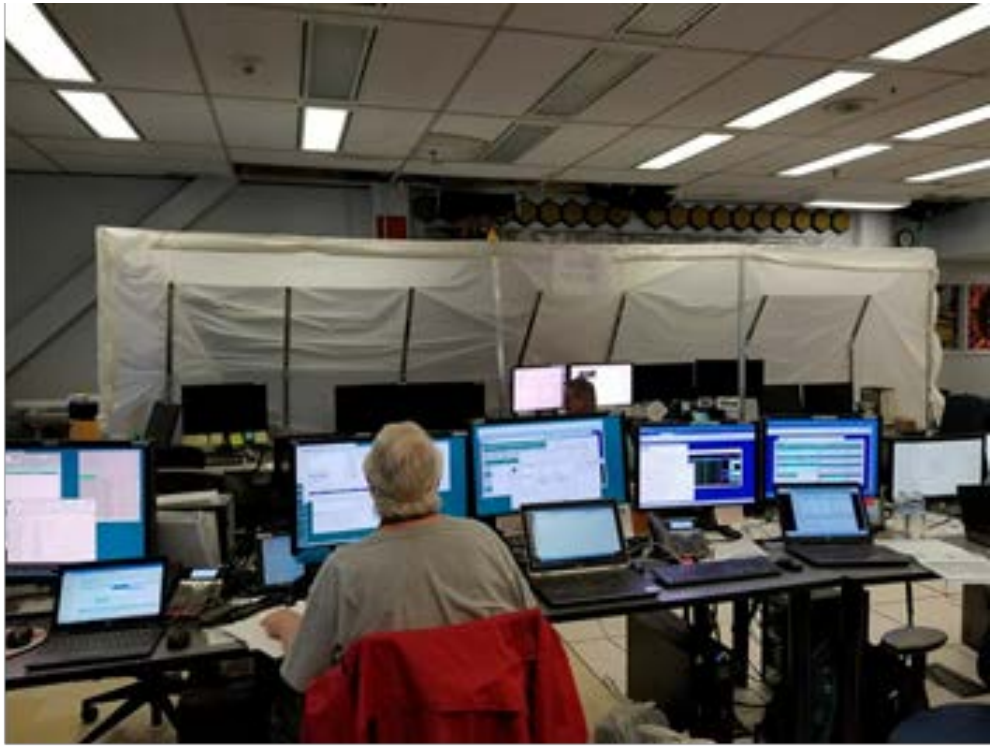
Impact to Test

- OTIS test continued, but optical testing temporarily curtailed

JSC Parking Lot B32 (Photo Credit: L. Feinberg)

Dealing with Harvey: During, after Landfall

Water Damage in B32 OTIS Control Room, despite pre-test roof repairs



Plastic Sheeting installed to Protect control computers and data stations

Dealing with Harvey: Several Days after Landfall

- Hurricane was slow moving, bands of intense rainfall, winds persisted for 4 days
- Carpools organized using high ground clearance trucks/SUV's to ferry personnel to/from hotels because of local road flooding
- 12 hour shifts until local flooding eased
- Road flooding in Houston prevented timely LN2 deliveries for ~ 3 days (only had 5 days reserve on-hand before LN2 shroud would warm, causing premature test warmup). Great efforts made to bring in LN2 from alternate supplier
- Fortunately, JSC area did not lose commercial power, which would have resulted in premature test end
- Commercial air travel from local airports was impacted for several days after the hurricane. NASA GSFC, NGAS, BATC made special arrangements to provide replacement test support crews

(Photos Credit: L. Feinberg)

Payoff of the OTIS Off-Nominal Planning

Pre-test planning resulted in a highly successful TV/TB test;

- Extreme flexibility, redundancy built into the facility and GSE thermal controls and data systems enabled flexible and rapid reaction to small differences between modeled and actual transient performance.
- No unplanned warmup/cooldown due to off-nominal events
- Extremely detailed and careful pre-test thermal modeling resulted in 1 brief constraint violation during cooldown, 4 during warmup, none considered serious enough to warrant Problem Failure Report
- Pretest securing of critical electronic GSE with plastic sheeting protected that equipment and helped safeguard the payload during the hurricane. Project dealt with severe hurricane conditions without major impact to test schedule
- Plans were ready to conduct unplanned partial/complete payload warmup if conditions worsened during the hurricane.

Recommendations for Off-Nominal Planning for TV/TB Tests of Flight Payloads (1 of 2)

Enhance personnel and flight hardware safety with appropriate planning:

- Low hanging fruit should always be addressed:
  - Provide spares for critical GSE power supplies, make sure personnel trained to replace them
  - Provide/install redundant sensors for controlled heaters, and redundant GSE heater circuits
  - Provide/install backup power supply for critical thermal boundaries, power supplies, test measurement equipment, data systems, control electronics, facilities, to allow continued testing or safe test end (UPS, diesel generator)
  - Make sure well trained test support personnel available to replace scheduled shift personnel in case of illness, accidents

Recommendations for Off-Nominal Planning for TV/TB Tests of Flight Payloads (2 of 2)

- Prior to major thermal vacuum tests, projects should list potential events and their effects, and evaluate risks of failures of GSE, flight hardware, flight software, facilities, utilities, personnel evacuations, etc. in terms of impact to flight hardware damage and potential programmatic impact for repairs; schedule; cost. Project must be willing to accept remaining risks.
- Make as many facility, utility provisions as robust as possible. Demonstrate pre-test (without risking flight hardware).
- Even if certain potential facility or utility failures cannot be prevented, evaluate potential damage, devise test workarounds or emergency procedures

Acknowledgement for All Test Teams

- The authors wish to acknowledge the hard work and dedication of the Project and Test Directors, Payload Thermal, GSE Thermal, Contamination, Cryo Support, Instrument, Optics, Facilities, and all other support teams for a successful test.
- Payload Thermal support team on shift during Hurricane Harvey shown below