Systems Engineering on the James Webb Space Telescope

Michael T. Menzel[a], Marie Bussman[a], Michael Davis[a], Gary Golnik[a], Sandra Irish[a], Jon Lawrence[a], Richard Lynch[a], Peiman Maghami[a], Landis Markley[a], Kimberly Mehalick[a], Gary Mosier[a], Danniella Muheim[a], Keith Parrish[a], Shuan Thomson[a], Paul Geithner[a], Joe Pitman[b], James Wehner[c], Jon Arenberg[c], Brian Costanza[c], Satya Anandakrishnan[c], Bill Burt[c], Reem Hejal[c]

[a]NASA Goddard Space Flight Center, Greenbelt, MD, USA 20771
[b]Exploration Sciences, PO Box 24, Pine CO 80470
[c]Northrop Grumman, Redondo Beach, CA 90278 USA

ABSTRACT

The James Web Space Telescope (JWST) is a large, infrared-optimized space telescope scheduled for launch in 2014. System-level verification of critical performance requirements will rely on integrated observatory models that predict the wavefront error accurately enough to verify that allocated top-level wavefront error of 150 nm root-mean-squared (rms) through to the wave-front sensor focal plane is met. This paper describes the systems engineering approach used on the JWST through the detailed design phase.

Keywords: Systems Engineering, Space Telescope, JWST, James Webb Space Telescope

1. INTRODUCTION

The JWST observatory is NASA's next great space observatory, scheduled to succeed the Hubble Space Telescope (HST) in 2014. System development is led by Goddard Space Flight Center (GSFC) and the Prime Contractor Northrop Grumman (NG), with Ball Aerospace, the European Space Agency (ESA), the Canadian Space Agency (CSA), the Space Telescope Science Institute (STScI), the Jet Propulsion Laboratory (JPL) and the University of Arizona as major contributors. Its mission is to detect the first light sources that turned on in the early universe approximately 13 billion years ago. To see these faint sources the observatory must have at least 25 square meters of light gathering area and extremely low infrared noise levels. These are provided by a 6.3 meter diameter light weight cryogenic telescope and a suite of state-of-the-art science instruments. To realize the cryogenic temperatures necessary for low background noise, the observatory will be operated at the 2nd Earth-Sun Lagrangian (L2) point, located approximately 1.5 million kilometers from the Earth and use a tennis-court sized sunshield to allow cooling of its telescope and science instruments. The Project successfully passed its Mission Critical Design Review (CDR) in April of 2010.

This first-of-its-kind mission presents several challenges to the Systems Engineering (SE) process. This paper will describe four of these, mass and resource control, interdisciplinary trade studies, integrated modeling and verification.

2. SYSTEM DESCRIPTION

System architecture is shown in Figure 1. An Ariane 5 Launch Vehicle (LV) will put the JWST observatory into a direct trajectory toward the L2 point. Immediately after separation of the observatory from the upper stage of the LV, it will perform a series of Delta-V maneuvers to correct LV dispersions followed by deployment of the sunshield and telescope. During these critical events, the Ground Segment shall provide continuous communication coverage via NASA and European Space Agency (ESA) assets. After the deployments, the observatory begins to cool down to its operational temperatures. When the telescope and science instruments (SI's) attain these temperatures, images from the SI's will be used to align and phase the telescope. After a roughly 100-day cruise period, the observatory performs some minor Delta-V maneuvers to place it into its operational orbit around the L2 point. During the operational phase of the mission, high-data-rate science data is transmitted to the ground segment thru a Ka band link, using the Deep Space Network (DSN) 34-meter antennas.

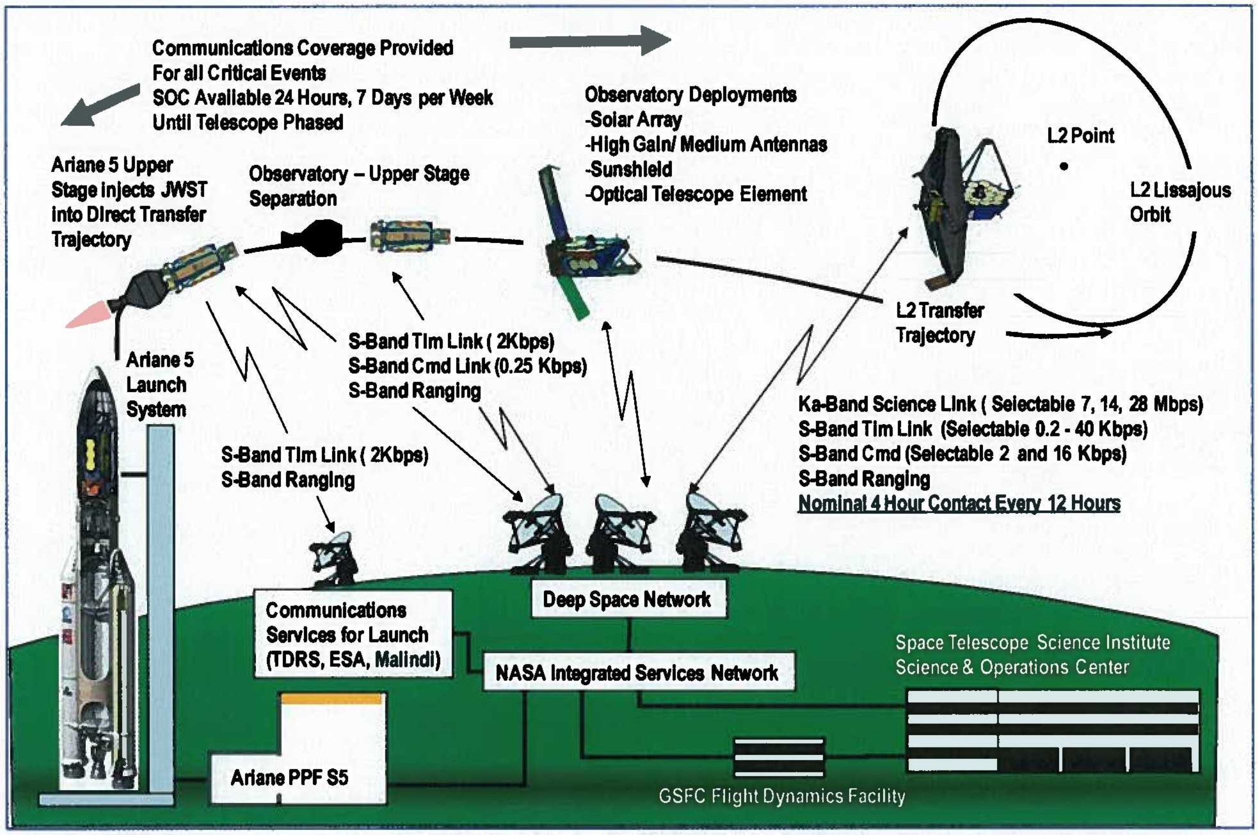
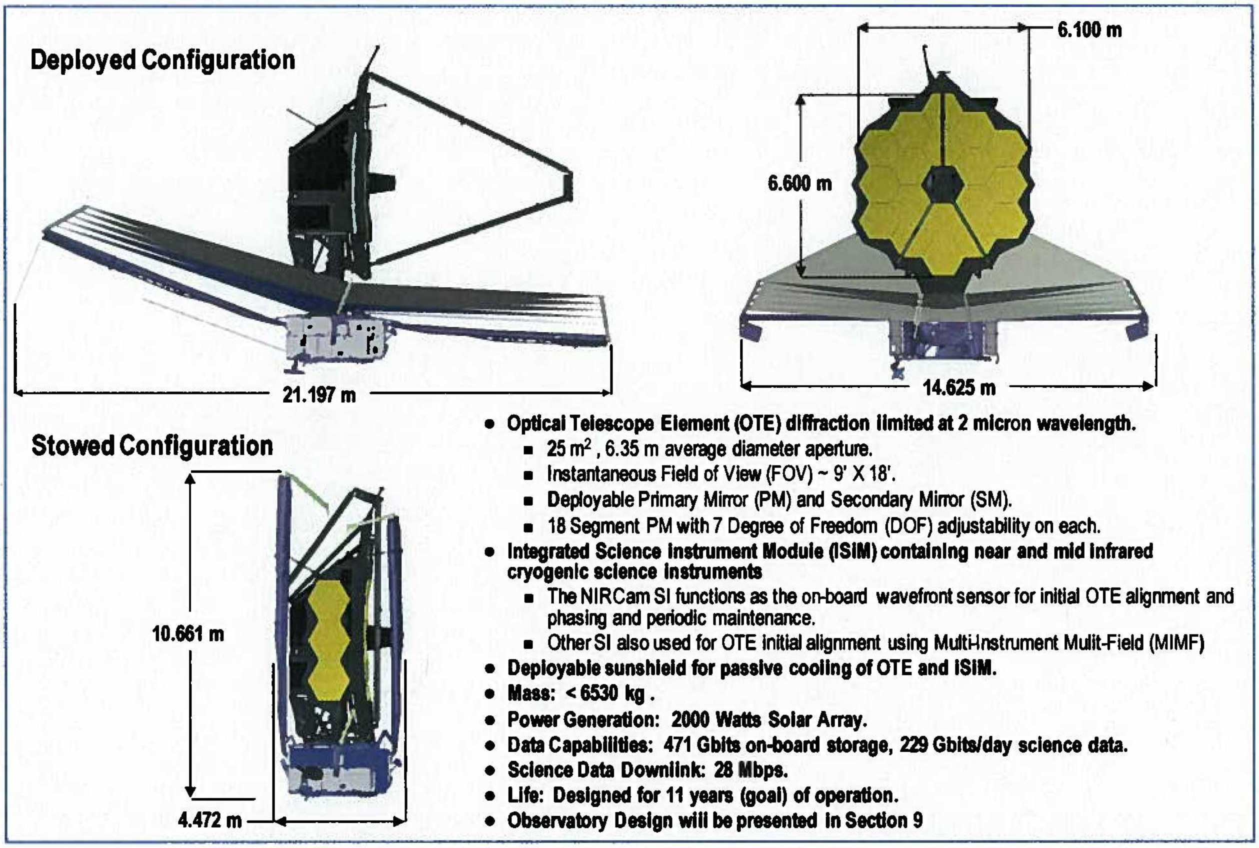


Figure 1. The JWST Systems Architecture

Figure 2 illustrates the overall dimensions of the stowed and deployed configurations of the observatory as well as list of the top level capabilities. Figure 3 illustrates the architecture of the observatory and its major assemblies and elements. The first of these is the Integrated Science Instrument Module (ISIM) which is provided by GSFC. This element consists of five infrared SI's, the meter structure that keeps them co-aligned and the electronics to processes their data. The four SI's are:

- The Near Infrared Camera (NIRCam), which provides imagery in the waveband from 0.6 to 5 microns.
- The Near Infrared Spectrograph (NIRSpec), which provides multi-object spectroscopy in the waveband from 0.6 to 5 microns.
- The Mid Infrared Instrument (MIRI), which provides imagery and spectroscopy in the waveband from 5 to 20 microns.
- A combined Tunable Filter Instrument (TFI), which provides adjustable narrow band imagery in the waveband from 1.6 to 4.9 microns and Fine Guidance Sensor (FGS), which provides fine guidance pointing error signals for the observatory Fine Guidance Control (FGC) loop.



- **Optical Telescope Element (OTE) diffraction limited at 2 micron wavelength.**
  - 25 m^2 , 6.35 m average diameter aperture.
  - Instantaneous Field of View (FOV) ~ 9' X 18'.
  - Deployable Primary Mirror (PM) and Secondary Mirror (SM).
  - 18 Segment PM with 7 Degree of Freedom (DOF) adjustability on each.
- **Integrated Science Instrument Module (ISIM) containing near and mid infrared cryogenic science instruments**
  - The NIRCam SI functions as the on-board wavefront sensor for initial OTE alignment and phasing and periodic maintenance.
  - Other SI also used for OTE initial alignment using Multi-Instrument Mulit-Field (MIMF)
- **Deployable sunshield for passive cooling of OTE and ISIM.**
- **Mass: < 6530 kg .**
- **Power Generation: 2000 Watts Solar Array.**
- **Data Capabilities: 471 Gbits on-board storage, 229 Gbits/day science data.**
- **Science Data Downlink: 28 Mbps.**
- **Life: Designed for 11 years (goal) of operation.**
- **Observatory Design will be presented in Section 9**

Figure 2. The JWST Observatory Stowed and Deployed Configurations and Capabilities

The next element, the Optical Telescope Element (OTE), has a 6 meter diameter Primary Mirror (PM) made up of 18 individual controlled hexagonal Primary Mirror Segment Assemblies (PMSAs). Each has 7 degree of freedom (DOF) control to align and phase them so that they act as one coherent reflector. They are supported on the Backplane Structure. This is a critical metering structure that has very strict specifications on its allowable distortion as the observatory changes attitude and thermal conditions to slew to different targets. The OTE has its Secondary Mirror Assembly (SMA) supported on a deployable Secondary Mirror Support Structure (SMSS). This mirror has 6 DOF control. The Tertiary Mirror (TM) and Fine Steering Mirror (FSM) are housed in the Aft Optics Subsystem (AOS). The FSM is controlled by a Fine Guidance Control (FGC) loop at rate of about 1 Hz to correct for pointing errors by using data provided by the FGS in the ISIM. Finally, the OTE provides the cryogenic radiators that cool the SI's as part of the ISIM enclosure which surrounds the ISIM.

The final observatory element is the Spacecraft Element (SCE), which consists of two sub-elements; the Sunshield and the Spacecraft Bus. The Sunshield is a deployable structure with five specially coated kapton membranes which provides the thermal insulation necessary to allow the OTE and ISIM to radiatively cool. The Spacecraft Bus contains the traditional subsystems; Electrical Power Subsystems (EPS), Attitude Control Subsystem (ACS), Reaction Control Subsystem (RCS), Command and Data Handling (C&DH) Subsystem, Thermal Control Subsystem (TCS) and the Structure Mechanism Subsystem (SMS), along with the MIRI Cryo-Cooler, which is the active cooling system required to get MIRI detectors to their operational temperatures lower than 7K.

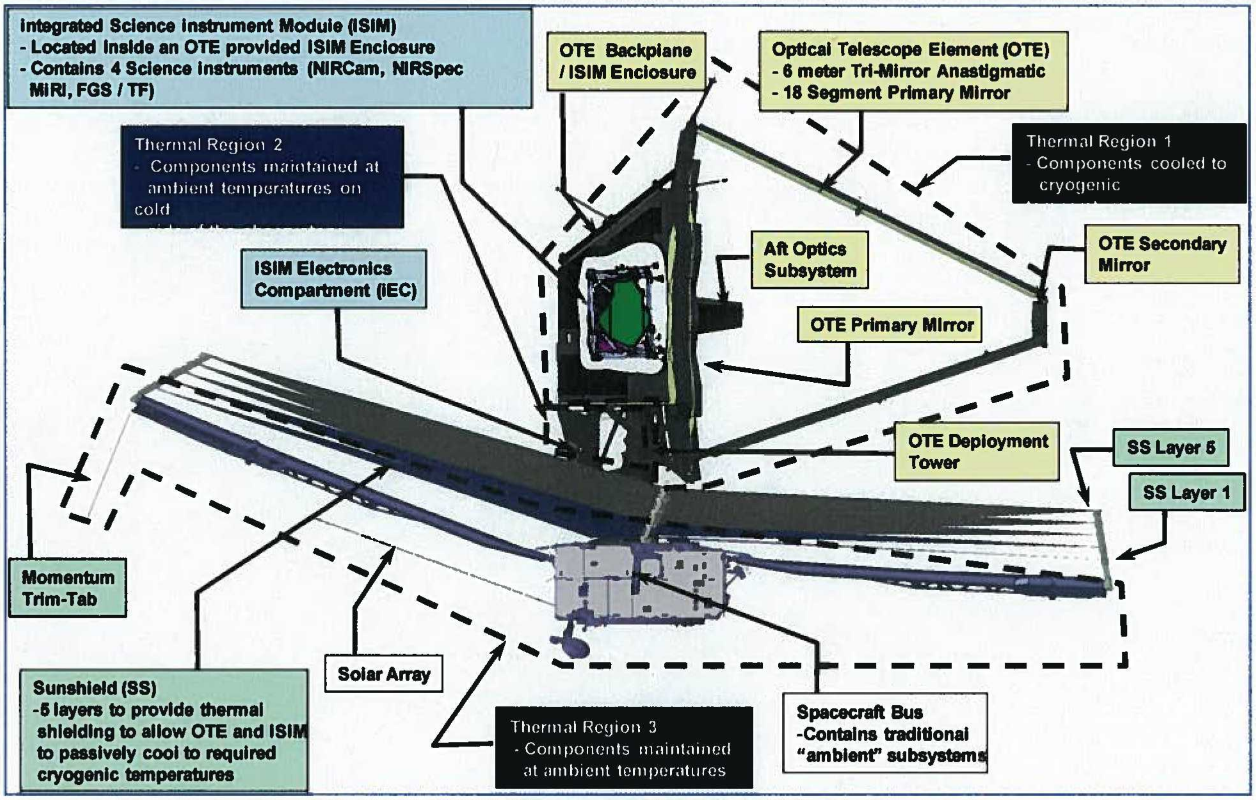


Figure 3. The JWST Observatory Elements and Thermal Regions

Figure 2 also illustrates thermal architecture of the Observatory. It is divided into three thermal regions. Region 1 contains the hardware that must operate at temperatures between 50K and lower and Region 3 contains the hardware that operates at normal spacecraft temperatures. These two regions are insulated from each other by the 5 layer sunshield, which effectively attenuates the roughly 91,000 watts of solar energy that impinges on it by a factor of 5 x 10^{-6} such that less than 1 watt is allowed to leak thru to the cold side. The temperature on the hot side of the sunshield is roughly 400K while the temperatures on the cold side average 50K or below.

Region 2 is an intermediate thermal region on the cold side of the observatory that contains processing electronics for the SIs that must operate at temperatures typical of electronics boxes (i.e. at room temperature, 290K). These warm electronics must reside on the cold side of the sunshield to minimize the length the electrical signals traverse from the SI detectors to limit electrical noise. These electronics are housed in the ISIM Electronics Compartment (IEC), which dumps their 200 watts of dissipated heat thru a series of directional radiators to prevent this energy from impinging on the aft sunshield where it could be reflected and directed toward the ISIM cryogenic radiators resulting in a thermal back-load.

3. MASS AND RESOURCE CONTROL

JWST's large size and distant operational location challenge designers to obtain high mass efficiency in order to stay within the launch capabilities of the ESA-provided Ariane 5 Launcher, projected to be 6530 kg to the required direct inject transfer trajectory. The magnitude of this challenge is evident when one compares JWST to the HST and realizes that it must have over five times the light collecting area with roughly half the mass. The SE program addresses this mass challenge with three techniques:

- Design Optimization
- Mass Control Plan With Continuous Risk Management

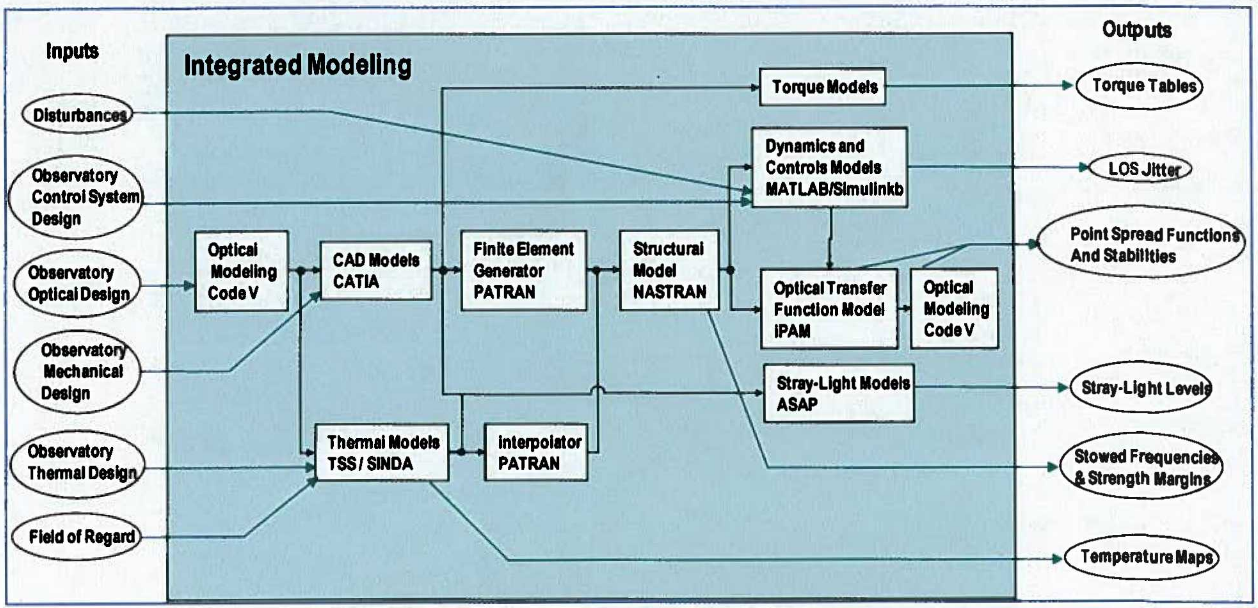
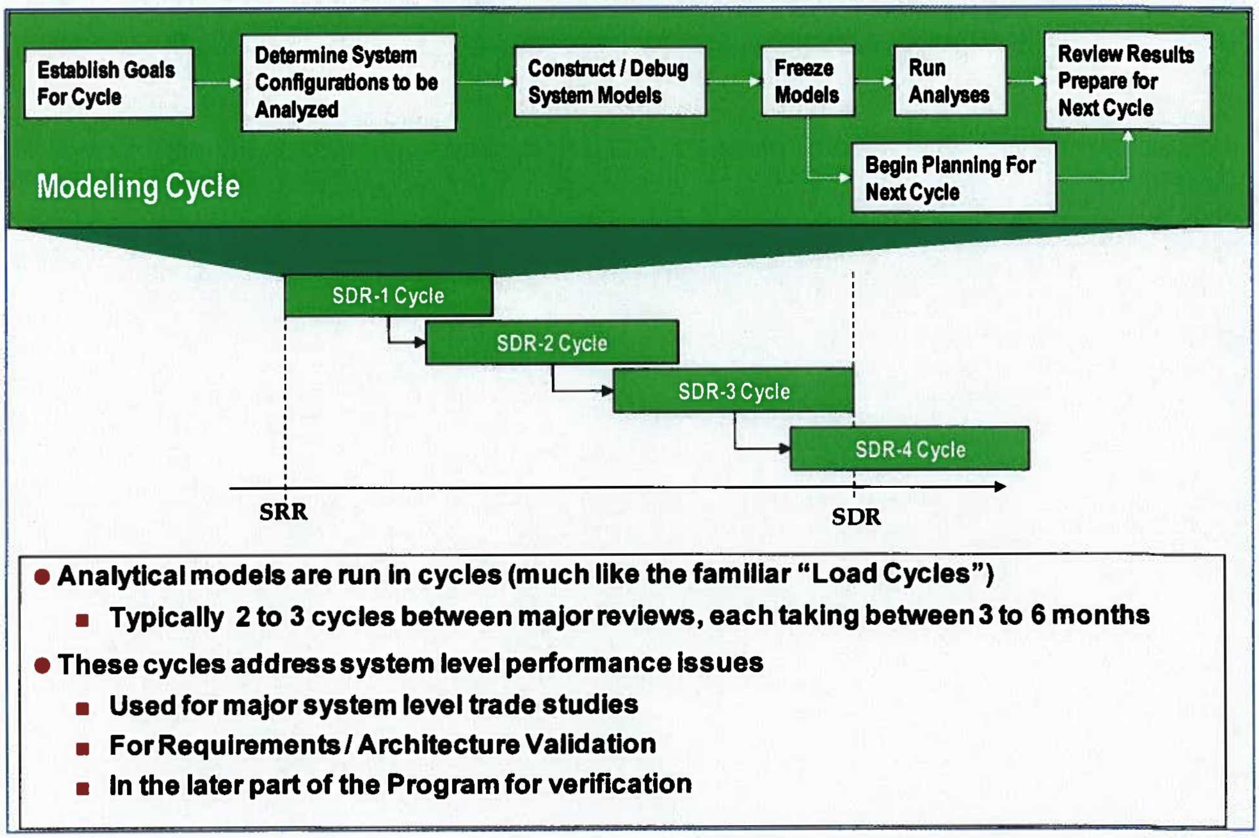


Figure 6. The JWST Integrated Modeling Process



- Analytical models are run in cycles (much like the familiar “Load Cycles”)
  - Typically 2 to 3 cycles between major reviews, each taking between 3 to 6 months
- These cycles address system level performance issues
  - Used for major system level trade studies
  - For Requirements / Architecture Validation
  - In the later part of the Program for verification

Figure 7. Integrated Analysis Cycles

An important aspect of the Integrated Modeling Process is the rigorous configuration control of the models. This includes not only the careful recording of all changes to the models, but also the recording of all differences between the models and the actual hardware design. Lists of these differences, called Liens and Threats Lists, are maintained along with rough estimates of the impact these liens and threats represent to the computed performance. SE reviews these lists and updates the models to incorporate these liens and threats with each subsequent integrated modeling cycle. Since these models are a critical element of the system verification program, it is extremely important that the configuration management and pedigree of these models be meticulously monitored and tracked.

6. VERIFICATION

Verification is the bottoms-up process of ensuring that the as-built system constituents and the integrated system itself meet their documented requirements. This is normally a straight forward incremental process, consisting predominantly of tests, which follows the requirements documentation tree of the system. The size and cryogenic nature of the JWST Observatory significantly restricts the amount of testing that can be used for the verification. With a sunshield roughly the size of a tennis court and with thermal zones that span temperature ranges from 400K to 40K, JWST cannot be tested practically at the observatory level of assembly in a thermal vacuum chamber. SE must rely on the analytical models for verification to a much larger extent than many past missions. With this in mind many of the verification processes must take special care to insure the fidelity of these models is sufficient to represent the performance of the as-built hardware.

Test results at lower assembly levels are used to anchor / correlate analytical models to the hardware. These models are then used in system-level analyses to verify performance. It therefore becomes important to guarantee that lower assemblies are tested in a manner that not only verifies their individual requirements but also meet the needs of these higher-level analyses. For example, it is common practice to specify component performance for worst-case conditions for that device. However, the worst-case conditions for a component does not always ensure simulation of the worst-case conditions for the system, which can be a complex combination of many such components. In order to make these assessments, the JWST observatory verification program is broken down not only in terms of its constituent products, but also in terms of performance “threads”. These threads include optical, thermal, mechanical, and electrical performance. Thread leads ensure that component and subsystem test results are properly coordinated and combined to satisfy the needs and conditions of the system verification, especially when this is by analysis. Figure 7 summarizes the verification of key JWST performance requirements using combinations of tests and analyses.

The test portions of the verification program are implemented as part of the JWST Integration and Test (I&T) Program which is illustrated in Figure 8, color coded along product lines.

In addition to the tests shown on this flow, there are two key system level engineering unit tests that are used to correlate the analytic observatory thermal models. The first, illustrated in Figure 9 is a full-scale thermal test model of the observatory CORE region between the Spacecraft Bus and the OTE-ISIM. This is a thermal transition volume between the warm temperature spacecraft and the cryogenic OTE-ISIM where complex radiative couplings and conductive loads must be accurately modeled. This full-scale model was used for thermal balance testing to correlate the observatory thermal models for this region. The second unit, illustrated in Figure 11, is a 1/3-scale thermal test model of the sunshield, which was also subjected to thermal balance testing to correlate the sunshield thermal model. Testing on both of these units has been completed and the data is being used for these correlation activities.

Requirement	Verification Method (Analysis / Test)	Model Validation
Thermal Requirements: • MR-91: Cryogenic margin >50% • OBS-176: Passive cooling of NIR detectors to operational temperatures • OBS-480: OTE-ISIM-SCE thermal interfaces	• Verification by analysis using the observatory thermal model to predict on-orbit temperatures of the NIR SI detectors and cryogenic radiators at extreme attitudes • Nominal EOL "hot-biased" or "cold-biased" properties	• Observatory thermal model assembled from thermal models of elements which are validated by thermal balance tests. • Tests are conducted at the Spacecraft, ISIM and OTE/ISIM levels. • The sunshield thermal model is validated by thermal balance testing of a 1/3 scale model.
Optical Requirements: • MR-110 and 116: Strehl > 80% at wavelengths of 2 microns and at 5.6 microns • MR-121 and 122: Stray light at NIR and MIR wavelengths	• Verification by analysis using optical test data obtained at OTE component levels, and at the SI and ISIM levels, and alignment data from the OTE/ISIM test input into the observatory optical model. • Optical model uses outputs from deployed dynamics models and thermal distortion models to compute overall WFE, Strehl and EE. • Optical model employs routines to compute WFSC performance • Stray light computed using observatory level stray light models, derived from CAD models using temperatures computed from observatory thermal models.	• Optical models validated by tests at the PMSA, SMA, and AOS levels of assembly as well as alignments measured at the OTE/ISIM assembly. • Thermal distortion models validated as described in the previous cell. • WFSC model / algorithm validated on the Telescope Test Bed, and crosschecked using blind testing with scenarios generated by independent optics team. • Stray light models validated by BRDF test data at the coupon / component levels.
Deployed Dynamic Requirements: • OBS-2031: Image motion < 0.007" for a 10,000 sec exposure • OBS-1619 & 1624: Image motion allocation for OTE and ISIM outside of fine guidance bandwidth	• Verified by analysis using deployed structural model with input disturbances for the Reaction Wheels and Cryo-Cooler.	• Observatory deployed structural model assembled from element models validated by ambient modal surveys, and cryogenic damping tests for a representative OTE backplane section (BSTA) and cryogenic Tuned Magnetic Dampers. • Disturbance models validated by tests at the assembly levels.
Thermal Distortion Requirements • MR-113, 114 and 115: Encircled energy stability and conditions. • OBS-289: OTE thermal WFE stability. • OBS-290: Cumulative change in daily average OTE WFE.	• Verified by analysis using temperature outputs from observatory thermal model applied to the observatory structural model. • Displacements between Hot and Cold attitudes are input into optics models to compute WFE changes.	• Models are validated by materials testing at cryogenic temperatures, displacement vs temperature tests done on Backplane Stability Test Article (BSTA) and ISIM Breadbox Structure, PMSA tests at MSFC, tests of the AOS and SMA, with a final test of the OTE/ISIM at JSC.

Figure 8. The Verification of Key JWST Performance Requirements

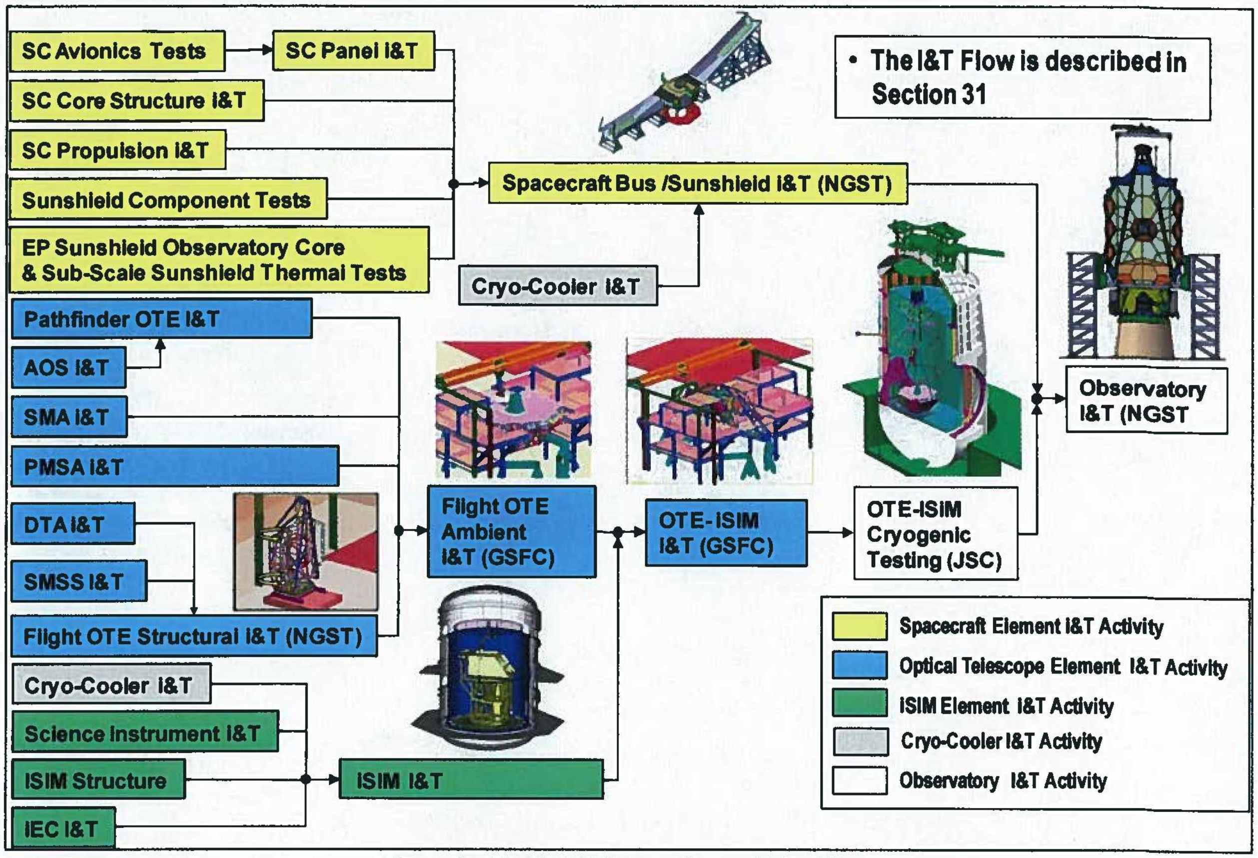


Figure 9. The JWST Integration and Test Flow

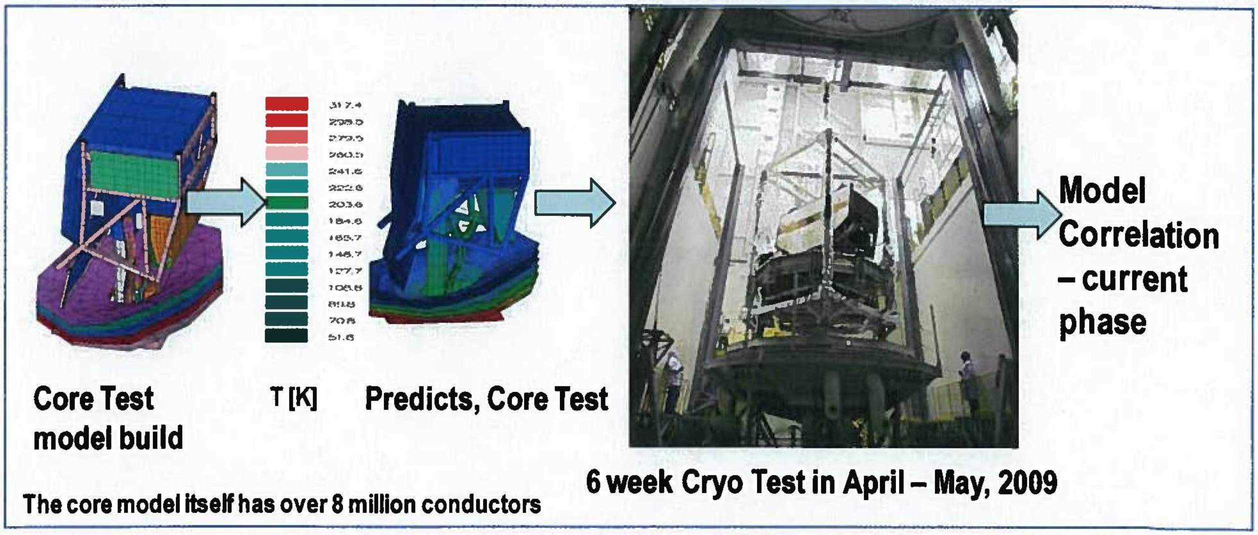
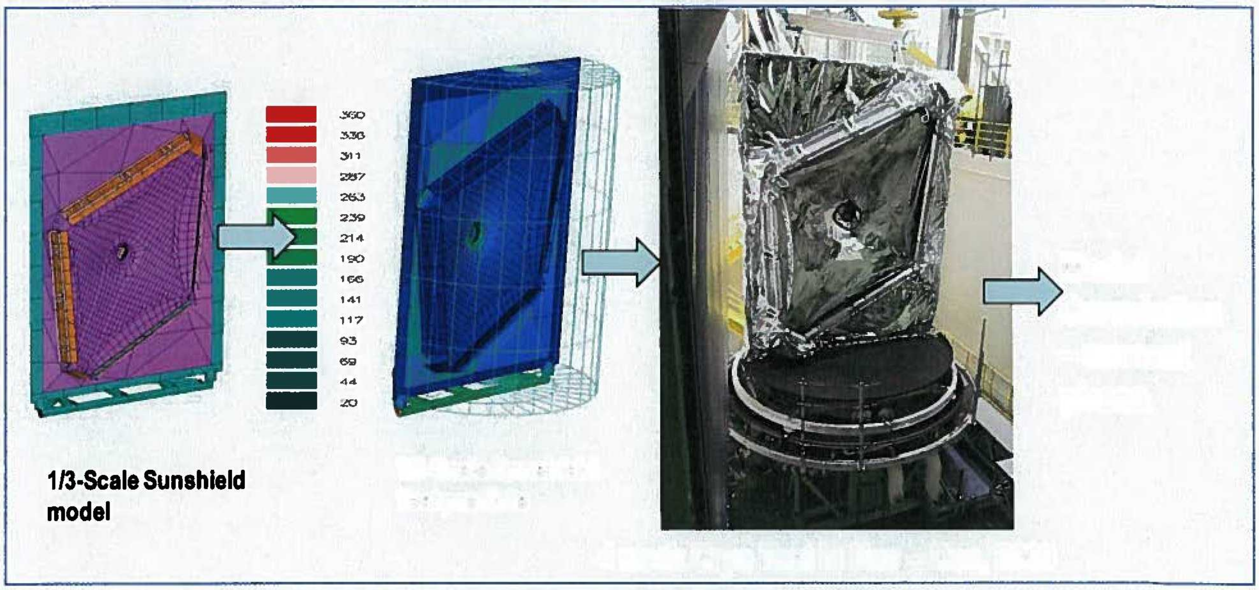


Figure 10. The Full Scale CORE Thermal Test Model



8. ACKNOWLEDGEMENT

The authors would like to thank the very large team across the world working on the JWST System including but not limited to key teammates; ESA, CSA, the STScI, Northrop Grumman, Ball Aerospace, the University of Arizona, Lockheed Martin, and the Jet Propulsion Laboratory.

REFERENCES

[i] "Mass Properties Control for Space Systems", American Institute of Aeronautics and Astronautics S-120-2006 (2006)