CRYO TESING OF THE JAMES WEBB SPACE TELESCOPE'S INTEGRATED SCIENCE INSTRUMENT MODULE

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ABSTRACT

The Integrated Science Instrument Module (ISIM) of the James Webb Space Telescope will be integrated and tested at the Environmental Test Facilities at Goddard Space Flight Center (GSFC). The cryogenic thermal vacuum testing of the ISIM will be the most difficult and problematic portion of the GSFC Integration and Test flow. The test is to validate the coupled interface of the science instruments and the ISIM structure and to sufficiently stress that interface while validating image quality of the science instruments. The instruments and the structure are not made from the same materials and have different CTE. Test objectives and verification rationale are currently being evaluated in Phase B of the project plan. The test program will encounter engineering challenges and limitations, which are derived by cost and technology many of which can be mitigated by facility upgrades, creative GSE, and thorough forethought. The cryogenic testing of the ISIM will involve a number of risks such as the implementation of unique metrology techniques, mechanical, electrical and optical simulators housed within the cryogenic vacuum environment. These potential risks are investigated and possible solutions are proposed.

INTRODUCTION

Hubble has enjoyed the clear, unobstructed view of space from outside the confines of our lower atmosphere, but the scientific goals of the JWST mission require that the location of this telescope be further improved. JWST will require the cold, quiet, and clarity of interplanetary space. However, along with many of the benefits of moving further away from earth come many environmental and functional challenges that are new to space-based telescope design. Spacecraft located outside of Low Earth Orbit (LEO) cannot be serviced by astronauts and must have a high probability of success and high reliability to justify their cost. In order to design and build a robust telescope capable of performing the proposed science, the ground testing of the telescope will have to be well thought out and rigorously performed.

JWST Orbit

The orbital destination for JWST is at about 1.5 million km from earth at a point where the sun and the earth-moon barycenter will always remain along a fixed line relative to the observatory. This point is known as L2, or the second Lagrange point.

There are several relevant environmental considerations of the L2 orbit. The cryogenic temperatures that are beneficial for detecting infrared light from stars creates problems for the many mechanisms that are needed on a telescope that has a wide range of capabilities. The transition from warm launch temperature to cold orbit temperatures creates mechanical distortion and gross movement of instruments that must be precisely aligned and orientated. Although many other spacecraft have been launched into cold, interplanetary space, none have had the tight alignment and stability requirements of this high performance telescope. Furthermore, the radiation environment is much harsher than encountered by ground and LEO telescopes, and the detectors required for sensitive IR imagery tend to be very sensitive to radiation upsets. Lastly, the fine pointing stability that is necessary for the planned long exposures of this telescope will be difficult to achieve due to the perturbation force of the solar wind on the large sunshield.

JWST Observatory Architecture

JWST observatory, shown in Figure 1, is comprised of three main elements;

1. Optical Telescope Element (OTE)
2. Spacecraft Element (Spacecraft)
3. Integrated Science Instrument Module (ISIM) Element

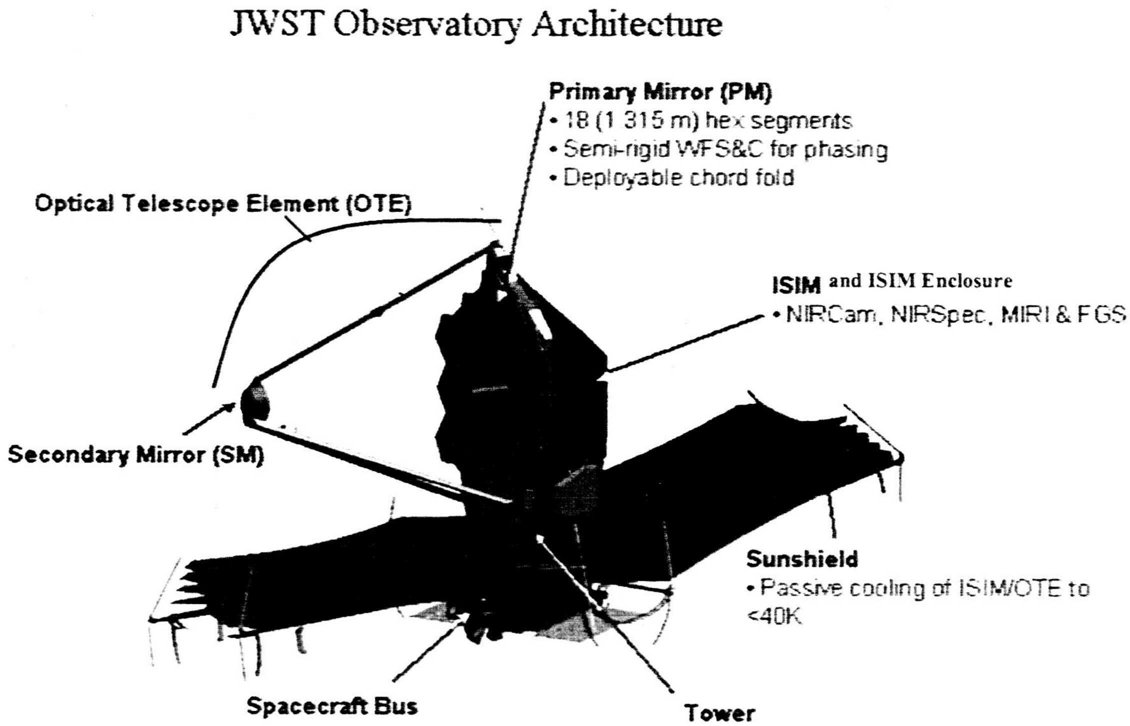

Figure 1. JWST Observatory Architecture [2]

The large primary mirror, which is part of the OTE, and the ISIM are located on the cold shaded side of the giant sunshield. The spacecraft, containing much of the electronic systems, the solar arrarys and the communication antennas are located on the warm, sun and earth facing side of the sunshield. The L2 orbit allows the use of a one sided sunshield because the earth, moon and the sun are always on the same side of the observatory. Moving in a small halo orbit around the L2 point keeps the observatory out of the shadow of the earth and thereby removes the need for heavy, unreliable batteries since the solar arrays will always be exposed to the sun. Remaining in continuous solar illumination affords the observatory the luxury of a constant thermal environment where it does not have to deal with the temperature cycling issues that LEO satellites face.

ISIM Description

The ISIM is a distributed system that includes a cryogenic module containing the science instrument payload, a fine guidance sensor, supporting structure, a Dewar, and passive thermal control systems. The ISIM system also includes an Instrument Command and Data Handling (ICDH) system, located within the Spacecraft, and other warm instrument electronics located close to the instrument module. The science instruments include a near infrared camera (NIRCam), a near infrared multi-object spectrograph (NIRSpec), a mid infrared instrument (MIRI) and a near-infrared tunable filter camera (FGS-TF).

The ISIM Structure is a frame made of square graphite fiber reinforced plastic (GFRP) tubes held together with gussets and clips, and with metal fittings for the Optical Telescope Element (OTE) and SI interfaces. It supports the 4 instruments, the electrical harnesses for the instruments, and the thermal control system.

All instruments are attached to the ISIM structure, which is connected to the telescope with stress-free mounts. The structure and instruments are surrounded by an enclosure, which provides a physical, stray light, and contamination protective shield. It also forms a thermal barrier against radiation from the back of the sunshield, and will help the passively cooled instruments efficiently radiate heat into deep space. The enclosure has no physical contact with the optical bench and is supported by the OTA attachment fixtures used for the optical bench. The ISIM is shown in Figure 2 with the enclosure as an outline mounted to a portion of the OTE backplane.

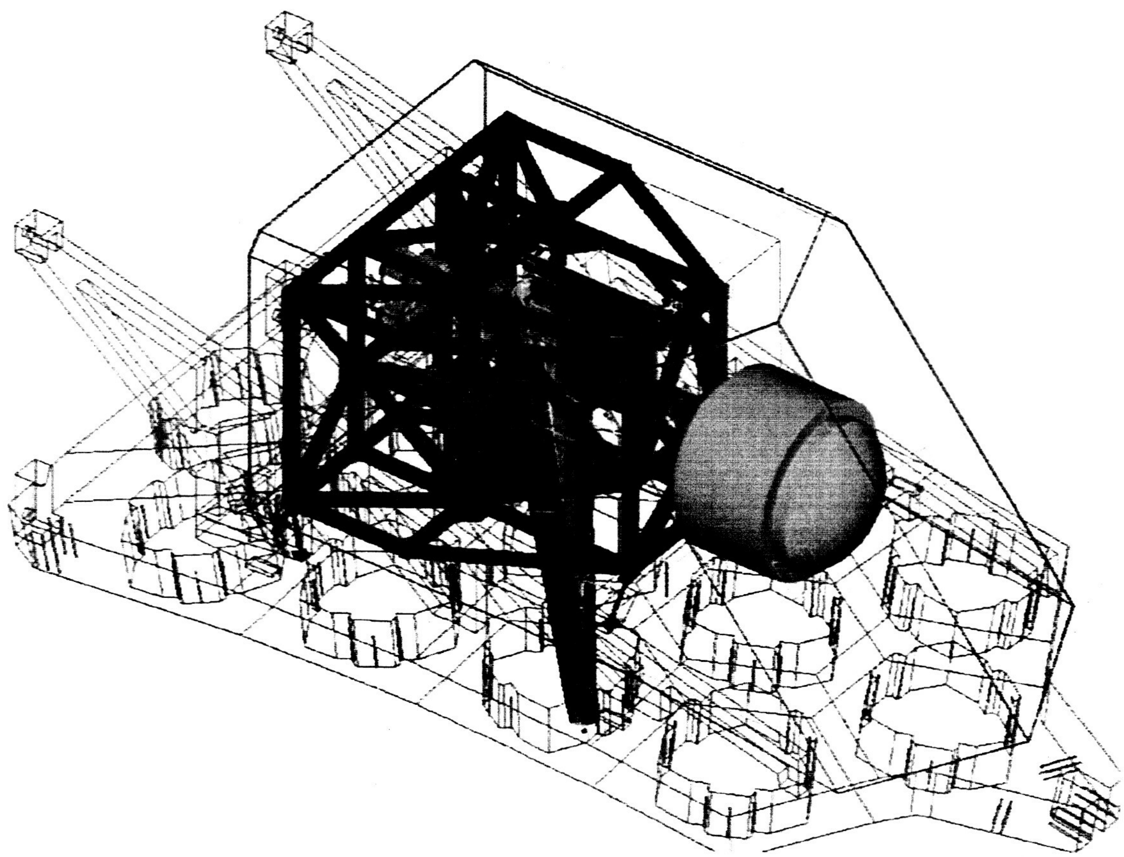

Figure 2. ISIM with integrated SIs. The enclosure and a portion of the OTE backplane is shown in outline. [2]

Testing at ISIM Level

Cryogenic testing of the OTA and ISIM will be the most difficult and problematic portion of the Integration and Test (I&T) flow. Therefore, building and testing the ISIM module as an entity separate from the OTE will have many advantages. The risk of repeated test breaks during the Observatory level cryotests, where testing of the ISIM integrated with the OTE will occur, will be extremely expensive and schedule consuming. The probability that problems will exist between the science instruments and the ISIM structure or between two science instruments is enormous. For instance, problems were found with the Cassini instruments during the observatory level test that were not found in sub-assembly tests. [3]

ISIM LEVEL TEST PROGRAM FLOW AND RATIONALE

The sequence of testing for the ETU ISIM level testing is illustrated in Figure 5. The flight test flow is very similar.

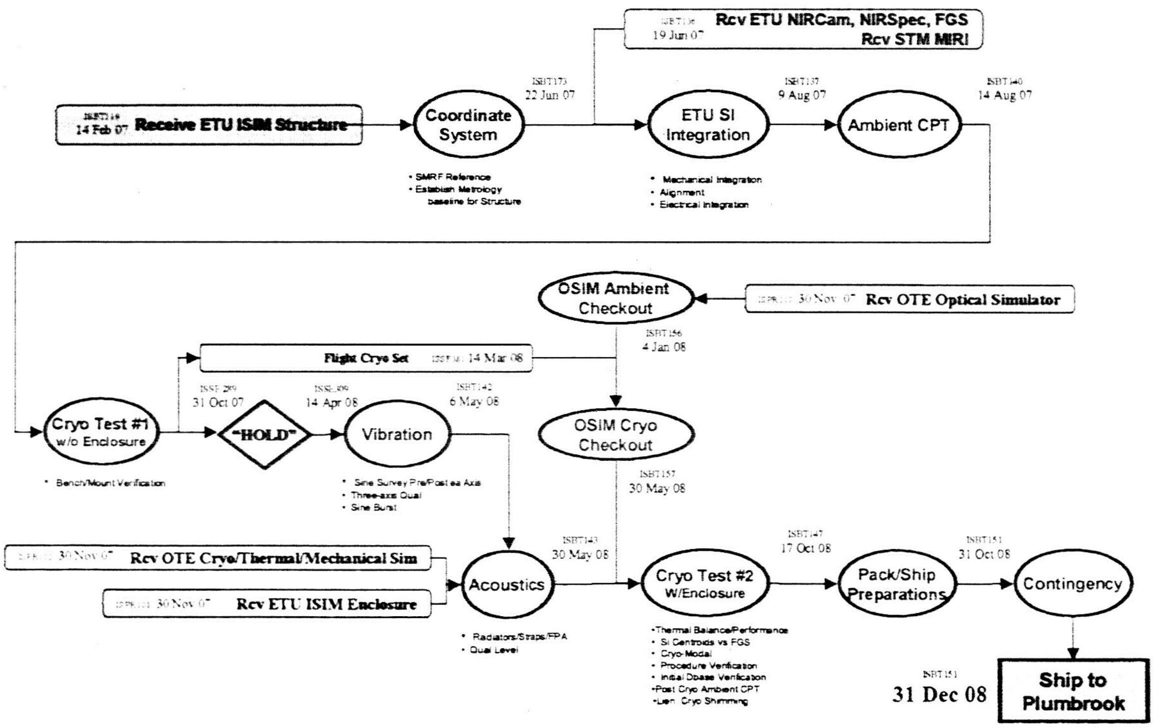

Figure 5. ETU ISIM I&T Flow [2]

The ISIM will undergo Cryogenic Test #1 early in the test program. This test includes the characterization of cryogenic alignment between SIs, establishing Focal Plane Assembly (FPA) operations profiles, and demonstrating ISIM data systems and FSW functions. This test will include all the GSE, except, possibly, the OSIM. The ISIM will not be integrated with the ISIM enclosure during this test and therefore the heat straps that would typically go to the ISIM Enclosure will be connected to actively cooled cryoplates.

Following Cryo Test #1, the ISIM is subjected to ambient vibration testing to demonstrate that the design will survive the expected mission vibration environments. These tests will include a sine survey test performed before and after a three-axis random vibration test. Next, a qualification level acoustics test is performed.

After the environmental exposure tests, the ISIM is integrated to its Enclosure and the electronics boxes are integrated to the Instrument Electronics Compartment (IEC) supplied by the OTE. This assembly is then integrated to the Mechanical OTE Backplane Simulator (MSIM) and installed into the thermal vacuum chamber for Cryo Test #2. This cryotest will include thermal balance testing, cryogenic performance testing and optical testing. Optical testing will include image quality, and image quality stability and relative Line of Sight (LOS) stability between the SIs and the FGS. These optical tests will use the OTE Simulator (OSIM) to provide an optical input beam. This test will be the final performance test conducted on the ISIM before delivery to Observatory level I&T for mating to the OTE.

Simulators and Critical GSE Requirements

ISIM Integrated Test System

At the current time, the spacecraft simulator consists of the spacecraft command and data handling unit, solid-state recorder, the FGS command and data handling system and the extendable power unit. The spacecraft simulator, combined with the ETU ICDH and the Eclipse system (the ground system), make up the Integrated Test System (ITS). Figure 4 depicts a functional block diagram for the ISIM.

ISIM Block Diagram

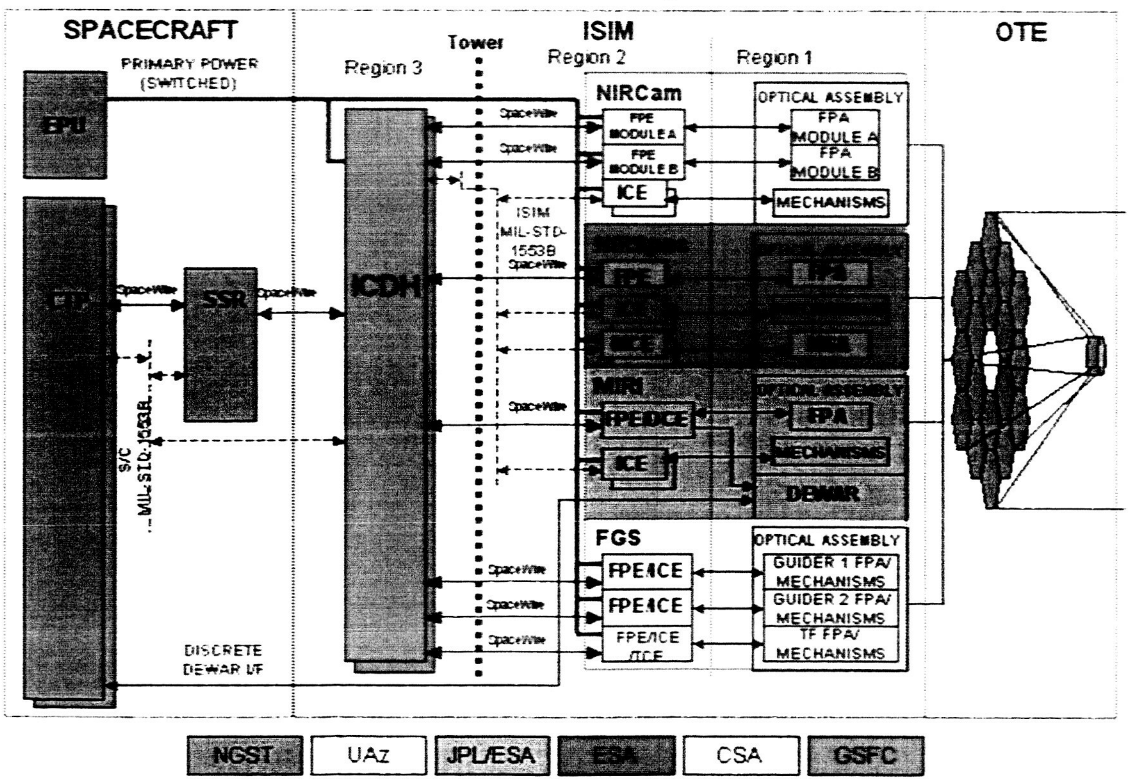

Figure 4. ISIM Block Diagram. [2]

Optical Telescope Element Simulator

An OTE Simulator (OSIM) will be installed as part of the thermal vacuum test configuration to provide the light stimulus to the science instruments. This will allow measurement of the system's stability at the SI detector pixel level. This simulator has the critical function of establishing, at cryogenic temperatures, the optical performance of the SIs in flight configuration while mounted to flight kinematics. This simulator will provide a means to verify that the SI performance, as measured prior to shipping to GSFC, has not changed as a result of the integration into the ISIM. The optical performance will also quantify the uncorrelated motion between the FGS and the other instruments.

Because this unit will be simulating the light from the telescope, it will likely be large in size and mass. This simulator will operate inside of the vacuum chamber, but may or may not operate at cryogenic temperature. A non-cryogenic simulator will be much less expensive and quicker to build because it will not need to accommodate motions of beam-line components or changes in optical properties that occur between room temperature and cryogenic temperature. However, the high background IR coming from warm optics in the OSIM may swamp the instruments sensitive detectors. If this simulator is warm, there will need to be a cold-shutter, possibly with a cryogenically cooled window and a neutral density filter, where the beam of the OSIM passes through the shroud. Opening this shutter will have to be minimized because heat-leaks into the payload, especially right along the optical path, will be destructive to the thermal environment.

The OSIM will need to incorporate a method to measure and compensate for the misalignments that will be inherent between the OSIM and the ISIM after the ISIM is cooled to cryogenic temperature. Furthermore, this simulator will have to be rigorously tested such that problems with it do not cause a costly test interruption.

Photogrametry Metrology System

A photogrametry system will be used to measure targets on the ISIM during thermal vacuum testing to determine the movement of the ISIM structure and the SIs in three-dimensional space.

The photogrammetric measuring process involves three essential phases:

- Data acquisition, i.e. photography of the object
- Image coordinate measurement
- Image processing

Photographs of a targeted object are taken with one or more cameras from several directions. The photographic images of the object target array represent perspective projections of the three-dimensional scene onto a two-dimensional plane. The image coordinates (xy) of the targets in turn are used to reconstruct the coordinates of the marked points in object space (xyz).

The thermal design of this system will be critical since the camera must run at ambient conditions and the ISIM payload cannot tolerate a view of warm regions of the test setup without significantly increasing in temperature.

As with the OSIM, the photogrametry system will need to be robustly designed and tested such as to not comprise the test schedule.

Vibration Isolation System

The Vibration Isolation System (VIS) is designed to support the weight of large payloads on three isolators. The vibration isolators provide extremely low resonant frequencies for the six rigid body modes of the system. This isolation system is expected to provide approximately 40 dB attenuation of all inputs above 10 Hz.

The Vibration Isolation System consists of three major components: the payload table, three isolators and a counterweight system. The payload table is a stainless steel, ribbed structure. The vibration isolators consist of a pneumatic pressure vessel or air spring that is suspended on three rods from an intermediate cylinder that is, in turn suspended on three rods from the outside cylinder to simulate a long pendulum arm. The vibration isolators must stay at room temperature and therefore are blanketed and instumented with heaters. The underside of the payload table will be the "warm" area of the setup and will include the isolations and any other GSE that must be kept at room temperature. A counterweight system has been included to insure stability of payloads having high centers of gravity. This counterweight is a large mass located under the table that brings the Center of Gravity of the VIS and payload to a low and stable position relative to the top of the vibration isolators.

The vibration isolation system proposed to be used in the ISIM cryotests is a modified version of the system currently used in HST instrument testing. This system has had many problems with leaks significant enough to degrade the vacuum in the chamber. It has been noted that very low facility induced vibration was experienced during the HST testing with the VIS even with the system de-energized. It is thought that adding the large mass of this system, approximately XXX kg (2,000 lbs), into the vacuum chamber helped to reduce what the chamber transmitted.

Helium Backfill System

Cool-down times for the thermal vacuum facilities could be dramatically increased by the use of high partial pressure Helium in the chamber during cool-down. This process includes a system that allows the facility to be pumped down to hard vacuum (<1x10-6 torr) and then provides a micro-valved pressure feedback system to raise the facility pressure to 1x10-4 Torr by a controlled backfill of Helium. The Helium creates a conductive thermal path between the cryogenically cooled walls and the ISIM payload. A turbopump would be able to pump the introduced Helium out of the chamber once the desired payload temperature was achieved.

This system is not currently in the baseline test setup since there is a concern that the Helium will be difficult to pump out of the heavily blanketed test setup. Helium trapped in blankets could cause a virtual heat leak by providing a conduction path between the layers of the blankets. This method of increasing the speed of the payload cooldown may not be necessary because of the proposed radiator simulators, which are described below.

Radiator Simulators

During the first cryotest, the ISIM Enclosure, which is also the radiator for the ISIM assembly, will not be part of the test setup. Radiator simulators will be used to cool the instruments through their flight heat straps. These simulators will likely be aluminum plates that are actively cooled to the predicted flight temperature of the radiator cover. Although this is a significant deviation from the flight configuration, this active cooling will allow the ISIM assembly to cool at a much faster rate then is expected during flight. It is a goal to keep the test cooldown time to only 30 days whereas the flight cooldown is expected to take much longer.

During the second cryotest, the ISIM Enclosure will be integrated, however, it is again desired to have a short cooldown time. To help the ISIM cool, non-flight heat straps may be attached between the ISIM Enclosure and an actively cooled plate. This plate will be cooled to the predicted Enclosure temperature and will help cool the payload much more quickly then relying purely on thermal radiation between the ISIM Enclosure and the chamber shrouds.

Because it is desired to perform a flight-like thermal balance during the second cryotest, the Enclosure to cryoplate heat straps would preferably allow the Enclosure to be thermally isolated from the cooling plate during the thermal balance portion of the cryotest. Several methods of accomplishing this have been proposed. One option is to include a low thermal conductance material in the path between the plate and the chamber feedthrough, preventing the plate from changing the Enclosure temperature significantly when the plate is not actively cooled. A second option would be to have a mechanical switch attached to the heat strap.

Mechanical OTE Backplane Simulator

The Mechanical OTE Backplane Simulator (MSIM) is a structural/thermal model of the center portion of the flight OTE backplane structure. Engineering Model OTE Backplane may be used for this simulator. This simulator is used during ISIM level testing to simulate the interface between the ISIM and the OTE structure.

The MSIM will need to interface both with the chamber payload table and with the ISIM assembly in a flight-like manner. It will also need to allow the chamber payload table to remain at room temperature while minimizing heat flow into the cryogenically cooled ISIM assembly. Finally, it will be important that the MSIM blocks as few photogrametry targets as possible.

Test Instrumentation

The ISIM will be integrated with optical cubes and targets to verify or validate the optical test data. The provisions for metrology targets, which are compatible with the laser tracker system and optical cubes, will be mounted on flat surfaces to cross reference data. In addition, reflective flats will be mounted for photogrammetry, which is the method for measurement of structure movement at cryogenic temperatures. Secondary metrology references will be mounted on each joint interface (i.e. Dewar, kinematic mounts, SIs etc.) throughout the ISIM for data comparison and modeling verification. The ISIM will be instrumented with silicone diodes for thermal monitoring during cryo testing. For structural testing, the ISIM will be instrumented with the standard instrumentation (strain gauges, deflection gauges, accelerometers and force gauges as necessary).

ISIM LEVEL REQUIREMENTS VERIFICATION DURING CRYOTESTING

During the ISIM test program, the primary testing objectives are with regard to the cryogenically cooled region. The instruments are integrated and the coupled interfaces quantified. Components are subjected to 35K ±2 K by an externally cooled thermal shroud in a large thermal vacuum test chamber.

Two ISIM Electrical Compartments (IECs) are located relatively close to the cryogenic ISIM region to minimize the noise picked up by the harness between the instruments and the electronics. The two IECs weigh ~ 260 kg and have a thermal dissipation of ~ 200 watts. The IECs are mounted to the MSIM (simulated backplane structure for the OTE).

Other simulators include simulators of the spacecraft, propulsion system, attitude control system, sunshield, communications systems, the ISIM command and data handling and the FGS command and data-handling units. These simulators are located in an ambient region of the test facility where they are thermally isolated from the ISIM test setup.

The SIs and the FGS are designed such that they can only be operated at cryogenic temperature. Therefore, all SI performance testing at non-cryogenic temperatures will be limited to mechanical and electrical functional checks.

Image Quality

The first cryogenic thermal vacuum test will establish a baseline FPA operations profile. This profile will be compared to the images taken during SI level testing to determine if the instrument image is degraded from integration into the ISIM. This will be a difficult comparison for several reasons. It will require that the SIs be tested on their flight mounts and in the same orientation relative to gravity that they will be tested in at the ISIM level and at the Observatory level. Several of the SIs do not have the facility space available to test in this orientation, and it could be costly to find alternate test facilities. Analytical and/or test characterization of each SI as a function of orientation should be done.

For both the image quality and ISIM-OTE stability test, the MSIM must provide a representative flight interface and must have the same thermal and thermal deformation characteristics as flight. The image quality test must show that the image quality is not compromised by distortions induced by the back plane into the ISIM. A gravity off-load system may be required for the ISIM structure.

The MSIM common path motion from its reference plane to the ISIM reference plane must be negligible during cool down. Similarly, the induced structural and thermal disturbances from the facility should not transmit to the OSIM optics when mounted on the VIS in the chamber. The OSIM itself must provide a source that is stable to $1/20^{th}$ of a pixel at the SI focal planes.

Image motion due to facility vibration and thermal drift between the OSIM and the ISIM will make the data taken on the OSIM difficult to interpret. Thermal drift may occur due to test setup limitations. The ISIM will be very sensitive to temperature fluctuations and could be difficult to thermally stabilize. Having a robust and thoroughly tested OSIM will mitigate many of these problems as will having margin in the capacity of the facility's thermal system.

To fully quantify the optical performance of the instruments after being subjected to launch loads and acoustics environments, a second cryogenic thermal vacuum test will be performed. This test will verify that the instrument performance has not changed from the Cryo Test #1 baseline as a result of the integration of the enclosure and the vibration and acoustical testing. Images from this test will quantify the uncorrelated motion between the FGS and the other instruments under flight thermal conditions.

Stray light

Stray light in terms of an Infrared telescope is not just visible light that bounces around the chamber, but also includes IR radiation from warm surfaces in view of the payload. No viable way to measure stray light has been identified. Furthermore, stray light from the setup within the chamber could make any proposed stray light check invalid. Presently, stray light levels will be verified by analysis.

Thermal Performance

The first thermal vacuum test will be performed without installing the ISIM Enclosure. In flight configuration, the ISIM enclosure provides radiative cooling to the near infrared FPAs. In the test configuration the FPAs will receive cooling by a heat strap connected to a Helium source. Verification of the thermal model will therefore take place during the second thermal vacuum test where the ISIM is in flight configuration with the enclosure in place. During the second test, a quantitative analysis of the ISIM harness thermal design will also be performed.

Heat leaks from GSE within the facility will be the most difficult variable in this test to manage. Time to cool the payload down will be the greatest cost and schedule driver in the ISIM I&T program.

Six-DOF SI Alignment

Cryotest #1 will establish a cryo-metrological/alignment baseline prior to exposure to vibration and acoustic environments. This test will characterize the alignment between the SIs and the ISIM structure at the operating temperatures (32-37K) by using a photogrametry system within the thermal vacuum facility. Since the SIs and the ISIM structure are comprised of different materials, the coefficient of thermal expansion (CTE) for each unit is different. The test will measure distortions and stability of the ISIM structure and the SI interfaces to determine the change in the instruments' position. The positions of the SIs will not be verifiable after vibration and acoustic testing because the enclosure will block the view of the photogrametry system from many of the internal targets. Viewable targets will be measured during the second test and compared to the baseline. Images from the detectors, using the OSIM, will be the only indication of instrument alignment.

Mechanical Strength and Stiffness

The integrated ISIM, after the first thermal vacuum test is complete, will be subjected to vibration testing. The Objective of this test is to understand the dynamic effects of the ISIM design and to quantify the expected loads at the coupled interface (kinematics).

The ISIM with the instruments is then subjected to a sound pressure field to verify the ability to survive the lift-off acoustical environment and to provide a final workmanship test to verify the integration of the instruments. Secondary objectives are to uncover any thermal shorts in the ISIM system prior to the cryo thermal verification test and to validate at acceptance levels the interfaces of the FPA, radiators, and thermal straps.

During the second thermal vacuum test, a cyro-modal test will be performed. This test will correlate the ambient modal survey to the characteristics at the predicted cryo conditions expected on orbit. This test will require the development of modal GSE that is compatible with both cryogenic temperatures and vacuum. The instrumentation used on the ISIM must not degrade the thermal performance of the payload.

Mechanical Functionality

Mechanical functionality of all mechanisms will be verified during both of the thermal vacuum tests. This system has many mechanisms and they are traditionally unreliable at cryogenic temperatures.

ISIM to OTE Stability

The MSIM interface with the ISIM and the MSIM thermal characteristics must be flight like. This will allow the MSIM common path motion from its reference plane to the ISIM reference plane during cool down to be flight-like except for errors induced by gravity.

A metrology system must be provided to measure the OSIM bore sight, or suitable reference, to the ISIM side of the ISIM/MSIM interface. For diagnostic purposes, it is desirable to make this measurement during cool-down. It is expected that the OSIM might then have to re-align to remove common path errors. Furthermore, a measurement of the movement of the ISIM interface reference relative to the MSIM interface reference is needed for this test. The most cost effective approach to achieve this may be to use the same OSIM metrology system to measure the OSIM to MSIM motion along with the OSIM to ISIM motion.

SUMMARY AND CONCLUSIONS

The ETU test program for the James Webb Space Telescope's Integrated Science Instrument Module is essential for a program of this size, complexity, and uniqueness. The cryogenic aspect of this observatory introduces a great number of potential problems that will need to be systematically addressed during I&T. The cryogenic tests to verify the ISIM level of assembly will be long, involve a great deal of GSE and custom setup and will consume many months.

A clear definition of test objectives early in the program is allowing the design of cost effective and specialized simulators and GSE. Early decisions concerning I&T activities at the ISIM level will insure that the subsystems build a robust test program that compliments the ISIM I&T program.

REFERENCES

[1] Stockman, H. S. "The Next Generation Space Telescope, Visiting a Time When Galaxies Were Young." The JWST Study Team. JWST Public Documents Library. 1997. <http://www.ngst.nasa.gov/>

[2] Diaz, C. "James Webb Space Telescope Project, Integrated Science Instrument Module, Engineering Test Unit Integration and Test Plan" JWST Public Documents Library. Pending. <http://www.ngst.nasa.gov/>

[3] Mentzel, M. "James Webb Space Telescope Project, Integrated Science Instrument Module, Verification Plan" JWST Public Documents Library. Pending. <http://www.ngst.nasa.gov/>