The components of the James Webb Space Telescope undergo tests at many levels as they are assembled into an increasingly complex system. These tests, which culminate in a fully qualified astronomical observatory, involve a variety of hardware, including assemblies of detectors; mechanisms for filters, pupils, and focus; optical elements, such as filters and gratings; and myriad electronics boards. These are a few examples of the subsystems that were tested in the assembly of the Webb science instruments (SIs)—Near Infrared Camera (NIRCam), Near Infrared Spectrometer (NIRSpec), Mid-Infrared Instrument (MIRI), and Fine Guidance Sensor/Near Infrared Imager and Slitless Spectrograph (FGS/NIRISS).

The SIs were extensively—but not completely—tested in a cryogenic environment, and verified by the development teams at their integration facilities, in California, Germany, the United Kingdom, and Canada. The four SIs were delivered to the Goddard Space Flight Center, where they have been assembled into the Integrated Science Instrument Module (ISIM). As the test program was originally conceived, the ISIM was to have undergone two extensive cryo-vacuum (CV) test campaigns to verify that its performance meets requirements. The campaigns were to have been separated by a series of ambient environmental tests, including acoustic and vibration, electromagnetic interference, and gravity release tests.

A variety of circumstances forced a considerable modification to this plan, however. For example, a design flaw in the detectors for the near-infrared instruments, which caused long-term degradation, requires that they be replaced with new, robust detectors in which the defect is eliminated. The performance of the microshutter array (MSA) assembly for NIRSpec was found to be unacceptable: an excessive number of shutters became immovable after acoustic testing, which requires replacement of at least some of the MSA quadrants. In fact, all SIs have some components that need to be replaced, either in their optical module or warm electronics boxes. The long lead times for such replacements have dictated that this work must be done well after the SIs were delivered to Goddard. Additional modifications of the testing plans were required by the fact that MIRI and FGS/NIRISS arrived considerably earlier than NIRCam and NIRSpec. Note that these are not new developments; the need for making these hardware changes—and the budget and schedule changes they precipitated—have been known for quite some time. For example, the decision to procure new NIR detectors was made in 2011 and new MSAs in 2012.

Rather than delay CV testing until all SIs arrived and all components and subassemblies were replaced, the ISIM project at Goddard scheduled a preliminary test using the hardware in hand. It recognized that the ISIM-level CV tests are complex and challenging in many ways, even beyond verification of ISIM performance.

The thermal and mechanical performance of ISIM and its extensive ground support equipment (GSE) had been modeled in detail, but had not been verified with the SIs. The Optical Telescope Element (OTE) Simulator (OSIM), which provides point-source and extended-source light to ISIM during CV testing, had been verified in two CV campaigns of its own, but it had not yet been used with the SIs. The data flow through the ISIM command and data handling system and the GSE data recorders had not been exercised with multiple SIs in a flight-like configuration. The system for rapidly re-planning the optical tests, which is always needed in such a complicated program, had not yet been operated in a true test environment. Even the way the personnel interact—test director, SI teams, and test operators—had never been exercised as a group before. Therefore, an additional CV campaign was inserted before the two already planned. The goal of this new campaign—CV1RR—was not to verify requirements, but to reduce risk by gaining experience with the hardware on hand.

The high-level objectives of CV1RR were:

- To demonstrate that the test configuration, which includes large amounts of new GSE, is able to support the test requirements of the ISIM verification program and to identify any hardware fixes needed before CV2.
- To dry-run critical test procedures, to learn how to formulate and execute the procedures most efficiently, and to analyze the results and identify any necessary improvements to procedures and test logistics before CV2.

These objectives demonstrate that CV1RR is as much of an engineering test of both the flight and ground support hardware as it is a performance test of ISIM with these science instruments. CV2 and CV3, of course, will have a heavier emphasis on performance and verification of requirements.
The CV1RR Test Campaign

All ISIM CV testing takes place in Goddard’s largest vacuum tank, the 9-meter diameter, 13-meter tall cylindrical Space Environmental Simulator (SES). In addition, enormous preparation was required well before CV1RR was ready to begin, much of which took place after the SIs were delivered to the nearly 37,000 m³ high-bay cleanroom at Goddard. In summer 2013, multiple hardware components—the ISIM, the ISIM Electronics Compartment (IEC), the electrical harness radiator, a flight-like MIRI heat exchanger stage assembly (the flight unit will be installed at a later date), and other associated hardware (Figure 1)—were installed into the SES Integration Fixture (SIF). The SIF is a truss-like structure that also contains a sophisticated GSE thermal management system to simulate the thermal environment of the observatory (Figure 2).

On August 10, 2013, the SIF was carefully lifted and placed into the SES tank. Figure 3 shows the arrangement of the test hardware. As an example of the thermal engineering challenges, the electronics in the IEC, running at room temperature, are separated by only a couple of meters from FGS/NIRISS, operating at less than 45K, and from MIRI, actively cooled to just 6.7K!

CV1RR began on August 29 and the test ran largely as planned through pump-down, cool-down, and initial testing. Mechanisms and electronics were checked. Dark exposures and exposures with internal lamps verified that the instruments were performing as they did prior to delivery to Goddard. The testing team was eagerly anticipating the first illumination with the external OSIM sources on October 1, 2013, when the federal government shut down, and the team was required to put the hardware into a safe-hold configuration. No testing was permitted during this frustrating period until the furlough ended on October 17. To preserve the overall schedule, Webb management directed that CV1RR must end at about the same time.
time as it would have without the furlough. Therefore, the team developed an abbreviated test plan,
preserving the highest priority tests, including the critical risk-reduction activities. CV1RR ended on
November 11, 2013.

Despite the shortened duration, the team ran many important tests in CV1RR, including:

- Functional testing with ISIM systems in vacuum at room temperature.
- Functional and performance testing with ISIM systems in vacuum at the nominal cryo operating
temperature.
- OSIM+SI checkout. The ability of OSIM to place point sources at the desired locations in the SI
fields of view was demonstrated. The OSIM light-source intensities were calibrated, although
more time will have to be devoted to this task early in CV2.
- Optical baseline, consisting of external flat fields, a through-focus exposure sweep, and a mea-
surement of the pupil alignment of the SIs. This test will be repeated in future CV campaigns
to identify trends in performance.
- A variety of thermal tests to measure the heat load into the instruments, particularly MIRI, and
for correlating these measurements with the ISIM thermal model.
- Preliminary assessment of SI alignment and image quality at the ISIM level, including phase-
retrieval analyses of wave-front error.
- NIRISS performance characterization. Due to a rather late change in the design of this instru-
ment, NIRISS was never operated in its current end-to-end optical configuration in SI-level
cryogenic testing. Therefore, this “first light” test measured the NIRISS image quality, plate
scale, wave-front error, ghosting, vignetting, stray light, and the orientation and location of
grism spectra on the detector.
- Operations script subsystem (OSS). In ground testing, the SIs can be commanded with low-level
scripts or with the Python-based OSS. In flight, only the OSS will be used for normal operations,
and some test time was therefore devoted to this method of commanding.
- ASIC tuning. Application Specific Integrated Circuits (ASICs) perform two tasks: driving the NIR
detectors and doing initial processing of detector output signals. Each ASIC must be tuned to its
specific detector, and since all NIR detectors will be replaced, ASIC tuning will be an important
activity in upcoming CV campaigns. CV1RR provided the first opportunity to practice ASIC tuning.
- Electromagnetic interference from the MIRI cryo-cooler. While the NIR instruments are passively
cooled to below 45K in flight, MIRI has an active cooler so that it can operate at about 6.7K.
This test was to demonstrate that the cooler does not introduce noise into the sensitive signal
outputs from the detectors.
Institute personnel fully participated in CV1. Approximately 20 scientists and engineers provided a wide variety of support functions including serving as test conductors and operators, providing quick-look data analysis for all three instruments, and preparing and running OSS tests. Their subsequent activities include more detailed analyses of test data and working with the SI teams and the Goddard optics team to define the tests to be executed in CV2.

**CV1RR Results**

By almost any measure, CV1RR was a great success. Referring to the test objectives listed above, the test configuration was shown to be fully capable of supporting CV2 and CV3, when ISIM performance will be verified. Many test procedures were successfully run, despite the government shutdown. The team gained valuable experience crafting the tests, modifying them in real time, and learning which areas of staffing need augmentation. Along with these successes it is not surprising that some problems were discovered and must be addressed. Examples of each include:

- Safe cool-down, warmup, and the ability to achieve thermal balance were demonstrated.
- The six-degrees-of-freedom alignment and pupil alignment of the SIs were measured to be within requirements.
- The image quality was good in all SI channels. This was particularly important for the MIRI medium-resolution spectrograph, because image quality was not well measured during SI-level testing in England. Phase-retrieval analysis performed on focus sweep data demonstrated the ability to precisely determine wave-front errors in both SIs (Figure 4), which were excellent.
- Demonstrated satisfactorily stray-light background for conducting the ISIM-level optical test program. This was viewed as a high risk going into this test because of the difficulty of shielding so many warm components, which emit strongly, especially at mid-infrared wavelengths.
- Data acquisition and processing methods to improve signal-to-noise performance in the MIRI detectors. Unexpectedly low signal-to-noise levels were observed during SI level testing due to detector drifts. The detector team developed mitigation strategies on flight-like hardware at JPL. These methods were successfully demonstrated with the flight instrument, closing out the problem report that had been generated at SI-level testing.
- Demonstrated acceptable contamination control through a full CV test cycle.
- Externally induced mechanical jitter was acceptably low. Based on previous jitter measurements during OSIM cryo-testing, the use of a floating vibration isolation system was removed from CV1RR because of the concern that it might introduce more risk of optical misalignments than it would reduce in the case of jitter; the low jitter observed validated that decision.
- The most serious problem with the SIs was an occasional but recurring communication dropout with both FGSs and NIRISS. This problem has been traced to a coding problem in the SI’s field-programmable gate arrays (FPGA). The instrument team is building new FPGA boards to eliminate this problem.
- Significant ghosting was observed with the NIRISS GR700 grating. This effect was modeled by the Goddard optics team and the source is now well understood. A fix has already been identified and will be implemented before CV3.
- The NIRISS and FGS best-focus positions (Figure 5) were not at the expected locations. The offsets are well within the range of their focus mechanisms. Nevertheless, the team members want to be sure they understand the origin of this discrepancy.
- The SES helium cooling system had several brief (approximately one hour) failures during the test, which caused frozen N₂ and O₂ to sublimate and possibly (temporarily) condense on MIRI optics. This constitutes a contamination risk. The faulty parts have been identified and will be replaced prior to CV2.
- The GSE cryo-cooler measured an unexpectedly high heat load into MIRI. This heat load is scrutinized carefully because of the importance of maintaining sufficient performance margin for the flight MIRI cryo-cooler. Therefore, any unexplained heat load is a cause for concern. The cooler team at JPL and the ISIM team at Goddard are examining this excess to ascertain whether it represents an actual, flight-relevant load or a parasitic load caused by the test configuration.

In summary, despite the issues encountered, CV1RR was very successful. It served its purpose in significantly reducing risk heading into CV2 and CV3, and has prepared the team well for those even more ambitious tests.

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**Figure 4:** A map of the optical wave-front error (WFE) of NIRISS after the effects of the OSIM have been removed, using the method of phase retrieval. The measured WFE is 48 nanometers rms, fully consistent with requirements for this portion of the total optical error. This was measured close to the center of the NIRISS field. In CV2 and CV3 the WFE will be measured at multiple field locations. The dark circles are artifacts arising in the OSIM illumination system. (Courtesy of D. Aronstein, GSFC.)
A Look Ahead

As this article is being written, NIRCam and NIRSpec have just completed electrical testing and optical metrology in preparation for their installation into ISIM, which will then house all *Webb* science instruments for the first time. A very fortunate development is the faster-than-expected production of replacement NIR detectors. As a result, the full complement of ten detector arrays has already been installed into NIRCam heading into CV2, which is currently scheduled to begin in late spring or early summer of 2014, and to last about 100 days, about 60 of which will be at a stable, cryogenic operating temperature.

After CV2 a considerable amount of hardware will be replaced:

- The remaining NIR detectors (two arrays in NIRSpec, three arrays in FGS/NIRISS).
- Some or all of the NIRSpec microshutter assembly quadrants.
- A new, more efficient NIRISS GR700 grating, to be installed in a rotated position to eliminate the ghosting problem.
- NIRCam, FGS/NIRISS, and MIRI electronics boards, to address some shortcomings observed at SI-level or ISIM-level testing.

CV3 is scheduled to begin in mid-2015 and represents the final test of ISIM at Goddard. It will then be integrated with the OTE in the Goddard cleanroom. The full-up telescope and instrument suite will then travel to Johnson Space Center for end-to-end optical and thermal testing, and then to Northrop Grumman for integration and testing with the spacecraft and sunshield.

The extensive test program, at ever-increasing levels of complexity, is designed to discover and correct problems early, when they are easier and less expensive to fix, in both time and dollars. We are now seeing the benefits of this approach with SI-level testing and with CV1RR. This approach gives us high confidence that the *Webb* observatory will perform as designed when it is launched in 2018.

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Figure 5: Energy contained in the brightest $3 \times 3$ pixel region as a function of focus position for the two FGSs and NIRISS, and the encircled energy within the first dark Airy ring for MIRI. The X-axis label AIMGFSOFT is a telemetry mnemonic meaning the actual image focal surface offset, which is to say the OSM focal position relative to the focal plane of the Optical Telescope Element. All best focus locations are well within the range of the focus mechanisms for the NIR instruments. MIRI has no focus adjustment mechanism so it is particularly important to verify that it is in proper focus during ground testing. (Courtesy of R. Telfer, GSFC.)