Status of the James Webb Space Telescope Mission

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ABSTRACT

The *James Webb Space Telescope* (*Webb*) is the largest space telescope realized to-date, with a 6.5 m segmented primary mirror that must be folded to fit within its Ariane 5 launcher fairing. This infrared telescope is passively cooled using a five-layer sunshield that will keep the optical telescope and its four science instruments in the shade throughout the lifetime of the mission in an L2 orbit. *Webb*'s science instruments include near- and mid-infrared imagers and spectrometers that cover the spectral range from 0.6-28.5 μm. The *Webb* mission has a long history with numerous first of its kind technology developments, ground support equipment innovations, and algorithmic characterization advances. This conference proceeding summarizes the technical progress over the past two years, from the Spacecraft Element environmental testing to the Observatory integration and testing, and the final Observatory test plans leading up to launch, on-orbit commissioning, and science operations.

Keywords: James Webb Space Telescope, Integration and Testing of Space Telescopes, Infrared Space Telescopes, Observatories, Mirrors, First Light, Exoplanets

1. INTRODUCTION

The *Webb* space telescope was originally conceived in the mid-1990s as an infrared complement and flagship successor to the *Hubble Space Telescope* (*Hubble*). The original concept was designed to address four broad scientific pillars outlined by the *HST and Beyond Report*[1]: 1) first light and reionization, 2) the assembly of galaxies, 3) the birth of stars and protoplanetary systems, and 4) planets and the origins of life. The science observations required a cryogenic large aperture space telescope with a primary mirror that exceeded the diameter of the existing launch fairings. These compelling science questions and an early *Webb* concept were given the top recommendation in the 2000 Astrophysics Decadal Survey, "Astronomy and Astrophysics in the New Millenium".[2] Over the next 20 years, *Webb*'s science case has remained at the forefront of the astrophysics community and the need for *Webb*'s capabilities have continued to expand.[3,4] An illustrious example is that exoplanetary transit spectroscopy has advanced dramatically throughout *Webb*'s development, and it is now expected that *Webb* will answer key questions in this area.[5] *Webb* will have far greater sensitivity than previous observatories and will feature far more sophisticated instrumentation for a space-based mission, including integral field spectroscopy and multi-object spectroscopy.

The *Webb* mission is being led at NASA's Goddard Space Flight Center (NASA Goddard), with major contributions from our international partners the European Space Agency (ESA) and the Canadian Space Agency (CSA). The Observatory contractor is Northrop Grumman Space Systems (NGSS), whose Space Park campus is located in Redondo Beach, California. The entire Observatory has been at NGSS since February 2018. The Science and Mission Operations Center is located at the Space Telescope Science Institute (STScI) in Baltimore, Maryland. STScI leverages vast personnel experience and infrastructure that has been developed as it carries out the science operations for *Hubble*. Numerous other aerospace industry and academic partners have contributed to the development of *Webb*.

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Space Telescopes and Instrumentation 2020: Optical, Infrared, and Millimeter Wave, edited by Makenzie Lystrup, Marshall D. Perrin, Proc. of SPIE Vol. 11443, 114430T · © 2020 SPIE
CCC code: 0277-786X/20/$21 · doi: 10.1117/12.2562425

Figure 1: *Left:* OTIS integration of the science instruments with the telescope at the NASA Goddard's high bay clean room. *Right:* After environmental testing, OTIS was delivered to NGSS for integration with the Spacecraft Element.

Webb has four science instruments: 3 near-infrared instruments and 1 mid-infrared instrument. These instruments cover wavelengths from 0.6 μm to 28.5 μm with a broad range of modes and specialized capabilities, the full details of which are kept current on the JWST User Documentation website.[6] NIRCam, a near-infrared camera, was led by a team at the Univ. of Arizona. NIRCam has special wavefront sensing capabilities that will be used to align the telescope during commissioning and maintain the telescope alignment throughout the life of the mission. NIRSpec, a near infrared spectrograph, was a contribution from ESA. NIRSpec is capable of slit spectroscopy, integral field spectroscopy, and multi-object spectroscopy for a wide range of applications. MIRI, a mid-infrared instrument, was designed and built by a European Consortium and the Jet Propulsion Laboratory. MIRI has imaging and slitless, slit-based, and integral field spectroscopy modes that cover $\sim$5-28.5 μm. The NIRISS instrument, a fine guidance sensor (FGS) and near infrared imager and slitless spectrograph (NIRISS), was a contribution from CSA. The FGS provides sensing for target acquisition and closed loop control of the fine steering mirror to improve the line of sight pointing stability. The NIRISS instrument has imaging and slitless spectroscopy capabilities with specialized modes for aperture masking interferometry. Select parallel science instrument observations can be made simultaneously (e.g., NIRCam imaging and MIRI imaging), which increases the efficiency and science potential for some programs.

2. INTEGRATION & TEST PROGRAM

Webb is composed of four major assemblies: the spacecraft bus, the sunshield, the Optical Telescope Element (OTE), and the Integrated Science Instrument Module (ISIM). The OTE and ISIM were integrated at NASA Goddard in 2016 to form the OTIS that underwent its environmental testing and was delivered to NGSS in 2018 (Figure 1). The spacecraft bus and sunshield were assembled at NGSS and integrated together to form the Spacecraft Element. Over the past two years, the Spacecraft Element successfully completed its testing program, final OTIS activities were completed at NGSS, the OTIS and the Spacecraft Element were integrated together to form the Observatory, and the Observatory-level environmental test sequence is nearly complete. This section provides a top level summary of the recent integration and test program. A more technical discussion can be found in an accompanying conference proceeding on the *Webb* integration and test program.[7]

2.1 Spacecraft Element: Test Completions

The superstructure comprised of the spacecraft bus and sunshield is called the Spacecraft Element (Figure 2 left). This structure has numerous individual components with separate deployments on the spacecraft bus and the sunshield. The Spacecraft Element was independently tested to the protoflight levels with exposure to acoustic, sine vibration, and thermal vacuum environments. During the test program, two electronic boxes on the bus showed anomalous behavior: the traveling wave tunable amplifier and the command and telemetry processor. While these boxes have redundant units, both boxes were replaced with new flight qualified ones to ensure

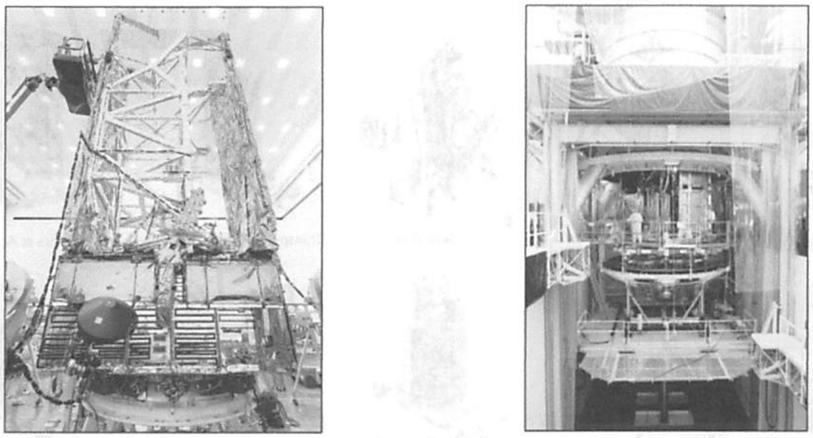

Figure 2: *Left:* The Spacecraft Element in its stowed, and environmental test, configuration. The exterior of the electronics panel is shown below, with the telescope simulator mounted in the middle above the spacecraft bus. The telescope simulator is a truss-like structure wrapped with reflective insulation that included representative center of mass and dynamical properties, and it also had mechanical interfaces at the bus as well as through bipods that attach the top of the telescope to the unitized pallet structures which hold the membranes. All five of the sunshield membranes are folded and pinned to the unitized pallet structures and then protected with covers. *Right:* The Spacecraft Element mounted on the lid of the vacuum chamber, just before the start of the thermal vacuum test. Credits: NASA/NGSS.

the redundant capabilities exist at launch. A subsequent root cause investigation concluded that component degradation unrelated to the environments was responsible for the anomalous behavior.

The Spacecraft Element first went through acoustics and sine-vibration testing at protoflight levels. In the spring of 2019, the Spacecraft Element then underwent a thermal vacuum test to verify performance under vacuum in the thermal conditions at protoflight levels and transition temperatures. This test was completed in the stowed configuration, as constrained by the test chamber (Figure 2 right). The sunshield thermal performance is anchored by a 1/3 scale sunshield thermal balance test and is used as an input to system-level integrated modeling predictions. The Spacecraft Element test obtained thermal balance data, verified the proper sizing of the thermal control system, and evaluated the system performance, both thermally and electrically, at the temperature extremes. The thermal vacuum test consisted of four thermal cycles and a hot and cold thermal balance. The test began with a series of functional tests on the lid of the vacuum chamber to ensure all of the hardware was properly functioning and verify basic workmanship of the test equipment. There were also 23 membrane release devices fired at cold temperature to verify their performance.

2.2 OTIS: Final Activities before Integration

OTIS went through its own environmental test program at protoflight levels. The sine-vibration and acoustic tests were completed at NASA Goddard and the cryogenic thermal vacuum testing was completed at NASA's Johnson Space Center in Houston, TX.[8,9] At the OTIS level sine-vibration testing, the composite bonded structure had less damping than anticipated, which resulted in testing below the desired levels at some key frequencies. It was decided to add particle dampers to the Aft Optics System (AOS) and the Secondary Mirror Support Structure (SMSS) in order to improve the damping on these key mechanical structures. The OTIS cryogenic test uncovered a problem with the installation of the frill surrounding the primary mirror, which did not have the requisite slack. In this condition, changes in frill temperature would create thermal distortions on the primary mirror shape. In February of 2018, OTIS was delivered to the NGSS Space Park. Several outstanding issues were addressed after delivery, including a cleaning of all the primary mirrors on the center section and the wings, a repair of the soft-structure frill that surrounds the primary mirror, and the addition of Observatory-level test accelerometers to the structure. While the Spacecraft Element finished its testing, OTIS was stored in a clean tent within the larger clean room to prevent contamination.

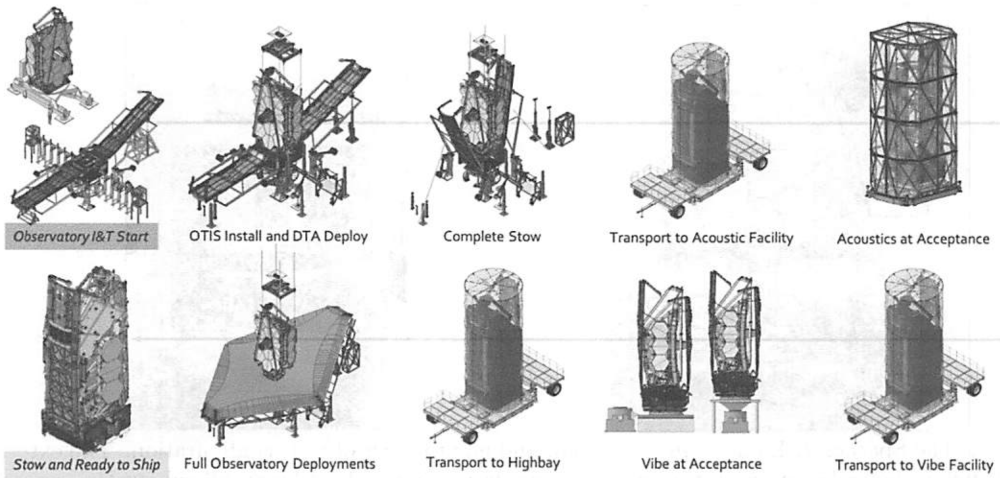

Figure 3: The *Webb* Observatory integration and test sequence includes pre- and post-environmental deployments and functional testing. The acoustics and vibration tests facilities were located on the NGSS Space Park's campus but required moving the Observatory between buildings.

2.3 Observatory Integration

Webb is nearing the completion of its integration and test program and is currently carrying out the final Observatory deployments and functional checkouts prior to shipping to the launch site. A summary of the Observatory integration and test sequence is shown in Figure 3. In the fall of 2019, OTIS was lifted in its stowed configuration by an overhead crane and moved from its stand to a position over the Spacecraft Element, with the sunshield structures deployed and the membranes folded (Figure 4). OTIS was then slowly lowered onto the Spacecraft Element with precise control of the motion to avoid contact with cryocooler hardware in the core area. OTIS has six pads that connect to the Spacecraft Element – four on the bottom corners of the telescope support structure and two at the base of the instrument electronics compartment. Once OTIS and Spacecraft Element super elements were attached, final mechanical and electrical connections were made to complete the Observatory integration. Optical metrology verified the expected positions of OTIS relative to the Spacecraft Element and electrical testing ensured the functionality of the electrical connections. Finally, soft structure closeouts and insulation were applied to the Observatory.

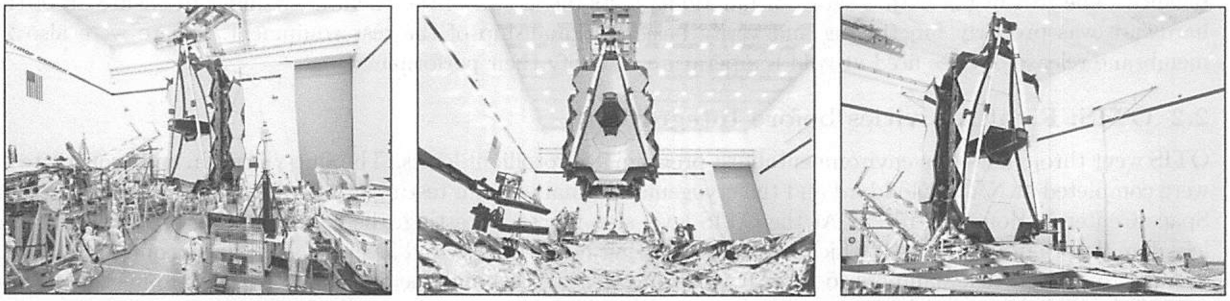

Figure 4: OTIS was lifted by a crane (left) and moved over the Spacecraft Element with the sunshield pallets deployed (center) and then lowered onto the Spacecraft Element where the mechanical and electrical interfaces were connected (right). Credit: NASA.

2.4 Observatory Testing

The Observatory testing program followed the traditional pre-environmental testing, environmental exposure, and post-environmental testing sequence (see Figure 3). The pre- and post-environmental test programs included mechanical deployment tests and functional comprehensive systems tests. These are intended to confirm the as-built functionality was nominal prior to environmental exposures and verify the test environment does not affect the performance. The environmental testing at the Observatory level only included acoustic and 3-axis sine vibration testing at the acceptance levels, which cover the expected Ariane 5 launch environment. The primary objectives at the Observatory level were to confirm the system interactions between OTIS and the Spacecraft Element were as-predicted and to verify the mechanical and electrical interfaces between these two superstructures. The OTIS and Spacecraft Element environmental testing carried out acoustic and 3-axis sine vibration testing at the protoflight levels, or 3 dB above the expected Ariane 5 launch levels. The OTIS and Spacecraft Element also carried out complex thermal vacuum tests, which verified their performance at operational temperatures. Due to the very different environmental operational conditions and equipment needed to verify the OTIS and the Spacecraft Element the thermal vacuum tests were carried out independently and are not repeated at the Observatory level. For example, OTIS needed to be deployed for optical verification, whereas the Spacecraft Element could not be tested at its operational temperature in the deployed configuration.

Deployments: Major deployments are required to transform the Observatory from its stowed to its operational configuration (Figure 5). The Observatory deployments were tested pre- and post-environmental exposure to ensure design and workmanship meet requirements. The final secondary mirror deployment was completed before the Observatory integration, as the current configuration is not amenable to offloading the secondary mirror deployment. The secondary mirror test was done with the telescope on its side, with the deployment commanded by the spacecraft bus via an extender harness and driven using flight scripts. There is a secondary mirror deployment mechanism flinch test in the Observatory level deployment test program.

Shortly after integration, OTIS was deployed using its deployable tower assembly with offloading support from a specialized overhead crane and counterweight system. The 5-layer sunshield was then deployed and tensioned as part of the Spacecraft Element post-environmental testing and Observatory pre-environmental testing. Laser trackers were used to measure key metrology points on the Observatory, such as fiducials on the spreader bars, to ensure the correct deployment shape was reached. As expected at ambient temperatures, the sunshield layers visibly sag at room temperature and in one gravity. Models are used to predict the on-orbit sunshield shapes and use this shape to estimate the thermal performance – for the sunshield layer 5, the top layer in Figure 5, the operational temperature is about 70 K. Sunshield modifications to the tensioning system and corner interfaces were completed, along with some repairs needed due to handling. There was a check of the membrane cable lengths that used offloaded testing of the membrane tensioning system. The momentum trim tab, solar array, and radiator shades were all removed from the Observatory for offline testing and updates as needed, which took place in other facilities at NGSS. Following the deployments, the sunshield was folded back to its stowed configuration, OTIS was lowered back onto the Spacecraft Element, and the Observatory was stowed for environmental testing. The momentum trim tab and the solar array were reinstalled for the environmental tests, but the deployable radiator shades remained off as they were qualified at the Spacecraft Element level and needed additional repairs.

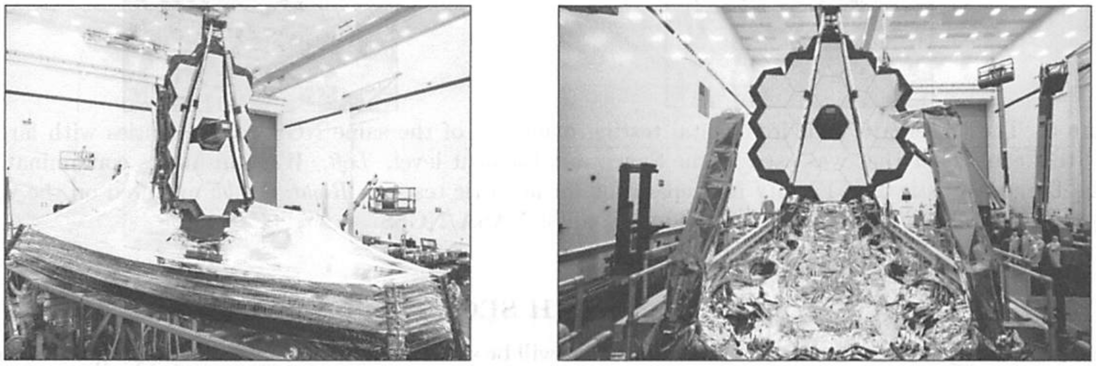

Figure 5: *Left:* The *Webb* Observatory with its tower and the sunshield fully deployed. *Right:* The primary mirror wings in their deployed configuration with the sunshield stowed onto their pallets. Credits: NASA/NGSS.

Comprehensive Systems: The Comprehensive Systems Tests (CSTs) are electrical and functional tests of the Observatory's systems, including redundant systems and cross-strapped configurations. These Observatory-level systems tests build upon the lower level system functional for the Spacecraft Element, which carried out the Comprehensive Systems Tests (1-,2-,3-), and OTIS with its Warm Telescope Functional and Warm Science Instrument Functional Test programs. All of the Observatory level testing will be carried out at ambient temperatures, relying on the sub-system and unit-level testing to qualify the thermal performance across the operational temperature ranges. CST-4 was the first Observatory-level system test, and it established the system functionality and performance before the environments. CST-5 is scheduled to be run following the Observatory environments in late January 2021, which repeats the tests and verifies that functionality is preserved and performance is within trending expectations. A limited CST-6 will be carried out at the launch site prior the launch itself.

Environmental: After the Observatory was fully stowed, it was transported to the Large Acoustic Test Facility for acoustic testing at the acceptance level (Figure 6, left). The Observatory level testing used the same test facility, with largely the same test equipment, team, and analysis as used at the Spacecraft Element level. The Observatory acoustic testing went smoothly and met the Ariane specifications in all octave bands and in the total sound pressure level. The team successfully managed the high-frequency input to protect the sensitive NIRSpec microshutters, which were known to be susceptible to high-frequency degradation from prior test campaigns.

The Observatory was then moved over to the vibration test facility a few blocks away, also on the Space Park campus, where it was exposed to sine vibration in three orthogonal axes (Figure 6, right). The vibration testing also provided good coverage to the flight environment. The test signatures were all nominal, as well as the pre- and post-test response trending, therefore showing no signs of structural degradation. The OTIS particle dampers on the AOS and SMSS both worked as designed and enabled the Observatory to meet the Ariane 5 requirements.

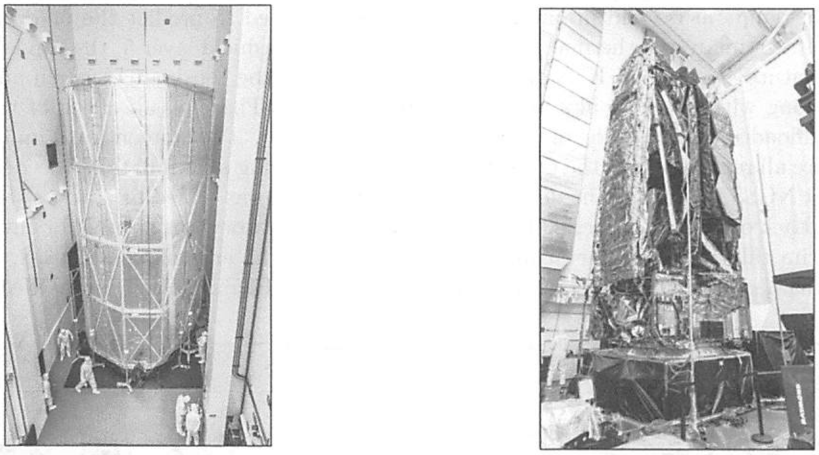

Figure 6: The Observatory environmental testing made use of the same NGSS test facilities with largely the same test equipment that was used at the Spacecraft Element level. *Left:* *Webb* inside its contamination tent at the Large Acoustic Test Facility in preparation for acoustic testing. *Right:* *Webb* mounted on the vibration table, which was located within a clean room. Credits: NASA/NGSS.

3. LAUNCH SEGMENT

When *Webb* completes its integration and test flow, it will be stowed and installed into a shipping container called the Observatory Space Telescope Transporter for Air Road and Sea (OSTTARS). *Webb* will be transported from the NGSS Space Park in Redondo Beach, CA to the European Spaceport in Kourou, French Guiana, where it will be functionally tested, fueled, integrated with the Ariane 5 launcher fairing, rolled out to the launch pad, and finally launched. There will be approximately 3 months of launch site activities from the time of *Webb*'s arrival until liftoff. The launch date is currently planned for October 31, 2021, but the actual launch date will depend on when *Webb* is delivered to the launch site and how it fits into the launch queue. There are regular launch opportunities available for *Webb* to reach the desired L2 halo orbit destination.

4. COMMISSIONING

The post-launch commissioning process for *Webb* will take the payload from its stowed launch configuration to its fully deployed, cooled state, with the telescope aligned and the instruments checked out and ready for scientific observations. The goal is to ensure the Observatory is prepared to take science quality data during the Cycle 1 observing program, but the full suite of calibration data will be acquired during calibration time set aside in each of the observing cycles. This commissioning process is planned to be completed in less than 6 months. Detailed descriptions of commissioning and preparing *Webb* for science observations are presented in accompanying conference proceedings.[10, 11]

4.1 Commissioning Timeline

The baseline sequence of commissioning activities has been developed, with all constraints, pre-requisites, and resulting products well-defined. Figure 7 illustrates the high level commissioning phases and milestones. The timeline is separated into three major phases that include: 1) orbital insertion, spacecraft, and deployments, 2) telescope alignment, and 3) the science instruments commissioning. However, in practice there is substantial overlap in the commissioning phases. For example, the telescope alignment requires sensing capabilities which rely on the NIRCam instrument.[12]

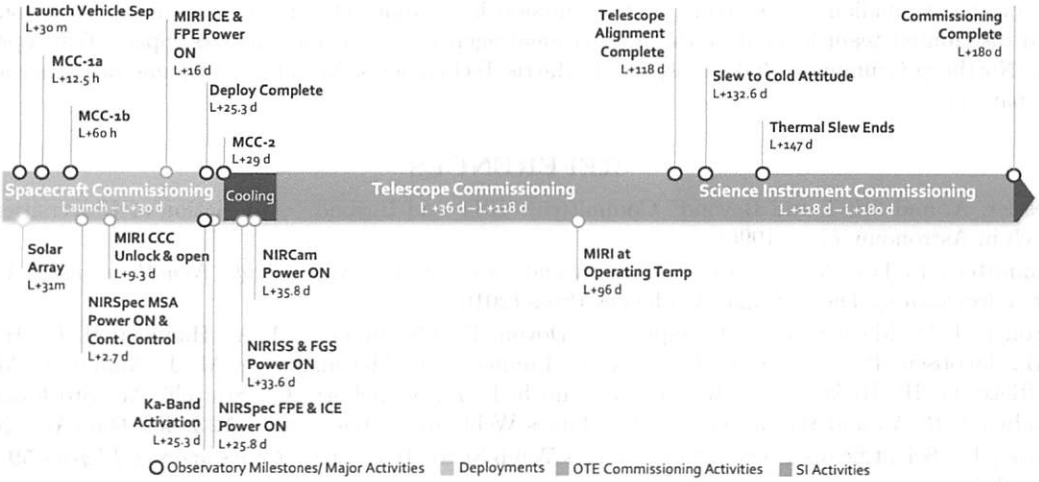

Figure 7: This schematic of the commissioning timeline color codes the major phases and annotates several key activities and milestones (MCC = Mid-Course Correction; ICE, MSA, and FPE are instrument subsystems).

4.2 Rehearsals

The *Webb* team will continue to focus on its execution with rehearsals up until the launch. The full Mission Operations Team, or MOT, will carry out the Observatory commissioning and is comprised of individual, smaller teams for the spacecraft, mid-course correction, deployments, wavefront sensing and control, science instruments, science operations, and flight control. There are team rehearsals that focus on internal cross-training for team-specific activities and prepares for the full MOT rehearsals. The team rehearsals are more dynamic in nature, responding to specific team needs, and will continue until launch. The MOT rehearsals exercise cross-team interactions and focus on critical commissioning activities while ensuring the team can conduct operations throughout commissioning and in normal operations. The rehearsals themselves make use of a high fidelity

Observatory Testbed simulator that is a digital twin of the flight Observatory, running the flight scripts and presenting flight-like telemetry on the consoles. The MOT rehearsals often involve more than 100 people, from NASA, NGSS, Ball Aerospace, Raytheon, the science instrument development teams, and STScI. All phases of commissioning and operations are rehearsed from launch through normal science operations. To date, the *Webb* team has completed 22 MOT rehearsals and 7 additional MOT rehearsals are scheduled between now and launch.

5. PERSEVERANCE DURING THE PANDEMIC

The global COVID-19 pandemic has resulted in a significant death toll and will have lasting effects on public health. The *Webb* project responded to the pandemic cautiously but was able to maintain technical progress throughout this difficult time. For the integration and test personnel, the project implemented enhanced personnel safety protocols such as mandatory personnel protective equipment, daily health screenings, additional personnel barriers in crowded work environments, revising work orders as needed to enable social distancing, and adding new work protocols to promote a healthy work environment. Much of the *Webb* team was placed under mandatory telework requirements, restricting access to their home institutions in addition to project-level travel. The project relied on enhanced remote participation options using a variety of videoconferencing and collaborative tools for both technical and programmatic meetings. This was especially true for our international partners, many of whom were either unable to travel to the United States or would require a prohibitively long quarantine period. The project schedule was adjusted in July 2020 and accounted for schedule inefficiencies related to the pandemic.

ACKNOWLEDGMENTS

The *Webb* mission is a joint project between the National Aeronautics and Space Agency, European Space Agency, and the Canadian Space Agency. This mission has important contributions from an astronomically large and distributed team located at the international agencies, academic partners, Space Telescope Science Institute, Northrop Grumman, Ball Aerospace, L3Harris Technologies, NeXolve, and numerous other aerospace industry partners.

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