LAUNCHING AND DEPLOYING THE JAMES WEBB SPACE TELESCOPE

Keith A. Parrish[a], Carl Starr[b]

[a] *NASA Goddard Space Flight Center, 8801 Greenbelt Road, Maryland, USA, keith.a.parrish@nasa.gov*
[b] *NASA Goddard Space Flight Center,8801 Greenbelt Road, Maryland, USA, carl.w.starr@nasa.gov*

Abstract

On December 25, 2021, at 12:20 UTC, the James Webb Space Telescope (JWST or Webb) lifted off and onward to its destination in orbit at the second Lagrange Point (L2). With more than two decades in development, and an international collaboration between the National Aeronautics and Space Administration (NASA), the Canadian Space Agency (CSA), and the European Space Agency (ESA), Webb is one of the most anticipated science missions ever launched. After a dramatic and flawless launch, Webb's toughest and riskiest days lie ahead. Unprecedented in its complexity and ambition, over the next two weeks Webb would undergo the most complex on-orbit deployment sequence ever attempted, with any single deployment anomaly carrying the risk of full mission failure. An exquisite design, years of ground testing, an exhaustively trained and rehearsed operations and engineering team, and an unprecedented level of contingency planning, all resulted in a fully and successfully deployed Webb observatory, on its way to L2, and nominally cooling to its cryogenic temperatures. Although Webb still had many more months of commissioning left, there was a collective sigh of relief heard round the world. This incredible achievement was not by chance but was years in the making. We go behind the scenes of Webb's first month on orbit, starting with the unique and challenging launch itself, the time criticality of its mid-course corrections, and a summary of nearly 14 days to undergo nearly 50 major deployments. We discuss how years of robust and detailed contingency planning were prepared for unanticipated events and on-orbit spacecraft behavior. And finally, we provide a brief overview of the entire commissioning process, which successfully completed on July 10th, 2022.

Keywords: (JWST, Telescope, Commissioning, Ariane5, Deployments, Operations)

1. Introduction

At 9:01AM Eastern Standard Time (15:01 UTC) on December 31st, 2021, ground controllers in the Mission Operations Center (MOC) in Baltimore, Maryland, sent commands to the Webb to begin releasing its final row of hold downs that would allow for the first major deployment of the observatory's large Sunshield. After six days in orbit, the observatory was performing flawlessly. The mission was now in its most challenging and risky phase, two weeks of nearly continuous deployments. Webb had begun the slow and methodical process of transforming itself from a tightly folded rocket payload, into the largest and most powerful space telescope ever launched.

The Missions Operations Team (MOT), consisting of over 150 on-shift operations and engineering personnel, awaited confirmation from the Deployment Operations Engineer that the release devices fired correctly, and that the five layers of Sunshield membranes were now free to be pulled from their folded-up launch configuration. No confirmation came. Telemetry should have indicated that at least one of the two redundant reed switches had tripped, indicating a protective cover had also released and rolled up and out of the way.

Prior to launch Webb would be widely known in both the technical and public communities for its reliance on 178 release devices. While commonly used in nearly all space missions, Webb used them in unprecedented numbers and in new and unique ways, with 107 used solely to support and hold down the Sunshield's five folded membranes. Any failure of just one of the devices potentially meant complete mission failure and at best, would severely degrade the mission's scientific performance.

Non-explosive electrically redundant actuators were used to initiate action and motion of springs designed to pull or push and release location specific release pins and bolts. The risks related to these single point mission failures (SPFs) were the focus of Webb's engineering team for many years. From detailed design optimization, unprecedented ground testing and quality control measures, to extensive on-orbit contingency planning,

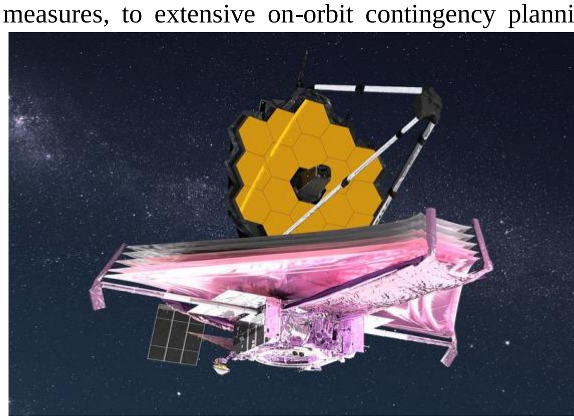

Fig. 1:Artist Rendition - Webb Fully Deployed On-Orbit

the successful release of all 178 devices dominated all aspects of Webb's final years prior to launch. And while confident the team had done all due diligence to minimize the risks to a level acceptable for the launch of a NASA flagship mission, the releases and deployments on Webb were the most ambitious in space flight history.

Because no confirmation was received, the team began to follow a highly reviewed and carefully planned contingency response procedure that started with the simple step of re-sending the release commands. As the morning lingered on and with still no confirmation after several steps in the contingency response flow, the team reluctantly considered the possibility of a failed release device. A deployment anomaly was declared, and the hard work began. The teams' collective expertise from years of commissioning planning, team training and rehearsals, ground testing and inspections, and contingency and operational procedures, were all fully brought to bear to solve this potentially mission ending problem.

By early afternoon, and after extensive flight telemetry reviews, analysis reviews, and even the use of the full-scale Sunshield test model, the team concluded the release device did in fact work correctly but the cover had rolled up in an unexpected way and did not trigger the switches. Six days into the fourteen needed to complete all of Webb's deployments, the team had passed its first test.

2. Mission Overview

An international collaboration of NASA, ESA, and CSA, Webb is a large aperture (6.5m diameter) telescope cryogenically cooled to below 50 Kelvin for infrared observations of the early universe, planetary and star formation, and solar system objects. Webb is the largest space telescope ever launched. Passive cooling of the telescope and four scientific instruments is achieved by sending Webb to L2 deploying a large Sunshield capable of blocking both the light and the heat of the Sun and Earth. One of Webb's instruments, the Mid-Infrared Instrument (MIRI) is further cooled to 6K by use of a mechanical cryo-cooler.

Shown on-orbit and fully deployed in Figure 1, Webb consists of three main sections or elements. The Spacecraft Element (SCE) houses typical spacecraft functions like power and communications but also consists of the very large and unique Sunshield; the Optical Telescope Element (OTE). The third element, the Integrated Science Instrument Module (ISIM) (Figure 2) contains the four instrument suite of the Near-Infrared Camera (NIRCam), the Near-Infrared Spectrograph (NIRSpec), the aforementioned MIRI, and the Fine Guidance Sensor/Near-Infrared Imager and Slitless Spectrograph (FGS/NIRISS). Webb is shown fully stowed in Figure 3. Figure 4 shows Webb during final observatory level deployment testing with its Sunshield

Fig. 2: The ISIM Being Lowered During Installation with the OTE in 2016 [1]

Fig. 3: Webb Stowed in Launch Configuration [1]

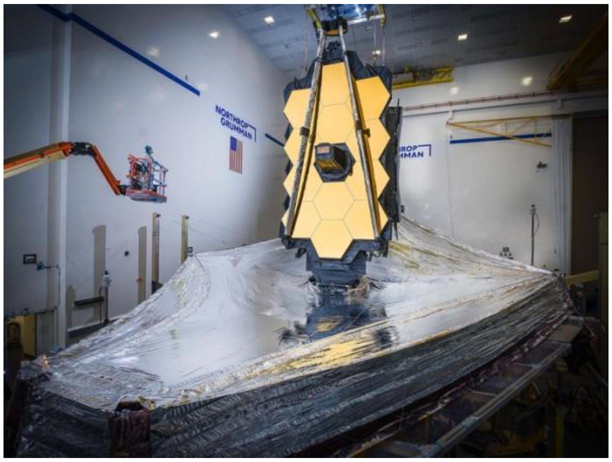

Fig. 4: Webb During Final Deployment Testing [1]

fully deployed and its Deployable Tower Assembly (DTA) raised separating the OTE from the spacecraft.

Launched on December 25th, 2021, aboard an ESA provided Ariane 5 launch vehicle (Fig. 5), Webb had to be completely folded up to allow the large mirror and Sunshield to fit within the five meter diameter fairing. Webb's large size, light weight (6200kg), cryogenic operating temperatures, and number of deployments needed to unfold into an operational observatory, combined to create one of the most difficult design and engineering challenges in space flight history.

After nearly two years of observatory level testing and two full deployments tests, Webb began final folding and stowage operations in May of 2021 with shipment to the launch site in French Guiana in September 2021. After launch, Webb began a six-month long commissioning process culminating in readiness to begin science operations.

3. Commissioning Overview

Commissioning Webb (Figure 6) began with launch and concluded with the calibration and enabling of each of the scientific instruments' observation modes. The complexity and coordination of over five hundred distinct commissioning activities required years of pre-launch planning. Each of these activities were well defined and rehearsed with clearly defined entry and exit criteria, operational constraints, and typically had unique one-time-use operational products. Additionally, contingency plans and related flight products were created for each commissioning activity. One of the complexities of commissioning was the continually changing temperatures and configurations of the observatory as it deployed and cooled down to cryogenic temperatures. These temperature changes created, in most cases, a very clear order of activities as complex telescope and instrument alignment activities were very thermally sensitive and could only occur when certain temperatures and temperature stabilities were achieved.

The MOC, located at the Space Telescope Science Institute (STScI), in Baltimore, Maryland, stayed in nearly continuous ground contact with Webb via use of NASA's Deep Space Network (DSN) for the first five months of commissioning. Backup redundant facilities were brought online for critical activities such as launch, deployments, and critical propulsive maneuvers needed to adjust Webb's orbit and trajectory. Additionally, a backup MOC, or bMOC at NASA's Goddard Space Flight Center, was available for command and control, if there were any issues at the MOC.

All commissioning activities were captured in a configuration-controlled Commissioning Activity and Sequence Timeline (CAST). The CAST was years in the making with a specific amount of time allotted to each activity. As the timeline matured, any requested changes to duration, or an additional or deleted activity, had to undergo thorough engineering review and management approval. As a testament to the timeline coordinators

Figure 5: The Ariane 5 Powers Webb to Orbit [1]

who created and managed the timeline's details down to the minute, the total duration of commissioning was nearly constant at six months for several years, with actual commissioning finishing in nearly the allotted period. Prior to launch, the CAST underwent several formal reviews to ensure activities were compatible with overall observatory configuration, system level parameters, and that operational products were tested and

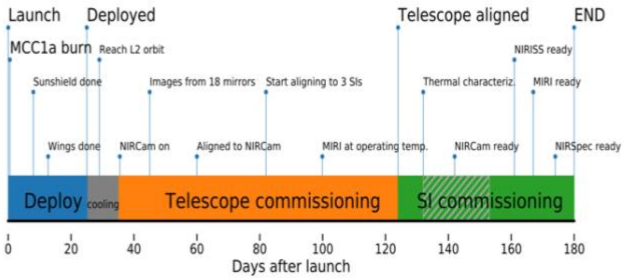

Fig. 6: Webb's Commissioning Timeline [2]

available. While activities among the telescope, science instruments, and spacecraft were scattered over the entire six-month period, the timeline was broken into three main phases where most of each element's activities were located.

3.1 Spacecraft Commissioning Phase

The first thirty days of commissioning was primarily focused on spacecraft and deployment activities. As this also included launch and three critical mid-course corrections (MCCs 1A, 1B, and 2), this phase was considered the most challenging. This phase also included the beginning of the cryogenic cool-down as the Sunshield was deployed, scientific instrument turn-on, and spacecraft subsystem checkout activities. The last half of this phase was focused on deployment of each of the primary mirror's eighteen mirror segments. Hundreds of actuators were exercised to move the mirrors out of their launch configuration in preparation for telescope alignment to occur in the next phase. Spacecraft Commissioning, as a phase, ended officially with completion of the third orbit corrections maneuver, MCC2. MCC2 was a short firing of Webb's on-board propulsion system to ensure entry into a halo orbit about L2. After MCC2 Webb was considered on-station in its final orbit. For the life of the mission, Webb would then undergo short station keeping burns to maintain the proper orbit.

3.2 Telescope Commissioning phase

The telescope commissioning phase, approximately 90 days, was focused on aligning the telescope. Cryogenic cooling continued during this phase with key milestones related to state changes on the mechanical cryogenic cooler for MIRI. Individual scientific instruments continued checkout activities as they reached cooling thresholds that would allow their infrared optimized detectors to begin operations. Of specific importance was the activation and checkout of the FGS. The FGS provided the high levels of accuracy and precision for specific guide star tracking needed for Webb's science target pointing and stability. Use of the FGS was needed to enable fine guiding of the observatory as it observed specific stars used for telescope alignment. NIRCAM images were also critical during alignment as the data provided wave front performance used for the next alignment steps. Spacecraft checkouts continued during this phase as the entire attitude control system, in concert with the FGS, provided fine pointing, while momentum dumps and station keeping maneuvers continued. Telescope commissioning officially ended with the telescope aligned in the optimal way to serve all four science instruments.

3.3 Science Instrument Commissioning Phase

The last months of commissioning were focused on instrument calibration activities and bringing each 17 operational modes on-line. Webb was fine guiding and taking images and operating as it would during normal science operations with the science observing plan software running the entire observatory. Spacecraft operations, data transfers to the ground, and general maintenance activities became more routine as operations began to be transferred from the commissioning team over to the flight operations team. Also, during this phase, the spacecraft completed its final commissioning activity with the successful tracking of moving targets such as asteroids within the solar system. The final system level engineering test was also performed. This was a thermal stability test of the entire optical system performed by observing targets at attitudes that would force a gradual and tiny temperature change during long observations.

4. Commissioning Planning and Management

Regardless of the number of rehearsals and experience with the observatory during ground testing, it was a foregone conclusion that actual on-orbit experience with Webb would be completely new. The overall focus of planning in the last three years prior to launch was not only on the detailed reviews of the activities, but also on ensuring the team was prepared to interact and solve issues with the very large MOT. To assist with these final preparations and reviews, the entire commissioning timeline was further broken up into large sections of activities that were conducive to individual management. Organizationally, the team was organized under a Commissioning Manager with leads for each of the three phases, and then activity leads who would manage a set of like activities. The activity lead was fully responsible for the success of their activity which not only included knowledge and execution on-orbit, but also for ensuring final integration and test activities and test results were properly accounted for. Additionally, each activity lead was responsible for contingency plans related to their activity. Commissioning management would work directly with the Mission Operations Manager to ensure both the engineering support, operational products, contingency plans, and final timeline adjustments were ready for launch. Finally, dedicated commissioning systems engineering was added to provide a top-down look at all activities to ensure compatibility and that observatory level system interactions were accounted for. Seven distinct activities were identified, each with a designated lead.

4.1 *Launch and Ascent Lead*

The launch and ascent activity lead were responsible for all activities on the spacecraft starting with liftoff through solar array deployment, and attitude control and communication subsystem activation. This phase ended with Webb being safely on orbit, power positive, and communicating with ground controllers. This phase was dominated by on-board stored command sequences executed by flight software with fault management software protective measures. Contingencies during this phase, if not covered by fault management, were centered ground interventions to establish command and control, handle solar array deployment anomalies, and any attitude control and power subsystem anomalies. Given the routine nature of these types of activities, special attention was given regarding solar array deployment anomalies, and necessary ground communications to enable ranging to determine orbit determination solutions for Webb's first critical MCC1A burn, scheduled at launch plus 12.5 hours.

4.2 *Mid-Course Correction Lead*

For thermal reasons Webb could never do a post launch braking burn to scrub any excess velocity imparted by the Ariane 5. Doing so would expose the sensitive optics directly to the Sun. Because of this, the Ariane 5 was intentionally targeted low, to essentially underperform, to prevent such a scenario. Webb would need to provide its own additional velocity to account for any launcher dispersions around this targeted velocity. And the earlier the velocity could be added the more remaining fuel for on-station science mission life. To account for a variety of contingencies, execution delays, and large launcher errors, the first MCC was nominally planned to take place at launch plus 12.5 hours. A burn so soon after launch, with a new spacecraft, and considering the amount of tracking data and processing needed for NASA Goddard's Flight Dynamics Facility team to determine a burn solution, was one of Webb's biggest early orbit challenges. The MCC lead was solely responsible for the planning and execution of this first burn, MCC1A. MCC1B, scheduled for about a day later, was intended to be a small error correction burn, but was not deemed as time critical. MCC2, conducted 29 days after launch, would place Webb into its final orbit.

4.3 *Spacecraft Systems Activity Lead*

This lead was responsible for spacecraft checkout and execution of routine spacecraft housekeeping functions. These included data recorder operations, communications, momentum management and unloads, station keeping burns, and general subsystem health. These activities were scattered and repeated throughout all of commissioning.

4.4 *Line of Site Activity Lead*

This lead was responsible for both the spacecraft's attitude control subsystem and observatory science fine guiding, requiring system interactions among the OTE's fine steering mirror and the FGS. This interplay of hardware and software was extremely difficult to simulate on the ground. Verification of the fine guiding system was via separate simulations and tests as closing the fine guiding control loop fully was not possible in ground testing. As such, it was fully expected this activity would be challenging on-orbit, as the team adjusted operational procedures and updated on-board software as they learned about the system's performance.

4.5 *Cool Down Activity Lead*

The cool down activity lead was responsible for ensuring all operational planning accounted for the rapidly changing temperatures during commissioning. Of specific concern was the risk of water ice contamination on optics as warmer observatory components outgassed. A series of contamination control heaters were used throughout the instruments and telescope aft-optics to mitigate such concerns. The strategic and well-coordinated turn-off of these heaters was critical throughout commissioning. A series of consent to proceed reviews were used to gain management approval for letting the observatory enter its next state of cooldown. Figure 7 demonstrates Webb's actual cool down of the telescope and instruments which matched pre-launch predictions almost exactly.

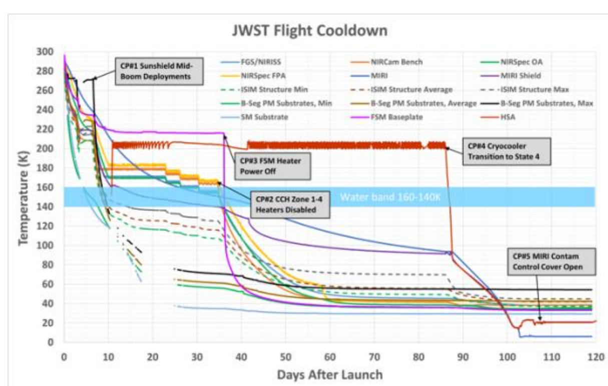

Fig. 7: Webb's Cool-Down History [2]

4.6 *Deployments Activity Lead*

Webb had nearly fifty major deployments. Each deployment was managed and executed by the engineer responsible for building and testing the hardware. The Deployment Activity lead was responsible for making sure the operational and contingency planning was ready to support these individual engineers and their deployments. Each of the individual engineers was also responsible for supporting system level contingency planning. Additionally, the deployment systems lead engineer worked with the activity lead to ensure all system level interactions were accounted for, using a variety of system simulation tools, ground test data, and hardware simulators.

4.7 ISIM Systems Activity Lead

This activity lead was responsible for overseeing the planning of all ISIM activities including individual instrument turn-on and checkout. Additionally, the lead was responsible for overseeing cooler operations and worked closely with the cool-down lead, instrument teams, and OTE phase lead, as all ISIM activities were very intertwined with these other activities.

5. Contingency Planning

Given the importance of the Webb mission, its lengthy development time, and its ambitious on-orbit deployments, contingencies were a constant consideration in all commissioning planning. In the final three years prior to launch, mission ending and crippling scenarios were further examined for any possible recoveries. Time critical activities such as solar array deployment and MCC1A were given specific focus along with mission ending scenarios related to deployment failures and long deployment delays.

5.1 Contingency Planning Process

Throughout the design, development, and testing of Webb many different organizations developed their own contingency plans and responses. Early in the rehearsal campaign, the need for a contingency or anomaly standard became apparent. The term anomaly for Webb meant an abnormal behavior, out-of-specification performance, or unexplained occurrences in the flight system or flight operations, including processes, procedures, and human factors.

Contingency planning considered a wide variety of scenarios from mission critical emergencies to redundancy access, to alternative flows and timeline delays. Specific scenarios were explored to identify and develop needed operational products and procedures. For example, troubleshooting flows for loss of communications and failure to fine guide, assist the team in identification troubleshooting of the issue. Whenever feasible, and specific to the issue, the team developed a series of Pre-Coordinated Responses (PCRs), which were highly detailed, scripted responses intended to resolve time critical anomalies such as solar array deployment issues, burn aborts, and engineering data downloads. Many individual safing response and recoveries were developed such as powering on and off hardware, re-commanding hardware, enacting parameter changes, and recovering from safing modes.

Special contingency studies and assessments were identified that enabled recovery or responses but stopped short of subsequent flight product development. These special studies identified the anomalies such that the team would not have to start from scratch should they be encountered. For example, a partially deployed configuration while executing a maneuver or OTE alignment activities without a NIRCAM. The team also explored contingency scenarios that encompassed mitigation via changes to the baseline commissioning flow, a design, or an operational change. For example, adding additional heaters to minimize the water ice migration risk. The special studies and assessments can be thought of trying to identify and understand the unknown unknowns.

5.2 Tactical Contingency Planning

As the CAST was developed, a Contingency Operations Working Group (COPS) provided a tactical examination of planned activities with an anomalous outcome. The group made recommendations based on these examinations that sometimes included changes to hardware, software, the ground segment, or to test scenarios on test beds. COPS was also tasked to examine all activity lead contingency planning to ensure it was compatible with the overall hardware configuration, timeline status, and that needed operational products were ready to go.

5.3 Strategic Continency Planning

Strategic contingency planning consisted of identifying and prioritizing additional 'what if' scenarios. It defined and prioritized critical anomalies that had the potential for mission loss or severe degradation. The strategic contingency planning group did not concern itself with operational products or expected responses to telemetry. For example, strategic contingency planning investigated how to efficiently get the bMOC up and staffed to support time critical MCC1A. Other planning included investigations on how to proceed with MCC2 in a partially deployed configuration or if changes in deployment order were feasible once on-orbit. Sometimes these 'what if' scenarios resulted in additional operational products or even on-board software changes. For instance, the attitude control subsystem was modified prior to launch to allow the observatory to achieve a spin about any select axis. This would only be used in a severe deployment failure to impose static loads on a potentially stuck mechanism. Other scenarios investigated operational work arounds if cool down temperatures were significantly different than expected.

5.4 Deployment Contingencies

Deployments had its own dedicated tactical working group to examine each deployment step and develop procedures and products needed to diagnose and remedy a host of situations. Responses included ever increasing interventions if the issue continued. Invasive responses included using spare side electronics, alternating deployment sequences, or even using more desperate measures like spinning the spacecraft. Each step in their response flow was reviewed by systems engineering and deployment systems personnel. Of specific importance was for the group to identify secondary and tertiary indicators of if a deployment step had or had not happened in the absence of telemetry or anomalous telemetry. Such indicators could be temperature changes, rates sensed by the gyros, or bus currents and voltages. And similar to the deployments group, the mirror deployment and telescope alignments team, and the line of site team, had similar processes with extensive prepared contingency plans.

6. On-Orbit Performance

Commissioning officially completed on July 10, 2022, 197 days after launch, versus the pre-launch final CAST of 180 days. This minor exceedance speaks to the incredible on-orbit performance of the entire observatory due to its exquisite design, extensive ground testing, and team familiarity with its operations via numerous rehearsals and simulations. It also speaks to the years of detailed and meticulous planning by the timeline team. The 180 days in the CAST was the best estimate at a nominal timeline duration. While each event had some amount of contingency time built in it was, in general, success oriented. Prior to launch it was very conceivable, and even expected that even a minor deployment anomaly or issues with mirror alignment, would extend the complete date significantly. Learning how the observatory operates with the typical but numerous small anomalies along the way was expected to add several weeks.

But there were challenges, and fortunately time savings in two key areas more than offset the needed extra time. Several difficulties along the way had to be resolved. Several safing events were encountered as the team conservatively handled the attitude control system and learned the on-orbit behaviors of all the subsystems. Surprisingly, unplanned DSN outages resulted in delayed activities. And as expected, the fine guiding software had to be tuned based on on-orbit performance. And numerous other unexpected behaviors, not catastrophic or damaging, had to be well understood prior to moving on in the timeline. In summary, the extent of issues was well within and much lower than expected for such a complex system and resolutions never required the use of any redundant hardware. Offsetting this extra needed time was a much faster than planned mirror alignment process, and the ability to cut short a 14-day thermal stability test because of faster than expected settling times.

6.1 Launch and Ascent

Due to launch site processing delays, Webb's launch slipped from December 12th to the 19th and finally to December 24th. As roll-out to the pad approached a review of the weather indicated that only Saturday, December 25th, had favorable conditions. Forecasted conditions for the following several days were bleak. At 12:20:00 UTC on December 25th, the Ariane 5 lifted off at the opening of the window and disappeared quickly into the tropical cloud cover. The countdown was nominal except for one anomaly with the spacecraft propulsion line temperatures. Because the telescope had to be pre-cooled to 12C to better handle the heating of launch, it was expected that Ariane 5 upper stage cryo-tanking would result in the use of heaters to keep the spacecraft's propulsion lines warm and ready to support post separation attitude control. However, thermal modelling underestimated the cooling effect of the upper stage cryogenic tanks combined with the high flow rates of the 12C air-conditioned fairing air. At approximately one hour prior to launch the propulsion line temperatures were trending quickly towards their lower limits which would result in a launch constraint violation and a countdown hold or a scrub. Teams both at the launch site and MOC, on two different continents, worked quickly together to resolve the issue and developed new commanding and procedures on the fly to engage a second string of back up heaters. Propulsion line temperatures recovered, and a hold was never required.

After lift-off the Ariane 5 trajectory was completely nominal with the following key event sequences in Mission Elapsed Times (MET):

- Fairing Jettison: L+3.456 minutes
- Main Stage Cut-off: L+8.759 minutes
- Second Stage Ignition: L+8.927 minutes
- Second Stage Shutdown: L+24.916 minutes
- JWST Separation: L+27.187 minutes

Following fairing jettison, the MOC began receiving Webb telemetry via the Space Relay network's Tracking and Data Relay Satellite System (TDRSS) allowing the engineering and operations team to monitor the status of the ascent stored command sequences. A nominal separation (Figure 8) with very little tip-off body rates, allowed Webb to deploy its solar array at the soonest possible time. At approximately 45 minutes after launch, Webb was safely on orbit, oriented correctly, generating power, and communicating and gathering needed tracking data from the Malindi ground station in Kenya.

Fig 8: Webb On-Orbit After Separation

At one hour after launch, Arianespace provided dispersion data to the Webb team indicating nominal velocity and direction. The launch was essentially perfect. The Ariane 5, Webb, all ground assets, and personnel performed flawlessly. If the time critical MCC1A burn could be executed nominally at L+12.5 hours, then Webb would have enough fuel to last well beyond 20 years and extensively exceed the 10-year fuel minimum.

6.2 MCC1A Burn

With Webb safely on-orbit the team was now on the clock to gather the needed tracking data from both Malindi and the Canberra and Madrid DSN stations, determine a burn solution, checkout the spacecraft subsystems, test the burn plan on simulators, and finally upload and execute the burn plan. Spacecraft operations also required a successful test burn and an attitude maneuver to the required burn attitude. At exactly 12.5 hours after launch on, December 26, at 00:50 UTC, Webb fired its main thruster for 64 minutes to add a mere 20 meters per second to Webb's velocity. The team had done it. Webb was on its way to its L2 orbit with the promise of over two decades of on-station science mission life fuel.

6.3 Deployments

On December 28th, after successfully deploying its solar array and gimbaled antenna assembly the prior days, the team began the unprecedented multi-step deployment of Webb's Sunshield. Stretching the width and length of a tennis court, the Sunshield consists of five individual Kapton layers, fan folded for launch and support by two large composite structures, the Unitized Pallet Structures (UPS). A series of 107 pins skewered the multiple fold stacks to the structure providing support during the shaking and loads of launch. By the end of the day the deployment and ops team released 25 of the 107 pins and lowered the forward and aft supporting structures. Figures 9 and 10 show this UPS deployment activity during ground testing in early 2021.

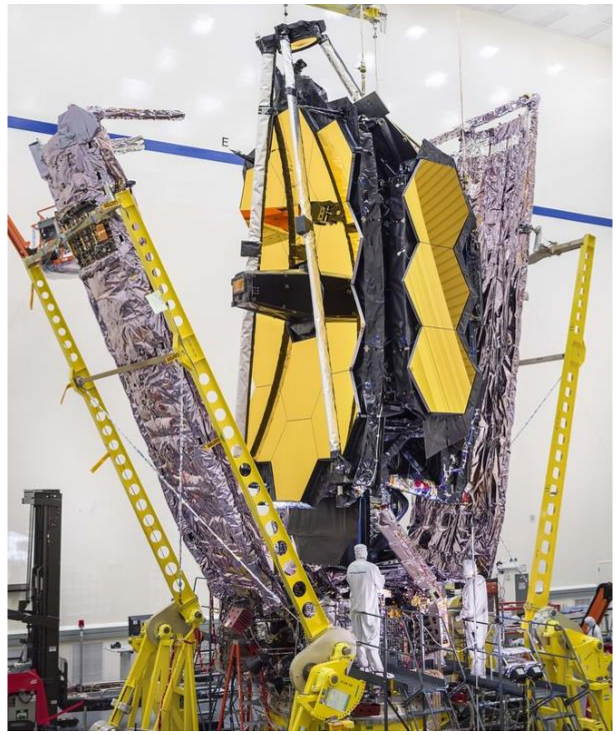

Figure 9: Webb Shown with Forward UPS Partially Deployed [1]

Fig.10: Webb Shown with Both Forward and AFT UPS Deployed [1]

On December 29th, the deployment and ops team released another 9 release devices which held the OTE to the spacecraft bus and Sunshield and began the multi-hour process of raising the OTE and separating it from the warmer spacecraft.

On December 30th, the deployments and ops team released four more devices freeing the cryocooler assembly within the spacecraft and the aft flap on the aft Sunshield UPS. The aft flap or 'momentum flap' is used to better balance and minimize the accumulation of solar torque. The team also commanded the majority of release devices, approximately 63, holding the membranes to the UPS. Covers that protected the membranes, illustrated in Figure 11, from solar exposure during launch, rolled up more and more with each released row of hold down devices. At the end of the day, a single row of release devices on each side of the two UPS kept the membranes in place and from billowing up and possibly snagging on the bottom of the OTE. The last rows were kept in place over night to ensure a safe configuration.

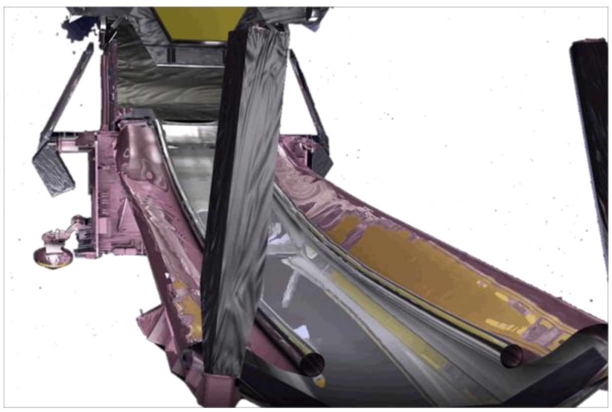

Fig. 11: Protective Covers Shown Partially Rolled up on Forward UPS

On December 31st the plan was to release the last row on the two sides on both UPS and then deploy both of Webb's telescoping booms, pulling out all five layers of the Sunshield. As mentioned in the introduction, the team did not get confirmation that the final row of release devices actuated. Reed switches, which were intended to engage at the end of the cover's travel, gave no indication of proper cover motion. Possible scenarios included failed reed switches, a stuck release device, or a wayward cover that unrolled in an unexpected shape and manner.

After the team was authorized to refire all release devices, even the ones done prior on December 30th, and with no resolution, an anomaly review board meeting was called where the three scenarios were discussed. While there was no real reason to believe both reed switches had failed, or the cover had rolled up in an anomalous fashion, the alternative of a stuck or malfunctioning release device was unthinkable. The Deployments Anomaly Response Team (DART) gathered and began investigating and reviewing all flight telemetry, looking for those secondary and tertiary indicators that could indicate the devices had correctly released. In parallel other teams had gathered to configure ground test hardware, like the full-scale Sunshield test article (Figure 12), to begin the search for clues, and analysis teams began to review and possibly repeat simulations of the release and rollup of the cover.

After about two hours of investigation there was a glimmer of hope. Thermal engineers had found flight data for a temperature sensor that rapidly dropped in temperature after the commanded release. Computer models of the observatory geometry showed that the only way to shadow the temperature sensor and create the large temperature drop was if the cover had in fact rolled up.

Fig. 12: The Sunshield Integration Validation Article (IVA) [1]

Subsequent releases of the other three rows and covers showed similar behavior. The covers simply did not engage the reed switches. While not fully proven, the likely reason for the anomalous roll-up was that the springs were much colder than predicted resulting in a much more energetic roll-up thus positioning the rolled cover out of reach of the reed switches. Further study showed there was no concern with the suspected final position of the covers. With the anomaly resolved, the team then proceeded to deploy both the port and starboard telescoping booms and the OTE and ISIM were finally plunged into the cryogenic darkness the Sunshield was designed to provide. The deployments and operations teams greeted 2022 after one very long and challenging New Year's Eve. Webb's Sunshield 'wings' were finally spread. (Figures 13 and 14)

The MOT continued the next several days with final Sunshield deployments, which included the careful and meticulous tensioning of all five layers by winding in over 90 individual cables. Prior to tensioning, higher than predicted tensioning system motor temperatures were cooled by re-orienting Webb with respect to the Sun. The maneuver cooled the motors sufficiently and subsequent tensioning operations were nominal and went faster than expected. Deployment of the OTE's

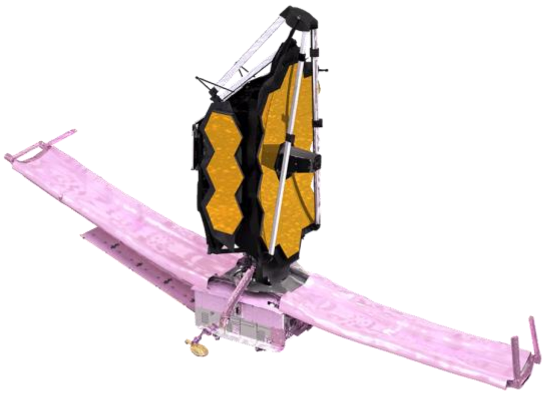

Fig. 13: Webb's Configuration the Morning of 12/31/21

Fig. 14: Webb's Configuration the Evening of 12/31/21

secondary mirror and two primary mirrors wings soon followed. On January 8th, Webb was fully deployed (Figure 15). Several engineers had spent a good part of their careers in designing and building Webb's deployment structures and mechanisms and they had now completed the most ambitious unfolding of any spacecraft ever.

6.4 Telescope and Science Instruments Performance

At the completion of commissioning, the performance of each of JWST's 17 science modes were reviewed against pre-launch criteria for sensitivity, image quality, wavelength calibration, astrometric calibration, ghosts, and stability. The instruments have substantially better sensitivity than was predicted pre-launch and have far exceeded all performance requirements. This result is due to higher science instrument throughput, sharper point spread functions, cleaner mirrors, and lower levels of near-infrared stray light background compared to pre-launch expectations.

7. Conclusion

After completing Webb's 14 days of deployments, the entire MOT became more relaxed and began to settle in for the long six months of remaining commissioning activities. While numerous challenges awaited, built in redundancy could be relied on for any major issues and the notorious SPFs were now down to a number similar to any typical space mission.

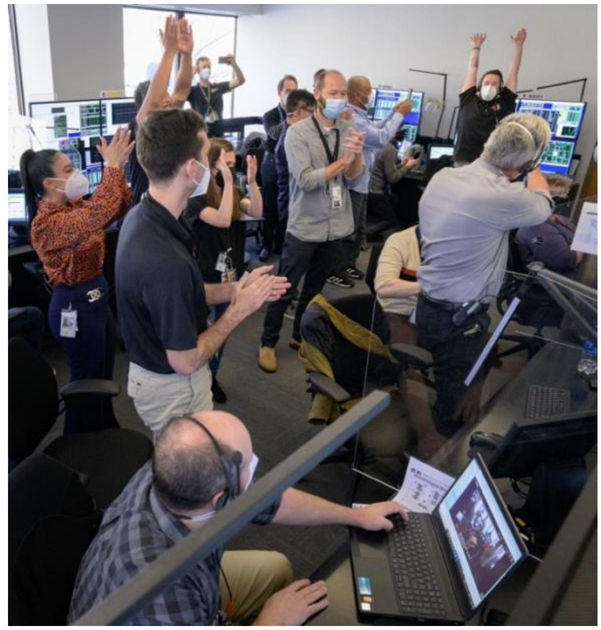

Fig. 15: Webb's Deployment Team Celebrates a Fully Deployed Observatory, 01/08/2022

The success of Webb's commissioning started long before launch. It started with its design, with its unprecedented amount of testing, and the training and preparation of the entire MOT. The challenges of just the coordination and training of nearly 700 mission operations team members from all parts of the country and world cannot be overstated. It should also be mentioned that Webb launched during the surging first wave of the Omicron Covid-19 variant in the United States. In fact, the prior 21 months of pre-launch training and preparation was during the pandemic and Covid safety protocols were factored into everything the Webb team did. Webb had faced many challenges in its nearly 20 years of development and the entire Webb team rose once again to the occasion to prepare, launch, and commission Webb in the new reality of the pandemic world.

Webb would release its first engineering image after final telescope alignment in mid-March (Figure 16), just shy of three months in orbit. The relatively short exposure shows numerous galaxies unexpectedly in the background, giving a hint of Webb's power and sensitivity. The perfect star in the foreground, with Webb's now signature diffraction spike pattern, demonstrated the telescope was optically perfect. It literally could be no better. It was in those late February and early March days, that the Webb team began to realize they had built something special, they were operating something special, something that was exceeding the performance anyone dared dream.

Four more months were still to go, and the pace of commissioning never ceased with new challenges every day. And on July 12, 2022, with final commissioning steps completed, the world got its first peak at the new era in astronomy the Webb Telescope had heralded in. (Figure 17). Commissioning Webb, operating one of the most complex machines ever built by humans, remotely, one million miles away, is undoubtedly one of the great achievements in space operations.

Fig. 16: Webb's First Engineering Image after Final Telescope Alignment

Figure 17: Webb's First Science Image Release, July 12, 2022

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