

Lessons Learned from Operating NASA's James Webb Space Telescope

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Abstract

NASA's James Webb Space Telescope started its exciting journey when it launched on Christmas Day in 2021. Over the past three years, our Flight Operations Team at Space Telescope Science Institute (STScI) in Baltimore, Maryland has had, like all new missions, a variety of surprises as we navigated through commissioning and early operations. This paper will provide an overview of Webb's operational architecture and then focus on the lessons learned from the perspective of its management team, including the Project Manager, Mission Operations Manager, Flight Operations Manager, and Mission Systems Engineer. Topics will include:

- Onboard event-driven operations
- Real-time commanding activities
- Trending approaches
- Ground system automation
- Handling of observatory versus ground anomalies
- Early safing events and mitigations
- Micrometeoroid hits
- Fuel usage
- Priorities going forward

Keywords: Webb, JWST, Lessons Learned

Acronyms/Abbreviations

Attitude Control Subsystem (ACS), Actuator Deployment Unit (ADU), Backup Mission Operations Center (bMOC), Chandra X-Ray Observatory (CXO), Deep Space Network (DSN), Deployment Anomaly Response Team (DART), Discrepancy Review Board (DRB), Fine Guidance System (FGS), Flight Operations System (FOS), Goddard Space Flight Center (GSFC), Ground Management Board (GMB), Hubble Space Telescope (HST), Integrated Science Instrument Module (ISIM), Lagrangian Point 2 (L2), Lateral Ingest Telemetry Archive (LITA), Mid-Infrared Instrument (MIRI), Mission Operations Center (MOC), National Aeronautics and Space Administration (NASA), National Oceanic and Atmospheric Administration (NOAA), Near-Infrared Camera (NIRCam), Near-Infrared Multi-Object Spectrometer (NIRSpec), Near-Infrared Imager and Slitless Spectrograph (NIRISS), Northrop Grumman Space Systems (NGSP), Notification and Response System (NRS), Operational Scripts Subsystem (OSS), Space Telescope Science Institute (STScI)

1. Introduction

1.1 Paper Objectives

This paper is intended to share the experiences of the Webb operations team from commissioning through early operations. It will provide an overview of the mission, then discuss lessons learned regarding the observatory and the ground system.

1.2 Mission Overview

The James Webb Space Telescope (JWST) is a large, 6.5m diameter aperture telescope capable of providing high-resolution imaging and spectroscopy in the optical to mid-infrared wavelengths. Webb was launched December 25, 2021, from Kourou, French Guiana aboard an Ariane 5 launch vehicle. It was designed as a 5-year mission with a 10-year goal. Webb is a complement to the remaining NASA Great Observatories programs, namely the Hubble Space Telescope (HST) and Chandra X-Ray Observatory (CXO). It has continued the NASA tradition of

making scientific breakthroughs, including advancements in the origins of the earliest stars, galaxies, and the foundations of life. Its science objectives are shown in Figure 1.

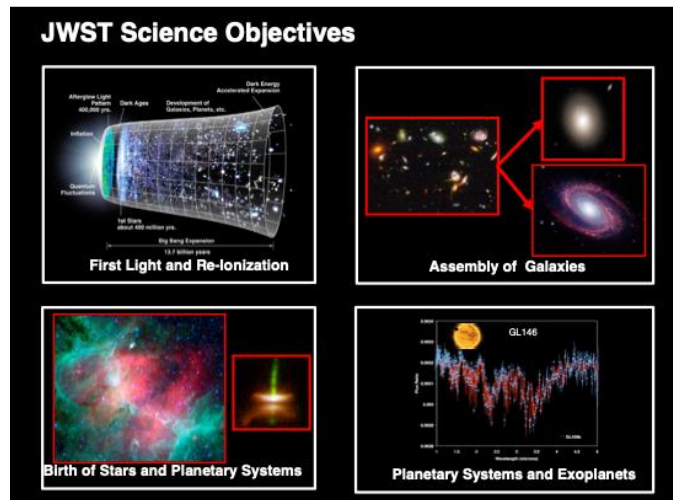


Figure 1. JWST Science Objectives.

Contributions to the Webb project were made by partners across the globe, including:

- Project management located at Goddard Space Flight Center (GSFC)
- Observatory prime contractor Northrop Grumman Space Systems (NGSP) with major subcontractor BAE Space and Mission Systems
- Integrated Science Instrument Module (ISIM) located at GSFC
- Ground communications via the Deep Space Network (DSN) located in California, Spain, and Australia
- Near-Infrared Camera (NIRCam) provided by a team led by the University of Arizona
- Near-Infrared Multi-Object Spectrometer (NIRSpec) provided by the European Space Agency
- Mid-Infrared Instrument (MIRI) provided by an international collaboration led by the Jet Propulsion Laboratory
- Fine Guidance System (FGS) and Near Infrared Imager and Slitless Spectrograph (NIRISS) provided by the Canadian Space Agency
- Science and Operations Center located at the Space Telescope Science Institute (STScI) located in Baltimore, MD

1.2.1 Observatory Description

The Webb observatory consists of the Optical Telescope Element (OTE), the Integrated Science Instrument Module (ISIM), the sunshield, and the spacecraft bus (see Figure 2). Light from space enters through the OTE and is routed through a series of mirrors to the ISIM, where the science instruments are housed. These instruments are kept at extremely cold temperatures (<50K) by the large sunshield, which protects the OTE and ISIM from the heat of the sun, earth, and spacecraft bus. The spacecraft bus performs the attitude control, electrical, communication, command and data handling, propulsion, and thermal control functions.

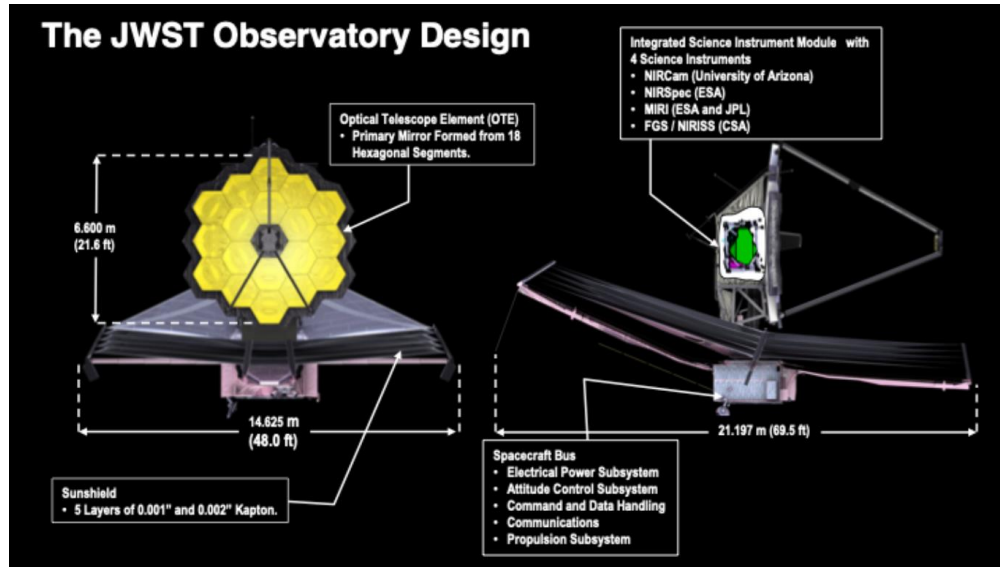


Figure 2. JWST Observatory.

1.2.2 Onboard Event-Driven Operations

A novel aspect of Webb is its onboard event-driven approach to operations. This is implemented via the Operations Scripts Subsystem (OSS), a set of scripts onboard the observatory that control science execution. These scripts allow for automated efficient scheduling that can adjust in real-time to onboard issues such as guide-star acquisition failures or instrument unavailability due to an anomaly. When events with variable timing, such as mechanism movements, are complete, the science plan can continue immediately. As shown in Figure 3, in contrast to absolute timing, this approach has been very successful in maximizing Webb's science efficiency. To date, Webb is obtaining science data >80% of the time.

Operationally, the team uplinks an observation plan to the observatory once a week. This is typically done with a few days of margin, ensuring that approximately three to ten days of observations are always onboard. Each observation plan contains an ordered list of desired observations, called "visits", each with a corresponding time window for execution.

A key to Webb's success with onboard event-driven operations is keeping it simple. Although it is sometimes tempting or convenient to address items like Fault Management within OSS, the project has attempted to define and maintain a clear scope.

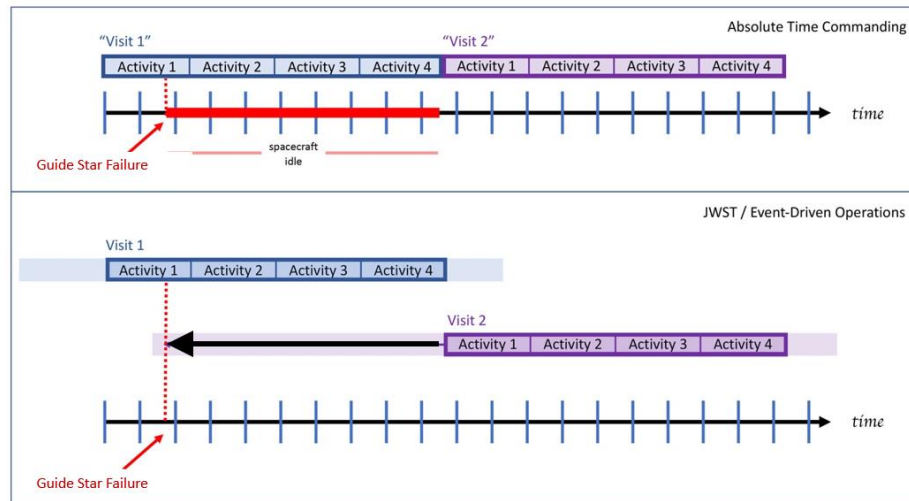


Figure 3. JWST Event-Driven Operations versus Absolute Time Commanding [1].

1.2.3 Real-Time Engineering Visits

In order to interweave real-time ground commanding into the onboard event-driven operations discussed in Section 1.2.2, Real-Time Engineering Visits are used. Like science observations, these visits have a window of allowable execution, typically designated to a specific ground contact. A delicate hand-shaking procedure then transfers observatory control from OSS to the ground. After the ground has completed its required commanding, typically engineering calibrations or station keeping activities, control is handed back to OSS.

Pre-launch, it was anticipated that these Real-Time Engineering Visits would occur approximately every six weeks. However, post-commissioning, as offline subsystem engineers adjusted from around-the-clock monitoring to weekday monitoring, there was a surge of Real-Time Engineering Visits, sometimes multiple per week. Over three years this has subsided to a more sustainable cadence of two to three a month.

1.2.4 Project Reference Database (PRD)

Pre-launch, when the observatory components were spread out across the globe, multiple command and telemetry databases, all of the same general format, were created. This allowed teams to sync database updates with their own development and test schedules. However, as launch approached, it was necessary to combine these into a single database that would house all items required for real-time operations of the flight system, such as command and telemetry, table definitions, display pages, and commanding scripts.

The database itself, known as the Project Reference Database (PRD), uses open-source eXtensible Markup Language (XML) for the database exchange format. This was specifically chosen over other proprietary options to ensure easy compatibility for multiple users. The PRD is maintained at the Science and Operations Center (S&OC). Users can access a configuration-managed copy at any time. Each database item has a corresponding certification level and associated documentation. Level 1 items have functional syntax, but are not tested. Level 2 items have been full-path tested on a simulator. Level 3 items have been executed using flight hardware. At launch, a minimum certification level was required for each data type. High-risk items, such as command, telemetry, and scripts, were required Level 3 certification. Lower-risk items, such as display pages, only required Level 1 certification.

Updates to flight products are governed by the Mission Operations Configuration Change Board (CCB), chaired by the Mission Operations Manager (MOM). The process is detailed in Figure 4. In normal operations, the flight database is updated quarterly, with occasional additional updates as required. Prior to each database release, a detailed review process is conducted to ensure that "ripple-effect" changes to one product are properly accounted for in other products. This review process is a combination of database tools, including a cross-referencing (X-REF) system, as well as manual searches and investigation.

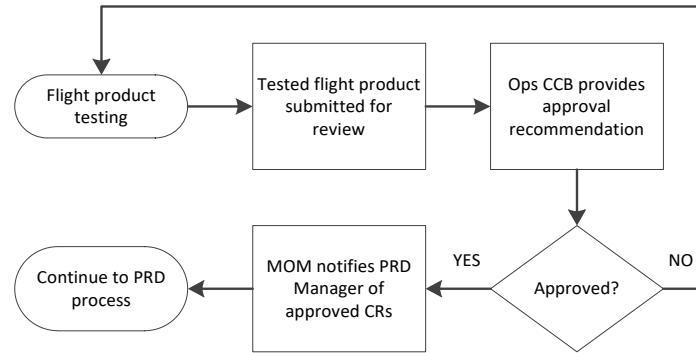


Figure 4. Operations Configuration Change Board (CCB) Process. [2]

2. Observatory Lessons Learned

2.1 Early Safing Events and Mitigations

Starting at Launch, the Webb team followed a strict process for all anomalies. All anomalies that pose a threat to mission performance or health and safety are governed by the Anomaly Management Board (AMB), consisting of major mission stakeholders. Most excitement to date has occurred during the six-month commissioning period, an excerpt of which is discussed in Section 2.1.1. Upon transitioning to Normal Operations, anomalies have generally consisted of standardized safings due to flight software corner cases, as discussed in Section 2.1.2.

2.1.1 Deployment and Power Anomaly

As discussed in Section 1.2.1, the observatory design is very complex. In order to fit the 6.5m diameter telescope with a 21m sunshield into the launch vehicle's payload fairing, 50 major deployments were required. Throughout this process, there were 344 single point failures that all had to perform properly in order for the mission to achieve. This risk was generally mitigated by making the majority of the deployments similar and simple. However, not all went according to plan.

In keeping with the Observatory's penchant for holiday excitement, the deployment that occurred on December 31st, New Year's Eve, 2021 was non-standard. Upon commanding the deployment of the +J2 Aft Cover, two of the four reed switches, expected to read "DEPLOYED", remained "STOWED". The team was faced with the possibility that one of these single point failures had failed, which could have mission-ending consequences. They launched all of their available resources: contingency personnel, telemetry reviews, full-scale sunshield hardware test model, and computer models. Their goal was to provide positive confirmation or denial of the deployment via secondary indicators.

Meanwhile, the team paused in the deployment sequence, prolonging the period of time that the observatory remained in the partially-deployed configuration. This partially-deployed configuration and the resulting thermal gradient across the solar array had not been accounted for when establishing the initial power subsystem settings. Performance of the solar array at the higher temperatures along with the default settings limited the array power and was insufficient to meet observatory needs, particularly given significant heater duty cycling. The battery, which was only intended for launch and emergencies, began discharging at a low level. This became a secondary, possibly equally threatening anomaly, that had to be managed.

A few hours later, the Deployment Anomaly Response Team (DART) returned with their assessment of the deployment anomaly. They had uncovered thermal indications of a successful deployment- a thermal sensor at the top of the ISIM that went from hot to cold simultaneous with the commanded deployment. A successful deployment was the only plausible explanation for such a shadow. After careful consideration, the team concluded that the deployment had been successful, but that the cover had rolled up in an unexpected manner that did not elicit the telemetry response. [3] The team agreed to proceed with the deployment sequence. While the deployment sequence was successful, the power anomaly persisted. The team performed load shedding to maintain power margins until the next critical steps in the deployment sequence were completed. At that point, all power subsystems were adjusted, all load shedding actions were backed out and the team returned to regularly-scheduled commissioning activities.

Lesson Learned: Having a wide range of resources and rehearsed processes are critical for time-sensitive anomalies.

2.1.2 Normal Operations Anomalies

After several years of demanding pre-launch exercises and a Christmas Day launch in 2021, the team was anxious for some downtime. It was assumed that after six months of relatively smooth normal operations, the 2022 holiday season would be a welcome respite. Unfortunately, the observatory had other plans. Starting with a Safe Haven transition on December 7, 2022, the observatory experienced a series of five science-halting anomalies over the next 15 days, finally ceasing on December 22, 2022. All five of these anomalies were associated with software or configuration issues within the complicated interfaces between the Attitude Control Subsystem (ACS), Fine Guidance System (FGS), Actuator Deployment Unit (ADU), the Operational Scripts Subsystem (OSS), and real-time commanding operations. Following initial clean-up and restoring the observatory to science operations, the team initiated a three-month study to look into the root causes. This group focused on the processes associated with observatory slews, the Fine Guidance loop, the transition from real-time to OSS-driven operations, pending OSS updates, and software testing practices (see Figure 5). A series of associated improvements were implemented in summer 2023. These updates have been successful in both preventing reoccurrences and improving science efficiency. Overall, the mission was improved by these events, but they left their emotional toll on the staff, who have nicknamed the timeframe, "December To Remember". [4]

Lessons Learned:

- (1) The most common vulnerabilities were related to subsystem interfaces. Prelaunch ground testing did not eliminate all corner-cases. Create working groups as needed to facilitate interface discussions.
- (2) Following ground-commanded activities, it is important to return the observatory to a consistent, highly-defined initial state (i.e. telemetry checklist) prior to resuming science operations to prevent any unintended downstream consequences.
- (3) Anomalies will occur at the worst possible times.

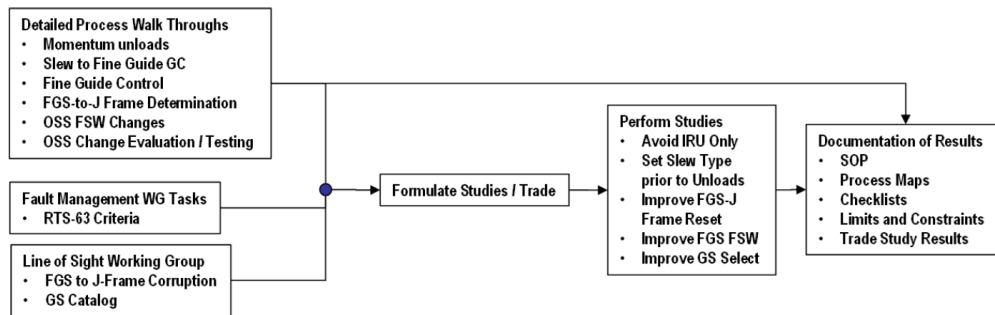


Figure 5. Working Group Study Process.

2.2 Space Environment

Webb resides in a "halo-orbit" around Lagrangian Point 2 (L2) (see Figure 6), a relatively unpopulated environment. As such, the prelaunch knowledge of the space environment was limited. The observatory was designed conservatively, but on-orbit data was still anxiously anticipated. To date, the combination of observatory hardware, L2 space environment, and admittedly luck, has led to the observatory being relatively impervious to space weather activity, being categorized here as geomagnetic storms, solar radiation events, and micrometeoroid activity.

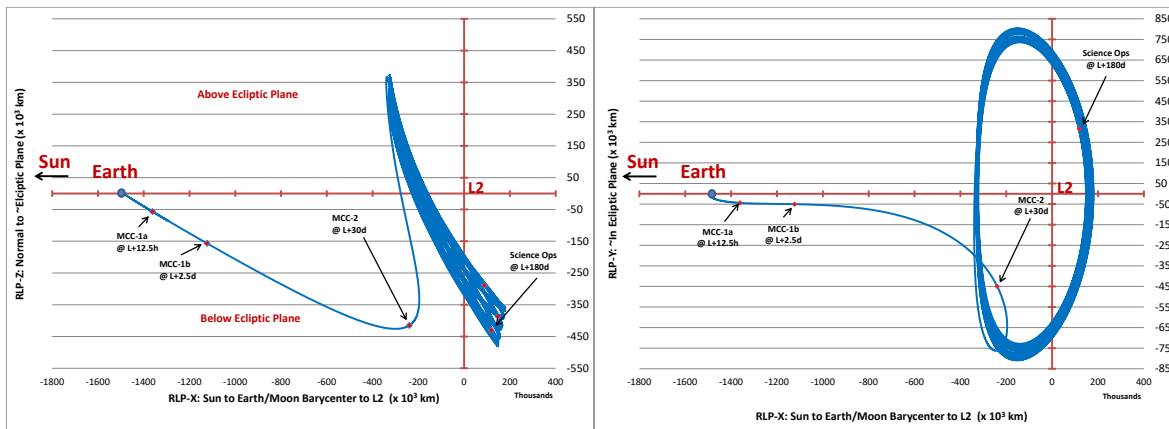


Figure 6. Webb's "Halo" Orbit around Lagrangian Point 2.

2.2.1 Geomagnetic Storms

To date, Webb appears relatively immune to geomagnetic storms. The largest event to have occurred on-orbit is the May 11th, 2024 event, which rated a G5 "extreme" rating on the National Oceanic and Atmospheric Administration (NOAA)'s geomagnetic scale. Although this event wreaked havoc for several low-altitude satellites, there were no measurable changes on the observatory.

Lesson Learned: Either due to the L2 space environment, Webb hardware design, or luck, Webb does not appear to have any sensitivity to geomagnetic activity. No precautionary measures have been deemed worthy of action.

2.2.2 Solar Radiation Storms

Webb does, however, have some sensitivity to solar radiation storms. The largest on-orbit event was on October 10-11, 2024. This storm was rated an S3 "strong" on NOAA's solar radiation storm scale and had higher proton levels than the May 2024 G5 event. Onboard, there were three noticeable effects: (1) an observable decrease in solar array output (~1%, expected and within design margin), (2) increases in one of Webb's instrument's background counts in which one science observation was affected and rescheduled at a later date, and (3) memory errors on another instrument.

Lesson Learned: Either due to the L2 space environment, Webb hardware design, or luck, Webb appears to have mild but manageable sensitivity to solar radiation storms, particularly proton events. No precautionary measures have been deemed worthy of action.

2.2.3 Micrometeoroid Activity

When analysing micrometeoroid risk, the team considers two distinct populations:

- (1) Constant risk from the sporadic background flux
- (2) Time-bounded and highly directional risk from meteor showers

Of the ~80 micrometeoroid impacts that have caused detectable wavefront error thus far, the vast majority are believed to be the result of sporadic background micrometeoroids. Of these, there has been one significant outlier: an impact to the C3 mirror in May 2022. This micrometeoroid was very roughly estimated at an energy level of somewhere around 8 J, and it raised the telescope's best achievable overall wavefront error from ~50 nm to ~59 nm (rms). This nonetheless continues to represent outstanding imaging performance, with wavefront error well below the science requirement of 130 nm rms, and significantly below pre-launch expectations.

All other micrometeoroid impacts have contributed a total of ~2 nm of uncorrectable wavefront error thus far, and Monte Carlo simulations using the observed population of impacts, rates, and effects indicate that the telescope's wavefront error will continue to be well under both requirements and pre-flight expectations, after 25 years.

Although the effects on science performance appear negligible, out of an abundance of caution, following the C3 hit, the team decided to take proactive steps to protect the observatory's exposed optics from some of the more energetic micrometeoroid strikes. Because JWST's orbital velocities are generally comparable in magnitude to those of typical micrometeoroids, by implementing an operational reduction in the amount of time that the primary mirror faces into the spacecraft's velocity vector, the mean kinetic energy of impacts can be reduced by biasing away from these potential "head-on collisions". This was implemented in the form of a 75-degree cone around the velocity vector, where the science scheduling seeks to limit observations pointed within that cone to ~20% of the time. To date, this has had a

marginal but acceptable impact on science efficiency, and a marginal but non-zero reduction in the energy distributions of micrometeoroids that affect the mirrors' wavefront errors.

For showers, the Micrometeoroid Environments Office at NASA's Marshall Space Flight Center generates an annual JWST-specific micrometeoroid shower forecast for the operations team's review and actioning. To date, only the 2024 Geminids have had flux forecast greater than the background flux, the threshold established by the team to warrant further inspection. For this shower, the team made moderate efforts to limit the amount of science observations facing the radiant during this time period.

Lesson Learned: Webb's open telescope design means it is vulnerable geometrically to micrometeoroid collisions. However, as pre-flight modeling suggested, these cause minimal degradation in the excellent science performance of this infrared observatory. Future observatories, especially if operating at UV wavelengths, will want to consider protecting the optics or otherwise mitigating the issue. In the meantime the JWST operations team will continue amassing a detailed long term empirical sampling of micrometeoroid distributions and effects at L2, which can inform such future missions.

2.3 Fuel Usage

In designing for a 5-year mission life, Webb was launched with 168 kg of hydrazine and 133 kg of oxidizer. Approximately 70% of this fuel was budgeted for the three orbit-insertion maneuvers during commissioning known as Mid-Course Corrections. Due to a fortuitous launch date and successful Mid-Course Correction burns, less than 25% of the onboard fuel was actually used, leaving Webb with significant fuel margins for its remaining life. Once in normal operations, the team found that station keepings and momentum unloads also used less fuel than expected, as shown in Table 1.

Table 1. Fuel Expenditures in Normal Operations

	Actual / Budgeted (%)	Cause
Station Keeping	67%	- Stable orbit - Burn frequency decreased from every 3 weeks to every 6 weeks
Momentum Unloads	4%	- Successful use of visit planning to manage momentum accumulation

Coupling all of these together, Webb has fuel reserves sufficient for a 20+ year mission.

Lessons Learned:

- (1) Station Keeping has only required two-thirds the expected fuel due to a stable orbit and operational decrease in burn frequency.
- (2) Attitude management has been sufficient to keep momentum unload fuel usage to an order of magnitude below expectations.

2.4 Limited Life Items

The known limited life items onboard the observatory are tracked weekly by the Flight Operations Team. This is currently accomplished via a series of macros within an Excel spreadsheet, inputting a week-long chunk of comma-delimited telemetry. Although successful for tracking limited life usage pre-launch and for the first few years of normal operations, this approach is not sustainable long-term. The large data sets and weekly data-ingests are overloading the tool. Efforts are underway to update the process to use a python-based Jupyter notebook interface to an HDF5-telemetry archive known as the Lateral-Ingest Telemetry Archive (LITA). This will result in a more extendible product which is more sustainable in the long term. Weekly updates can be performed automatically with only 10 minutes of processing. Subsystems can be queried individually and new plotting features provide an easily discernible summary. It also has the added benefit of being able to re-process all on-orbit limited life usage in less than an hour, a task not possible for the Excel-based version.

The limited life item list mainly consists of instrument mechanism movements, lamp pulses, EEPROM writes, and valve cycles. A scrub of the allowed thresholds was conducted 3 years into the mission to adjust some thresholds from "expected usage" to qualification test values. To date, no limited life items are expected to impact operations for a 20-year mission.

Lesson Learned: Limited Life thresholds should be based on best-known-lifespans, not expected usage.

3. Ground System Lessons Learned

3.1 Ground System Guiding Philosophies

Through normal operations, the management team has converged on two guiding philosophies for the ground system to maximize uptime and operations effectiveness:

1. Define and prioritize "must-haves" over "nice-to-haves":

Setting clear, upfront expectations of ground capabilities is extremely important. Without it, team members may good-naturedly exert too much effort in restoring non-critical systems or inadvertently delay restoring critical systems. In the case of Webb, these expectations are defined in Table 2.

Table 2. Ground Capability Priorities

	Capabilities	Expected Mean Time to Resolve (MTR)	Tracked Via
Must-Haves (Impacts cannot be worked around during real-time contacts)	Command and Control at both the Mission Operations Center (MOC) and Backup Mission Operations Control Center (bMOC)	Hours	Ground Management Board (GMB)
High Nice-To-Haves (Impacts can be worked around during real-time contacts)	Remote web access Observatory alarm text message notification system Project webpages Ticket tracking system	1-2 Days	Daily Reports and Weekly Meetings

2. To the extent possible, control your own destiny:

Create a proactive team culture. Make plans that have minimal external reliance. When external issues arise, coordinate, advocate for yourself, and follow-up. In the case of Webb, the team already excelled in this area, but including it as a guiding philosophy helped to reinforce the culture.

Lesson Learned: Define ground priorities and expectations clearly pre-launch.

3.2 COVID Impacts

COVID significantly impacted the pre-launch exercises, launch, and commissioning of Webb. This was most visible via the control center's workstation footprint. Originally, it was intended that all 300 personnel per commissioning shift would support in the 4600 sq ft MOC, often sharing workspaces. However, in attempts to maintain social distancing, a multi-pronged approach was implemented:

- 27 offices (4000 sq ft) were temporarily added to the MOC footprint, outfitted with additional workstations.
- Existing workstations were spread out. In some cases, this required labelling functional workstations unusable.
- Higher reliance was placed on remote work. This was supported by a web interface for telemetry viewing and remote access to project webpages and ticket tracking systems. Voice loops were also available remotely, allowing external personnel to communicate with onsite personnel.

Throughout 2020-2022, the usage of the workstations was constantly in flux depending on the desired personnel density. When local COVID risk levels were high, occupied workstations maintained a minimum of 6+ ft. When COVID risk eased, all available workstations were restored. As commissioning ended and onsite staffing needs decreased, control center workstation space was returned to normal office space.

During Webb's COVID commissioning, the team demonstrated an ability to adequately monitor telemetry and troubleshoot using the web interface. This paved the way for using the web interface post-commissioning, particularly in off-hours when staff are offsite and timing is critical and/or the amount of support required is minimal. However, when ground commanding requires subsystem support, the expectation is for all required personnel to be onsite. This is because the telemetry web interface is categorized as "nice-to-have" and cannot be guaranteed.

Lesson Learned: An agile facility that is easily reconfigured plus a web interface for remote operational support will provide flexibility for both changes in mission phase and unforeseen world events.

3.3 Handling of Observatory vs Ground Anomalies

Pre-launch, the observatory anomaly management process was clearly defined and practiced. As discussed in Section 2.1, it included large-scale (300+ person) meetings with primary stakeholders voting on a path forward. In contrast, ground issues were managed through a weekly Discrepancy Review Board (DRB) after resolution. During commissioning, this approach for the ground worked well, given that both ground experts and management were available around-the-clock, allowing them to work problems together in real-time. Upon transitioning to normal operations, however, as both ground engineers and management transitioned to on-call, the lack of a high-level governing board for time-critical discrepancies caught up to the team. In November 2023, there were ground issues that prevented the control team from using the Mission Operations Center (MOC) to command the observatory. Twice, back-to-back, the team had moved operations to the Backup Mission Operations Center (bMOC), located at Goddard Space Flight Center (GSFC). This larger impact forced management to re-evaluate their processes. In January 2024, management instituted a Ground Management Board (GMB) process, a modified version of the observatory's Anomaly Management Board (AMB) process, customized for the ground stakeholders. The intent was to increase awareness and coordination for anomalies that impacted the "must-have" command and control capabilities at the control center and backup control center. This effort has been successful, as demonstrated by a more-coordinated bMOC failover in August 2024.

Lesson Learned: Define ground anomaly processes pre-launch, keeping expectations on-par with observatory processes.

3.4 Automated Alarm Notification

A novel aspect of the Flight Operations System is an automated alarm notification system, in which both observatory and ground telemetry out-of-limit events result in text message notifications to on-call personnel. This system, known as the Notification and Response System (NRS), allow management to schedule on-call personnel by subsystem. When a telemetry item exceeds its limits, a text message is sent to the on-call subsystem engineer's cell phone. The typical work flow is for the recipient to acknowledge the notification within a pre-defined amount of time, currently set to 20 minutes. By acknowledging the text, the subsystem engineer is committing to investigating the alarm and recruiting support as needed. If the on-call engineer does not respond, the alarm is escalated to the next person in the escalation list, typically increasing up the management chain. This process has been hugely successful in facilitating prompt response of telemetry alarms.

Activating NRS required several months of tweaking alarm limits and filtering nuisance alarms. This was a tedious but necessary process. The result is that currently, most text messages are "real" alarms worthy of further investigation.

An added benefit is the system's ability to keep management aware of anomalous behaviour via an "info only" text messages. These text messages do not require response, but provide real-time logging of all alarms and subsystem engineer acknowledgements. This aspect has been more heavily utilized than originally anticipated, with four managers typically being scheduled for each subsystem.

Lesson Learned: Flight Operations Teams should prepare to dedicate several months to tweaking alarm limits and filtering nuisance alarms, both for the observatory and the ground, upon transitioning to normal operations. If automated alarm notification systems are available, they are highly valuable for the consistent, automated, prompt reporting.

3.5 Trending Approaches

As discussed by Kauffman, Hunter, and Arvai [5], it was identified pre-launch that the Flight Operations Team would need access to a fast and agile telemetry analysis system. However, development efforts for Webb's flight operations system was focused on maintaining compatibility with the multiple ground stations required during commissioning. As such, it was decided to offload this requirement to an offline toolset. This toolset, known as the Lateral Ingest Telemetry Archive (LITA), was built from a base of open-source software developed by NASA's Chandra program, modified for Webb's telemetry set. Although the Flight Operations System (FOS) is still used for real-time telemetry monitoring, LITA has been successful in meeting the team's telemetry trending needs:

- Weekly trending, including automated anomaly detection intended to capture changes within alarm limits
- Monthly trending, including life-to-date plots
- Annual subsystem presentations

Lesson Learned: Fast, agile telemetry analysis systems, critical for triage, troubleshooting and trending, should be included in the baseline ground system design.

3.6 Ground System Automation

As control centers evolve in the 21st century, a consistent theme is increased automation. Implemented correctly, it promises improved efficiency, consistency, and cost savings. These benefits must be weighed against the risks. Webb, as a Class A mission, is risk-adverse, but is still taking cautious steps towards automation of its "typical" commanding to reap some low-hanging benefits. The approach is tiered:

1. Manual commanding only – Used during commissioning
2. Monitored automation of ground setup and teardown of DSN contacts – Began in fall 2023
3. Monitored automation of both ground setup/teardown and typical spacecraft commanding – In work

In this context, "monitored automation" refers to automation that is being monitored by control team members, intervening as necessary. To date, this has been successful in providing consistency in ground setup and teardown, while also offloading the repetitive commanding from the control team members, allowing them to focus on monitoring observatory telemetry and ground connections. When real-time changes are required, the control team has the option of adjusting the timing or manually taking control. For example, if a ground antenna is having a hardware issue, the control team can delay the bind connections until an all-clear is issued by the station.

Lesson Learned: Automation has its time and place. Even if wholesale lights-out adoption is not practical for a given application, there are likely smaller variations that can be cautiously considered.

3.7 bMOC CONOPs Change

Like most backup control centers, the Backup Mission Operations Center (bMOC) at Goddard Space Flight Center was designed for health and safety only. It was not designed for science operations. Although this was helpful for clarity of purpose and design pre-launch, post-launch realities have exposed the real-world implications. Webb has already encountered four instances when the bMOC has been activated:

- In 2024, the Muller building that houses the Mission Operations Center (MOC) required some power-upgrades. To support this, Webb operations had to be transferred to the bMOC for a one-week period.
- Throughout 2023 and 2024, there were three instances of Flight Operations System (FOS) anomalies that prompted operations to be transferred to the bMOC for one day each.

Throughout these events, the team made small modifications to the bMOC CONOPs, including allowing the uplinking of pre-made observation plans and downlinking of science data from the bMOC. This allowed science operations onboard to continue. The CONOPs is not fully redundant and cannot guarantee continuity of operations, but it does increase the odds. This need has been further reinforced by real-world events, such as annual hurricanes along the east coast and the 2025 California wildfires impacting JPL. It will also be beneficial for future Flight Operations System hardware and software updates.

Lesson Learned: Although backup ground systems are often designed for health and safety, using reasonable efforts to expand their capabilities to support science operations provides flexibility and a higher chance of continuity of operations in the event of a ground anomaly.

4. Conclusions

With its complex design and challenging COVID launch environment, Webb charted a difficult but successful path through launch, 6-months commissioning, and 3-years operations. The Webb management team has noted the following lessons learned that may be applicable to future missions:

- Establish Working Groups (WGs) early and concentrate on interfaces: Even with robust ground testing, corner-cases in flight software still exist. In Webb's case, most vulnerabilities were related to subsystem interfaces. Establishing working groups to facilitate communication between subsystem teams was essential to optimizing future operations.
- Create detailed telemetry checklist to return observatory to a known configuration: The team found it beneficial to create a detailed telemetry checklist to ensure a consistent, highly-defined observatory state following any ground commanding.
- The L2 environment is not harsh: Webb does not appear to have any sensitivity to geomagnetic activity. It does, however, have mild but manageable sensitivity to solar radiation storms, particularly proton events. To date, these events have not been significant enough or predictable enough to warrant preventative action. The team does, however, statistically minimize attitudes at higher risk of micrometeoroid collisions. To date, the cumulative effects of micrometeoroid collisions has had a minimal effect on Webb's optics, but future missions may still wish to consider mitigation options.

- Momentum can be effectively managed with attitude: Even with its large sunshield and corresponding torques, attitude management has been very successful in minimizing momentum accumulation and decreasing momentum unloads to a frequency of approximately one every six weeks.
- Don't forget about ground issues: To the extent possible, it is beneficial to keep expectations for ground monitoring, trending, and anomaly management on-par with observatory expectations. This will support quick triage and presentation of failover options to management.
- Offline trending systems need to be fast and agile: telemetry analysis systems are critical for triage, troubleshooting and trending.
- Backup control centers should be enhanced, not just for health and safety anymore: Reasonable efforts to expand backup control center capabilities beyond health and safety can help ensure continuity of operations and science during ground anomalies.

With fuel, power, and Limited Life Item margins for 20+ years, the foreseeable future for the Webb mission looks bright. The team focus going forward will include:

- Personnel development: cross-training, troubleshooting and analysis training
- Documentation: engineering guides, procedure updates
- Ground automation
- Strengthening ground processes

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