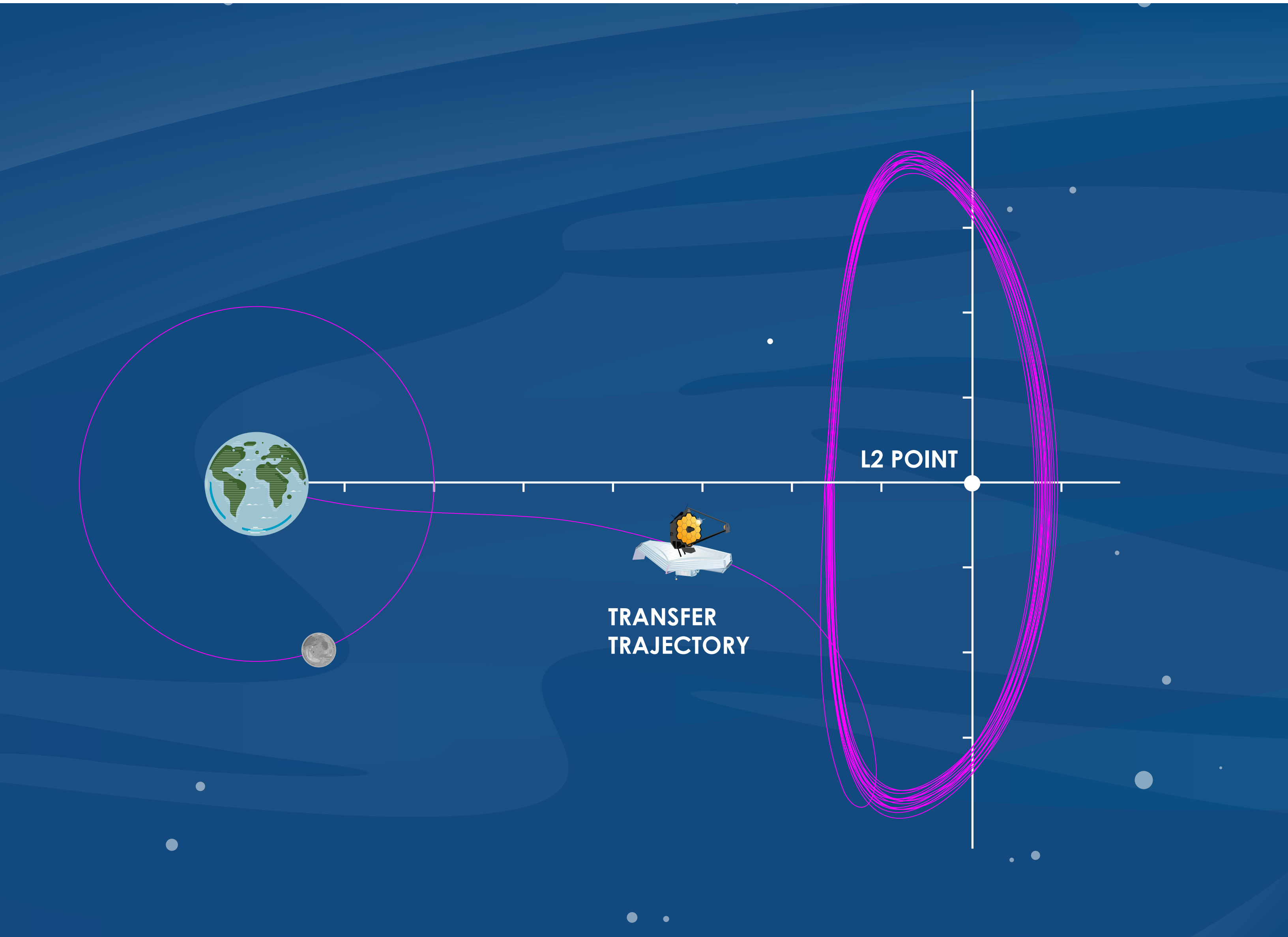
Flight Dynamics Planning And Operations Support For The JWST Mission

Written by: Karen Richon[*], Jeremy Petersen[†], and Ann Nicholson[‡]



AAS 22-611

FLIGHT DYNAMICS PLANNING AND OPERATIONS SUPPORT FOR THE JWST MISSION

Karen Richon,[*] Jeremy Petersen,[†] and Ann Nicholson [‡]

The James Webb Space Telescope (JWST) was launched from Kourou Spaceport on December 25, 2021, at 12:20 UTC on an Ariane 5 launch vehicle. The launch vehicle inserted JWST into a 30-day transfer trajectory to the Sun-Earth-Moon (SEM) Lagrange point L2 region. JWST executed three mid-course correction maneuvers (MCCs) to insert the spacecraft into a quasi-halo orbit about SEM L2; JWST will maintain its trajectory about L2 for at least 5.5 years, with a goal of at least 10.5 years. This paper summarizes the flight dynamics support for JWST, including the prelaunch nominal trajectory design, the launch window analysis, contingency planning for trajectory-related anomalies, mission operations support for the first 6 months, and a comparison of the planned and achieved actual JWST trajectory results. The orbit determination strategy, both planned and executed, will be summarized, and the method of addressing the anomalies as they occurred will be included.

INTRODUCTION

The James Webb Space Telescope (JWST) is a deep space infrared observatory investigating the history of the universe. JWST was launched December 25, 2021, at 12:20 UTC from Kourou Spaceport, French Guiana on an Ariane 5 with a cryogenic upper stage, the ESC-A+, into a transfer trajectory to the Sun Earth-Moon (SEM) L2 region. After injection, JWST performed mid-course corrections (MCCs) using a bi-propellant propulsion system to finalize injection into a quasi-halo orbit about the SEM L2 region one month after launch; station-keeping orbit maintenance began approximately 21 days later.

This paper will give a brief overview of the JWST mission and the transfer trajectory, followed by a discussion about prelaunch support, focusing on the trajectory-related aspects of the mission. There will be a brief summary of the support provided by the personnel, the Flight Dynamics Team (FDT) and facilities, primarily the Flight Dynamics Facility (FDF) at NASA God-

---

[*] Navigation and Mission Design Branch/595, NASA GSFC, 8800 Greenbelt Rd, Greenbelt, MD 20771, karen.v.richon@nasa.gov

[†] Aerospace Engineer, a.i. solutions, Inc., 4500 Forbes Blvd. Suite 300, Lanham, MD 20706, jeremy.petersen@ai-solutions.com.

[‡‡] Aerospace Engineer, a.i. solutions, Inc., 4500 Forbes Blvd. Suite 300, Lanham, MD 20706, ann.nicholson@ai-solutions.com.

dard Space Flight Center (GSFC). The launch events and MCCs as flown will be compared to prelaunch nominal predictions and the impacts will be discussed, followed by conclusions.

Mission Overview

Figure 1 is a graphic of the JWST mission interfaces and communications assets from launch through the start of science operations at Launch (L) +6 months[1]. Starting at the left of the Figure, the Ariane 5 launch vehicle (LV) and its upper stage delivered JWST to the transfer orbit, with separation of the LV and the observatory at L + 27 min. JWST deployed the solar array immediately after separation.

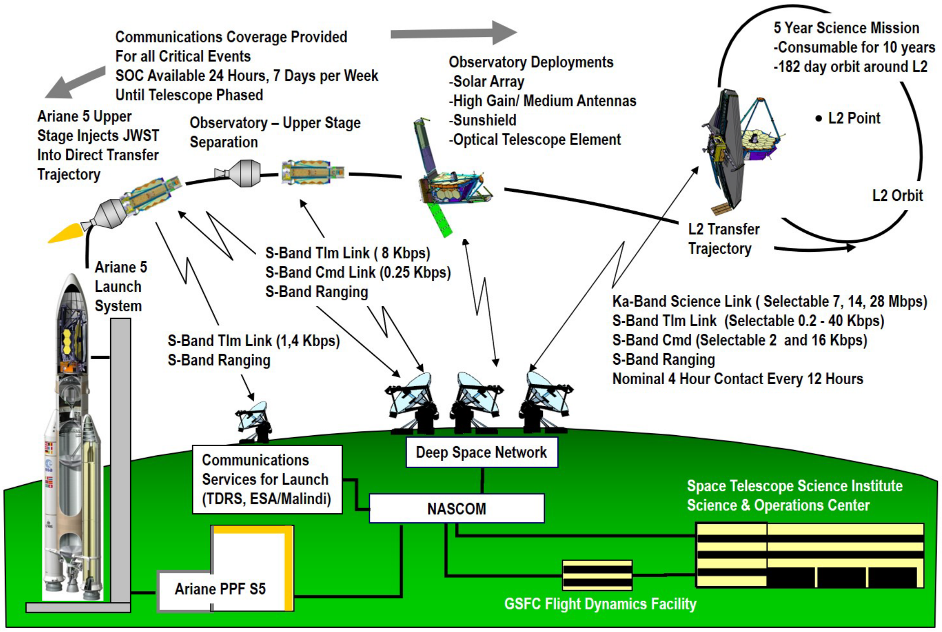


Figure 1. JWST Mission Overview from Launch to Science Mission Operations.

During powered flight, NASA's Space Relay (SR) Tracking and Data Relay Satellites (TDRSs) TDRS-W and TDRS-Z provided low-rate telemetry, continuing after separation until acquisition at Malindi less than 10 minutes later. The SR operated in non-coherent mode, so no usable tracking measurements were available. SR backup emergency support continued until L+6 hours.

The European Space Tracking (ESTRACK) network's Malindi 10-m ground antenna in Kenya, provided S-band range and range rate data in addition to telemetry and command for the first and third ground station contacts, filling in the gaps in NASA's Deep Space Network (DSN) coverage through L+ 6 hours. Usable tracking data from Malindi started at L+41 min.

NASA's DSN, consisting of 34-m beam wave guide antennas at Goldstone, Canberra, and Madrid, provided S-band telemetry, command, range, and range rate during all contacts, starting at L+110 minutes with DSN Canberra for the second ground contact of the mission. Near-continuous contacts started around L+6 hours using the Madrid 34-m antenna, followed by Goldstone support, which started around L+13.5 hours. Continuous DSN coverage was required by JWST for the first 120 days, dropping to 16 hours per day until the end of the Commissioning phase at L+6 months. High-rate telemetry from JWST's high gain antenna via DSN Ka-band downlink services started at L+25 days, concurrent with the S-band 2-way services. After Commissioning ended in mid-July, 2022, the contact requirements dropped to eight hours a day, ideally four hours from two different DSN stations; this amount of DSN coverage will continue for the life of the mission. The FDT receives tracking data whenever the DSN S-band services are active, which provides the orbit determination (OD) process ample tracking data. It was easier for network schedulers and operators to enable ranging for the entire DSN contact than scheduling partial-pass tracking services. After the first DSN contact, the JWST transponder has remained in coherent mode, enabling range rate data whenever a 2-way contact occurs. The FDF, the Space Telescope Science Institute's (STScI) Science and Mission Operations Center (S&OC), and the tracking networks used NASA Communications (NASCOM) to interface with each other, as shown in the bottom of Figure 1.

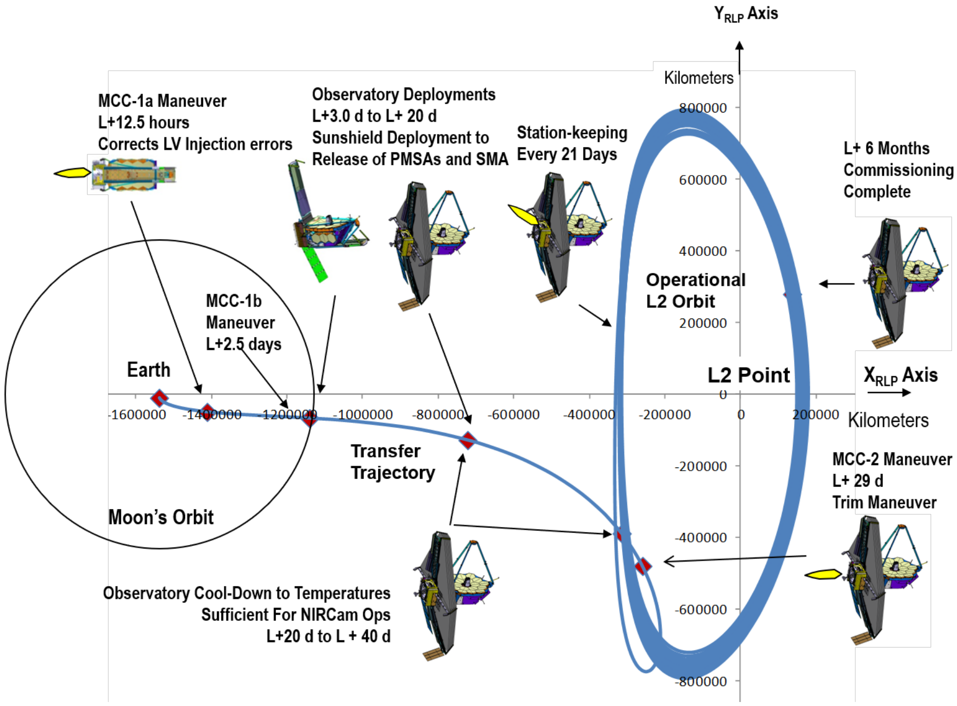


Figure 2. Timeline for the JWST transfer trajectory.

Trajectory Design and Mid-Course Correction Maneuvers

The transfer trajectory events are shown in Figure 2[1]. The targeted separation state energy provided by the Ariane 5 LV was deliberately biased low to ensure JWST did not overshoot the L2 region, because energy could not be easily removed during the transfer phase. The energy required to reach SEM L2 and correct any LV dispersions was added through execution of the three MCC maneuvers, resulting in arrival at the SEM L2 approximately 30 days after launch. The first two MCCs, MCC-1a and -1b, were performed at L+12.5 hours and L+2.5 days respectively, while JWST was in its stowed configuration. MCC-2, performed 29 days after launch, was the first trajectory maneuver after observatory deployments. Because the spacecraft center of mass changed so significantly after sunshield deployment, the MCC-1a/1b Secondary Combustion Augmentation Thruster (SCAT) could not be used for subsequent trajectory maneuvers. A SCAT aligned along the post-deployment center-of-mass was utilized from that point on for the MCC-2 and all station-keeping (SK) maneuvers. See References 2 and 3 for details about the MCC support and results of MCC maneuvers.

THE JWST FLIGHT DYNAMICS TEAM AND OPERATIONS FACILITIES

This section describes the flight dynamics engineers who supported the mission, the operations centers they used to support the mission, and the staffing plan for the first 72 hours of the mission.

NASA GSFC's Navigation and Mission Design branch (NMDB) provided the flight dynamics support for JWST. The JWST FDT consisted of NASA civil servants and Flight Dynamics Support Services-III contractors (a.i. solutions, Omitron and Pearl River Technologies). The FDT provided the software development, trajectory design, orbit maneuver support, and OD for the prelaunch, launch and commissioning phases of the mission out of the FDF in GSFC Building 28. This support will continue for the life of the mission.

The multi-mission FDF provided the infrastructure for the flight dynamics prelaunch and mission operations support, including tracking data ingestion and processing, as well as interfaces with tracking networks and S&OC in Baltimore, MD. As mentioned earlier, the FDF and the S&OC are shown at the bottom of Figure 1 as part of the overall JWST facility support structure.

The FDT used a combination of mission-specific and FDF flight-proven software to support JWST. The JWST Flight Dynamics Ground System (FDGS) ingests pre-processed telemetry from the S&OC and tracking data measurements provided by the DSN, performs sequential filter OD, trajectory maneuver planning and reconstruction, and creates ephemerides and mission planning products. The FDGS core computation engines are a.i. solutions' FreeFlyer and ANSYS Government Initiatives' (AGI's) Orbit Determination ToolKit (ODTK). ODTK provides the primary OD functions while FreeFlyer provides the remaining astrodynamics functionality including maneuver planning, reconstruction, and calibration, view period generation, slant range calculations, and all non-OD related analysis. The batch least squares functionality from NASA's Goddard Trajectory Determination System (GTDS) was used as the primary OD tool prior to MCC-1b. GTDS processed S-band radiometric range and range rate measurements from Malindi in addition to DSN for the first 6 hours. The FDGS is described in Reference 4.

FD Support Facilities

The FDT real-time operations, including prelaunch rehearsals, simulations, and operational software testing, were supported out of the FDF Mission Operations Room (MOR) in GSFC's Building 28. The JWST FDF backup facility in Building 13, referred to as the backup MOR (bMOR), was also tested and ready for support if the prime FDF was unavailable. A generator for the FDF MOR was tested and staffed for emergency power support in case a power failure to the FDF occurred during the launch countdown through the first 24 hours of the mission, or until MCC-1a was complete.

Figure 4 shows the FDF MOR floor plan for launch and early orbit operations. The workstations with the green box around them indicate the JWST-specific consoles; other consoles were manned by FDF staff supporting the launch and the first few hours. At a minimum, the maneuver planning team and OD teams were staffed with a primary and back-up member to ensure quality assurance for all product generation. Due to COVID-19 protocol, the console set ups for the maneuver planning team and OD team were altered slightly to enable screensharing while maintaining a minimum proximity. Each workstation is a dual monitor setup however, the secondary monitor is a mirror of the primary monitor of a partner computer. This mirror screen setup enabled each pair to double check the processes run by the primary operator while maintaining COVID-19 distancing protocols.

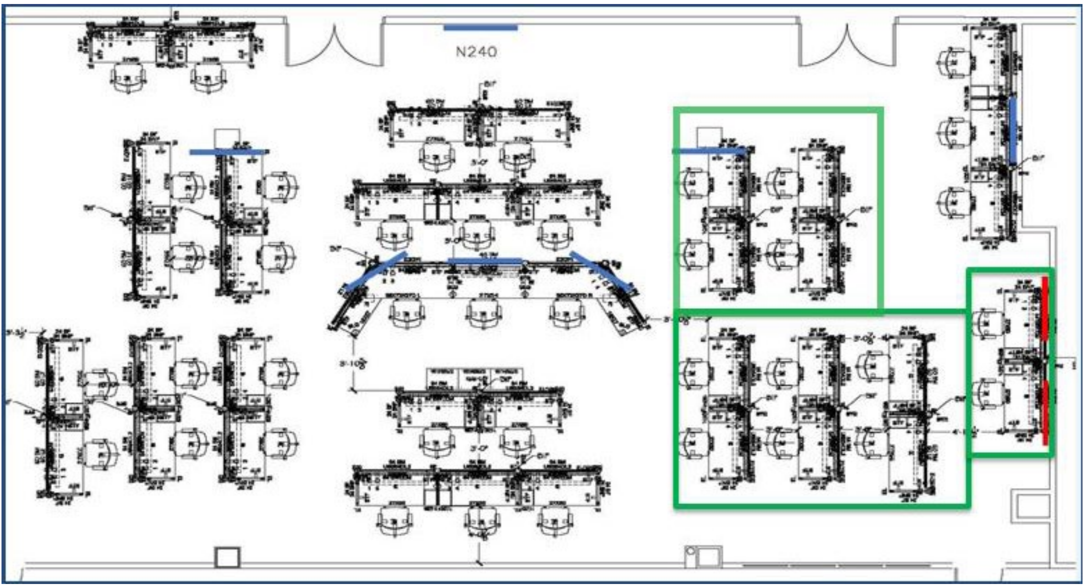


Figure 3: FDF MOR floorplan for JWST operations. The region in highlighted was reserved for the JWST FDT[5].

The bMOR for JWST FD support is shown in Figure 5. All operations except launch support could be performed in this location in an emergency situation. The bMOR was not large enough to host all the personnel needed for the first few hours of the mission but could be used for other support periods if needed. While most of the operations and rehearsal support was done in the FDF MOR, the FDT supported simulations and interface testing at the bMOR with the S&OC and its backup, the backup Mission Operations Center (bMOC), in GSFC's Building 29 to ensure that all facilities could provide support across any configuration of MOR/bMOR and MOC/bMOC staffing.

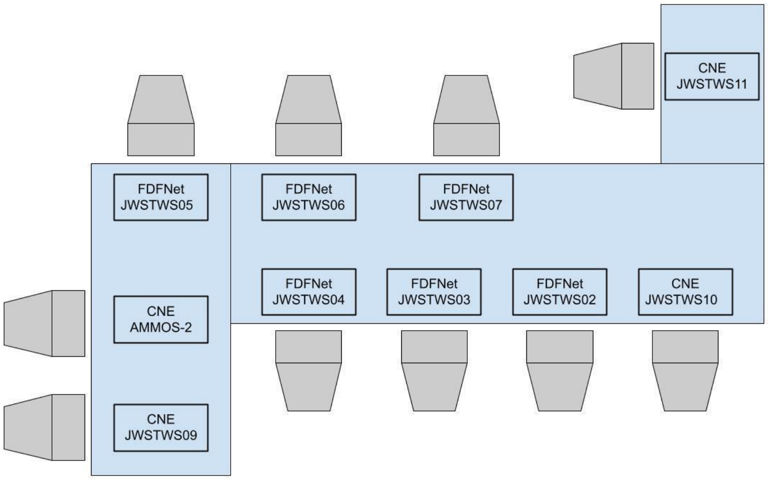


Figure 4. Layout of the FDF backup MOR for JWST operations[5].

Flight Dynamics Launch and Early Orbit Staffing and Shift Support

The FDT/FDF real-time, around-the-clock support began at L-6 hours and continued to L+72 hours. Early orbit operations consisted of two 12-hour shifts staffed with flight dynamics engineers (FDEs), primarily, who performed analysis and operations support. The early orbit operations shifts included:

- 4 FDEs for mission planning and maneuver planning, monitoring, reconstruction and calibration, view period predictions, and product generation and delivery
- 4 FDEs for OD and DSN/Malindi acquisition data
- 1 FDE shift lead
- 1 FDE liaison to the S&OC

Additional real-time support for shorter shifts around launch and critical maneuver operations (such as MCC-1a and MCC-1b) included:

- 2 FDT/FDF software developers for the FDGS and GTDS
- 2 FDEs for TDRSS acquisition data generation
- 1 FDF systems administrator/engineer for facility operations, hardware maintenance and IT security
- 2 NASA GFSC electricians to test and operate the backup generator during launch and MCC maneuver critical operations

All roles except the S&OC liaison were assigned to the FDF in the original staffing plan. The S&OC liaison provided technical and communications support to the mission Flight Operations Team (FOT), the Mission Systems Engineers (MSEs), and Project Management (PM). Pre-pandemic plans required two FDT liaisons, one at the S&OC in Baltimore, MD, and the other at the bMOC in Building 29 at GSFC. After the pandemic shutdown occurred, restrictions in the number of personnel allowed to support at STScI and at the bMOC resulted in the S&OC liaison position being moved to the FDF and reduced to one per shift. Required support was provided to the MOC and bMOC staff using two voice loop systems, Quintron and Mission Operations Voice Enhancement system (MOVE), text, email, and videoconferencing. The voice loops contained several subchannels which were beneficial for direct communications to specific subsystems without having to disrupt the main PM channel.

Once the MCC-1b maneuver was successfully executed and preliminary calibration performed, FDT support dropped from around-the-clock to daily 8 hour shifts through L+30 days until the day after the MCC-2 maneuver. Thereafter, support was generally 8 hours/day with a reduced on-console team through L+6 months. The FDGS will be updated to a final post-launch release no later than August 31, 2022, accommodating product updates to and from the S&OC for the Cycle 1 science operations support. Cycle 1 is the first year of science operations after the six-month commissioning phase. FDF multi-mission operations staff will support JWST starting in August 2022 and will continue support throughout the mission lifetime.

PRELAUNCH SUPPORT

Three FD prelaunch activities are addressed in this section: Malindi tracking site criticality and FDF certification, launch window analysis and prelaunch product deliveries, and special considerations for launching during a pandemic.

Criticality of Malindi Tracking Data Interface

The Malindi support for the first and third ground station contacts of the mission was critical to the success of the JWST mission, providing vital telemetry, tracking, and command to supplement the DSN support, since DSN was not always in view the first 6 hours of the mission. The MCC-1a burn plan and associated products were due to the S&OC no later than 4 hours before maneuver start time. The maneuver planning team required 1 hour to generate and double check the final MCC-1a maneuver plan from the FDT. The combination of the timing requirements resulted in the tracking data cutoff at L+7 hours. If the post-launch OD did not have usable Malindi data, additional tracking data would be required to converge on a reliable solution. Reference 7 describes the early mission orbit determination. Previous analysis showed that delaying MCC-1a from L + 12.5 hours to L+19.5 hours would be needed in order to allow for the collection of additional tracking data from the DSN to properly plan the maneuver.

Figure 6 shows the expected view periods of the Malindi and DSN antennas for the JWST early orbit, with the minimum required duration of usable tracking data noted above the bar for each antenna with the blue brackets. The 1.5 sec SCAT test burn was scheduled for L+7 hours, after the tracking data cut-off. The primary MCC-1a start time was L+12.5 hours, with a fully planned and tested backup MCC-1a at L+14.5 hours. Note the MCC-1a burn start time spans an hour; the concept of operations was to use the same MCC-1a duration and attitude for up to an hour before delaying to the L+14.5 hour plan. Similarly, the burn duration and optimal attitude for a L+14.5 hour MCC-1a could be used up to L+15.5 hours. Previous analysis had shown the delta-velocity (Δv) penalty was small for up to an hour delay[10]. With this concept, the S&OC could accommodate minor delays without a major replan and new upload to the observatory.

Prelaunch analysis showed that at a minimum, 30 minutes of tracking data was required from Malindi, 90 minutes of tracking data was required from Canberra, and 60 minutes of tracking was required from Madrid to guarantee an OD solution with sufficient quality that could be used for MCC-1a planning at the L+7-hour cutoff time. If 30 minutes of usable tracking data from Malindi were not available, the primary MCC-1a execution time would be delayed from L+12.5 hours to L+19.5 hours to allow for collection of one hour of tracking data from Goldstone, which was available after L+13.5 hours. Because Malindi tracking data was necessary for executing MCC-1a at L+12.5 hours, it became critical to certify Malindi tracking data for use in the FDF.

If the 30 min of usable tracking data from Malindi were not available, both the nominal and backup plans were delayed to L+ 19.5 and L+ 21.5 hours respectively. This was to allow at least an hour of Goldstone tracking so that the OD solution could converge. As seen in Figure 6, Goldstone 2-way tracking could not start before L+13.5 hours. Reference 2 describes the procedures for the 12.5 and 14.5 hour plans, while Reference 3 details the real-time contingency strategies and support of MCC-1a. The nominal MCC-1a burn scenario required early Malindi tracking, which is why the certification for FDF was critical.

Malindi Certification

FDF certification includes testing which demonstrates the facility can receive and correctly process tracking measurements from an antenna; in this instance, it was Malindi 2a, the 10-m S-band antenna that would be used for JWST tracking during the first 6 hours from launch. Themis spacecraft were used for testing due to their highly elliptic orbits that are similar to JWST's transfer trajectory early in the mission.

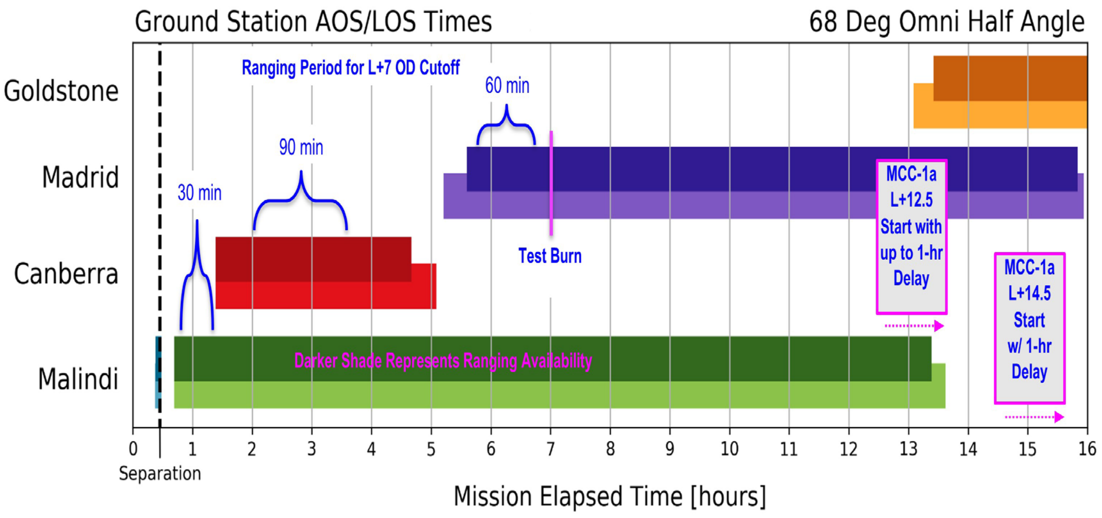


Figure 5. Early orbit view periods with DSN and Malindi. Blue brackets highlight the minimum required tracking data to support OD at L+7 hours[11].

The original plan was for FDF to complete its Malindi data certification by mid-2020. The certification campaign started in late 2019 with 7 passes, with the expectation of additional passes in early 2020. However, the entire certification campaign was halted for a year due to the pandemic shutdown. Themis mission operations and the Malindi tracking site were limited to critical mission support only and JWST's FDF certification did not qualify as such. Even after the pandemic restrictions were partially relaxed in late 2020, personnel working at the sites had short hours and limited availability for the JWST test passes. Table 1 lists the certification passes, with the 5 additional passes in 2020 and 5 more in 2021 that were needed to complete the testing.

Table 1. Malindi 2a Certification Passes

Spacecraft	Date	Start (UTC)	End (UTC)	Duration (min)
THEMIS-D	2019-11-15	19:41	19:57	16
THEMIS-A	2019-11-20	13:42	14:10	28
THEMIS-E	2019-11-21	19:49	20:06	17
THEMIS-A	2019-11-25	16:49	17:17	28
THEMIS-D	2019-11-27	13:20	13:47	27
THEMIS-A	2019-12-03	16:05	16:33	28
THEMIS-D	2019-12-04	13:06	13:21	15
THEMIS-A	2020-11-24	16:11	16:31	20
THEMIS-D	2020-11-25	15:52	16:09	17
THEMIS-A	2020-12-02	15:41	15:59	18
THEMIS-E	2020-12-11	14:52	15:19	27
THEMIS-E	2020-12-18	15:03	15:29	26
THEMIS-A	2021-02-01	08:35	08:58	23
THEMIS-A	2021-02-26	05:02	05:23	21
THEMIS-D	2021-03-02	10:03	10:26	23
THEMIS-D	2021-03-08	08:04	08:30	26

THEMIS-E	2021-03-10	09:49	10:00	11

Range and range-rate tracking data from Malindi 2a antenna were received and evaluated against operational orbit solutions for THEMIS-A, -D, and -E. Criteria for certification were:

- There must be at least five (5) passes on a satellite, each providing usable measurements
- Range-rate measurements must also be coherent 2-way
- Either the five (5) most recent, or eight (8) out of ten (10) passes must meet the Root-Sum-Square (RSS) requirements of 40 meters range and 0.004 m/s range rate.
- Certification must be complete no later than L-6 months

There were 17 events within the certification period. The 7 passes from the 2019 certification campaign required much editing and reprocessing, with only 4 successful events. The measurement model needed to include a range ambiguity resolution that had to be computed in OD systems, requiring modifications and testing for GTDS and ODTK, which were completed before the 2020 passes began. The 2019 certification campaign data were not included in the overall statistics to demonstrate compliance with criteria.

The 2020 and 2021 certification campaigns had a total of 9 successful events within the certification period. This satisfied the criteria for number of successful passes required for certification. Utilizing all events within the certification period for the 2020 and 2021 campaigns provided a total Range RSS of 35.82 meters, within the certification criteria of 40 meters. The total range-Rate RSS of 0.03 m/s is also within the certification criteria of 0.04 m/s[10]. FDF analysts were able to complete the analysis and certification in April 2021, within the 6-month requirement for an October 31st launch. Proficiency passes were required every three months until launch to maintain certification. The FDF and S&OC also verified the timing requirements for the Malindi data delivery to FDF in real-time testing prior to launch. While the certification process took longer than expected, it was an essential to the success of JWST's launch and MCC1-a planning.

JWST Launch Window Updates

JWST's launch date slipped frequently during the last nine months before launch, seemingly planned to slip to every major American holiday in the last quarter of 2021, though this was not by design. The launch date as of March 2021 was Halloween (October 31). By July 2021, the launch had slipped to the day after Thanksgiving (November 26), then to Hanukkah (November 28-December 4), to December 18, and then finally to Christmas Day, December 25, 2021, when JWST was launched at the opening of the launch window at 12:20 UTC.

The FDT generated the JWST launch window using the final predicted separation state provided in June 2021 by Arianespace. Figure 7 shows the launch window as of July 2021, with the UTC launch time of day on the vertical axis and launch date on the horizontal axis. Although this is not the final launch window, it is representative of all the dates considered for late 2021, from October 1 through December 31, 2021. The final launch window is more focused on the actual launch times and is presented in Reference 2.

The launch window was generated in three phases. The first phase was performed by the JWST FDT to calculate the valid launch opportunities based on orbit geometry and Δv requirements. The second phase was performed by Arianespace, National Centre for Space Studies (CNES), European Space and Operations Centre (ESOC), and the European Space Agency (ESA). The second phase focused on LV requirements, observatory thermal requirements during powered flight and at LV separation, and LV upper stage disposal requirements. The third phase, not shown in Figure 7 but available in Reference 2, was performed by the JWST FDT by reducing the launch window from 5-minute increments down to 1-minute increments three months out from launch.

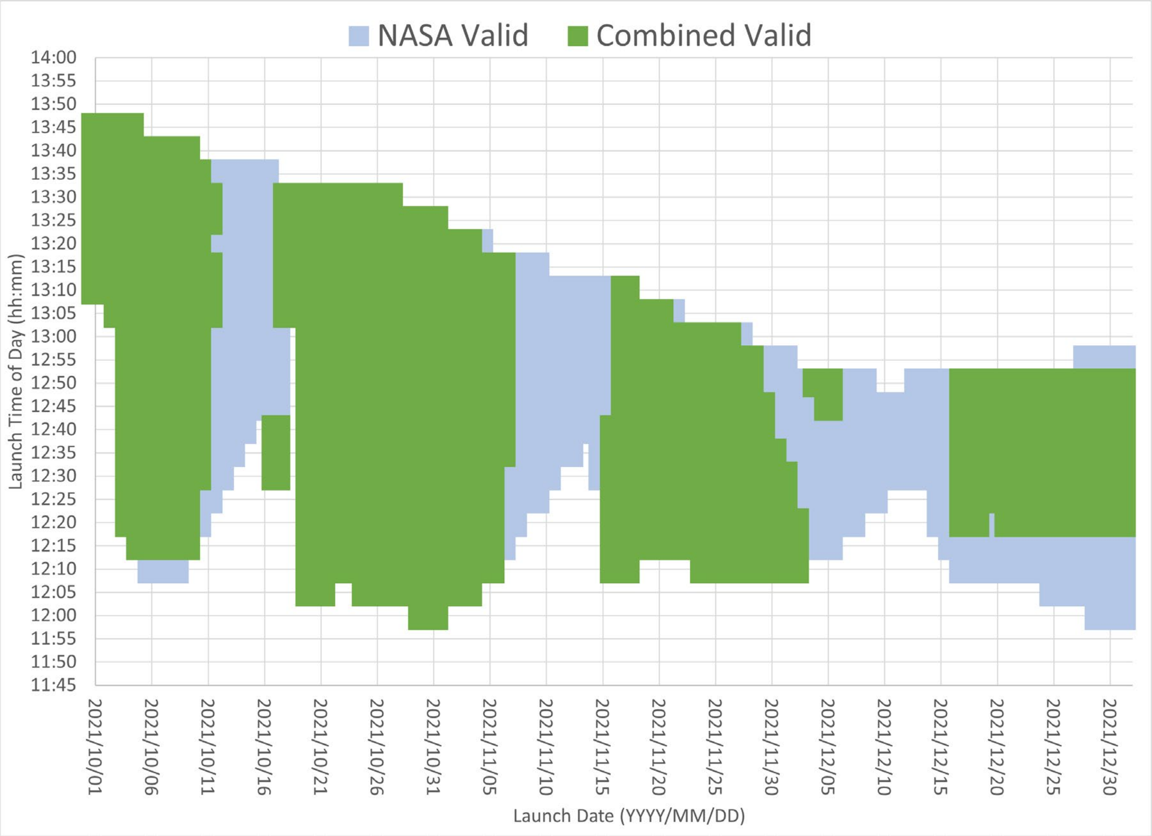


Figure 6. JWST launch window as of July 2021

The green region shows the launch opportunities which met the requirements levied by both phases of the launch window while the light blue show the launch opportunities after the first phase of the launch window process. The light blue region was useful to see how the introduction of the second phase of the launch window from the European partners impacted the first phase of the launch window generated by NASA. Two specific requirements from the second phase of the launch window that had a significant impact on the second phase of the launch window included: thermal requirements during powered flight and at LV separation, and upper stage disposal requirements. First, the multi-day cutouts occurring approximately once a month are primarily due to lunar perturbations preventing the upper stage from escaping into its desired disposal orbit. Second, while this set of launch window opportunities shows combined valid launch times earlier than 12:20 UTC, subsequent iterations of the launch window resulted in a combined window starting no earlier than 12:20 UTC, as shown in the final launch window presented in Reference 2, to meet thermal requirements during powered flight.

FD Prelaunch Products

Leading up to launch, the FDT was required to deliver numerous product sets to various end-users. The FDT delivered preliminary products at L-8 months, in March 2021. The first sets of official prelaunch products, based on the final LV trajectory data, were delivered in September

2021, at L-90 days. The FDT regenerated and re-delivered the set of files each time a different launch epoch was selected, usually when the launch date changed significantly. There were more frequent updates, for more contiguous launch days as the mission converged to a late December launch. Some end users, such as DSN, needed to plan multiple alternate schedules for support with their other customers in case the launch slipped. Each set of products included data corresponding to a trajectory with the MCCs modeled as the ‘burn’ products, and data with no MCCs, the ‘no-burn’ products as shown in Table 2. The no-burn products were useful if a MCC was delayed.

Table 2. Prelaunch Products

Delivery Time	Product/Milestone	From	To
L - 8 months **L-90 days** **L-7 days**	*Launch Trajectory (.DAT)*	FDF	SOC
	Launch Window (.DAT)	FDF	SOC
	28-Day Antenna Views Periods (.DAT)	FDF	SOC
	2- Year Antenna Views Periods (.DAT)	FDF	SOC
	28-Day No-Burn Ephemeris (.OEM & U.OEM)	FDF	SOC & DSN
	28-Day Burn Ephemeris (.OEM & U.OEM)	FDF	SOC & DSN
	2- Year Predictive Ephemeris (.OEM & U.OEM)	FDF	SOC & DSN
	Sun Ephemeris (.OEM)	FDF	SOC
	Slant Range & SVE Angle Predicts	FDF	SOC
	28-Day No-Burn Antenna View Periods	FDF	SOC
L - 1 day **May require multiple sets for additional launch days**	*All products listed above plus*		
	Maneuver Plan (.DAT)	FDF	SOC
	SR Acquisition Data (.S)	FDF	SR

Launch slips required the FDT to regenerate all the prelaunch products, which included ephemerides, view period predicts, and maneuver planning information. If the launch slip was greater than a month, FDT was required to generate several sets of products. End users required multiple launch dates, usually just for the opening of the window although some end users required open and close of the launch window sets of products. Some end users needed the products to cover powered flight while other end users could not ingest variable step ephemerides with abrupt changes in velocity; the latter end users wanted trajectory products to start after observatory separation with vectors on 1-minute centers. While the onboard LV Flight Program was a fixed trajectory in Earth-rotating coordinates, the sun angle changed from day to day and over the course of a long daily window. The sun angle change caused a different attitude profile during powered flight through separation, which in turn affected the Acquisition of Signal (AOS) and Loss of Signal (LOS) times for the ground stations and the TDRSs. Malindi generated its antenna pointing predicts using the same Consultative Committee for Space Data Systems (CCSDS) orbit ephemeris message (OEM) file FDF delivered to DSN for their use. The SR required acquisition data in a totally different, but well understood, Improved Inter-Range Vector format.

Special Considerations for Prelaunch Support During a Pandemic

As mentioned earlier, the COVID-19 pandemic affected how the FDT and FDF prepared for launch; telecommuting and offsite support became the norm with only real-time rehearsal and operations support at the actual FDF MOR.

All non-operations support was done in a 'work from home' environment, dictated by the COVID-19 pandemic shutdown protocol. Only NASA-approved hardware, software, and NASA-controlled instances of interface tools (Microsoft Teams, WebEx, and Quintron applications) using the secure NASA VPN were allowed for JWST operations support. GSFC IT security protocols were always maintained. The FDF MOR had to be reconfigured so that personnel were not positioned within 6 feet of each other. An ultra-violet cabinet was used to sanitize keyboards, mice, and headsets unless separate headsets were provided to each person. It became standard operations procedures to wipe down all workstation surfaces with antiseptic wipes before and after finishing each shift on console. Masks were mandatory of course, which made it hard to communicate, especially while seated further apart. Meetings that had to be in person, such as shift handovers, were held standing in a large circle in either the lobby of the building or other large spaces.

The anxiety usually associated within the last months leading up to launch was increased significantly with the fears of contracting COVID-19 preying on people's minds. GSFC management did their best to keep people informed on the safety measures put into place and updated on the frequently changing status of the GSFC campus in terms of access, proof of vaccination, and mask mandates. The FDT teleconferenced with the GSFC Chief Medical Officer the week before launch to receive the latest information and advice and to allow team members to ask her questions directly. While none of the core FDT operations members contracted COVID in the last three months before launch, several were exposed in various non-work situations and had to be quarantined and undergo multiple testing events before they could work on console. One FDT member scheduled for early orbit support had been exposed to COVID through no fault of their own, and was not cleared to support until December 24, the day before launch.

The FDF and FDT leaders addressed the potential loss of critical mission support members by ensuring there were backups to every position who were trained and had supported real-time rehearsals in their alternate roles. Cross training between the mission planners and OD analysts was done, junior support staff were trained to assume leader roles, and members from each shift were able to perform any activity on the alternate shift. The shift leads and liaisons were cross-trained as well to assume each other's role and duties. Remote support by NMDB flight dynamics experts was provided the morning of launch as well, to assist in anomaly resolution related to launch and MCC-1a. These measures were all part of the flight dynamics 'no single point of failure' risk mitigation strategy.

LAUNCH AND EARLY MISSION SUMMARY

Launch and Upper Stage Disposal

The launch and early orbit events related to flight dynamics were essentially nominal, much to the FDT satisfaction. Launch occurred at the opening of the window at 12:20 UTC on December 25, 2021. Based on the post-launch report provided by Arianespace, the separation state was within 0.1-sigma in all six orbital elements and separation occurred within four seconds of the nominal timing. This behavior is corroborated by the FDT independent evaluation of the separation state based on the tracking data collected between separation and the tracking data cutoff at L+7 hours. The flight dynamics independent assessment also showed agreement in all six orbit elements within 0.1 sigma.

The FDT received the post-burn ESC-A+ state from Arianespace within the agreed upon time constraint of separation + 40 minutes. At this point the FDT propagated the upper stage trajectory for a year to confirm the upper stage disposal maneuver had placed the upper stage into a heliocentric trajectory and that there would be no long-term close approaches with JWST. Figure 8 shows a picture of the evaluation that was performed at roughly L + 2 hours by the FDT. The trajectories are shown in Rotating Libration Point (RLP) coordinates, with L2 at (0,0). RLP-X is along the Sun-(Earth-Moon-barycenter line, and RLP-Y is in the plane of the barycenter's motion about the Sun. The start of the trajectories is near Earth, just after the ESC-A+ has completed its disposal maneuver and propagated for 6 months. The trajectory that loops around and stays within the L2 region is the nominal JWST trajectory, while the trajectory leaving the L2 region is the upper stage trajectory after completion of the disposal maneuver. The dotted-line box shows the science orbit mission constraints for JWST. The ESC-A+ upper stage trajectory is clearly on a heliocentric trajectory, which confirms that the disposal maneuver was performed successfully and that the upper stage would always be ahead of JWST and therefore would eliminate any risk of collision with JWST. The FDT delivered Figure 8 to the MSEs to inform them of the successful upper stage disposal maneuver.

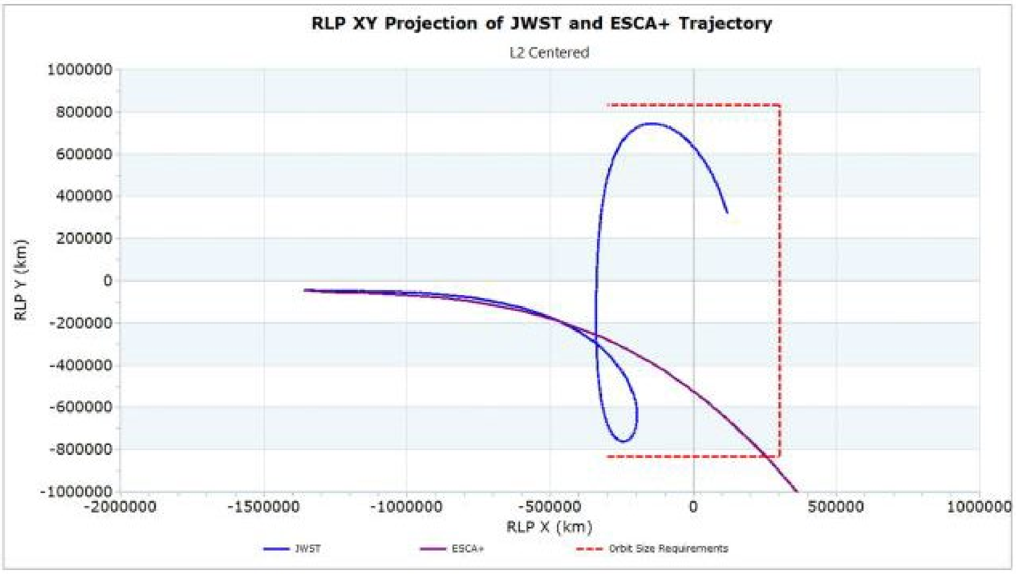


Figure 7. Long term orbit propagation for JWST and the ESCA+ shown in the RLP-XY plane.

Execution of the three MCCs

The nominal performance of the LV provided the foundation for a nominal execution of the three MCCs maneuvers. Enough tracking data was collected to ensure an OD solution could be generated by the tracking data cutoff at L + 7 hours. This kept MCC-1a execution on track for the nominal execution time at L + 12.5 hours. The Δv for the final MCC-1a plan required 20.202 m/s of Δv which is slightly less than the prelaunch nominal prediction of 20.468 m/s. This slight decrease in Δv is in line with the slightly hot performance of the LV with respect to the target apogee height of +0.08 sigma. The execution of MCC-1a occurred right on time on December 26, 2021, at 00:50 UTC. Post-maneuver calibration showed the maneuver was slightly cold, achieving 19.904 m/s of Δv (1.477% cold) based on the Δv along line-of-sight calibration method and 20.046 m/s of Δv (0.774% cold) using the post-maneuver OD method of calibration.

After the nominal execution of MCC-1a, the stress levels within the FDT reduced considerably. Execution of the mission's most important maneuver was near flawlessly which allowed the team to relax leading into MCC-1b and MCC-2 planning. Tracking data collection leading up to MCC-1b was also nominal. The Δv for the final MCC-1b plan required 2.780 m/s of Δv which was slightly more than the prelaunch nominal prediction of 2.518 m/s. This small increase aligned with the cold maneuver performance assessment for MCC-1a. A slight increase in the MCC-1b cost was necessary to correct the slightly cold performance of MCC-1a. The execution of MCC-1b occurred as planned on December 28, 2021, at 00:20 UTC. Post-maneuver calibration showed the maneuver was once again slightly cold, achieving 2.752 m/s of Δv (1.006% cold) based on the Δv along line-of-sight calibration method and 2.763 m/s of Δv (0.661% cold) using the post-maneuver OD method of calibration.

In-between MCC-1b and MCC-2 there were a series of challenges for the OD team to solve prior to MCC-2. The first and most obvious was the deployment of the sunshield. The deployment of the sunshield increased the solar radiation pressure (SRP) force and required the introduction of attitude knowledge into the OD process to properly orient the SRP force in inertial space. There were periods of time in which the complete attitude knowledge was not provided to the FDT, which reduced the quality of the sequential filter solution. The team was provided with SRP force models for the various phases of the sunshield deployment sequence and were therefore able to generate an OD solution most of the time. Second, the primary OD method successfully transitioned from a batch least squares in GTDS to the sequential filter in ODTK. Third, momentum unloading began which introduced perturbations into the OD solution. Momentum unloading for JWST is done on an as-needed basis and therefore could not be predicted ahead of time by the FDT. In total, 7 momentum unloads were performed between MCC-1b and MCC-2 in sizes varying from 0.057 cm/s up to 0.508 cm/s. A summary of these momentum unloads is available in Table 3. With proper knowledge of the start time, magnitude, and spacecraft attitude, the sequential filter could solve through momentum unloads with no issues.

Table 3. History of momentum unloads between MCC-1b and MCC-2.

Name	Date (UTC)	Duration (sec)	Delta-V (cm/s)
MU-001	2021-12-28 12:29	163.840	0.057
MU-002	2021-12-28 21:42	622.595	0.060
MU-003	2021-12-29 10:28	262.144	0.090
MU-005	2021-12-31 23:45	360.448	0.253
MU-006	2022-01-03 14:33	557.056	0.383
MU-007	2022-01-04 10:17	229.376	0.160
MU-008	2022-01-19 18:12	393.216	0.508

The execution of MCC-2 was nominally scheduled for L+29 days, however, this fell on a Sunday. Due to the nominal performance of both the LV, MCC-1a, and MCC-1b, it was a trivial decision by the S&OC to push execution of MCC-2 one day to Monday to better suit the operations cadence at the S&OC. The Δv for the final MCC-2 plan required 1.468 m/s of Δv which is slightly more than the prelaunch prediction of 1.267 m/s. Once again, the slight increase makes sense given the cold performance of MCC-1a and MCC-1b, along with the one day delay in the execution of the maneuver. MCC-2 was executed at launch + 30 days on January 24, 2022, at 19:00 UTC. Post-maneuver calibration showed the maneuver was slightly cold, achieving 1.461 m/s of Δv (0.491% cold) based on the Δv along line-of-sight calibration method and 1.457 m/s of Δv (0.702% cold) using the post-maneuver OD method of calibration. More information regarding the execution and calibration of the three MCCs can be found in References 2 and 3.

Table 4 contains an overall summary of the prelaunch Δv expectations as well as the performance of all 3 MCC maneuvers. Overall, the execution of the MCCs was nearly nominal and in line with prelaunch predictions which is a tremendous achievement. The Delta-V Along the Line of Sight (DVALOS) row represents the preliminary value computed for each MCC, using real-time Doppler monitoring data during the maneuvers. See Reference 3 for more information. The Orbit Determination row lists the best estimate of the maneuver based on several days of post-maneuver tracking data.

Table 4. Combined MCC summary table

MCC Costs for Launch on December 25, 2021, 12:20 UTC (m/s)				
Source	**MCC-1a**	**MCC-1b**	**MCC-2**	**MCC Total**
Prelaunch	20.468	2.518	1.267	24.253
Maneuver Plans	20.202	2.780	1.468	24.450
DVALOS	19.904	2.752	1.461	24.117
Orbit Determination	20.046	2.763	1.457	24.266

In terms of mission lifetime, a simplified version of Δv budget for the mission is provided in Table 5. The nominal Δv budget allotted up to 57.9 m/s of Δv for the 3 MCC maneuvers, to accommodate up to 3-sigma launch vehicle errors. With an additional 12.6 m/s of contingency Δv budget, the total budget for MCCs was 70.5 m/s. A conservative 26.5 m/s of Δv is allotted for 10.5 years of station-keeping, equating to 2.5 m/s per year for maintaining the observatory's trajectory about L2. Once it was agreed to fully load the propellant tanks, prelaunch analysis determined the fully loaded tanks could provide up to 109.8 m/s of Δv, assuming all unallocated propellant was available for Δv. The actual amount of Δv required for the 3 MCCs was approximately 24.2 m/s, leaving up to 84.9 m/s of Δv for the station-keeping operations.

The prelaunch preparation by the FDT and nominal LV performance set the team up for success for the 3 mid-course correction maneuvers and left the project with over 20 years of propellant remaining for station-keeping operations. Figure 9 helps visualize this tremendous success, clearly showing how much propellant is remaining for science operations.

Table 5. Simplified Δv budget for JWST.

Maneuver Type	Delta-V	Notes

	Allotment (m/s)	
MCC nominal	57.9	Accounts for up to 3-sigma LV dispersions
MCC contingency allotment	12.6	Extra Δv for delay of MCC-1a execution
Station-keeping for 10.5 years	26.0	Includes 2.4 m/s of contingency
End of life disposal	0.7	
Total Δv allocated pre-launch	97.2	
Full propellant load (possible Δv)	**109.8**	**Up to 12.6 m/s additional Δv available (109.8 – 97.2)**

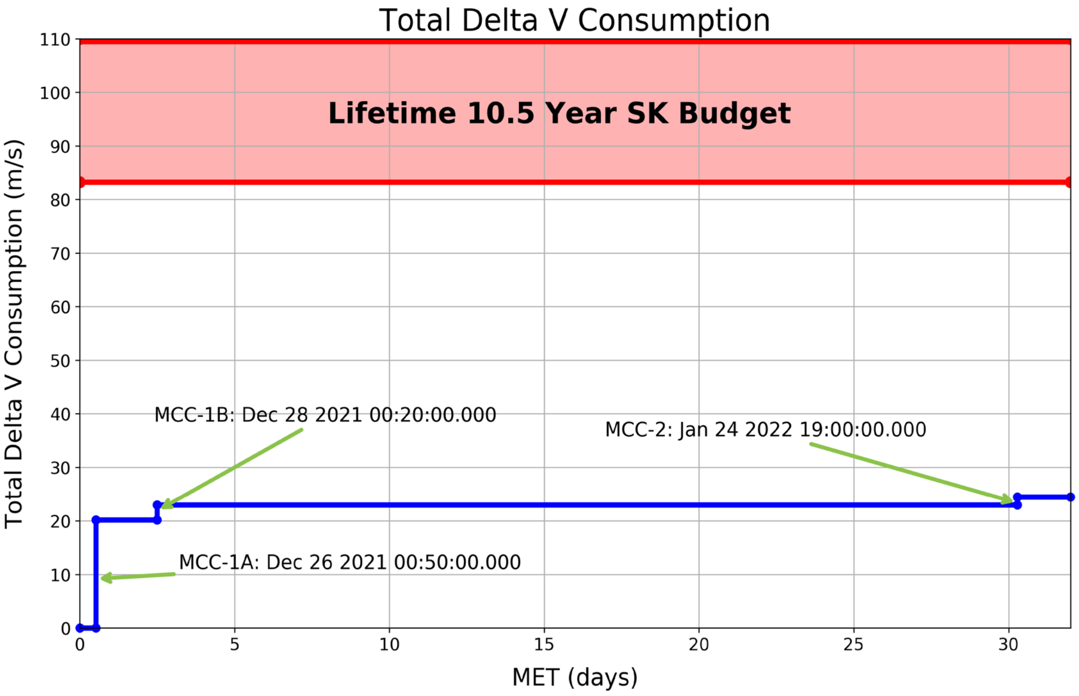


Figure 8. Visualization of the Δv required for the three MCCs and the amount of Δv remaining for station-keeping operations[11].

STATIONKEEPING OPERATIONS

The station-keeping maneuvers during the first 6 months of the mission have not followed the nominal 21-day cadence, as anticipated. The spacecraft and science instrument commissioning events took precedence over station-keeping maneuvers during the commissioning phase of the mission. However, the FOT and the FDT did start the weekly cycle of product deliveries as soon as possible after MCC-2. Station-keeping maneuvers will occur on Wednesday every three weeks. The nominal weekly FDT deliveries occur every Monday with the flexibility for delivery on Tuesday in the event of federal holidays on a Monday. FOT delivery of predicted attitude files occur on Thursdays, nominally, with extra products delivered if a SK occurred the day before.

To date, 4 station-keeping maneuvers have been performed. A summary of the station-keeping maneuvers is available in Table 6. Overall, all station-keeping maneuvers have been rather small. SK-001 was performed according to the nominal timeline three weeks after MCC-2 on February 16, 2022, and the execution was overall nominal. It was decided to skip SK-002 as the maneuver size was below 10 seconds which has been the metric used by the project to determine whether to execute a maneuver. SK-003 was performed on the nominal timeline three weeks after skipping SK-002 on March 30, 2022. SK-003 execution was nominal overall. It was decided to skip SK-004 as the maneuver size was below 10 seconds.

SK-005 was performed out of cycle to accommodate the commissioning timeline. The nominal schedule for SK-004 would have been April 20, 2022, with SK-005 on May 11, 2022. To accommodate the thermal commissioning activities throughout May 2022, it was decided to move SK-005 up to Tuesday, May 03, 2022. Thruster firings during the thermal commissioning activities would negatively impact the thermal environment and there was a concern that waiting to perform a maneuver until after the thermal campaign concluded in early June would have resulted in a maneuver size that was too large. In addition to being the first out of cycle station-keeping maneuver, SK-005 was the first station-keeping maneuver in which the FDT was provided with a predictive attitude plan to use in the maneuver planning process. Up to this point, the FDT had not received any predicted attitude plans and therefore had to assume an attitude for maneuver planning. In the absence of an attitude plan, the FDT assumes a spacecraft orientation that places the SRP force along the sun line and maximizes the SRP force magnitude. Colloquially, the team refers to this attitude profile as Sun Neutral. For the first time, the team was able to incorporate an attitude plan into the maneuver planning process. While the maneuver plan contained four weeks of predicted attitude, this altered the maneuver planned duration from approximately six seconds to 13.256 seconds. Execution of SK-005 did not go as smoothly as SK-001 or SK-003. An onboard fault triggered the spacecraft to enter safe mode immediately at the conclusion of the SK-005. The transition into safe mode required additional thruster firings resulting in approximately 1.3 cm/s of additional Δv added to the maneuver which is why the performance of SK-005 is out of family.

After the complications of SK-005, the project was able to recover the spacecraft successfully and implement a series of software patches to prevent the spacecraft from entering safe mode at the conclusion of a station-keeping maneuver. SK-006 was performed at the nominal scheduled time on June 01, 2022. The impact of SK-005 was that the maneuver direction for SK-006 would flip from anti-sunward to sunward. Too much Δv was applied in the anti-sunward direction during SK-005 and a sunward maneuver would be required for SK-006 to balance the energy.

At the time of this paper, the PM had waived SK-007, which was nominally scheduled for June 22, 2022. The observatory is transitioning out of the commissioning phase into the science phase of the mission; once in science operations, a long-range attitude plan will be provided to the FDT. The incorporation of the long-term attitude data into the maneuver planning process will probably necessitate the execution of SK-008 on July 13, 2022. A future paper will cover the follow up station-keeping maneuvers and the impacts of the long-term attitude plan into the station-keeping maneuver cadence.

In summary, the execution of the four station-keeping maneuvers so far have been quite small. Under nominal circumstance, the mission fell into a cadence of skipping every other maneuver during the commissioning phase. The FDT and FOT have agreed to wait until at least three station-keeping maneuvers have been executed during the science operations phase, which is set to begin roughly around July 01, 2022, to evaluate whether the 21-day cycle can be increase to 42-days or even higher.

Table 6. Summary of station-keeping maneuvers for the first six months of the mission

Name	Date (UTC)	Direction	Duration (sec)	Delta-V Plan (cm/s)	Delta-V Achieved (cm/s)	Performance (%)
SK-001	2022-02-16 21:55	Anti-Sunward	21.448	10.32	10.49	1.6
SK-003	2022-03-30 14:54	Anti-Sunward	17.352	8.40	8.78	4.5
SK-005	2022-05-03 14:49	Anti-Sunward	13.256	6.46	8.70	34.7
SK-006	2022-06-01 15:05	Sunward	7.112	3.17	3.18	1.0

POST-LAUNCH LONG RANGE VIEW PERIODS

During the commissioning phase, JWST required near-continuous coverage by DSN, dropping to 16- hours of coverage towards the end of the first six months. The trajectory JWST was launched into results in gaps in DSN coverage around the summer solstice. These gaps are caused by the reduction in view periods of the Northern hemisphere DSN antennas at Madrid and Goldstone. This effect became a scheduling concern about four months into the mission as the remaining commissioning events were being planned. The reduced view periods prevented the JWST mission planners at the S&OC from being able to schedule two eight-hour passes in May and June as they had assumed would always be available.

The gaps in coverage are highly dependent on the size and shape of the SEM L2 orbit, which is determined by the launch epoch for JWST. JWST does not have the fuel budget required to target a specific orbit shape, therefore the long-term orbit shape is dictated by the direct injection trajectory at the given launch epoch[8]. Launching at 12:20 UTC was somewhat advantageous from a communications perspective as it resulted in a tighter quasi-halo libration point orbit than would be achieved by launching later in the day; the later launch times would result in much looser quasi-halo orbits which resemble Lissajous orbits. While the tighter orbit provided less orbit shape variability from one six-month orbit period to the next, that effect is overshadowed by the solstice effects due to the alignment of the solstices and the maximum RLP-Z amplitudes of the orbit. When JWST's position is at the maximum negative RLP-Z, Madrid and Goldstone antennas have significantly shorter view periods because of the extreme Earth tilt relative to the ecliptic plane during the summer solstice. Madrid's latitude is 40.5 degrees N, five degrees greater than Goldstone at 35.3 degrees N, so the effects are greater for Madrid than Goldstone.

Figure 10 shows the predicted view periods for the DSN 34-m antennas over a 10-year span starting with the operational JWST orbit state after MCC-2. The view period duration (hours) is on the left vertical axis while the date is on the horizontal axis (mm/dd/yy). In addition to the contact durations for each station, the RLP-component of the orbit (thin blue line) is included and aligned with the right-handed vertical axis. As expected, the maximum and minimum view period durations between the Northern and Southern hemisphere DSN stations are out of phase by half a year. When northern hemisphere passes are short, Southern hemisphere passes are longer. Madrid has view periods less than four hours every day almost two months in 2022 and every summer solstice period thereafter. These periods decrease as the phasing of the RLP-Z amplitude maximums move away from the summer solstice and the orbit geometry changes slightly from year to year due to the nature of a quasi-halo orbit.

The complete drops in coverage that occur periodically in the Madrid data are caused by a violation of the azimuth constraint between 89.5 and 90.5 deg when the antenna must rotate 180 degrees in azimuth to continue tracking JWST as it flies directly over the antenna. Visually, these keyhole events can be found in Figure 10 when the purple dots are out of family and located near the bottom of the y-axis. These keyhole gaps in coverage in the middle of the contact are very short, less than 5 minutes, according to the DSN operators.

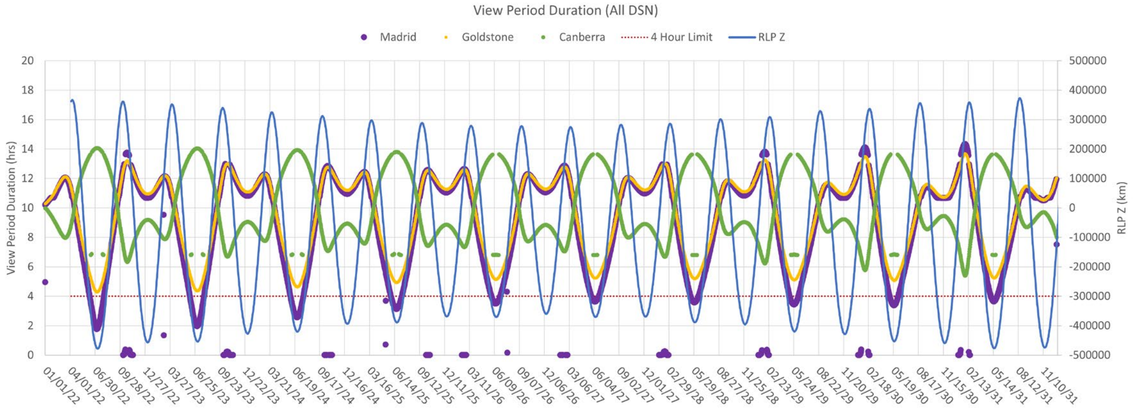


Figure 9. Long-term evolution of JWST DSN view periods using DSN antenna mask profiles and a 10-degree minimum elevation limit.

CONCLUSION

The JWST mission has been highly successful thus far with the FDT support providing critical trajectory design, maneuver support and OD. The LV delivered JWST to its planned transfer trajectory orbit within 0.1 sigma. The MCCs were executed as expected and calibrated to within 1% of the planned maneuver, using only 24.2 m/s of the 70.5 m/s prelaunch MCC Δv budget. The JWST mission will not only meet the mission lifetime goal of 10.5 years but could exceed that by another 10 years or more. The FDF certified the interface for Malindi tracking data use for JWST OD, which proved vital for the success of the early-orbit timeline. The FDT performed extensive planning for nominal, backup, and contingency operations for all aspects of FDT support. To minimize risk, FDEs were cross-trained, a backup FDF MOR set up and tested, and a two-level power failure backup plan was implemented with batteries and a generator. The FDT worked around the challenges of the COVID-19 pandemic, and was able to deliver products on time prelaunch and during the mission. Technical planning focused on successfully determining the post-separation orbit in time for the nominal MCC-1a plan delivery at L+8.5 hours. Meeting this time constraint was achieved with extensive practice and rehearsals of both nominal and non-nominal situations. Training included tested and rehearsed procedures for performing early OD without Malindi data, real-time monitoring of MCCs, responding to delayed and aborted MCC maneuvers, among others. Most of the contingencies did not materialize and the flight dynamics support has been following the nominal technical plans. Even though four SK maneuvers were completed successfully, FDT still needs to characterize the SK behavior in the science operations, which started mid-July, 2021.

ACKNOWLEDGEMENTS

The authors would like to acknowledge and thank the support of the entire JWST FDT. The JWST FDT is composed of the following members: Ty Burney, Michael Goff, Kennedy Haught, Arvind Kaushik, Jon Landis, James Logan, John Lorah, Steven Magnusen, Ann Nicholson, Annie Ping, Ishaan Patel, Jeremy Petersen, Taabish Rashied, Megan Renshaw, Karen Richon, Jose Rosales, Toni Santacroce, Michael Schmidt, Jeff Small, Eric Stoker-Spirt, Ben Stringer, Jennifer Yantorno, Wayne Yu, Charles Yu, Matt Zuckerman.

REFERENCES

[1] M. Menzel, "JWST Mission Systems Overview," NASA presentation, Oct 2022.

[2] J. Petersen, B. Stringer, and K. Richon, "Mid-Course Correction Analysis for James Webb Space Telescope," *AAS/AIAA Astrodynamics Specialist Conference, 2022.*

[3] W. Yu, T. Rashied, A. Santacroce, B. Stringer, and J. Lorah, "JWST Real-Time Mid-Course Correction Maneuver Monitoring Contingency Preparation," *AAS/AIAA Astrodynamics Specialist Conference, August 2022.*

[4] J. Levi, K. Richon, A. Nicholson and J. Landis, "The JWST Flight Dynamics Operations Concept and Flight Dynamics Ground System," *IEEE Aerospace Conference, 2019.*

[5] A. Nicholson, "JWST Post-Launch Report", FDSS-III-104-0040," June 25, 2022.

[6] J. Orozco, "Tracking Data Evaluation Station Certification for KENS Range and Range-Rate with THEMIS," NASA GSFC-595/FDSS-III, July 16, 2021.

[7] E. Stoker-Spirt, J. Small, A. Kaushik, C. Yu, A. Nicholson, W. Yu, "Orbit Determination for the James Webb Space Telescope During Launch and Early Orbit" *2022 AAS/AIAA Astrodynamics Specialist Conference, August 2022.*

[8] J. Brown, J. Petersen, B. Villac, and W. Yu, "Seasonal Variations of the James Webb Space Telescope Orbital Dynamics," *AIAA/AAS Astrodynamics Specialist Conference, 2015*.

[9] G. Andersen, "JWST PLAR MCC/SK Performance," draft slides for Post Launch Assessment Review, June 2022.

[10] B. Villac, J. Petersen, and K. Richon, "JWST MCC-1a Delay and Early Termination Analysis," NASA GSFC-595/FDSS III, December 16, 2016.

[11] G. Andersen, "JWST On Orbit Mid-Course Correction Plan," JWST-PLAN-045648*, October 29, 2021.*