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JWST REAL-TIME MID-COURSE CORRECTION MANEUVER MONITORING CONTINGENCY PREPARATION

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The NASA James Webb Space Telescope (JWST) mission successfully launched on Dec 25, 2021, at 12:20 Coordinated Universal Time (UTC). During the 30-day transfer to the second Sun-Earth-Moon (SEM) libration point (L2), JWST executed three mid-course correction (MCC) maneuvers to insert into a quasi-halo orbit about L2. This paper covers the design and modeling for these three maneuvers with a focus on the timeline around the execution of each MCC maneuver. It will summarize the actual on-board events as well as the contingency preparation done for maneuver planning, monitoring, and final post-burn reconstruction of all three MCC maneuvers.

INTRODUCTION

The NASA James Webb Space Telescope (JWST) launched on December 25, 2021, at 12:20 UTC and was inserted into the second Sun-Earth-Moon (SEM) libration point (L2) operational orbit using three Mid-Course Correction (MCC) maneuvers. The JWST MCC maneuvers are unique to other libration orbiters, due to attitude restrictions from thermal requirements and orbit determination challenges in the stowed and deployed sunshield configurations. This paper covers the application of MCC maneuver planning (MP), using both orbit determination (OD) knowledge and MCC burn monitoring and reconstruction. Finally, the paper reviews the long-term impact on propellant use and future JWST flight dynamics operations.

This is a part of a series of papers on JWST flight dynamics operations, with this paper focused on MCC real-time support. The overall JWST flight dynamics support is detailed in Reference 7. The finalized MCC design as a result of launch and impacts is seen in Reference 4, while the sunshield deployment orbit determination is more deeply detailed in Reference 9. Older papers have explored the impact of JWST MCC maneuver design from the initial launch insertion orbit effects,[11] resultant long-term libration orbit characterization,[1] Monte Carlo testing of nominal MCC burn designs,[5] and MCC contingencies and designs.[6] Finally, Reference 10 studies orbit determination ground stations contact schedule variations and their impact on maneuver design.

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Figure 1 shows the JWST configuration post-sunshield deployment. It contrasts the stowed configuration shown in Figure 2. Together, these two images demonstrate the different spacecraft models that were used during the MCC maneuvers.

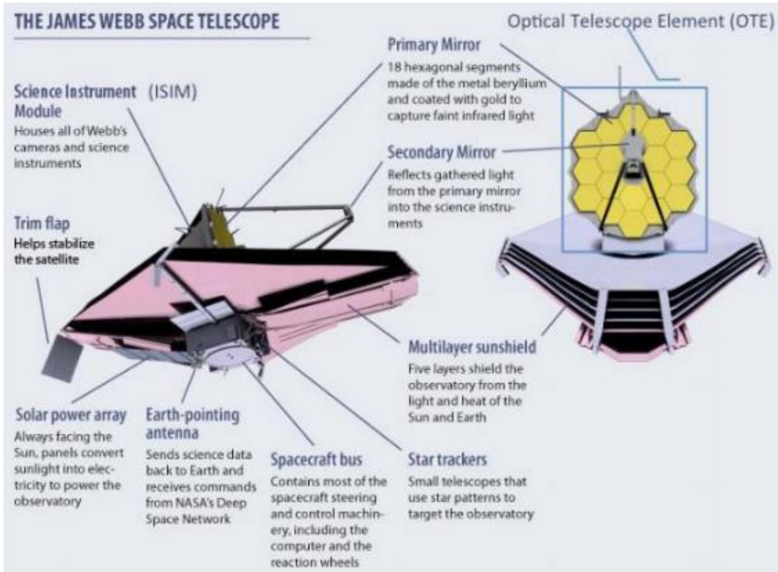

Figure 1. JWST Hardware Overview

JWST is a NASA flagship observatory that will observe astronomical phenomena in the near- to mid-infrared spectrum in the exploration of dark matter, first light from galaxies, exoplanets, and other astronomy research topics. A pre-launch image of the JWST observatory prior to rocket payload integration and with a stowed mirror can be seen in Figure 2. The launch window was designed for maximum opportunities throughout the calendar year, with monthly limitations due to the Moon and the use of a fixed launch trajectory profile. Further analysis on the on-orbit launch profile performance and launch window can be seen in Reference 11.

Figure 2. JWST Pre-Deployment Stowed Configuration[3]

MID-COURSE CORRECTION MANEUVERS AND UNIQUE CHALLENGES

The three MCC maneuvers are listed as MCC-1a, MCC-1b, and MCC-2 as seen in Figure 3. Not shown in the figure is a SCAT (Secondary Combustion Augmented Thruster) planned test firing of 1.5 seconds made prior to MCC-1a for hardware checkout. MCC-1a was a maneuver at Launch (L) +12.5 hours that made up for the difference in the launch vehicle insertion state for a direct L2 transfer trajectory. MCC-1b was performed at L+2.5 days to correct any maneuver execution errors in MCC-1a. Finally, MCC-2 was performed after the sunshield deployment at L+29 days and made up for any transfer trajectory perturbations caused by deployment.

In regard to flight dynamics, the science-driven thermal requirements of the instruments were primary drivers for the MCC maneuver design. From the thermal requirements, consider the following two JWST MCC hardware design traits and how the design propagated to MCC planning:

- The signature 5-layer Kapton sunshield protects the instruments and imparts a significant solar radiation pressure (SRP) acceleration onto JWST.[2] The sunshield was deployed and secured to the JWST frame so the SRP acceleration was dependent on the integrated JWST attitude. The effective SRP area increased by about a factor of 9 after deployment.[10]
- Derived observatory attitude restrictions limited the two (SCAT) thruster burn vectors to be primarily in the anti-Sunward (away from the Sun) direction. JWST's thrusters cannot fire directly towards the Sun, so the efficiency of a 'Sunward' maneuver which removes orbital energy is reduced. Recovering the spacecraft after an overshoot of L2 due to a launch vehicle overburn would require an inefficient 'Sunward' maneuver, which would be propellant-cost prohibitive.[5] SCAT thruster burn attitude control is maintained using 8 monopropellant rocket engine (MRE) thrusters.

With these traits in mind, the main concerns of the Flight Dynamics Team (FDT) were to design MCC-1a and MCC-1b to avoid an overshoot of L2, to maintain orbit determination throughout the sunshield deployment sequence, and to ensure that any post-deployment dynamics modelling uncertainty could be recovered by MCC-2. For MCC-1a and MCC-1b, the planned Ariane 5 launch vehicle JWST separation state and maneuver magnitudes were biased down from their optimal L2 orbit insertion values to account for any unknown thruster overperformance (see the yellow column in Figure 3). The JWST spacecraft model dynamics were based on the pre-deployment stowed configuration in Figure 2. MCC-2 was not biased down, and it made up for post deployment observatory dynamics uncertainty (see Figure 4 for a visual representation of how attitude uncertainty leads to large changes in the JWST surface area affected by SRP force). Figure 4 also shows how a Sun pitch value less than -53 degrees or greater than zero degrees risks exposing the primary or secondary mirror to sunlight. With the gradual instability of the L2 orbit dynamics primarily due to n-body perturbations, a station-keeping (SK) sequence started after MCC-2 and will persist for the lifetime of the mission.

MCC-1a	Perform 93%	12.5 hours after launch
MCC-1b	Perform 93%	2.5 days after launch
Sunshield Deployment	SRP starts to play a role	5 days after launch
MCC-2	Perform 100% *(1st station keeping maneuver)*	29 days after launch
Station Keeping	Perform 100%	Every 21 days during mission lifetime

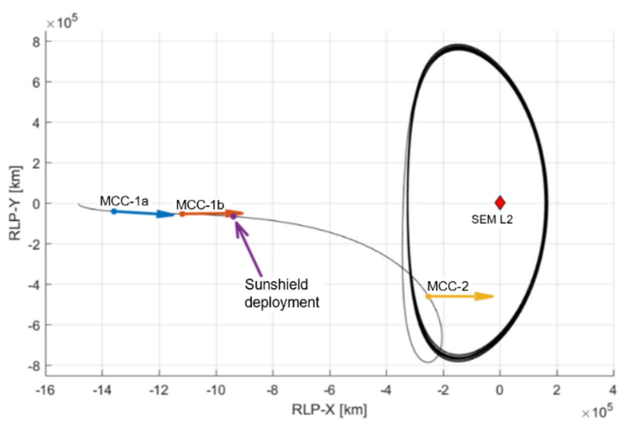

Figure 3. JWST MCC Maneuver Summary

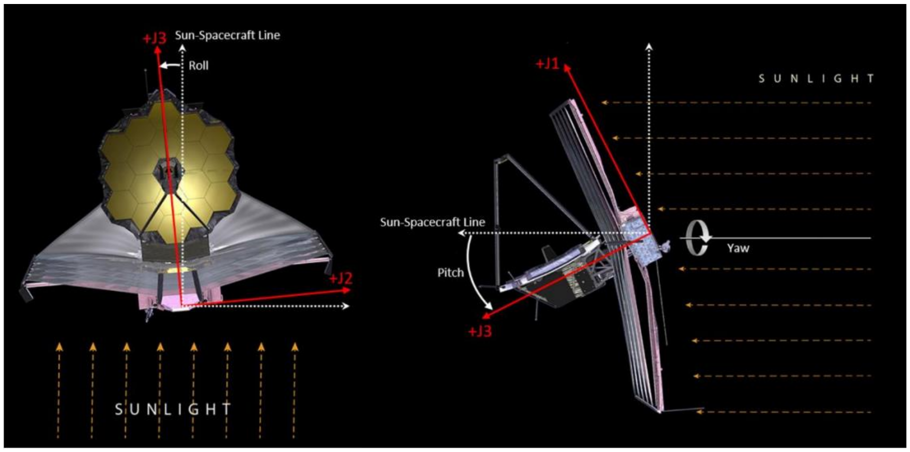

Figure 4. JWST Post-Sunshield Deployment Attitude Restrictions[6]

A summary of JWST force modelling and launch information is listed in Table 1.

Table 1. JWST Flight Dynamics Force Model / Hardware Parameters

JWST Property	Description	Value
Launch Epoch	UTC	December 25, 2021, 12:20:00.000
Separation Epoch	UTC	December 25, 2021, 12:47:11.217
Mass	kg	6161.449
SRP Area (Pre-deployment)	m^2	18.8
SRP Area (Post-deployment)	m^2	161.0
Coefficient of Reflectivity (Cr)	N/A	1.8
Earth Gravity Model (EGM)		EGM96
EGM Degree/Order		30/30
Solid Tides		Not Modeled
3rd Body Point Masses		Sun, Mercury, Venus, Moon, Mars, Jupiter, Saturn, Uranus, Neptune
Planetary Ephemeris		Development Ephemeris 430 (DE430)
SRP		See note in Section: Mid-Course Correction Maneuvers and Unique Challenges.

Note on SRP modeling: SRP was modeled using a polynomial table based on a proprietary 3D computer-aided design of the sunshield and defined by relative Sun angles off the Sun-Spacecraft line. The cannonball cross-sectional area was usable to first order in early operations until L+3 days.[2]

EARLY SPACECRAFT CONFIGURATION

Pre- and post-sunshield deployment configurations of JWST required the use of different thruster sets throughout the early operations period. MCC-1a and MCC-1b both occurred pre-deployment and used the primary maneuver thruster built for pre-deployment maneuvers (SCAT-1). If SCAT-1 was not performing ideally for these critical maneuvers, it was possible to switch to a redundant thruster (SCAT-2). These SCATs were aligned with the inertial velocity vector to maximize the efficiency of these maneuvers. MCC-2 occurred post-deployment and used the thruster built for post-deployment maneuvers (SCAT-3), which also had a redundant thruster (SCAT-4). MCC-2 and SK maneuver SCATs are pointed in a direction designed to minimize the angle between the thrust and the direction of the position components of the stable eigenvector of the monodromy matrix.

Early operations were supported by the NASA Space Relay (SR), Space Network, Tracking Data and Relay Satellites (TDRS), the European Space Agency's (ESA) Malindi ground antenna, and the Deep Space Network (DSN) 34-meter Beam Waveguide antennas located in Canberra/Australia, Goldstone/United States, and Madrid/Spain.[9] The DSN antennas were the primary source of JWST telemetry, tracking, and command during early operations, and will continue to provide these services throughout the mission life. However, during the first six hours of the mission, there were gaps in the DSN visibility, so data from the Malindi ground antenna was required for the initial OD solution used to plan MCC-1a.[10] Tracking data was routed to the NASA Flight Dynamics Facility (FDF) while telemetry was routed to the Space Telescope Science Institute's Science and Operations Center (S&OC) in Baltimore, Maryland. Telemetry sent to the S&OC was filtered for the different subsystems and the flight dynamics subset of data was sent to the FDF for flight dynamics engineers (FDEs) to use for daily operations. Two-way range and range-rate measurements were used for orbit determination for planning the MCC maneuvers and for reconstruction and calibration after the maneuvers were executed. Additionally, the DSN range-rate measurements were utilized to assess maneuver performance during each MCC maneuver in real-time. This gave FDEs an idea as to whether the burn was performing as anticipated and allowed them to shut off the engines in the event of an anomaly.

MANEUVER MONITORING AND RECONSTRUCTION

While pre-launch analysis showed that a maneuver performed at 93% of its optimal value would reduce the likelihood of an overburn, it was possible that the first MCCs could have errors greater than 3-sigma. To address the concern that the bias down was not large enough, FDEs were charged with making a tool that would be able to monitor the three MCC burns in real time: the maneuver monitoring tool. If an anomaly occurred during any of the three MCC maneuvers, the FDEs were to notify the S&OC to facilitate a decision on potentially aborting the maneuver. In order to detect anomalies in real time, the monitoring tool used an algorithm known as delta-v along line-of-sight (DVALOS) which is represented in Figure 5.

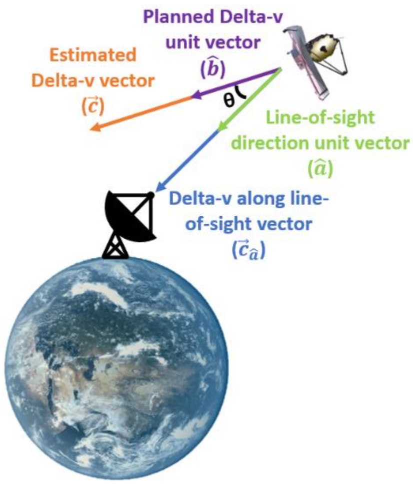

Figure 5. DVALOS (Delta-V Along Line-of-Sight) Algorithm Representation

Telemetry was sent from the S&OC to the FDF in 5-minute increments during the early orbit period. These deliveries were too infrequent to be used to monitor the MCC maneuvers in real time; therefore, tracking data was the only on-orbit information available to the maneuver monitoring tool. Tracking data was sent to the FDF from the DSN at a rate of one data point per every ten seconds and could be processed by the monitoring software in 1-minute increments. Maneuver performance could be assessed by projecting the change in range-rate values from the tracking data in the direction of the delta-v vector and comparing the result to the planned delta-v value. A predicted trajectory ephemeris and an ephemeris with no executed burn were also required for this algorithm.

$$\hat{a} \cdot \hat{b} = \cos(\theta) \tag{1}$$

In Equation (1), the first vector ($\hat{a}$) is the line-of-sight unit vector between JWST and the ground station currently tracking JWST, represented in Figure 5 by the green arrow. The second vector ($\hat{b}$) is the maneuver delta-v unit vector as calculated in the delivered maneuver plan, represented in Figure 5 by the purple arrow. To obtain $\hat{a}$ and the angle (θ) between the two vectors, the FDEs assumed that an ephemeris with no executed burn was the closest representation to the actual position of JWST in current time. Due to the maneuver delta-v executed mostly in the line-of-sight direction, angle (θ) errors between the ephemeris with no burn executed and the actual spacecraft were considered negligible. With these assumptions, this angle was then used to compute the estimated delta-v in real time using the following equation:

$$\|\vec{c}\|_{\hat{a}} = \vec{c} \cdot \hat{a} = \|\vec{c}\| \cos(\theta) \tag{2}$$

Equation (2) is the scalar projection of the dot product, in which the unknown value ($\|\vec{c}\|$) represents the estimated delta-v and information from vector ($\hat{a}$) and vector ($\hat{b}$) is represented by the angle (θ). The tracking data range-rate was assumed to be in the same direction as $\hat{a}$ since all the tracking data was only observed in the line-of-sight direction. This meant that the difference in range-rate values between the tracking data and the no-burn ephemeris during a maneuver was equivalent to the delta-v of the maneuver being applied in the line-of-sight direction ($\|\vec{c}\|_{\hat{a}}$).

Since the results of the DVALOS algorithm were known ($\|\vec{c}\|_{\hat{a}}$ and θ), Equation (2) could be solved for the estimated delta-v ($\|\vec{c}\|$). This value was recalculated at every point throughout the maneuver and assisted in contingency planning in case the estimated delta-v was non-ideal.

Tracking data updates were processed in 1-minute intervals allowing the continuous plotting of the estimated achieved delta-v in near-real time. Additionally, this actual delta-v knowledge was compared to the planned maneuver to provide the FDEs with a more accurate depiction of performance. Prior to launch, FDEs tested the tool against other missions at NASA GSFC and made test cases for JWST. A sample nominal test case is shown in Figure 6 and Figure 7:

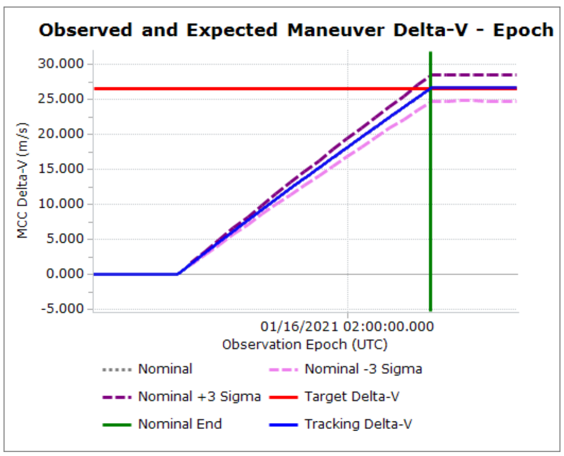

Figure 6. (Observed – Expected) Delta-V Nominal Case

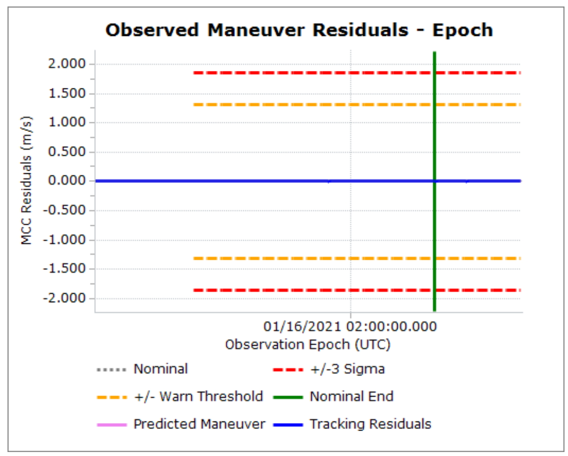

Figure 7. Observed Maneuver Residuals Nominal Case

Figure 6 shows the total delta-v throughout the maneuver. The dotted gray line, labelled as "Nominal," represents the planned maneuver. The solid blue line, labelled as "Tracking Delta-V," shows the estimated delta-v value in meters per second (m/s). It completely overlays the gray line in Figure 6, which indicates a nominal maneuver performance when compared to what was planned. The dashed purple and pink lines, labelled as "Nominal +3 Sigma" and "Nominal -3 Sigma" respectively, represent the +/- 3-sigma of the expected delta-v; these values are calculated as +/-7% of the expected current delta-v, which is why they grow farther from the gray line as the burn progresses and the expected delta-v increases. In Figure 7, the constant y value of zero represents the planned burn, highlighted by the "Nominal" dotted gray line, and the solid blue "Tracking Residuals" line represents the maneuver residuals, which communicate the burn's deviation from the plan. The dashed horizontal lines represent thresholds that indicate a large variance from the planned burn: yellow for the performance warn threshold, set at +/- 5% of the total expected maneuver delta-v and labelled as "+/- Warn Threshold", and red for the +/- 3-sigma, set at +/- 7% of the total expected maneuver delta-v and labelled as "+/-3 Sigma."

While the maneuver monitoring tool was used in real time to detect anomalies with the burn, the maneuver reconstruction tool gave an accurate representation of the burn in terms of propulsion and attitude control. This was done by utilizing the telemetry, attitude history, an ephemeris with no executed maneuver, and planned maneuver information. Telemetry files were parsed to obtain duty cycles, pulse width, pressure, and temperature information that could be put into propulsion software to recreate the maneuver. Attitude history files were required to accurately orient the thrusters in inertial space and reconstruct the SRP forces on JWST since its sunshield essentially acts as a solar sail.[2] The ephemeris provided the initial position and velocity of the spacecraft prior to the maneuver. Planned maneuver information was used to set the initial SRP reflectivity coefficients as well as the start time. Maneuver reconstruction could then take all these inputs, model the maneuver to match the telemetry, and propagate a spacecraft to generate a reconstructed ephemeris as well as the mass and pressure loss within the propulsion tanks. This information could then be used to bookkeep how much fuel and oxidizer remained.

MANEUVER CALIBRATION

To calibrate a maneuver, an accurate depiction of the maneuver execution is required, so calibration must occur after the maneuver has been reconstructed. The reconstructed maneuver was used as the baseline for calibration once information from tracking data became available. Tracking data provided an independent source of data for the most accurate JWST position and velocity, and which was calibrated against in multiple ways. JWST used two modes of calibration for the MCC maneuvers, which are referred to as DVALOS and OD calibration.

DVALOS calibration is a concept that has been used on multiple NASA missions in the past including ACE, WIND, SOHO, and DSCOVR.[8] This algorithm was meant to be the quickest way to calibrate MCC maneuvers since all information needed to calibrate a maneuver would be available approximately 30 minutes after it had completed. While DVALOS for maneuver monitoring used data that was approximated during a maneuver, DVALOS calibration used all tracking and reconstruction data. FDEs used the reconstructed maneuver position to compute the distance between the satellite and the ground stations to get the actual line-of-sight vector. The DVALOS was found from tracking data by computing the range-rate residuals for the entire maneuver, then differencing the average of residuals 15-30 minutes prior to the maneuver from the average of residuals 15-30 minutes after the end of the maneuver. Subtracting the two values provided the amount of delta-v achieved in the line-of-sight direction and was divided by the cosine of the angle between the line-of-sight vector and reconstructed delta-v unit vector to determine the observed achieved delta-v. The observed delta-v used all known maneuver information and was assumed to be the actual delta-v achieved. Calibration then occurred by adjusting the thrust scale factor (TSF) of the primary SCAT thruster until the delta-v achieved from reconstruction matched the delta-v observed from the DVALOS algorithm. Once this TSF was found, it was saved in a database and used to help plan the next maneuver.

While DVALOS calibration has been used for a multitude of spacecraft by NASA, it has limitations when it comes to certain maneuver directions. If a maneuver is performed perpendicular to the line-of-sight of the ground station, then the maneuver will not be seen by the tracking data since the maneuver will not be visible in the line-of-sight-direction. This geometry alignment is possible for a ‘Sunward’ SK maneuver when the MCC-2/SK SCAT thruster is aligned roughly with the negative RLP-Y axis. To accommodate this scenario and to provide an alternate method for calibration, a secondary calibration technique was developed. OD calibration followed a similar process to DVALOS calibration, with minor modifications. Once the orbit determination process had converged after completion of maneuver, typically within several days, a post-maneuver state was retrieved. Just like DVALOS, the TSF of the primary SCAT thruster was adjusted but this time the semi-major axis (SMA) of the post-maneuver state was used instead of the DVALOS delta-v. The TSF was adjusted until the post maneuver SMA matched the SMA of the orbit determination solution at the desired epoch, usually right at the end of the maneuver. The achieved delta-v was the amount of delta-v from the reconstruction process with the converged TSF applied. The process for both calibration techniques can be seen in Figure 8:

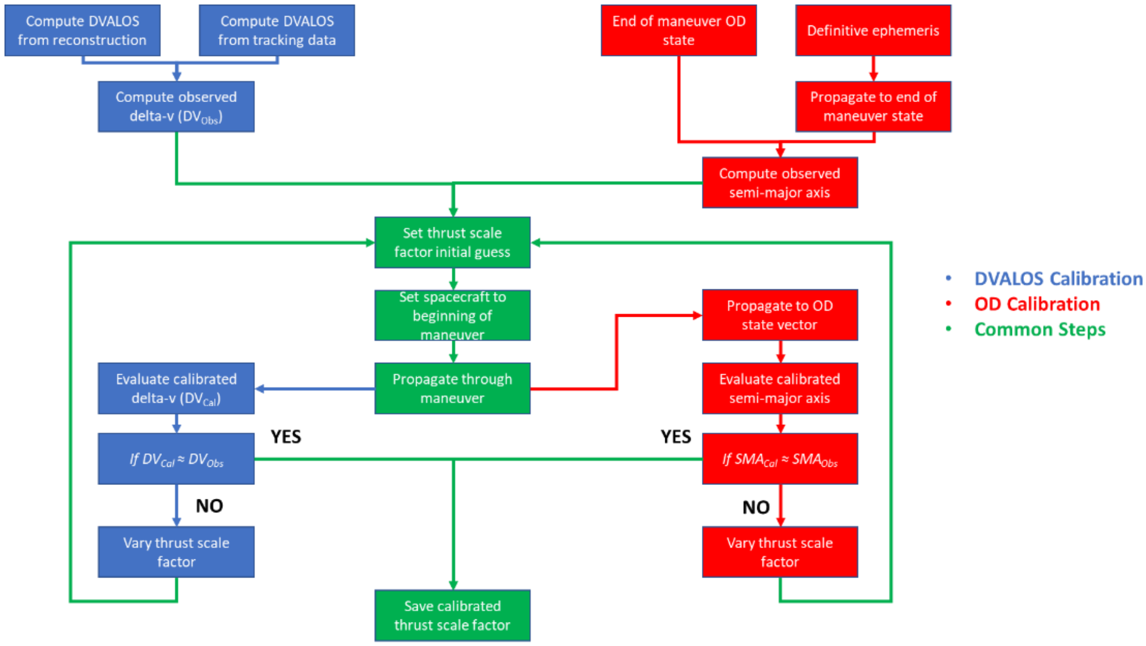

Figure 8. DVALOS & OD Calibration Methodologies

CONTINGENCY PLANNING

Nominal MCC-1a Monitoring Plan

The main priority of monitoring the maneuver in real time was to make certain that an overburn was not occurring, as a recovery from an overburn would be costly and potentially mission-ending. Other concerns due to either an overburn/underburn include loss of communication and damage to subsystems (instruments, etc.) due to the offset in the off-nominal trajectory. To determine the MCC-1a performance in real time, the FDEs designed a tool that would compare the expected maneuver performance with the actual performance. This was done by taking the range-rate values from tracking data coming from the DSN and computing the residuals of this range-rate with respect to the onboard planned ephemeris. If deviations occurred that were noted to be harmful to the mission, the FDEs would inform the S&OC and collectively the decision would be made to either continue with the maneuver or abort it. An example of a nominal maneuver performance mid-way through a maneuver is shown in Figure 9:

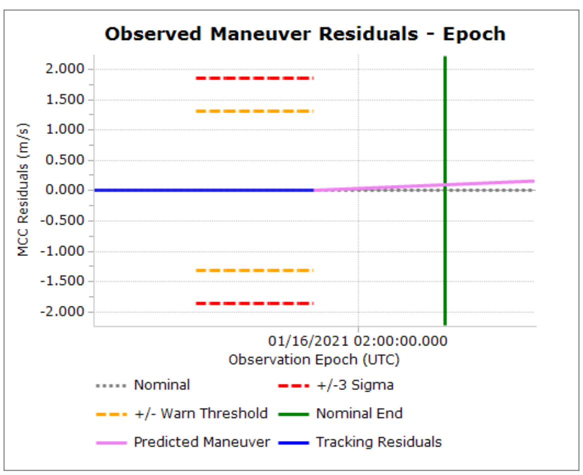

Figure 9. Mid-Maneuver Observed Residuals Nominal Case

Tracking data was ingested into the tool in approximately 1-minute intervals so that the FDEs could track what was occurring in real time. This tracking data would be processed, and the residuals would be shown on a plot similar to Figure 9. Once the actual maneuver residuals deviated from the expected residuals, the FDEs would know that the maneuver was burning hot or cold depending on which direction the line was shifting. A solid pink line in Figure 9, labelled as "Predicted Maneuver," shows where future tracking data residuals are predicted to be. Finally, the solid vertical green "Nominal End" line signifies the end of the burn for the maneuver.

A 15-minute tracking data settling time was applied to counter any false overburn data due to transient range-rate residuals, signal noise, and false maneuver start behavior. Past the initial settling period, the JWST team used a 3-sample fault policy to determine an over/under burn anomaly; the FDT grouped these samples into 4-minute periods of tracking data residuals.

Table 2. FDF Abort Criteria for a 50-Minute MCC Burn Duration

Case	Trigger Condition	Action
Inform Warning Threshold to FDF Team (Figure 10: Yellow Line)	• Approximately 19 minutes after burn start. • Predicted residuals (Figure 9: pink line) show >= 5% underburn/overburn (Figure 9: yellow line)	FDEs inform the Shift Lead and discussion starts within FDF team.
Inform Warning Threshold to S&OC (Figure 10: Magenta Line)	• Approximately 23 minutes after burn start. • Actual residuals (Figure 9: blue line) show >= 5% underburn/overburn (Figure 9: yellow line)	Shift Lead informs the S&OC that off-nominal maneuver performance is currently being seen by the FDEs.
Recommend Abort to S&OC (Figure 10: Red Line)	• Approximately 27 minutes after burn start. • Actual residuals (Figure 9: blue line) show >= 7% underburn/overburn (Figure 9: red line)	Shift lead recommends abort to S&OC for overburn.

Table 2 shows the criteria necessary to warn the S&OC and potentially recommend an abort of the burn based on what was being seen in Figure 9. The first 4-minute sample would alert the FDF team, the second continuous sample would warn the S&OC flight control team, and the third continuous sample violation would be grounds for a scheduled abort. Most of the criteria was meant for an overburn; an underburn required reporting but was deemed recoverable by the JWST operations team.

Scaled Burn Duration Flight Dynamics Engineer Policy

The earliest time at which an MCC abort was possible depended on the maneuver size. The red values included in Table 2 are based on a sample size that is directly proportional to the burn duration, as shown in Figure 10.

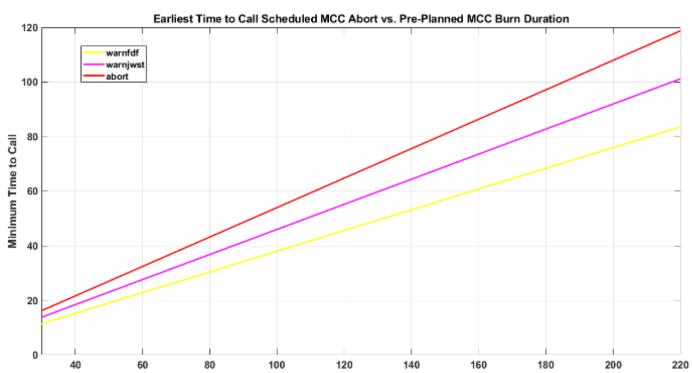

Figure 10. FDE Policy vs Planned Burn Duration for Burn Durations > 30 minutes.

In order to ensure time to command the spacecraft, the abort criteria was determined to be impractical for burn durations less than 30 minutes. Thus, for contingency MCC-1a maneuvers, MCC-1b, and MCC-2, it was decided that if an anomaly occurred at approximately 30% of the burn execution, the FDF would be in a warning status. If the anomaly was still occurring at 50% of the burn execution, the S&OC would be informed so an abort decision could be made.

Maneuver Anomaly Response Plan

The JWST operations team planned multiple scenarios to diagnose issues and to execute mitigation strategies had an off-nominal MCC maneuver occurred. The nominal trigger for an MCC abort would be fault management triggers of spacecraft subsystems, but triggers could also occur due to operational delays or a FDT command abort as stated previously.

In response to an MCC anomaly, the JWST operations team had two plan types: execute the stored command sequence with a stale burn epoch maneuver product (restart) or request the FDT to generate a delayed but updated burn plan (replan). In nominal MCC-1a operations, both the nominal (L+12.5 hours) and a backup restart plan (L+14.5 hours) were prepared. To accommodate a 3-hour MCC operational sequence setup, one plan was prepared at the S&OC Mission Operations Center (MOC) and the other at the backup MOC (bMOC). Should an anomaly delay the maneuver start beyond any pre-planned MCC restart, the FDT would be given an hour after a new burn epoch was decided to replan and deliver for the 3-hour startup sequence. For MCC-1b and MCC-2, any maneuver delay beyond an hour would use the restart plan. This overall delay tactic for all MCCs would be sufficient, on average, for 12 hours past the nominal MCC-1a burn epoch and more so for MCC-1b and MCC-2.

Training Cases

An important aspect of contingency preparation was experience with realistic and likely scenarios. Once the nominal procedure was established, several rehearsals were designed to give team members an opportunity to go through the steps in an operational environment. The goal was that with repetition and the gradual addition of simulated anomalies, the team would be comfortable executing the tools and responding to any events that might occur during the mission.

In the months leading up to launch, a test schedule was developed to address all aspects of launch and early orbit operations. This schedule included both internal FDF rehearsals, as well as project level rehearsals involving multiple mission teams. There were several opportunities during dry runs and project rehearsals for the team to run maneuver monitoring with a nominal data set. In these cases, the team would initialize the maneuver monitoring tool with data from the maneuver planning tool, and process simulated real time tracking data. When plotted in real time, this data would show the maneuver following the expected slope for the full burn duration and would stay within the error bounds. Due to the logistics of working with a smaller team, some of the internal FDF rehearsals were able to incorporate anomaly events for additional training. In these cases, the tracking data was prepared ahead of time by an FDE who was not assigned to maneuver operations. The remaining FDEs, who were unfamiliar with the specific test scenario, would monitor thruster performance and determine whether to call a maneuver abort.

The first test case used tracking data that showed an MCC-1a burn slightly overperforming from the start, and is shown in Figure 11 and Figure 12. The expected burn duration was 50 minutes, putting it above the 30-minute threshold for contingency response determination. As a result, the team waited 15 minutes for any tracking data noise to settle. Then a warning was issued after the reported delta-v residuals were larger than 5%, and finally a burn abort was called after three consecutive samples were reported above 7%. Once the abort request had been processed and the command issued to the observatory, the resulting maneuver was 30 minutes long with a delta-v of 11 m/s. This was just over 70% of the predicted delta-v, resulting in a significant underperformance compared to the expected burn even though the thruster was overperforming. This trade-off reflects the decision to prioritize mitigating the risk of an over-burn, and MCC-1b would have been replanned to be much larger as a result. Depending on the circumstances, MCC-1b may have been executed using the backup thruster set if the performance issue was not resolved.

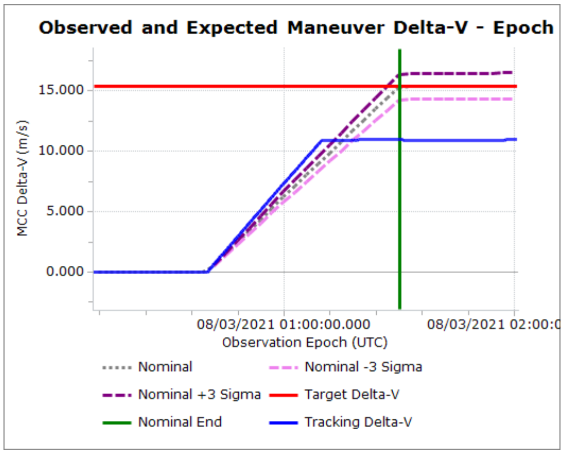

Figure 11. Delta-V for MCC-1a Overburn

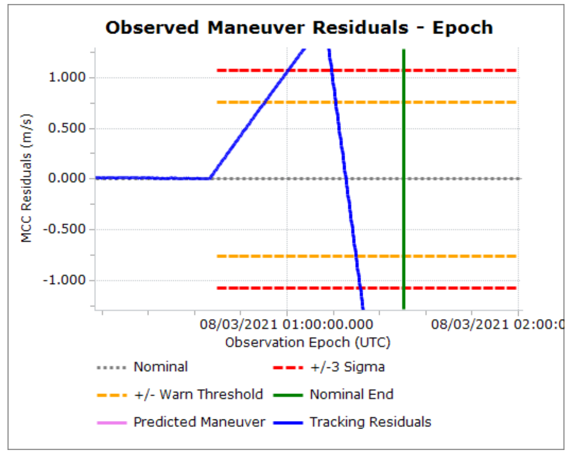

Figure 12. Residuals for MCC-1a Overburn

The second test case, shown in Figure 13 and Figure 14, was based on the same 50-minute MCC-1a maneuver. However, this time the tracking data showed a significant thruster underperformance. While the delta-v residuals soon passed the -5% and -7% thresholds, no burn abort was called in this case. The S&OC would still be notified of the unexpected behavior, but since there was no risk of over-burning the maneuver was allowed to continue for the planned duration to get the most delta-v out of the burn. In the end, the maneuver underperformed by 2.2 m/s, or about 15%. Again, MCC-1b would need to be larger to compensate.

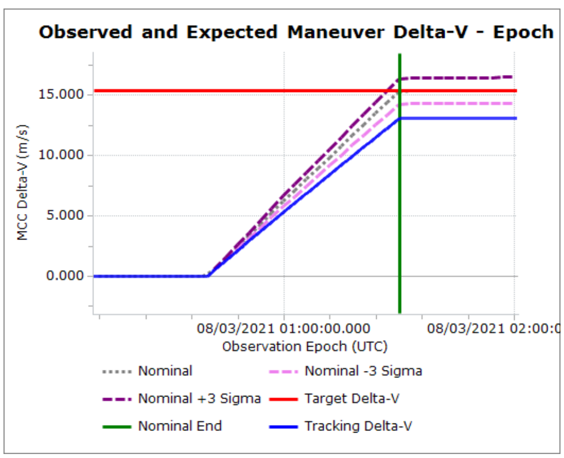

Figure 13. Delta-V for MCC-1a Underburn

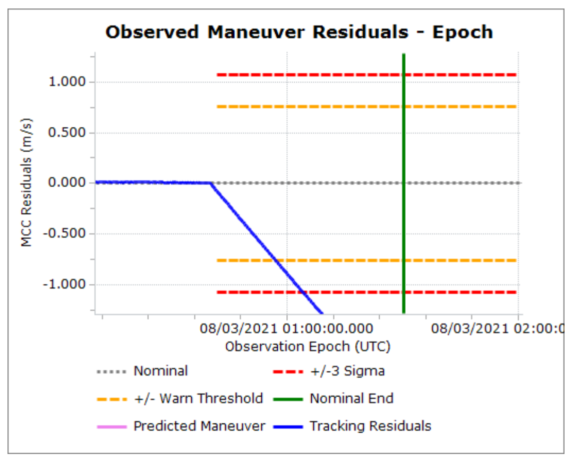

Figure 14. Residuals for MCC-1a Underburn

The final test case, shown in Figure 15 and Figure 16, involved a simulated MCC-1b maneuver with a planned duration of 10 minutes. The tracking data showed a significant overperformance from the start of the maneuver, which led the FDEs to call an abort after 5 minutes. Since the planned burn duration was less than 30 minutes, the abort needed to be called after three delta-v residual samples above the 7% threshold, but no later than half-way through the burn. The resulting maneuver achieved 1.75 m/s of delta-v and underperformed by 40%.

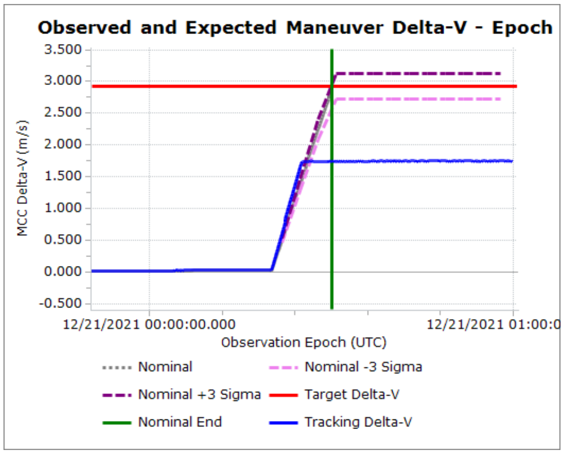

Figure 15. Delta-V for MCC-1b Overburn

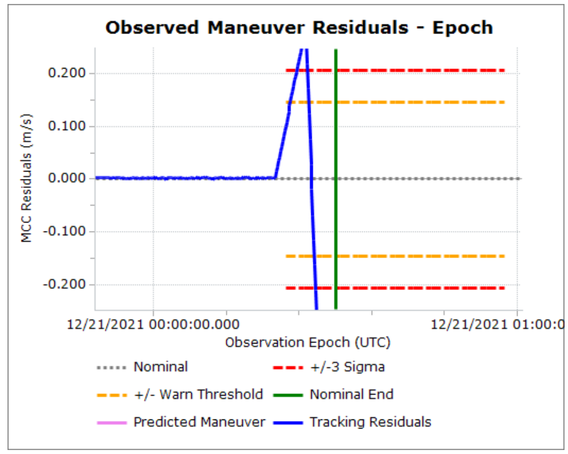

Figure 16. Residuals for MCC-1b Overburn

The objective of all rehearsals was to prepare the team to execute the operational procedures correctly and make decisions while working in a stressful operations environment. Comprehensive pre-launch testing of the monitoring tool presented a unique challenge for the FDEs since it was one of the few tools that used live data. This meant that the team needed to be prepared to make decisions and troubleshoot issues in real time. The additional training rehearsals allowed the team to refine the contingency procedures and emphasized the importance of the delta-v residuals as a factor when determining when to abort a maneuver early.

ON-ORBIT MANEUVER MONITORING, RECONSTRUCTION, AND CALIBRATION RESULTS

MCC-1a

Maneuver monitoring for MCC-1a ran for approximately two hours, beginning 35 minutes prior to the 65-minute maneuver, and finishing 35 minutes after its end. Throughout this duration, the FDEs expected to receive two-way S-band range-rate data via the DSN Madrid 54 antenna, which was successfully collected and processed by the tool. Due to the criticality of MCC-1a, the DSN had multiple antennas actively tracking JWST before, during, and after the maneuver. This resulted in one-way tracking data via the Goldstone 14 antenna and three-way data via the Madrid 56 antenna being delivered to the FDF in addition to the two-way data from the prime Madrid 54 antenna.[9] The one-way and three-way data types were excluded from the dataset passed to the monitoring tool, and the two-way data produced the results shown in Figure 17 and Figure 18.

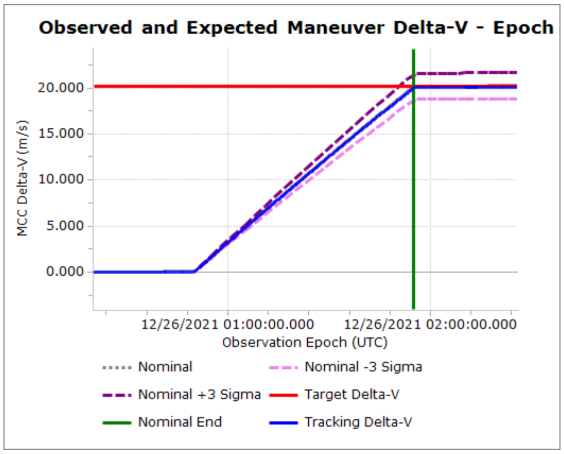

Figure 17. Observed and Expected MCC Delta-V versus Observed UTC Epoch

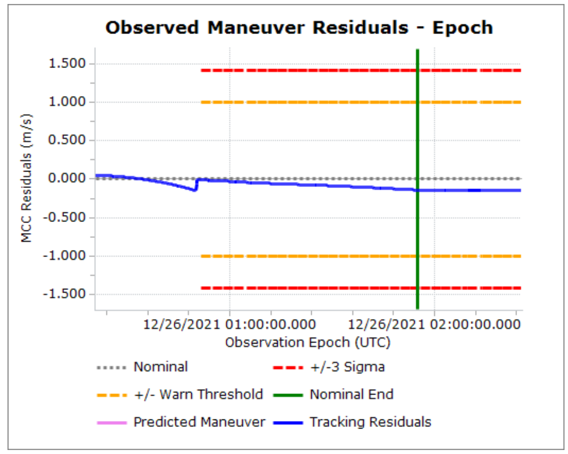

Figure 18. MCC Residuals versus Observed UTC Epoch

Each plot updated once per minute, in near-real time, upon receipt of a new minute-long tracking data file. With each update, the new data was added to each plot, with recently plotted points representing current data and previously plotted points representing historical data. After maneuver completion, the plots showed the entire profile of MCC-1a.

Figure 17 shows that overall, the burn was nominal. MCC-1a was able to achieve nearly all its planned delta-v within the expected duration. Figure 18 shows MCC-1a underburned slightly, though within the warn threshold and without large deviations from the plan. This is demonstrated by the solid blue Tracking Residuals line dipping below the x-axis. Additionally, the maneuver monitoring tool outputted an estimate of the total maneuver delta-v and the percent of the maneuver that had been completed based on that value. For MCC-1a, 99.8% of the planned maneuver delta-v was completed. Since the FDEs were able to observe the maneuver in real-time and would have been able to catch and report on an overburn scenario, and because the results were supported by maneuver reconstruction and calibration, MCC-1a maneuver monitoring was considered a success.

The final reconstructed MCC-1a maneuver information is shown in Table 3. The reconstructed delta-v, 20.033 m/s, is slightly lower than the planned delta-v of 20.202 m/s, which supports the maneuver monitoring results. It is likely this underburn was caused by inaccurate MRE thruster planning. While planning MCC-1a, MRE thruster firings were modeled similarly to a pre-launch project simulation, and post-MCC-1a analysis revealed that the planned on-time was higher than the reconstructed on-time. The MRE thruster performance values from MCC-1a were used to plan for MCC-1b in an effort to improve modeling.

Table 3. Comparison of the MCC-1a Planned and Reconstructed Maneuver Summary

Parameter	Units	Planned	Reconstructed	Difference
Maneuver Name		MCC-1a	MCC-1a	N/A
Start Epoch – Mission Elapsed Time	hours	12.5	12.5	0
Start Epoch	UTC	Dec 26 2021 00:50:00.000	Dec 26 2021 00:49:59.985	N/A
End Epoch	UTC	Dec 26 2021 01:54:54.728	Dec 26 2021 01:54:54.769	N/A
Burn Duration	sec	3894.728	3894.784	0.0560
Delta-V	m/s	20.202	20.033	-0.1698
Attitude at Maneuver Start				
Sun Pitch	deg	-12.745	-12.748	-0.003
Sun Roll	deg	0.000	0.001	0.001
Sun Yaw	deg	-100.821	-100.828	-0.007

The maneuver reconstruction tool also computed post-burn tank information. These results are listed in Table 4, and are shown to be consistent with the official values from the S&OC Propulsion Team that were used in MCC-1b planning. Any discrepancies between the FDF-computed values and S&OC-computed values are largely due to the two propulsion models using slightly different specific impulse values for the MREs.

Table 4. Comparison of Post MCC-1a Tank Values from FDF and S&OC

Property	FDF Post MCC-1a	S&OC Post MCC-1a	Difference
Fuel Mass (kg)	149.405	149.253	-0.152
Ox Mass (kg)	109.497	109.590	0.093
Fuel Pressure (psia)	284.666	285.190	0.524
Ox Pressure (psia)	255.281	253.850	-1.431

When DVALOS calibration was initiated for MCC-1a, the one-way and three-way DSN tracking data was once again removed, and only two-way data was processed by the tool, resulting in the plot in Figure 19. Additional DVALOS calibration results are shown in Table 5. Based on this information, the maneuver underburned by 1.477%, which is consistent with the monitoring results.

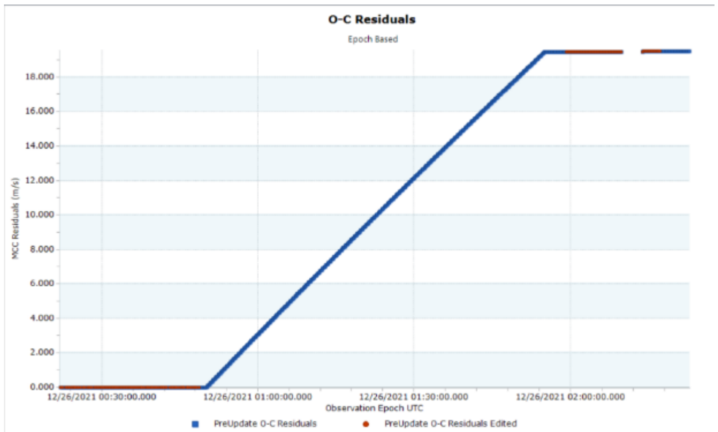

Figure 19. Observed Minus Computed MCC-1a Tracking Data Residuals

The results from the MCC-1a OD calibration runs can also be seen in Table 5. Even when calibrated against an OD state which was generated using more tracking data than DVALOS calibration, the TSF was still approximately one, suggesting the SCAT performed nominally; however, the overall maneuver performance was cold which supports the notion that the MRE contributions were over-modelled in planning.

Table 5. MCC-1a Delta-V Comparison Between Tools

	MCC-1a (m/s)			Performance	
	Delta-V	Diff w/ Planned	Diff w/ Reconstructed	TSF	%
Planned Maneuver	20.202	-	0.170	-	-
Reconstructed Maneuver	20.033	-0.170	-	-	0.841% cold
Propulsion Team	19.940	-0.262	-0.093	-	1.297% cold
DVALOS Calibration	19.904	-0.298	-0.129	0.994	1.477% cold
OD Team Estimate	19.987	-0.215	-0.046	-	1.064% cold
OD Calibration	20.046	-0.156	0.014	1.001	0.778% cold

As seen in Table 5, all the tools used to characterize MCC-1a agree, since the delta-v values show an underburn compared to the planned maneuver and differences are within the same range. One noted difference is that the TSF from DVALOS calibration was less than one, implying underperformance, while the TSF from OD calibration was greater than one, implying overperformance. This is explained by the DVALOS-calibrated delta-v being less than the reconstructed delta-v, while the OD-calibrated delta-v is greater than the reconstructed delta-v. The TSF was computed for the SCAT with respect to the reconstructed delta-v while the MRE parameters were the same in all calculations as they were pulled from telemetry. For

MCC-1b planning, OD calibration was deemed the most accurate for MCC maneuvers, and a TSF of 1.00 was used. With updated MRE thruster parameters, MCC-1b was expected to perform closer to its plan.

MCC-1b

As was the case with MCC-1a, the FDEs expected to receive two-way S-band range-rate data via the DSN Madrid 54 antenna. This data was successfully collected and used to run the maneuver monitoring tool for MCC-1b. The results of this run are shown below in Figure 20 and Figure 21:

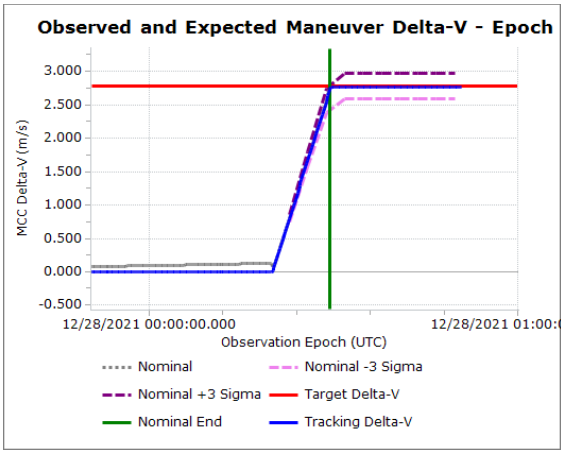

Figure 20. Observed and Expected MCC Delta-V versus Observed UTC Epoch

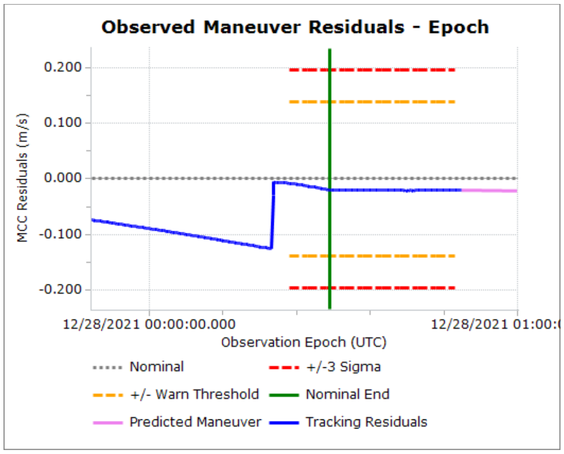

Figure 21. MCC Residuals versus Observed UTC Epoch

In Figure 20, the solid blue Tracking Residuals line does not quite reach the solid red Target Delta-V line. Additionally, Figure 21 shows that at the start of MCC-1b, the achieved delta-v was close to the planned, but as the burn continued, it did not keep up with what was expected. Therefore, maneuver monitoring showed a slight underburn on MCC-1b, similar to MCC-1a.

The results of the reconstructed MCC-1b maneuver are shown in Table 6. The reconstructed delta-v for MCC-1b was 2.77 m/s compared to the planned delta-v of 2.78 m/s, supporting the slight underburn seen in maneuver monitoring. The MRE contributions were approximately the same as the planned values, which was expected, as the MCC-1a MRE contributions were used in MCC-1b planning. The post MCC-1b tank values computed during maneuver reconstruction are listed in Table 7 with the official values from the S&OC Propulsion Team.

Table 6. Comparison of the MCC-1b Planned and Reconstructed Maneuver Summary

Parameter	Units	Planned	Reconstructed	Difference
Maneuver Name		MCC-1b	MCC-1b	N/A
Start Epoch – Mission Elapsed Time	hours	2.5	2.5	0
Start Epoch	UTC	Dec 28 2021 00:20:00.000	Dec 28 2021 00:19:59.860	N/A
End Epoch	UTC	Dec 28 2021 00:29:27.240	Dec 28 2021 00:29:27.156	N/A
Burn Duration	sec	567.240	567.296	0.056
Delta-V	m/s	2.780	2.773	-0.007
Attitude at Maneuver Start				
Sun Pitch	deg	-12.244	-12.244	0.000
Sun Roll	deg	0.000	0.001	0.001
Sun Yaw	deg	-85.902	-85.907	-0.005

Table 7. Comparison of Post MCC-1b Tank Values from FDF and S&OC

Property	FDF Post MCC-1b	S&OC Post MCC-1b	Difference
Fuel Mass (kg)	146.743	146.726	0.017
Ox Mass (kg)	106.424	106.430	0.006
Fuel Pressure (psia)	279.063	279.870	-0.807
Ox Pressure (psia)	247.287	245.760	1.527

Figure 22 displays the DVALOS calibration results for MCC-1b. There is a difference of approximately 2.7 m/s between the post- and pre-maneuver residuals, which is consistent with the achieved total delta-v, presented in Table 8 as 2.752 m/s, as well as the planned and reconstructed delta-v values. The overall maneuver performance was therefore 1.006% cold.

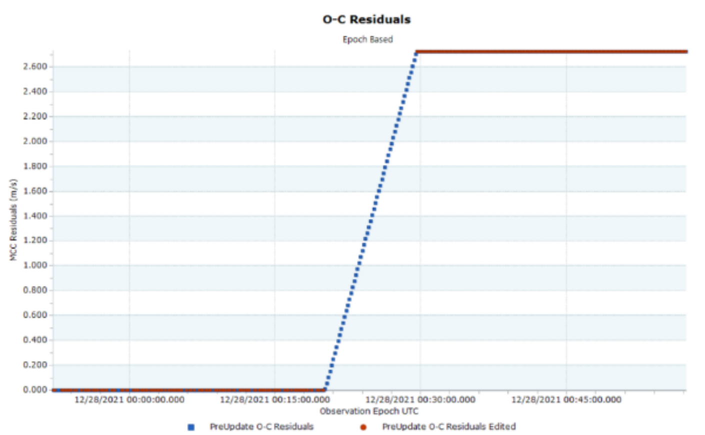

Figure 22. Observed Minus Computed MCC-1b Residuals of Tracking Data

From MCC-1b OD calibration, the achieved total delta-v was approximately 2.763 m/s, as seen in Table 8. The maneuver performance was 0.611% cold. Since both calibration types resulted in a TSF within the 0-5% threshold, MCC-1b was considered a success.

Like MCC-1a, results from all tools were used to characterize MCC-1b, and the result is shown in Table 8. All these values remain consistent with very small differences and show a slight underburn, as they did in the previous maneuver, which demonstrates good agreement on the MCC-1b profile. However, all maneuvers following MCC-1b used a new SCAT thruster set due to JWST sunshield deployment, so a TSF of 1.00 was used to plan MCC-2.

Table 8. MCC-1b Delta-V Comparison Between Tools

	MCC-1b (m/s)			Performance	
	Delta-V	Diff w/ Planned	Diff w/ Reconstructed	TSF	%
Planned Maneuver	2.778	-	0.007	-	-
Reconstructed Maneuver	2.773	-0.007	-	-	0.180% cold
Propulsion Team	2.77	-0.010	-0.003	-	0.288% cold
DVALOS Calibration	2.752	-0.028	-0.021	0.992	1.006% cold
OD Team Estimate	2.748	-0.032	-0.025	-	1.080% cold
OD Calibration	2.763	-0.017	-0.010	0.996	0.611% cold

MCC-2

MCC-2 was planned to occur on January 24, 2022, at 19:00:00.000. Like the previous maneuvers, two-way S-band range-rate data via the DSN Madrid 54 antenna was expected. This tracking data was collected and successfully processed, and the maneuver monitoring plots for MCC-2 are shown below in Figure 23 and Figure 24:

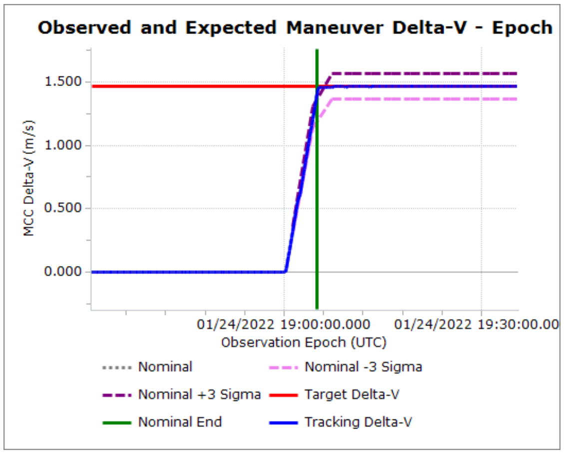

Figure 23. Observed and Expected MCC-2 Delta-V versus Observed UTC Epoch

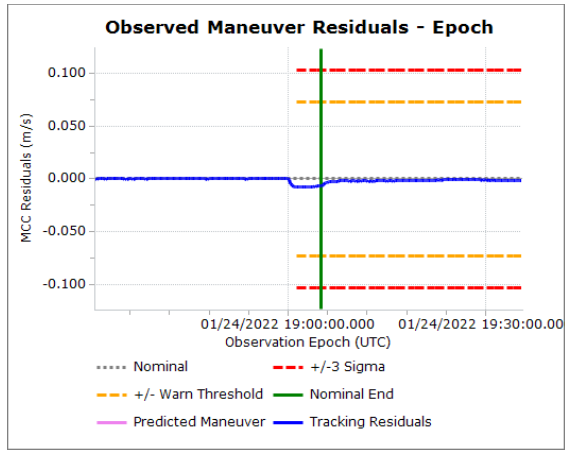

Figure 24. MCC-2 Residuals versus Observed UTC Epoch

Figure 23 shows that, while the actual Tracking Delta-V eventually reached what was expected, it had not achieved the full value at the expected Nominal End epoch. Figure 24 shows the same behavior in more detail: an underburn began at maneuver start, around 19:00 UTC, and reached its peak of -1 cm/s about one minute later. The performance then started matching the expected burn profile and as more data was received, the underburn became less severe. About 30 minutes after the burn ended, a steady state value was reached. This steady state showed that MCC-2 achieved 1.464 m/s of delta-v, which was approximately 99.8% of the expected 1.468 m/s.

Table 9. Comparison of the MCC-2 Planned and Reconstructed Maneuver Summary

Parameter	Units	Planned	Reconstructed	Difference
Maneuver Name		MCC-2	MCC-2	N/A
Start Epoch	UTC	Jan 24 2022 19:00:00.000	Jan 24 2022 18:59:59.836	N/A
End Epoch	UTC	Jan 24 2022 19:04:56.648	Jan 24 2022 19:04:56.540	N/A
Burn Duration	sec	296.648	296.704	0.056
Delta-V	m/s	1.468	1.484	0.017
Attitude at Maneuver Start				
Sun Pitch	deg	-0.760	-13.92	-0.632
Sun Roll	deg	0.000	0.000	0.000
Sun Yaw	deg	16.571	16.571	0.000

Table 10. Comparison of Post MCC-2 Tank Values from FDF and S&OC

Property	FDF Post MCC-2	S&OC Post MCC-2	Difference
Fuel Mass (kg)	145.288	145.261	-0.027
Ox Mass (kg)	104.781	104.890	0.109
Fuel Pressure (psia)	274.398	278.520	4.122
Ox Pressure (psia)	240.374	240.080	-0.294

When running DVALOS calibration for MCC-2, Figure 25 was generated. There is a major difference between this plot and the plots generated for MCC-1a and MCC-1b. The maximum delta-v shown in this plot is around 0.75 m/s, but the planned maneuver delta-v was 1.467718 m/s. This is because Figure 25 displays only the line-of-sight delta-v. While the MCC-1a and MCC-1b maneuvers were almost entirely in the line-of-sight, MCC-2 was not.

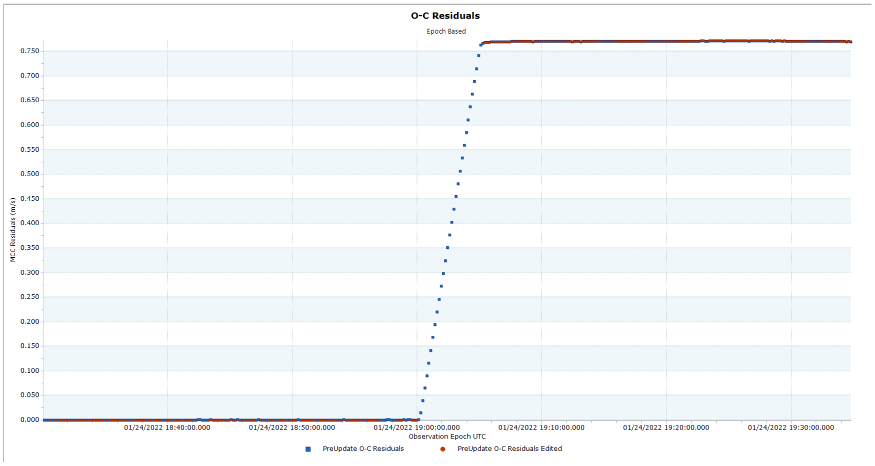

Figure 25. Observed Minus Computed MCC-2 Residuals of Tracking Data

Table 11 shows the DVALOS calibration results and performance of MCC-2. The planned maneuver delta-v, 1.468 m/s, was less than the reconstructed delta-v of 1.484 m/s. The observed delta-v was computed to be 1.461 m/s which resulted in a 0.490% cold maneuver. This maneuver performance was not as cold as MCC-1a or MCC-1b, and the discrepancy was likely due to the use of a new SCAT and differing MRE performance. To account for this in the future, the SCAT-3 TSF for the first SK maneuver was set to 0.984.

OD calibration was performed twice for MCC-2. OD calibration performed on January 26th showed a maneuver performance of 1.292% cold; roughly double the DVALOS calibration result. When OD calibration was performed on January 27th, the maneuver performance decreased to 0.702% cold, and a TSF of 0.982 was computed, which was very close to the DVALOS calibration assessment. More tracking data was available to use for orbit determination on January 27th; because of this, the resultant post-maneuver state and associated calibration run were deemed more reliable than the January 26th data. Additionally, this TSF was well within the 0-5% expectation, and MCC-2 was considered a success.

Table 11 shows the results of all tools used to characterize MCC-2. It demonstrates that MCC-2 underburned, but by a smaller amount than MCC-1a and MCC-1b. Some error was derived from the new MRE thruster performance seen in MCC-2. This performance was tracked for more accurate MRE modelling in SK maneuver planning.

Table 11. MCC-2 Delta-V Comparison Between Tools

	MCC-2 (m/s)			Performance	
	Delta-V	Diff w/ Planned	Diff w/ Reconstructed	TSF	%
Planned Maneuver	1.468	-	-0.016	-	-
Reconstructed Maneuver	1.484	0.016	-	-	1.090% hot
Propulsion Team	1.460	-0.008	-0.024	-	0.545% cold
DVALOS Calibration	1.461	-0.007	-0.024	0.984	0.490% cold
OD Team Estimate	1.453	-0.015	-0.031	-	1.022% cold
OD Calibration	1.457	-0.010	-0.027	0.982	0.702% cold

LONG-TERM JWST MANEUVER PERFORMANCE IMPACTS

The completion of MCC-2 concluded the series of MCC maneuvers that allowed the observatory to transition from the Earth to L2 transfer trajectory into the operational science orbit. For the rest of the mission lifetime, there will only be SK maneuvers and momentum unloads to maintain the orbit. Since the SK maneuvers are on the same thruster set as MCC-2, the FDEs use the results of the MCC-2 calibration to scale the thrust model when planning the SK maneuvers so the predictions will be more accurate. These future maneuvers will be too short to monitor in real-time, but they will still be reconstructed and the thrust scale factor will be further calibrated to improve accuracy over time and account for the gradual degradation of the propulsion hardware.

Looking ahead, JWST is estimated to have the propellant necessary to support these SK maneuvers for an optimistic estimate of 20+ years; significantly longer than the target of 10.5 years. This is due to a combination of factors including the selected launch epoch and excellent launch vehicle performance, but also the accurate execution of the three MCC maneuvers. Together, the maneuvers consumed 23% of the total propellant capacity while the maximum budget was 76% for this phase of the mission. This is illustrated in Figure 26: the portion of the plot with a white background represents the allotted MCC propellant budget, while the portion of the plot with a red-shaded background represents the allotted SK propellant budget. The solid blue line shows the amount of delta-v that was consumed during each MCC maneuver, and it stays well within the allotted MCC propellant budget.

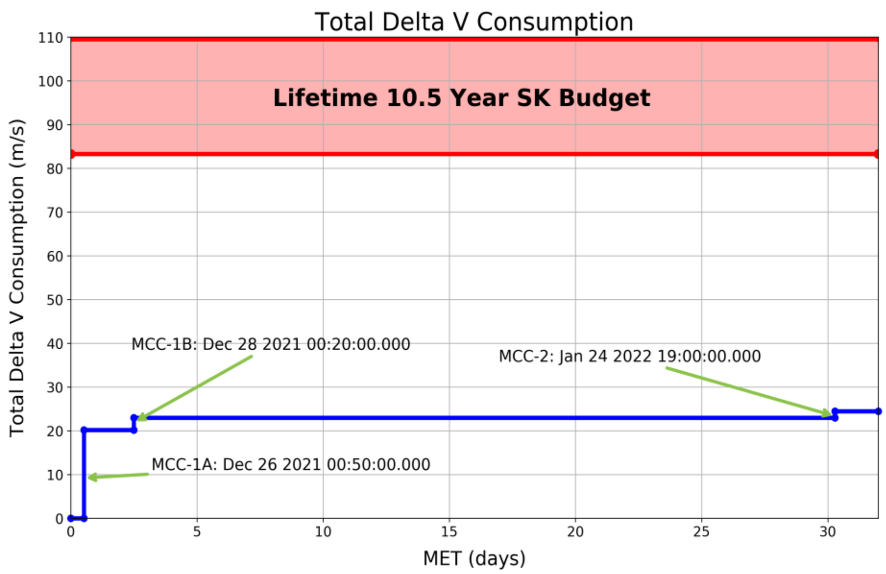

Figure 26. Total Delta-V Consumption of MCC Maneuvers versus Mission Elapsed Time (MET)

Performance data shows that the thrusters are still operating at optimal efficiency, though they are expected to gradually degrade over time and the TSF will have to be adjusted. Other variables will impact the capabilities of the scientific instruments over time, but with careful monitoring, availability of propellant should not be a limiting factor for an extended mission.

CONCLUSION

This paper summarizes the JWST FDT design, contingency planning, and ultimate result of early mission mid-course correction maneuver execution. JWST as an observatory had both burn attitude restrictions and a significant deployment sequence, which were the primary drivers of uncertainty in propulsion performance and observatory dynamics models. Off-nominal maneuver performance, particularly with an overburn of MCC-1a, could have put a risk to JWST operations and the spacecraft health and safety. Responding to real-time maneuver anomalies required both initial planning to design the maneuver and quick turnaround training responses to protect the flagship observatory.

Contingency was built into both the MCC design and execution prior to launch. A bias down was implicitly planned into MCC-1a and MCC-1b, maneuver monitoring abort conditions were trained for by FDEs using ground software, and reconstruction allowed FDEs to correct models for uncertainty in propulsion, attitude, and other errors. In response to anomalies, the JWST operations team could restart the MCC or replan additional maneuvers. These replans could cover any maneuver delays up to, on average, 12 hours after the nominal MCC-1a epoch and more so for MCC-1b and MCC-2.

On orbit, the maneuver performance executed around 1% cold relative to the planned maneuver, well within requirements for early mission performance. The monitored maneuver performance in real time had initial irregularities in plots which did not ultimately impact the observatory health or safety at any point of its execution. With the achieved launch performance of JWST, the overall propellant use can optimistically provide 20+ years of mission life, allowing margin to be used for station-keeping and achieving further JWST science objectives.

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