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PLANNING AND EXECUTION OF THE THREE MID-COURSE CORRECTION MANEUVERS FOR THE JAMES WEBB SPACE TELESCOPE

Jeremy Petersen,* Karen Richon,† and Benjamin Stringer*

The James Webb Space Telescope (JWST) was successfully launched on December 25, 2021 12:20 UTC on an Ariane 5 rocket out of Kourou, French Guiana on a direct, lower energy manifold transfer out to the Sun Earth-Moon (SEM) L2 point. Three mid-course correction (MCC) maneuvers, designated MCC-1, MCC-1b, and MCC-2, were required to provide the energy necessary to reach L2 due to a purposeful biasing down of the launch vehicle. This paper will document the prelaunch preparation, nominal planning, contingency preparation, and successful execution of the three mid-course correction maneuvers.

INTRODUCTION

The James Webb Space Telescope (JWST) successfully launched on December 25, 2021 12:20 UTC on an Ariane 5 rocket out of Kourou, French Guiana on a direct, low energy manifold out to the Sun Earth-Moon (SEM) L2 point. The injection state targeted by the launch vehicle was purposely biased lower than the required value to reach L2 to prevent the observatory from having to remove energy from the orbit during the transfer out to L2. Due to the mission requirements and primary thruster orientation during the transfer phase of the mission, the observatory is unable to remove energy from the orbit necessitating biasing of the launch vehicle injection state below the optimal value. The final injection into the science orbit was broken down into a series of three mid-course correction (MCC) maneuvers designated MCC-1a, MCC-1b, and MCC-2. The three maneuvers were nominally scheduled for execution at launch + 12.5 hours, launch + 2.5 days, and launch + 29 days, respectively. An example of the three-maneuver sequence in the rotating libration point (RLP) frame XY plane is visible in Figure 1.[1]

MCC-1a, nominally executed at launch + 12.5 hours, was the most important of the three-maneuver sequence as most of the energy required to reach SEM L2 is performed during this maneuver. As such, a great deal of work was performed to ensure the successful execution of MCC-1a. MCC-1b, nominally executed at launch + 2.5 days, is a smaller statistical clean up maneuver. MCC-2, nominally executed at launch + 29 days, is the final mid-course correction to provide the remainder of the energy to enter the long-term science orbit. This paper will document the prelaunch preparation, nominal planning, contingency preparation, and successful execution of the three mid-course correction maneuvers.

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* Aerospace Engineer, a.i. solutions, Inc., 4500 Forbes Blvd. Suite 300, Lanham, MD 20706.

† Aerospace Engineer, Navigation and Mission Design Branch, NASA GSFC, 8800 Greenbelt Rd, Greenbelt, MD, 20771.

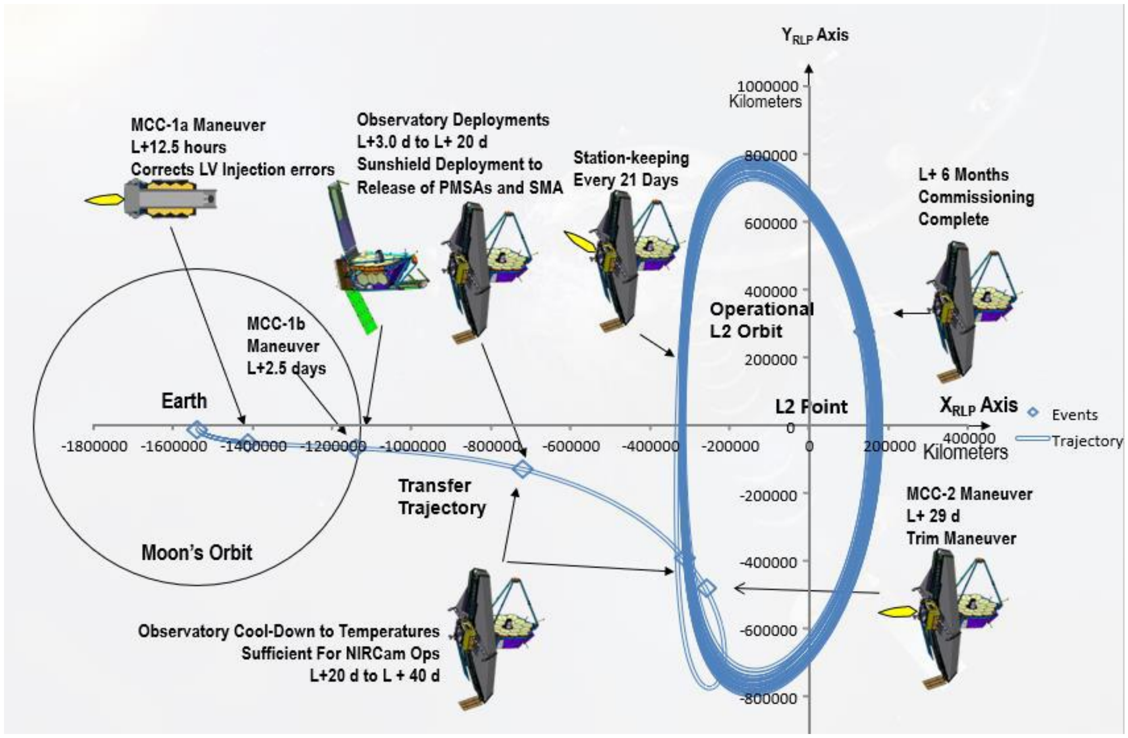


Figure 1. Sample JWST trajectory in the RLP-XY plane with the locations of the three MCC maneuvers.

LAUNCH WINDOW

The flight dynamics team was responsible for generating the first draft of the launch window for the JWST project. The first draft of the launch window was typically 1-year in duration with launch opportunities evaluated in 5-minute increments between 11:30 and 14:00 UTC for both sets of initial conditions provided by the launch vehicle provider Arianespace. The two sets of initial conditions, known as Trajectory 1 and Trajectory 2, each contain the state of the observatory immediately after separation from the Ariane 5 rocket and a dispersion matrix used to characterize the 3-sigma performance of the Ariane 5. The state and dispersion matrix were provided in an epoch independent reference frame tied to the launch site which allows for the states to be applied to any launch epoch through a simple coordinate transformation. The two sets of data are nearly identical; however, they do contain slight differences in the orbital elements, particularly inclination and longitude of the ascending node, which make them appropriate for specific times of year. Trajectory 1 was better suited for winter months while Trajectory 2 was better suited for summer months. The slight difference allows for more robust launch window coverage throughout an entire calendar year which was beneficial for the project while the launch date was unknown. The dispersion matrix was used to generate 3-sigma trajectories for the launch window calculations. The apogee height at separation was the primary orbital element that directly impacted the delta-v costs for the launch window calculation. To calculate the +/-3-sigma state for the launch window, the dispersion matrix was sampled 10,000 times and the +/-3-sigma states were pulled from samples representative of +/-3-sigma apogee height dispersions.

For the first phase of the launch window, a launch epoch was valid if the following criteria were met:

- For a given trajectory, the nominal, -3-sigma, and +3-sigma trajectories must meet the following constraints for 10.5 years following launch:
    - The maximum RLP-Y orbit amplitude does not exceed 832,000 km.
    - The maximum RLP-Z orbit amplitude does not exceed 520,000 km.
    - The trajectory does not contain any Earth or Moon shadows.
    - The maximum Sun-Vehicle-Earth angle does not exceed 33 degrees beginning 65 hours following launch.
- For a given trajectory, the -3/0/+3-sigma dispersion states result in all cumulative MCC delta-v values between 0 and 57.9 m/s. This range covers the amount of propellant budgeted for the MCC phase of the mission.
    - If a +3-sigma trajectory results in a JWST MCC delta-v cost of less than 0 m/s, the observatory would be required to remove energy from the orbit to achieve the required science orbit. Orienting the observatory so that the thrusters can remove energy from the trajectory places the observatory in an attitude that exposes the Optical Telescope Element (OTE) and Integrated Science Instrument Module (OTIS) to the Sun, violating a critical mission constraint. Effectively, energy cannot be removed from the orbit.
    - If a -3-sigma trajectory requires more than 57.9 m/s, the observatory may not have enough delta-v to ensure it reaches its operational orbit with enough delta-v remaining to achieve the mission objectives.

The final version of this initial phase of the launch window is visible in Figure 2. The launch window in Figure 2 spans October 2021 through June 2022. While both Trajectory 1 and Trajectory 2 are calculated, only the best of the two trajectories is selected for visualization in Figure 2. There are a few trends in the figure worth discussing. First, there is a cutout in the launch window during the spring equinox. The same drop out occurs during the fall equinox but is not available in this data set. The equinox dropout makes launching in March or September challenging for any year. These cut outs are due to a combination of lunar perturbations as well as the introduction of Earth and Moon shadows into the trajectory as the trajectory falls to the ecliptic plane when launching during the equinoxes. The second trend is that the launch window typically shrinks near the winter and summer equinoxes but is still viable. The trajectories during this period violate the long-term orbit requirements more frequently as the orientation of Earth with respect to the ecliptic reaches its cyclical extremes. Finally, there is a monthly period where the launch window shrinks dramatically or is cutout entirely due to the impact of lunar perturbations. The lunar perturbations during this monthly period typically increase the delta-v costs beyond the maximums of the delta-v budget making the launch opportunity invalid.

The first phase of the launch window was provided to the European Space Agency (ESA), the French space agency National Centre for Space Studies (CNES), the European Space Operations Centre (ESOC), and Arianespace for them to perform the second refinement phase of the launch window. The second refinement phase of the launch window introduces the following restrictions to the launch window:

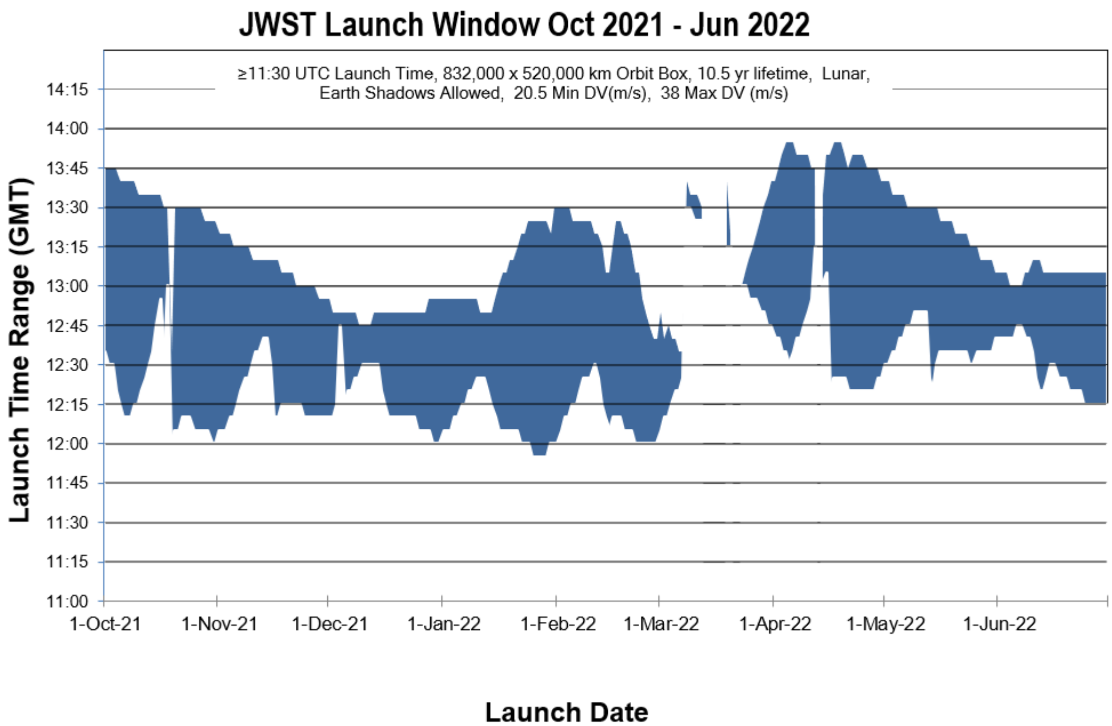


Figure 2. Visual example of the first phase of the JWST launch window.

- Restrictions to meet the thermal requirements during powered flight due to the yearly movement of the Sun vector on the observatory during powered flight.
- Restrictions to ensure that the upper stage escapes into a heliocentric orbit upon completion of the upper stage disposal maneuver after observatory separation.
- Restrictions to ensure Earth casualty risks are satisfied in the event the upper stage fails to perform the disposal maneuver.
- Restrictions to ensure that the roll laws during powered flight and the attitude restrictions at observatory separation from the launch vehicle are satisfied by the available flight programs.
- Restriction to ensure that a roll-over of an onboard launch vehicle timer counter cannot occur during flight.
- Restriction of the launch window due to collision risk with the ISS.
  - This requirement was checked closer to launch. No risk was found and therefore this requirement will not be discussed any further.

Upon completion of the second refinement phase of the launch window, the results were provided back to the flight dynamics team at which point the third and final refinement phase was performed. The third phase refinement increased the fidelity of the launch window from 5-minute increments down to 1-minute. Figure 3 and Figure 4 provide visual examples of the final launch window with the filters from all three phases applied between December 18, 2021 and February 02, 2022. For reference, the cutoff time of February 02, 2022 was selected to match the validity timespan of the attitude law used during powered flight.

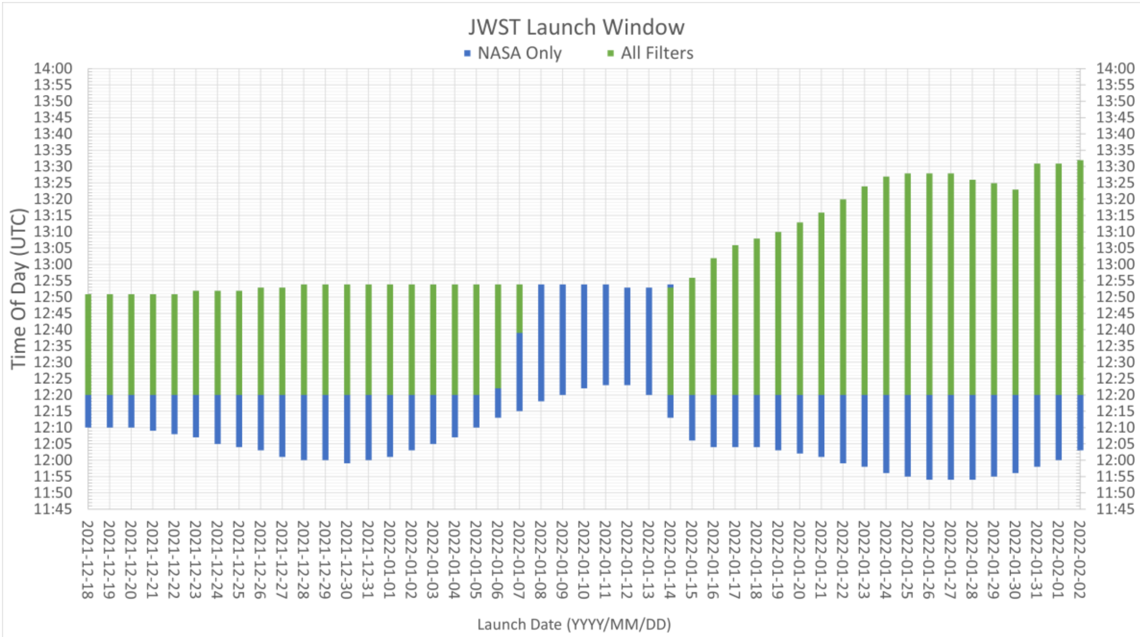


Figure 3. Visual of the final JWST launch window for December 18, 2021 through February 02, 2022. The green region is the official launch window with all launch window filters applied while the blue region shows launch opportunities that were removed after incorporating the launch window filters from the second and third refinement phase.

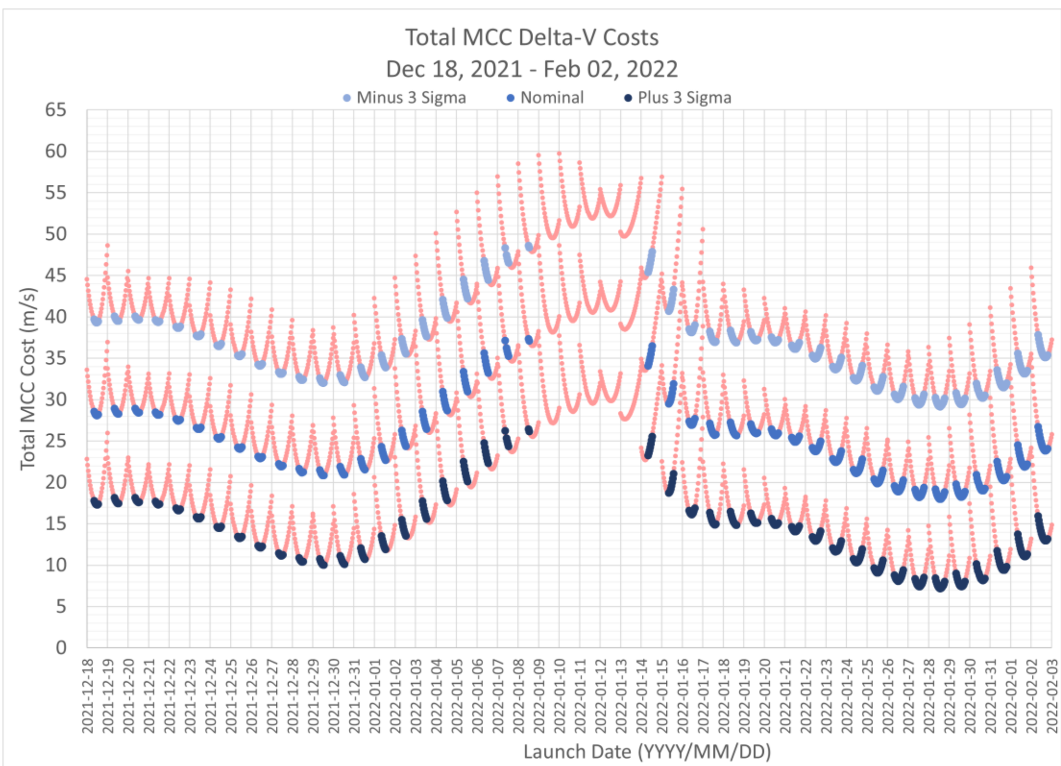


Figure 4. Total MCC delta-v costs (m/s) for all launch opportunities for December 18, 2021 through February 02, 2022. The red dots represent invalid launch opportunities while the various shades of blue represent valid launch epoch for varying levels of launch vehicle performance.

Figure 3 provides the launch window in two sets of colors: green dataset and blue dataset. The green dataset is the launch window with every launch window filter applied while the blue dataset is the launch window after the first phase of the launch window analysis. Any blue region is a launch opportunity that was valid after the first phase of the launch window but no longer valid after the second and third phase refinements were applied. Having both regions on the same chart helps visualize the impact of the second phase refinement of the launch window filters.

There are two requirements from the second phase that reduce the first phase launch window as seen in Figure 3. The first is the thermal requirements during powered flight. To simplify operations and ensure that the thermal requirements were satisfied over the course of an entire year, the launch window was adjusted to launch no earlier than 12:20 UTC. The second requirement to impact the launch window was the upper stage heliocentric escape. Around January 10, 2022, there is a cutout in the launch window as the analysis performed by ESOC showed that a heliocentric escape could not be guaranteed during this period. The cutout period coincides with the lunar perturbation period when the MCC delta-v cost reaches a monthly local maximum which can be seen in Figure 4. From a flight dynamics and delta-v perspective, the cutout due to the heliocentric escape is beneficial as it prevents launch during the most expensive time of month and therefore saves delta-v for station-keeping instead of high cost MCC maneuvers. The other requirements from phase two refinement of the launch window study did not impact the launch window between December 18, 2021 and February 02, 2022.

Figure 4 visualizes the total MCC cost (summation of MCC-1a, MCC-1b, and MCC-2) between December 18, 2021 and February 02, 2022. The red dataset indicates an invalid launch opportunity while the various shades of blue datasets represent valid launch epochs for varying levels of launch vehicle performance: nominal, +3-sigma, and -3-sigma. There are two trends worth discussing within the plot, both of which are a consequence of the separation state provided by Arianespace being fixed in the launch site frame. First, there is a U-shape curve for every day. The U-shape curve represents all launch epochs between 11:30 and 14:00 UTC in five-minute increments and are then color coded according to validity. The typical behavior is that earlier and later times of the daily U-shape correspond to higher delta-v costs and long-term orbit geometry that violates the orbit size requirements and are therefore invalid opportunities. The daily valid regions fall somewhere in the middle of the 11:30-14:00 UTC range, typically between 12:30 to 13:00 UTC. A specific example of the valid ranges per day can be seen in the first phase launch window visual provided in Figure 2. The valid launch epochs don’t always fall within the middle of the 11:30 to 14:00 UTC range. The second trend within Figure 4 is the monthly variation due to lunar perturbations. Each month there is a region of high MCC delta-v costs that end up being cut out of the launch window due to violation of the delta-v budget or violation of the upper stage heliocentric escape requirement. For this specific data set, the cutout is due to the heliocentric escape requirement. Because this behavior is due to lunar perturbations, the trend will be consistent for every month.

DIFFERENTIAL CORRECTOR

Given the uncertainty in the launch date for JWST, the flight dynamics team was requested to generate the launch window for a variety of timespans. Typically, the flight dynamics team was requested to generate the launch window for a year at a time in 5-minute increments between 11:30 and 14:00 UTC. To account for this variation, a robust algorithm was required to ensure that a maneuver plan could be generated for any potential launch epoch.

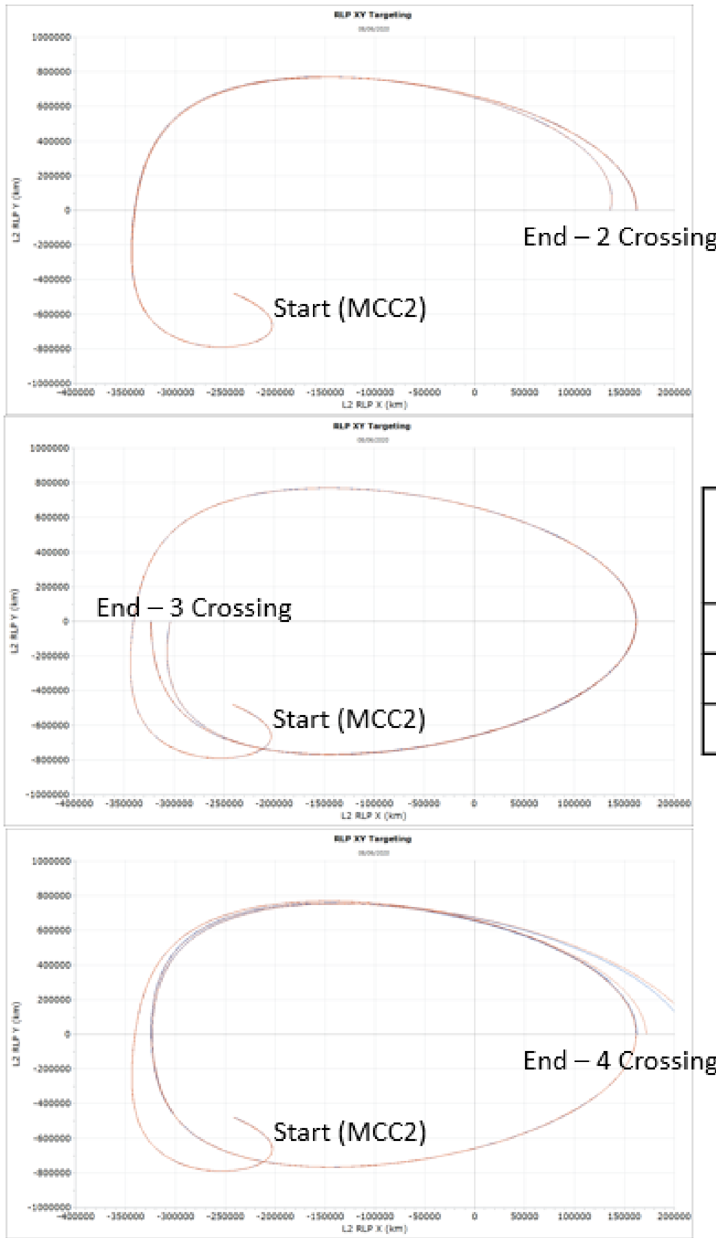
A simple differential corrector was used to calculate the burn duration and delta-v necessary to achieve zero velocity in the x-component of the rotating libration point frame at the third or fourth crossing of the RLP-XZ (RLP-Y = 0) plane. Figure 1 helps visualize this crossing scheme as the trajectory is roughly perpendicular to the RLP-X axis at each crossing.

Due to the sensitivities involved with SEM L2 periodic orbits, it is required to iterate up to the final solution. Without a proper initial guess for the differential corrector, the spacecraft propagation would likely transition into a heliocentric orbit by the third or fourth crossing and the differential corrector would not be able to converge on a solution. The algorithm for MCC-1a and MCC-1b starts with solving for the maneuver size required to achieve the perpendicular crossing constraint at the first crossing of the RLP-XZ plane that occurs after MCC-2 nominal execution time. The solution to achieve one crossing is used as the initial guess for extending propagation out to the second crossing of the RLP-XZ plane and then the solution for achieving the second crossing is used as the initial guess for extending out to the third crossing. The same iterative approach is used for station-keeping maneuver; however, it is recommended to start with two crossings and iteratively increasing out to four crossings. This approach is visually represented in Figure 5 which shows the iterative approach to generate the final solution by starting with the solution to two crossings, using the solution for two crossings as the initial guess for solving three crossings, and then using the solution for three crossings as the initial guess for the final solution at four crossings.

Targeting the crossing downstream at the third crossing for MCC-1a and MCC-1b and the fourth crossing for MCC-2 and station-keeping maneuvers ensures that the observatory will stay around L2 for at least orbit revolution. The downstream crossing method allows the natural dynamics of the SEM L2 orbit to evolve in the full force model with SRP perturbations and n-body gravity modeling without over constraining the trajectory and driving up delta-v costs. This method of energy balancing is the same that has been used in station-keeping algorithms for variation NASA SEM libration point missions (Advanced Composition Explorer (ACE), Wind, Solar & Heliospheric Observatory (SOHO)) and will be used for station-keeping for JWST.[2,3,4]

The primary difference between MCC-2/station-keeping planning and MCC-1a/1b planning is the orientation of the observatory at maneuver execution. For MCC-2 and station-keeping, the observatory is oriented to place the primary station-keeping thruster orientation in inertial space as close as possible to the position component of the stable eigenvector of the monodromy matrix.[4] For MCC-1a and MCC-1b, this process is simplified to align the primary thruster along the inertial velocity vector at the start of the burn to maximize the efficiency of the maneuver. For most launch epochs, aligning the primary thruster along the inertial velocity direction falls within attitude constraints. For the handful of launch epochs where the alignment falls just outside the attitude requirements, the thruster was placed as close as possible to the inertial velocity vector, usually within a few degrees, which would incur a slight inefficiency penalty that was easily absorbed by the delta-v budget.

While the differential corrector algorithm is simple in nature and not novel by any means, it is important to highlight the effectiveness of the crossing algorithm in generating a maneuver plan for MCC-1a and MCC-1b. The algorithm's efficiency was beneficial during operations to quickly generate a maneuver plan under a time constraint while also being beneficial during launch window calculations due to the low computation stress when calculating the MCC costs across an entire year of launch opportunities. Only a slight modification to the algorithm was necessary for the launch window calculation to catch boundary cases when launch epochs result in delta-v costs that are either too large or too small for the differential corrector to solve. The modification simply terminates the differential correction process and returns a flag indicating an invalid launch opportunity. Otherwise, the algorithm was identical in operations and launch window calculations which was a benefit for training and software development purposes.



Crossing	Initial Guess (cm/s)	Converged Solution (cm/s)
2	0.000	3.450
3	3.450	3.462
4	3.462	3.456

Figure 5. Iterative process example for the crossing method. This is an example for station-keeping when starting at two crossings and iterating out to four crossings. The three plots, in the RLP-XY plane, show the iterative progression out to four crossings. The table on the right shows the initial guess and converged solution for each crossing.

MCC-1A CONTINGENCY PLANNING

One of the final pieces of prelaunch preparation was contingency preparation. From a flight dynamics perspective, many of the possible contingency scenarios simplified to a delayed execution of MCC-1a which would require the flight dynamics team to deliver another maneuver plan to the spacecraft operators with the new maneuver execution time. Two paths were taken to simplify the flight dynamics response to a delay of MCC-1a: an agreed upon cadence of maneuver execution times in the event of minor delays and generation of a simple chart for the spacecraft operators to read to quickly estimate the impact of delayed MCC-1a execution.

MCC-1a Execution Timing

After many discussions with the spacecraft operators, a strategy was generated to simplify the flight dynamics team response to any variety of spacecraft contingencies for MCC-1a. Prelaunch, the flight dynamics team and spacecraft operators agreed upon a maneuver execution cadence with the primary execution at launch + 12.5 hours, a backup execution scheduled for launch + 14.5 hours in the event of a minor delay, and a further fallback execution at launch + 19.5 hours if the orbit determination solution was of insufficient quality to plan a maneuver for execution at launch + 12.5 hours.[5] The spacecraft operators required four hours to process a maneuver plan. Therefore, the flight dynamics team was required to deliver the maneuver plan at launch + 8.5 and launch + 10.5 hours for the primary and backup execution times of launch + 12.5 hours and launch + 14.5 hours.

In addition, it was agreed upon that the spacecraft operators could execute any maneuver plan within 1-hour of the nominal execution time in 15-minute increments. This provided flexibility to the spacecraft operators to delay the maneuver slightly without having to wait for a new maneuver plan from the flight dynamics team. It also provided a benefit to the flight dynamics team as the possible execution times would be known ahead of time which was a prerequisite for monitoring the maneuver in real time through the doppler residuals.[6] While this strategy would incur a delta-v penalty due to an attitude misalignment from the inertial velocity vector at the start of the maneuver and gravity loss effect due to performing the maneuver further away from perigee than planned, the impact was deemed minimal and insignificant relative to the flexibility benefits it provided. If the maneuver was delayed longer than 1-hour, the spacecraft operators would either fall back to the backup maneuver plan at launch + 14.5 hours or request a new maneuver plan at a new execution time at least four hours later.

Agreeing to this schedule helped structure the flight dynamics timeline between observatory separation from the launch vehicle and execution of MCC-1a as well as allowing the spacecraft operators the ability to execute the maneuver at a variety of opportunities without having to specifically request a new maneuver plan from the flight dynamics team. The maneuver plan could either be delayed slightly or a backup opportunity was already available on the file delivery system for the spacecraft operators to use.

MCC-1a Delay Charts

In the event the MCC-1a execution time was delayed outside of the agreed upon cadence, the flight dynamics team delivered a plot to the spacecraft operators that provided the MCC-1a delta-v cost and total MCC delta-v cost as a function of delaying MCC-1a out to launch + 28.5 hours. An early version of this plot was generated years ago, discussed in Reference 1, and is visible in Figure 6.

Leading up to launch, various modifications were made to help simplify the plot for the spacecraft operators and the project scientists. An example of the final product is shown in Figure 7.

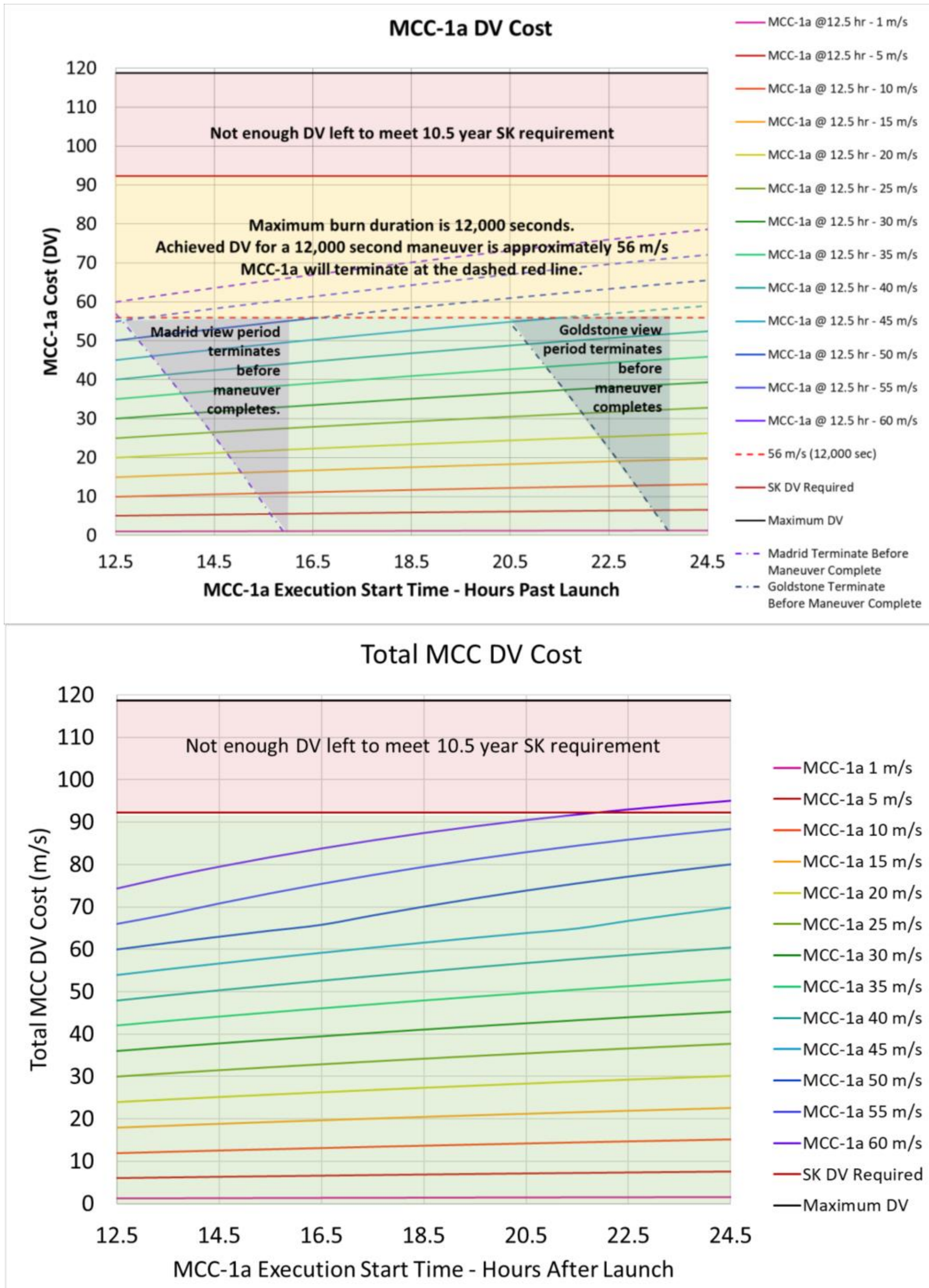


Figure 6. Example of the old format of the MCC-1a delay charts provided to the spacecraft operators. This format was provided prelaunch but proved to be a little too confusing as it required the flight dynamics team to inform every end user which curve follow based on the actual launcher performance.[1]

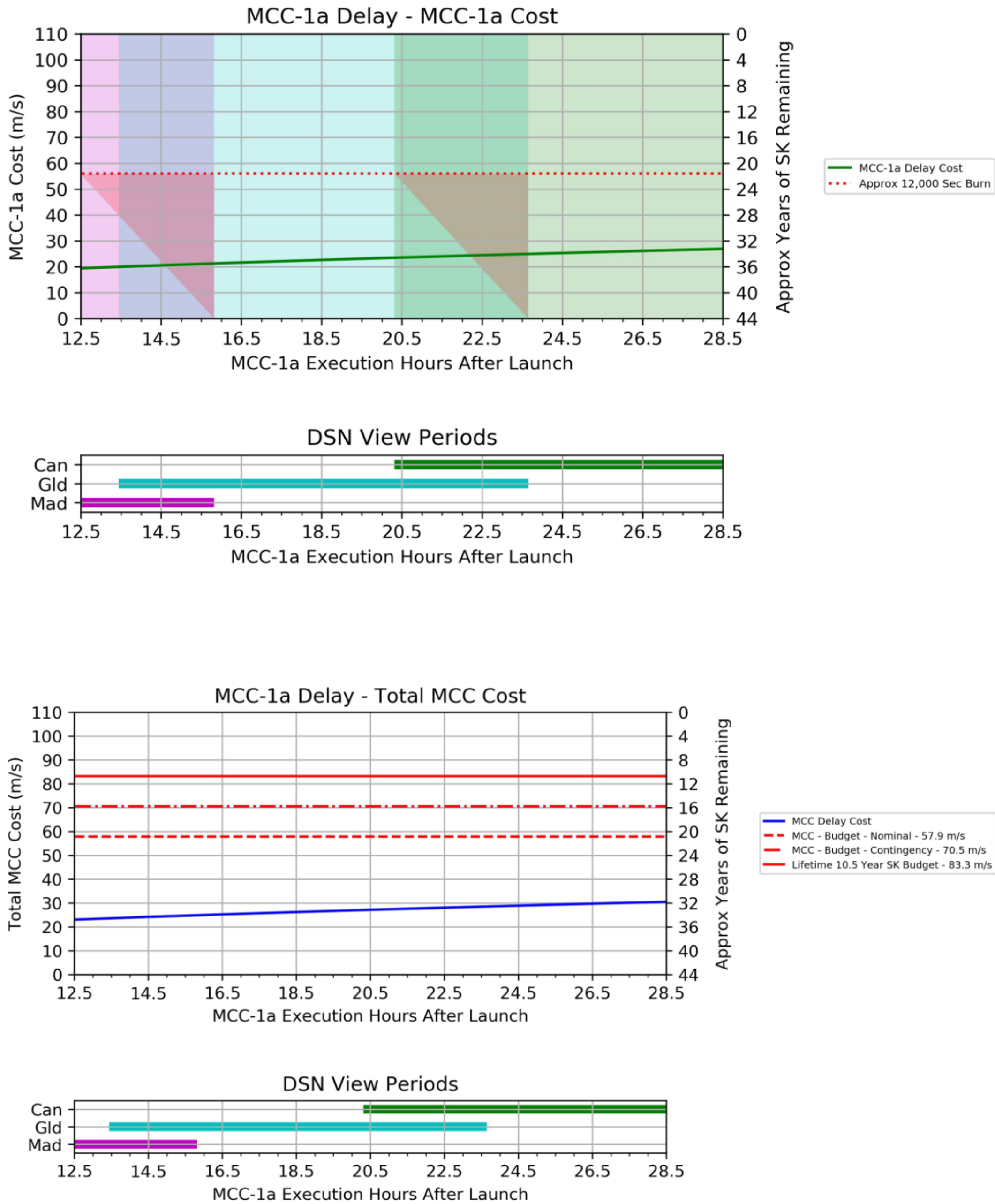


Figure 7. Updated version of the MCC-1a delay chart. This version is simplified to contain a single curve that is based on the actual launch vehicle performance, incorporates a secondary y-axis to show the approximate amount of station-keeping lifetime remaining, and a summary of the view periods during MCC-1a.

The first modification was to simplify the contents of the plot by reducing the dataset down to a single curve. The primary benefit of this change was the simplification of the plot for the end user. In the previous iteration, the flight dynamics team would have to tell each end user which curve to look at based on the launch vehicle performance. The drawback is that the plot could not be made available prelaunch. It was agreed with the spacecraft operators that the flight dynamics team would provide this plot at approximately launch + 3 hours once the launch vehicle performance was available from Arianespace.

The second modification was the introduction of the right-side y-axis label that shows the approximate years of station-keeping life remaining. The addition of the secondary y-axis was of great interest to the project scientists as it allowed them to quickly understand the long-term impacts to the lifetime of the observatory due to delays in MCC-1a execution time. To create the rough estimate of mission lifetime remaining, the station-keeping budget delta-v budget of 2.5 m/s of delta-v per year is divided into the approximate full tank capacity of 110 m/s of delta-v to achieve a maximum of 44 years of station-keeping lifetime. For the MCC-1a cost chart, a red dotted line is placed at an approximate 12,000 second burn duration as this is the maximum burn size allowable before having to split the maneuver into smaller segments an incur a delta-v efficiency penalty. For the total MCC cost chart, there are several red lines to denote specific delta-v budget milestones. The two dotted red lines are the delta-v budge limits for a nominal total MCC cost of 57.9 and a contingency cost of 70.5 m/s. The solid red line is the absolute maximum total cost of the MCCs at 83.3 m/s that still reserves the delta-v budget allotment of 26.5 m/s of delta-v for 10.5 years of station-keeping.

The third modification was the alignment of the DSN view periods with the delta-v cost charts. Each delta-v cost chart has a smaller bar chart underneath that shows the view periods with the DSN assets between launch + 12.5 and launch + 28.5 hours. For the MCC-1a cost chart, the vertical base of the triangle represents the end of a pass with the DSN. Any maneuver epoch that starts within the colored triangle is a maneuver that will extend across the end of a pass with the DSN. If the maneuver start time was to occur with the colored triangles, the spacecraft operators should transition communications to the following DSN site prior to the maneuver to ensure the entire maneuver occurs on a single pass to prevent a station handover during the middle of a burn.

MCC EXECUTION SUMMARY

MCC Strategy Summary

The three mid-course correction maneuvers for JWST, labeled at MCC-1a, MCC-1b, and MCC-2, were nominally scheduled for launch + 12.5 hours, launch + 2.5 days, and launch + 29 days, respectively. MCC-1a was the most important maneuver for mission success. Because the observatory cannot remove energy from the transfer orbit in the stowed sunshield configuration or remove energy efficiently in the fully deployed sunshield configuration, the separation state energy targeted by the launch vehicle was biased slightly low which requires the observatory to make up the missing energy through the three mid-course correction maneuvers. Most of the missing energy was applied during MCC-1a. Because the observatory cannot remove energy from the transfer orbit in the stowed configuration or remove energy efficiently in the deployed configuration, MCC-1a cost was biased down to 93% of the nominal maneuver size to account for a 5.5% uncertainty in the primary thruster performance and 1.5% variability in the attitude control thruster performance. Due to this biasing, MCC-1b acts as both a statistical cleanup for MCC-1a and a maneuver to provide the additional 7% that was missing from MCC-1a. The same

93% bias was applied for MCC-1b to prevent adding too much energy to the orbit. As such, MCC-2 was the final statistical clean up as well as application of the small amount of energy remaining from biasing MCC-1a and MCC-1b by 7% each.

Launch and MCC-1a Execution

By mid-Fall 2021, the window for the launch date for JWST was beginning to narrow in on late November 2021 to late December 2021. After a few minor delays, the launch date was officially set for Christmas Day 2021. The opening of the launch window on December 25, 2021 was 12:20 UTC and the window was 32 minutes long resulting in the closure of the window at 12:52 UTC. JWST launched at the opening of the window right at 12:20 UTC. Based on prelaunch analysis, the nominal total MCC cost was 24.253 m/s with a launch vehicle +/- 3-sigma performance spread of [13.478, 35.387] m/s. Looking at Figure 4 which shows the delta-v costs throughout the December 18, 2021 through February 02, 2022 timespan, launching on December 25, 2021 nearly aligned with the monthly local minimum delta-v cost, which is fortunate from a delta-v and mission lifetime perspective. Launching near the monthly local minimum will help extend the mission several years for virtually no cost or penalty.

Based on the tracking data collected between observatory separation from the launch vehicle and the nominal tracking data cutoff at L+7.5 hours, the flight dynamics team was able to verify that the launch vehicle performance was nearly nominal placing the observatory just slightly above the nominal apogee height by +0.08 sigma. The nominal launch was beneficial from a delta-v perspective as a -3-sigma performance would have resulted in an additional 10 m/s of delta-v required for the MCCs, which is equivalent to about 4 years of station-keeping delta-v. Overall, the launch was nearly nominal which helped reduce the stress of the maneuver planners considerably on launch day.

The flight dynamics team was able to generate a quality orbit determination solution by launch + 7.5 hours keeping the mission on track for a nominal MCC-1a execution at launch + 12.5 hours.[5] Prelaunch analysis MCC-1a cost was 20.468 m/s. The MCC-1a plan generated from the orbit determination solution was slightly lower due to the slightly hot performance of the launch vehicle and resulted in a maneuver plan of 20.202 m/s with a corresponding burn duration of 3894.728 seconds.

MCC-1a was executed right on time at launch + 12.5 hours on December 26, 2021 00:50 UTC. Preliminary reconstruction based on spacecraft telemetry showed the maneuver resulted in a delta-v of 20.033 m/s which is 0.836% cold relative to the nominal plan of 20.202 m/s. The slightly cold reconstruction result is attributed to the slight mismodeling of the closed loop attitude control thrusters during the maneuver planning process. The propulsion system for JWST is comprised of a primary delta-v thruster, known as a Secondary Combustion Augmented Thruster (SCAT), and a collection of eight attitude control thrusters, known as Monopropellant Rocket Engines (MRE) in a closed loop attitude control system. When generating the maneuver plan, the flight dynamics team must make an educated guess at the performance of the MRE thrusters during the burn based on prelaunch analysis. The maneuver plan assumed the MREs would fire for a combined 480 seconds while spacecraft telemetry showed they only fired for about one-fifth of that at 110 seconds. The MRE thrusters themselves are weak, so the underperformance only resulted in a very small delta-v shortfall.

The flight dynamics team relies on two calibration methods: Delta-V Along Line of Sight (DVALOS) and post maneuver orbit determination calibration. The DVALOS calibration method uses the doppler residuals before and after the maneuver to estimate the achieved delta-v.[6] The primary benefit of the DVALOS method is that the results are available within 30 minutes after the end of the maneuver. This is the same method that is used to assess maneuver performance for ACE, Wind, and SOHO.[2,3] The post maneuver orbit determination calibration method relies on using the converged orbit determination solution after the maneuver and calculates the achieved delta-v required from the maneuver to match the post maneuver semi-major axis from the post maneuver orbit determination solution. The DVALOS results showed an achieved delta-v of 19.904 m/s, which is 1.477% cold relative to the original maneuver plan. The orbit determination method resulted in an achieved delta-v of 20.046 m/s, which is 0.774% cold relative to the original plan. Both calibration methods were within 1.5% of the desired delta-v, indicating excellent maneuver performance for the first and most critical maneuver for the mission. Table 1 summarizes the delta-v values and percent errors relative to the final delivered plan for MCC-1a.

Table 1. MCC-1a planning and execution summary.

MCC-1a Maneuver Plan		
Prelaunch nominal	20.468 m/s	--
Final delivered plan	20.202 m/s	--
Reconstruction	20.033 m/s	0.836% cold
DVALOS	19.904 m/s	1.477% cold
Orbit Determination	20.046 m/s	0.774% cold

MCC-1b Execution

The nearly perfect execution of MCC-1a combined with the nearly nominal launch vehicle performance greatly reduced the stress for the flight dynamics team with regards to MCC-1b and MCC-2 execution. Prelaunch analysis showed that MCC-1b could be delayed for multiple days for virtually no delta-v penalty in the event of a nominal MCC-1a execution. This reduced the stress and criticality of performing MCC-1b on time at launch + 2.5 days in the event of contingency event between MCC-1a and MCC-1b or difficulty creating an orbit determination solution for MCC-1b maneuver planning.

Prelaunch analysis indicated that the nominal MCC-1b cost was 2.518 m/s. This value assumes a nominal launch vehicle performance and nominal MCC-1a execution. Based on the tracking data collected leading up to the maneuver at launch + 2.5 days, the final maneuver plan for MCC-1b required 2.780 m/s with a corresponding burn duration of 567.240 seconds, which is slightly higher than the prelaunch analysis and in line with the slightly cold MCC-1a performance. In addition, it was also decided to keep the thrust scale factor for the primary thruster at 1.000 since the performance of MCC-1a was only slightly cold. It was difficult to determine if the maneuver was cold because of the primary station-keeping thruster performance or if it was due to the overprediction of the MRE performance relative to the actual performance. To keep maneuver planning simple for MCC-1b, it was decided to update the MRE performance based on MCC-1a telemetry while keeping the thrust scale factor for the primary station-keeping thruster at 1.000.

MCC-1b was executed on time at launch + 2.5 days on December 28, 2021 00:20 UTC. Preliminary reconstruction based on spacecraft telemetry showed the maneuver resulted in a delta-v of 2.773 m/s which is 0.252% cold relative to the nominal plan of 2.780 m/s. The flight dynamics team predicted 16 seconds of MRE firings during MCC-1b while the spacecraft telemetry showed only 13 seconds of MRE firings during MCC-1b. DVALOS showed an achieved delta-v of 2.752 m/s, which is 1.006% cold relative to the nominal plan. The first post maneuver orbit determination solution showed an achieved delta-v of 2.763 m/s, which is 0.611% cold relative to the nominal plan. Once again, the reconstruction and two calibration methods, summarized in Table 2, confirm an excellent maneuver performance for MCC-1b.

Table 2. MCC-1b planning and execution summary

MCC-1b Maneuver Plan		
Prelaunch nominal	2.518 m/s	--
Final delivered plan	2.780 m/s	--
Reconstruction	2.773 m/s	0.252% cold
DVALOS	2.752 m/s	1.006% cold
Orbit Determination	2.763 m/s	0.661% cold

MCC-2 Execution

With a nearly perfect MCC-1a and MCC-1b execution, the observatory was safely on its way to its science orbit at SEM L2. For the following three weeks, the flight dynamics team was primarily generating orbit determination solutions during the sunshield deployment phase between MCC-1b and MCC-2 and monitoring the MCC-2 delta-v cost which hardly varied.

MCC-2 is unique relative to the other two mid-course correction maneuvers as MCC-2 is the first maneuver in the deployed sunshield configuration. Instead of orienting the station-keeping thruster along the inertial velocity vector, the thruster is oriented as close as possible to the position components of the stable eigenvector of the monodromy matrix.[4] In addition, MCC-2 would be the first maneuver on the primary thruster used for station-keeping maneuvers so any thruster calibration performed during MCC-1a and MCC-1b could not be used for MCC-2.

The final mid-course correction maneuver was originally scheduled for launch + 29 days which would have fallen on a Sunday. To assist the spacecraft operators, the decision was made to adjust the MCC-2 timing to launch + 30 days to place the maneuver on a Monday instead of a Sunday. The successes of MCC-1a and MCC-1b made this decision rather trivial as there was virtually no penalty involved when waiting one extra day to perform MCC-2.

Table 3 summarizes the results from MCC-2. Prelaunch analysis indicated that the nominal MCC-2 cost was 1.267 m/s. Based on the tracking data collected leading up to the maneuver, the final MCC-2 maneuver plan was 1.468 m/s with a corresponding burn duration of 296.648 seconds which is in line with the slightly cold performance of MCC-1a and MCC-1b. MCC-2 was performed at launch + 30 days on January 24, 2022 at 19:00 UTC. Preliminary reconstruction based on spacecraft telemetry showed a maneuver size of 1.484 m/s, which is 1.090% hot relative to the nominal plan of 1.468 m/s. For MCC-2 planning, the MREs were predicted to perform based on MCC-1b performance which resulted in a prediction of 7 seconds of MRE firing during MCC-2. Based on telemetry, the MREs fired for 43 seconds, which is a significant increase relative to the plan and the primary driver for the high reconstruction result relative to the plan. This discrepancy is reasonable as MCC-2 is the first maneuver with the sunshield deployed and therefore would be a different closed loop attitude control response relative to MCC-1b. DVALOS results showed an achieved delta-v of 1.461 m/s which is 0.491% cold relative to the plan. The first postmaneuver orbit determination solution showed an achieved delta-v of 1.457 m/s which is 0.702% cold relative to the plan. Given the underperformance based on tracking data relative to the telemetry results from reconstruction, it is suspected that the primary station-keeping thruster performed slightly cold. Future station-keeping maneuvers will help characterize the primary station-keeping thruster performance.

Table 3. MCC-2 planning and execution summary

MCC-2 Maneuver Plan		
Prelaunch nominal	1.267 m/s	--
Final delivered plan	1.468 m/s	--
Reconstruction	1.484 m/s	1.090% hot
DVALOS	1.461 m/s	0.491% cold
Orbit Determination	1.457 m/s	0.702% cold

MCC Summary

Overall, the three MCC maneuvers were executed on time and the percent performance was within 1.5% which is, in the opinion of this author, quite an impressive achievement considering MCC-1a and MCC-2 were the first maneuvers performed on each thruster.

Table 4 compares the delta-v costs from prelaunch analysis to the actual maneuver plans and achieved delta-v from tracking sources. The prelaunch nominal cumulative MCC cost based on the launch epoch was 24.253 m/s while the cumulative maneuver plan was 24.450 m/s, the cumulative achieved delta-v from DVALOS was 24.117 m/s, and the cumulative achieved delta-v from orbit determination was 24.266 m/s. Any metric used to assess the maneuver performance relative to prelaunch expectations demonstrates the nominal performance of both launch vehicle and the execution of three mid-course correction maneuvers.

One of the many keys to success for the three mid-course correction maneuvers was the prelaunch preparation regarding the propulsion system. Extensive prelaunch analysis was performed by Northrup Grumman to provide the flight dynamics team with a document that outlined the performance of the primary delta-v thruster as well as the attitude control thrusters. The equations outlined in the document were programmed into the flight dynamics ground system and proved to be instrumental in predicting the performance of the three maneuvers. In addition, an extensive validation effort was performed with members of the propulsion team at Northrup Grumman as well as the spacecraft operators. This provided the flight dynamics team the confidence that the flight dynamics ground system would generate a maneuver plan the team could trust and the results of the three maneuvers validates the amount of work put into the validation effort.

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

CONCLUSION

JWST was successfully launched at the opening of the launch window on December 25, 2021 12:20 UTC. Tracking data collected between separation and MCC-1a showed a slightly hot performance of the launch vehicle at +0.08-sigma with respect to the nominal apogee height at separation. The execution of the three MCC maneuvers was also nearly nominal as the summation of the three maneuvers achieved approximately 24.117 m/s or 24.266 m/s based on DVALOS and orbit determination calibration methods, respectively. The MCC cost summation is perfectly in line with the prelaunch expectation of 24.253 m/s. The near nominal performance of the launch vehicle combined with the nearly nominal execution of the three mid-course correction maneuvers leaves the project with over 30 years of propellant remaining for station-keeping for the long-term science orbit.

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