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MID-COURSE CORRECTION CONTINGENCY ANALYSIS FOR THE JAMES WEBB SPACE TELESCOPE

Taabish Rashied,[*] Benjamin Stringer,[*] Jeremy Petersen,[†] and Karen Richon[‡]

This investigation details two analyses performed as part of an early orbit contingency operations study related to the James Webb Space Telescope's limited ability to maneuver in a sunward direction. First, contingency planning developed by the Flight Dynamics Team and shared with the Science and Operations Center to quickly assess the available timeline in the event of a delayed mid-course correction maneuver is presented. Second, the methods for recovering from a maneuver overburn using observatory geometry to exploit the solar radiation pressure perturbation contributions from the large sunshield as well as adjusting the maneuver campaign to recover the observatory are examined.

INTRODUCTION

The James Webb Space Telescope (JWST) follows in the footsteps of the Hubble, Spitzer, and Herschel space telescopes continuing a legacy of powerful space observatories that help humanity understand its place in the universe. Covering a spectrum that ranges from long-wavelength visible light (0.6 μm) through mid-infrared (27 μm), it bridges the gap between the Hubble and Herschel telescopes, and it will also specialize in detecting redshifted light from the early universe. With 18 mirror segments that combine to form an aperture that is 6.5 meters wide, it will produce images with much higher resolution than the Spitzer telescope. JWST is the most recent Large Strategic Science Mission for the National Aeronautics and Space Administration's (NASA) astrophysics division. JWST is scheduled for launch in 2021 on an Ariane 5 rocket. After a low-cost direct transfer from Earth, it will enter an orbit in the vicinity of the Sun-Earth/Moon Barycenter (SEMB) L2 libration point where it will remain throughout the 10.5-year mission lifetime.

One of the main challenges for an infrared telescope is that it must be kept at an extremely low temperature. Excess thermal energy — infrared radiation — from the observatory itself could overwhelm or contaminate the instruments. Some previous missions have relied on a coolant such as liquid helium, but coolant is a limited resource and can be depleted in a few years, limiting the mission lifetime. Because of the sensitivity to infrared radiation of JWST's
strument Module (ISIM) and Optical Telescope Element (OTE) — both located on the
of the observatory — JWST will fly at an attitude where these elements are always protected from solar and Earth radiation. The other side of the observatory holds the rest of the necessary components such as the antenna, solar panel array, and thrusters. JWST relies on a large sunshield to block

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[*] Jr. Systems Engineer, Mission Engineering and Technologies Division, a.i. solutions, Inc., 4500 Forbes Blvd. Suite 300, Lanham, MD 20706.
[†] Sr. Systems Engineer, Mission Engineering and Technologies Division, a.i. solutions, Inc., 4500 Forbes Blvd. Suite 300, Lanham, MD 20706.
[‡] Flight Dynamics Lead, Navigation and Mission Design Branch, NASA Goddard Space Flight Center, 8800 Greenbelt Rd, Greenbelt, MD 20771.

the solar radiation from the cold side with a supplemental cryocooler for the Mid-Infrared Instrument (MIRI). The sunshield comprises five layers of Kapton and is approximately 21 m by 14 m, or about the size of a tennis court. The sunshield will maintain a temperature difference of over 300°C between the two sides, with the hot side expected to be at a temperature of 83°C and the cold side at a temperature of −223°C. Using primarily a passive method for temperature regulation greatly extends the possible mission lifetime. However, this unique spacecraft configuration also places significant constraints on observatory attitude and maneuver direction.

Since all the thrusters are on one side of the observatory, the ability to execute maneuvers in the sunward direction is limited. During the initial stages of the transfer orbit before the sunshield is deployed, the maneuver direction is further limited to protect sensitive instruments from stray light. The thrusters are only be able to inject energy into the orbit, not remove energy. Adding too much energy to the orbit could cause the observatory to escape its libration-point orbit (LPO) into a heliocentric orbit beyond the SEMB L2, effectively ending the mission. To prevent an overburn scenario the launch vehicle will intentionally deliver the observatory to a trajectory that falls short of the target destination. A series of three mid-course correction (MCC) maneuvers will be employed to provide the additional energy to deliver the observatory to its science orbit about SEMB L2.

Depicted in Figure 1, three maneuvers designated MCC-1a, MCC-1b, and MCC-2 will be executed at launch plus 12.5 hours (L+12.5 hours), L+2.5 days, and L+30 days, respectively. The sunshield deployment phase for JWST will occur between L+3 and L+14 days. Similar to the injection from the launch vehicle, the first two maneuvers will be biased down to 93% of the ideal maneuver to achieve the LPO to prevent an overburn in the event of overperformance by the thrusters. MCC-1b is intended to nearly complete the maneuver started by MCC-1a while MCC-2 will finally place JWST into its science orbit. MCC-1a is the most critical maneuver of the entire mission as it is largest maneuver and occurs shortly after launch. As such, it is important to consider and prepare for the possible case if this maneuver does not go as planned. This investigation focuses on two potential contingencies: 1) the execution of MCC-1a is delayed because of operational circumstances, or 2) MCC-1a overburns and places the observatory on an escape trajectory from its LPO.

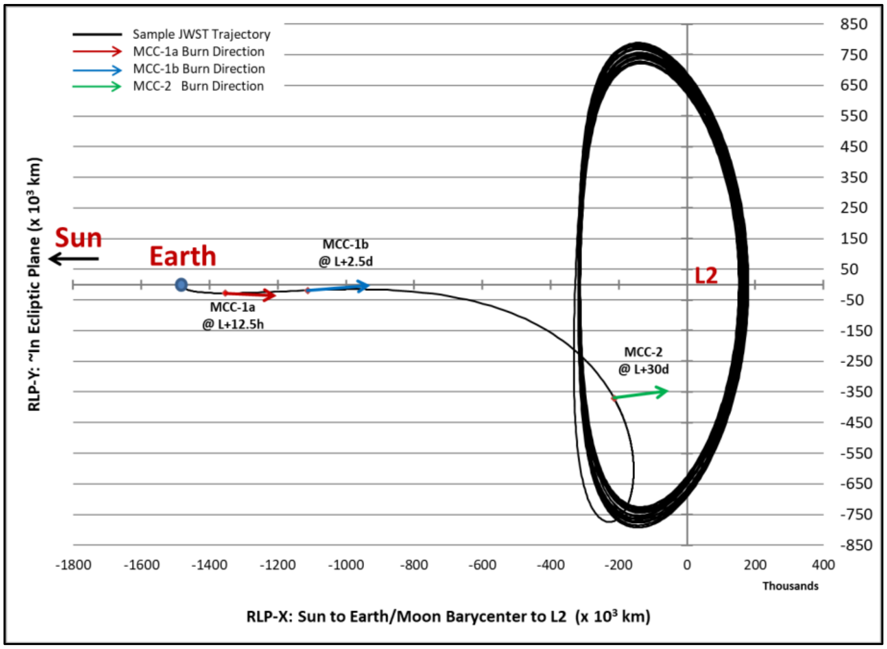

Figure 1. Sample JWST Trajectory Showing the Location of Mid-Course Correction Maneuvers

DELAYED MCC-1A CONTINGENCY

The first contingency analysis assesses the cost of delaying MCC-1a beyond the nominal execution time at L+12.5 hours. A delay could happen because of non-nominal spacecraft performance or trouble establishing contact during the first hours after launch. A delayed MCC-1a maneuver is one of the more likely contingency mitigation scenarios. Steps will be taken to mitigate these risks, but it is important that the operational schedule remain flexible to accommodate unexpected delays while minimizing the impact on the overall mission. Once the decision to delay MCC-1a is made, many factors need to be considered when determining the new execution time. Since early orbit operations is on a compressed schedule, and the longer MCC-1a is delayed the less effective it is to deliver JWST to its target LPO, time is limited. Nominally, a maneuver-plan product with the burn direction, magnitude, and duration would be generated using a high-fidelity propulsion model by the Flight Dynamics Team (FDT) and delivered to the Science and Operations Center (S&OC). However, the process for generating this maneuver plan is lengthy and the product only applies to a specific maneuver execution time. Identifying general trends allows for the aggregation of data from a wide range of cases and empowers the S&OC to quickly evaluate the increasing maneuver cost as a function of time without the needing to generate multiple maneuver plans.

Examining the Delayed Maneuver Scenario

The nominal MCC-series execution schedule is designed to mitigate risk while maximizing fuel efficiency, and the primary cost of delaying the MCC-1a maneuver is the additional fuel that would be expended to achieve the LPO for the science phase of the mission. Because of the use of passive temperature regulation strategies, the mission lifetime is largely determined by the availability of propellant and oxidizer to perform maneuvers that achieve and maintain the mission orbit. Based on current fuel budget predictions, propellant expended during the transfer from the Earth to L2 impacts available to maintain the LPO at a rate of approximately 1 year for every 2.5 m/s of delta-v (DV) consumed during the transfer; likewise, the mission can be extended by the same rate if DV is conserved during the transfer. For simplification, this analysis assumes that maneuvers use a proportional amount of fuel to achieve a given DV throughout the mission. However, the efficiency of JWST's propellant propulsion system is expected to vary during the mission, as will mass-flow rate, because the system is not pressure regulated.

Executing the JWST MCC maneuvers at a later point along the trajectory increases the DV cost to achieve the LPO in the vicinity of L2. Consider an elliptical orbit in a two-body system (assuming a nominal MCC-1a and prior to MCC-1b, JWST is in an elliptical orbit with a high apogee). As the spacecraft is on its way to apogee, it can either execute an impulsive maneuver at time t_1 or an impulsive maneuver at time t_2, where $t_1 < t_2$, to achieve the same desired target state further along the trajectory in either scenario. Since the initial trajectory is the same for either maneuver scenario, it can be assumed that the initial specific energy $\varepsilon_{initial}$ before any maneuvers are applied is the same; that is,

$$\varepsilon_{initial} = \frac{v_1^2}{2} - \frac{\mu}{r_1} = \frac{v_2^2}{2} - \frac{\mu}{r_2} \tag{1}$$

In this equation v is velocity, r is the radius from the central body, and μ is the standard gravitational parameter. Equation (1) can also be written as:

$$v_1^2 - v_2^2 = 2\mu\left(\frac{1}{r_1} - \frac{1}{r_2}\right) \tag{2}$$

Since the spacecraft is traveling away from the central body, at the respective maneuver times, $r_1 < r_2$ and $v_1 > v_2$. Because each maneuver targets the same final trajectory, the same final specific energy ε_{final} is the same. After applying a maneuver with magnitude Δv to each scenario, the equation becomes

$$\varepsilon_{final} = \frac{(v_1 + \Delta v_1)^2}{2} - \frac{\mu}{r_1} = \frac{(v_2 + \Delta v_2)^2}{2} - \frac{\mu}{r_2} \tag{3}$$

After some algebra, Equation (3) becomes

$$v_1^2 - v_2^2 + 2\Delta v_1 v_1 - 2\Delta v_2 v_2 + \Delta v_1^2 - \Delta v_2^2 = 2\mu\left(\frac{1}{r_1} - \frac{1}{r_2}\right) \tag{4}$$

Substituting $v_1^2 - v_2^2$ from Equation (2) results in

$$\Delta v_1(\Delta v_1 + 2v_1) = \Delta v_2(\Delta v_2 + 2v_2) \tag{5}$$

Therefore, if $v_1 > v_2$ because t_1 is closer to periapse than t_2, then $\Delta v_1 < \Delta v_2$, demonstrating that delays in the maneuver execution time for JWST will ultimately increase the maneuver magnitude.

The DV cost of MCC-1a depends primarily on the launch epoch and the launch vehicle performance. Since a launch epoch for the observatory has not been determined and has changed several times in the years prior to this analysis, it is prudent to consider a wide range of launch opportunities. The current JWST launch window analysis spans November 2020 through March 2021. Requirements dictate that the launch must occur between 11:30 and 14:00 UTC on a given day. The nominal launch trajectory corresponds to one of two unique flight programs that optimize valid launch opportunities based on the time of year: to account for seasonal effects cause by the orientation of the Earth with respect to the ecliptic plane, one flight program provides more opportunities for the months surrounding the winter solstice while the other provides more opportunities around the summer solstice.[2] However, a significant overlap of launch epochs from each flight program are valid throughout the year. An epoch is considered not valid if the corresponding trajectory fails to converge on an LPO in the simulation. The main difference between the two is that Flight Program 1 targets a lower apogee height than Flight Program 2. To account for variation in launch vehicle performance, the ±3σ trajectories are also considered,

where reÑf3ůers to the apogee height at separation
assessment of the Ariane V.

The maximum allowable burn duration for MCC-1a is 12,000 seconds, which corresponds to a maximum DV of approximately 56 m/s. This requirement is enforced for test cases in this analysis, and maneuvers that exceed this requirement are cut off at 12,000 seconds. Since MCC-1a is the largest of the three MCC maneuvers, cases where the total MCC cost exceeds 56 m/s likely include an MCC-1a maneuver that is cut short, requiring MCC-1b to make up for the remaining DV.

Launch cases comprising all valid combinations of launch epoch and flight program for a sample month in the window are evaluated to assess the impact of delaying MCC-1a. This assessment includes the nominal and Ñ3ů trajectories for e November 2020 is a suitable month for assessment because it is within the proposed launch window and contains many valid launch cases. Figure 2 depicts a comparison of the total MCC costs for the case where MCC-1a is executed at L+12.5 hours or at L+14.5 hours (both with MCC-1b and MCC-2 are modeled to execute at their nominal times), regardless of launch validity for illustration purposes. The six distinct curve parings on a given launch day correspond to the six unique trajectories that are considered. The top two comprise the ï3ů trajectories for each of the flight programs. These cases represent a launch vehicle underperformance, causing the total MCC cost to be higher to achieve the necessary orbital energy. The two curves in the middle are the nominal trajectories, and the bottom two curves are the +3ů trajectories, where launch vehicle overperformance necessitates smaller MCC-1a and total maneuver DV to achieve the target science orbit. Similarly, the data points representing Flight Program 1 (green) are consistently higher than those representing Flight Program 2 (purple) because Flight Program 2 inherently supplies more energy from the launch vehicle because it targets a greater apogee height. Note that as the total MCC cost increases, the difference between the MCC-1a cost at the two execution times also increases.

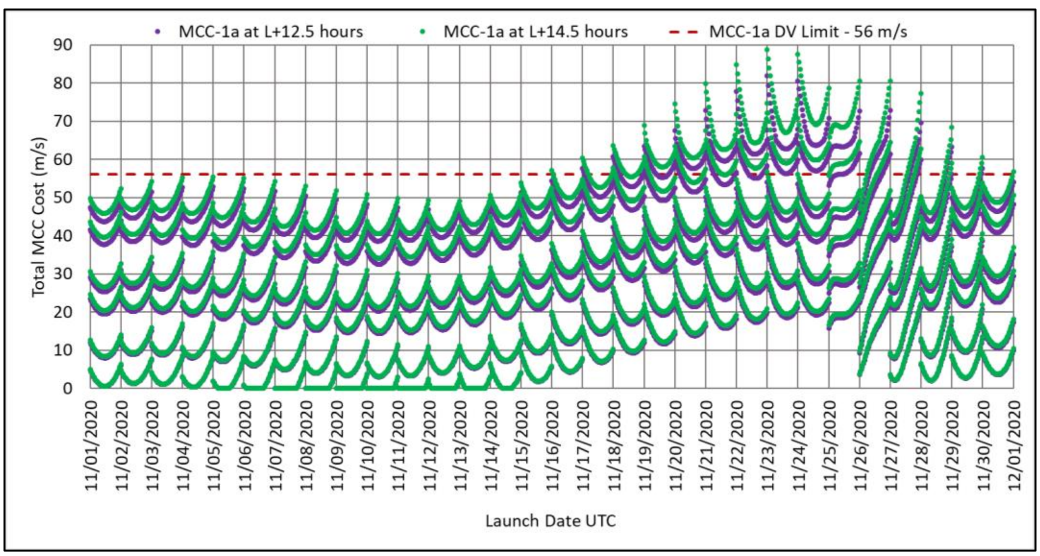

Figure 2. Total MCC Series Cost for All Possible Launch Cases in November 2020

The percent by which the MCC-1a and total MCC DV increases when the maneuver is delayed for each of the launch cases appears in Figure 3. While Figure 3 is based on the same set of trajectory data as Figure 2, the distinct flight program groupings are not visible; the percent increase of DV for a delayed maneuver has a negligible dependence on a non-nominal injection from the launch vehicle. However, two sets of outliers are apparent in Figure 3 and correspond to results from Figure 2. The collection of samples in Figure 3 between November 5 and 15 with an cost increase of 0% (orange dots) correspond to the samples in Figure 2 that have a total DV cost of 0 m/s, because the launch vehicle provides too much energy in a +3ů and the observatory's trajectory exceeds the LPO. Consequen these cases do not represent valid launch epochs (but are presented to illustrate pre-filtered results). The second group of outliers in Figure 3 between November 19 and 29 are samples where the MCC-1a burn duration limit is reached (orange dots in the lower right) and subsequent MCC maneuvers must compensate for the duration-limited MCC-1a burns, resulting in increased total MCC costs (blue dots in upper right). The trajectories from these launch cases are significantly impacted by gravitational effects from the Moon. Starting on November 25, the observatory can leverage the gravitational pull of the Moon through a swing by which significantly reduces the total MCC DV cost. However, in most cases the gravitational pull of the Moon negatively impacts the trajectory and the observatory is forced to increase maneuver size to reach the LPO. For each of the samples in this second outlier set, if the burn duration limit is reached by an MCC-1a maneuver at L+14.5 hours, the percent increase of the MCC-1a DV cost (orange) will be less than the average of 5.88% while the total MCC DV (blue) cost will be greater than the average of 4.96%. If the duration limit is achieved for MCC-1a at either L+12.5 and L+14.5, the percent increase for MCC-1a costs is zero. Most of the test cases fall into the two nearly horizontal lines in the middle of Figure 3 and are grouped by MCC-1a cost and total MCC cost. This trend indicates that, over a wide range of maneuver magnitudes, the cost of MCC-1a and the cost of the total MCC series each increase by a consistent percentage if MCC-1a is delayed by 2 hours.

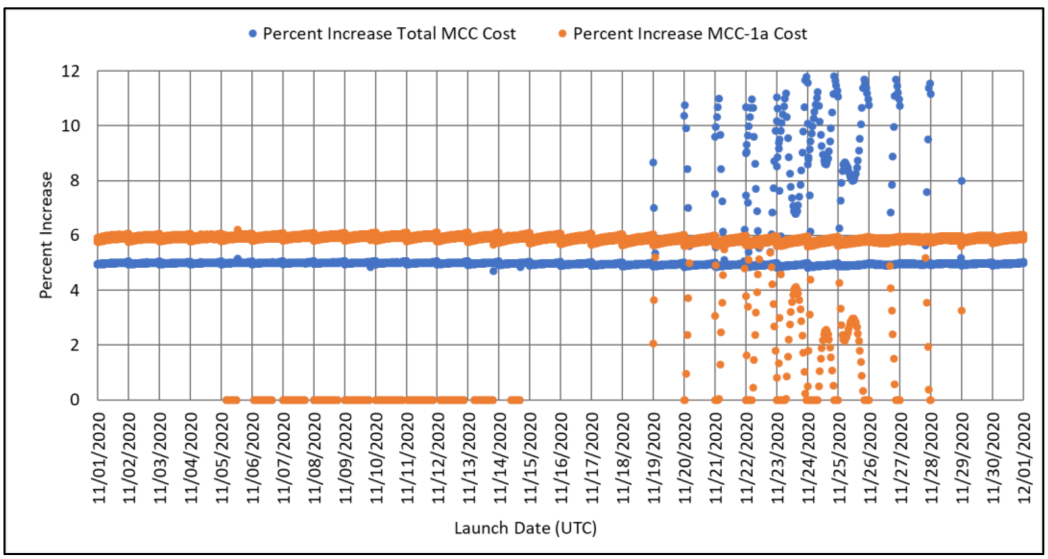

Figure 3. Increase in Maneuver Cost for a Delayed MCC-1a from L+12.5 to L+14.5 Hours for All Possible Launch Cases in November 2020

The average percent increases in maneuver cost over a range of delay times (excluding the special cases mentioned previously) appear in Figure 4. As expected, the maneuvers become more costly the longer the execution time is delayed. The trends of increasing cost are sufficient to fit a curve to extrapolate maneuver impacts of longer delays; nonetheless, a thorough analysis, such as what appears in in Figure 2 and Figure 3 is recommended prior to generating specific maneuver plans. However, this trend is convenient in an environment where speed is more important than accuracy, such as assessing an operational delay contingency when the new maneuver time must be determined quickly before the official maneuver plan can be generated.

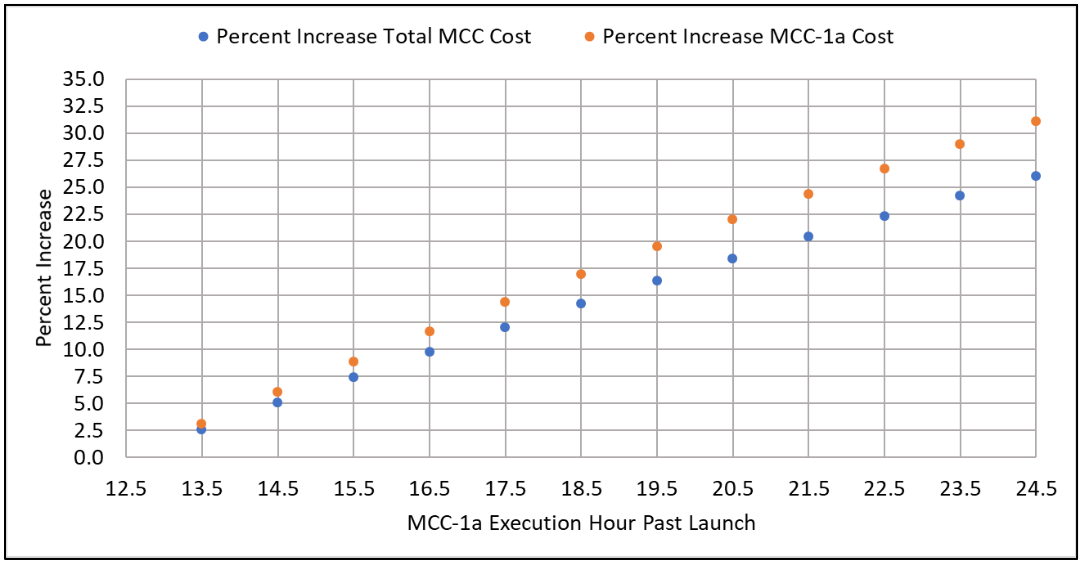

Figure 4. Increase in Maneuver Cost as a Function of MCC-1a of Delay

Operational Application

The trends presented in the previous section are directly beneficial to mission operators supporting the launch. Scaling a set of MCC-1a maneuver DVs. by the representative percentage increases (from Figure 4) results in generalized trends for a delayed MCC-1a of any reasonable magnitude. Curves for thirteen DVs. associated with an MCC-1a delayed by up to 12 hours after L+12.5 hours appear in Figure 5. The three rectangular regions represent critical considerations in how the cost of a given maneuver will impact the overall mission. Maneuvers in the green region satisfy all mission requirements. The yellow region represents MCC-1a maneuvers that will exceed the maximum burn duration and must be cut off prematurely. These cases are still acceptable but increase the cost of MCC-1b. The red region represents maneuvers that will expend more fuel than is reserved for the station-keeping (SK) maneuvers that maintain the science orbit for 10.5 years. MCC-1a maneuvers that would occur in the triangles in Figure 5 associated Madrid or Goldstone view-period termination violate a mission desire that at least one DSN ground station must observe the complete maneuver.

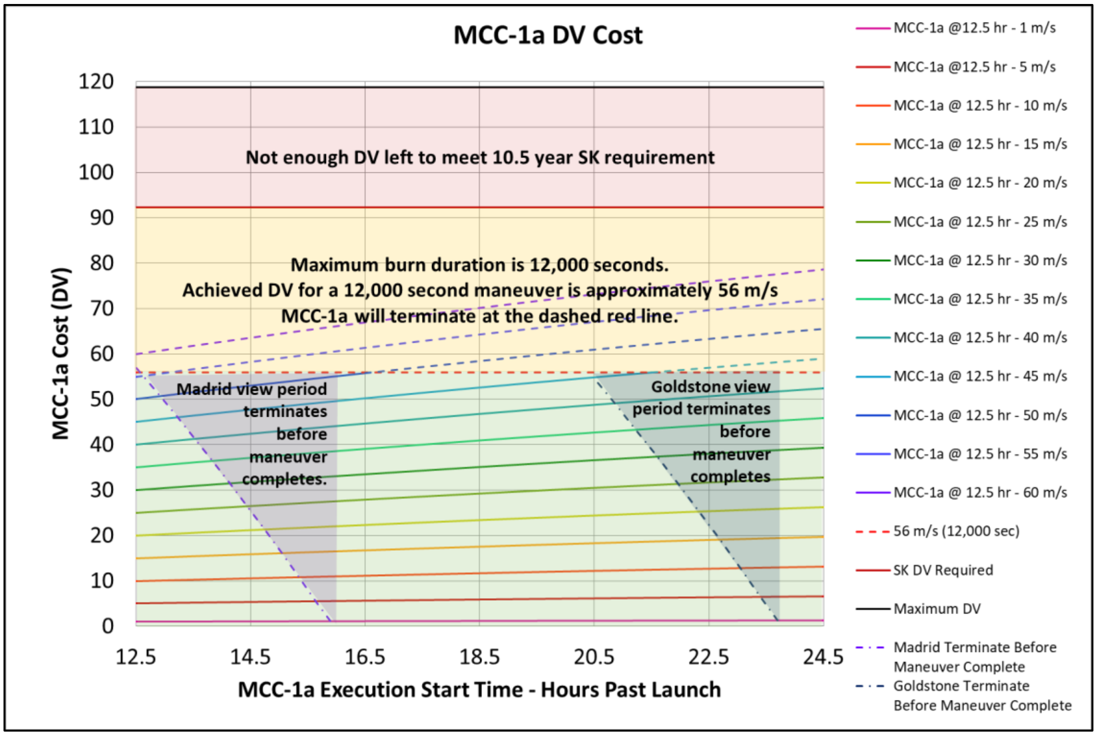

Figure 5. The Cost for a Range of MCC-1a Cases as a Function of Delaying MCC-1a

Considering that maneuver magnitude is assumed proportional to maneuver duration, it is possible to calculate the maneuver end epoch based on the nominal DV cost and start epoch. This information is useful in considering which ground station will be in contact with the observatory during the maneuver. A sample contact schedule for the available ground stations based on a trajectory assuming a nominal launch on November 1, 2020, appears in **Error! Reference source not found.**.

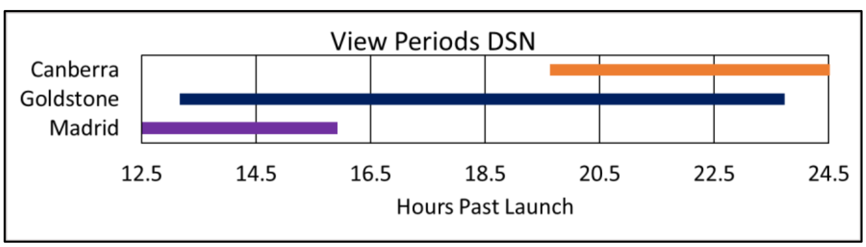

Figure 6. DSN Contact Periods for Nominal Launch Trajectory

This schedule is useful for identifying and select a single ground station to monitor the observatory throughout the entire maneuver. However, if the maneuver is delayed, the view period for the original ground station may end during the maneuver or before the maneuver starts. While it is possible to switch to a different ground station midway through a maneuver, doing so introduces additional complexity in trying to reestablish contact during a critical part of the mission and could lead to complications performing the initial maneuver performance assessment. Most likely, mission operators would select a ground station that provides coverage throughout the entire maneuver if the maneuver is delayed. By calculating the epoch associated with the maneuver ô cs ompletion and comparing that value to the contact schedule, it is possible to determine which maneuvers will continue past the end of the view period for the original ground station. In these cases, a new ground

Recovery from an MCC-1a Overburn Using Attitude Variation and SRP

To model the SRP for JWST, the FDT uses a polynomial curve fit provided by sunshield analysts. The polynomials are a function of Sun pitch and Sun roll that calculate the SRP force magnitude and direction in the observatory body frame. All three Sun angles are required to orient the SRP force vector from the body frame into the Earth centered inertial mean of J2000 frame for numerical integration. Unlike a cannonball model, the SRP force vector for JWST is not aligned along the Sun-to-Observatory vector. The off alignment can be exploited during flight after sunshield deployment (which occurs after the time MCC-1b would have been performed) through the execution of the recovery maneuver to help reduce the DV cost for the recovery maneuver. Example concentric cones of potential SRP force vectors relative to the Sun-to-Observatory vector appear in Figure 11. Each cone is made at a Sun-pitch value starting at 0° and incremented by ±13.25°, for illustration purposes, until the ±53° minimum limit is reached. The cones all have a Sun roll of 0° and vary the Sun yaw from ±180° to 180°. The cone comprising a Sun pitch of ±53° contains all SRP force vector directions W K D W D U H S R V V L E O H Z L W K L Q - : 6 7 ¶ V D W W L W X G

Figure 11. SRP Force Vectors for All Allowable Orientations of JWST.

Figure 12 through Figure 14 illustrate how changing each of the Sun-angle components separately over the timespan between sunshield deployment and the recovery maneuver affect how much DV is required in the event MCC-2, scheduled for L+30 days, acts as the recovery maneuver for a 1% overburn of MCC-1a (the limits of a recoverable overburn are discussed in a subsequent section). Sun-angle plots in the figures assume a default Sun-roll value of 0°, Sun-pitch value of ±53°, and a Sun yaw value of ±130°; two of the Sun-angle components are fixed at these default values in each of the figures, while the third Sun-angle component is varied, resulting in the necessary recovery maneuver DV cost at L+30 days.

Sun pitch has the largest impact on DV reduction, with a range of DV cost of approximately 1.6 m/s, as apparent in Figure 12. Sun yaw has the second largest impact, as seen in Figure 13, with the difference in range of 0.35 m/s. Finally, Figure 14 illustrates that Sun roll produces the smallest contributions to DV reduction with the difference in range of DV of 0.02 m/s, which is expected as the allowable Sun-roll range is only ±5°; therefore, Sun roll is not a focus of this investigation. Selecting an advantageous Sun-pitch and Sun-yaw combination helps reduce the DV necessary for the recovery maneuver.

Figure 14. Sun Roll vs. MCC-2 DV for a 1% MCC-1a Overburn Associated with a 11/09/2020 Launch Date

The results presented in Figures 12 through 14 show that fixing the Sun pitch and Sun yaw at ï53° and ï130°, respectively, during the period between sunshield deployment and maneuver execution for this launch epoch reduces the recovery maneuver size to a minimum value. This ballistic transfer period is the opportune time to reorient the attitude of JWST to reduce the recovery DV due to no major flight dynamics processes being scheduled during this time.

The next step in the investigation is to determine if these Sun-angle values remain consistent across multiple launch dates, in particular Sun yaw as it is expected that a Sun pitch of ï53° will always produce the minimum DV solution. Table 1 lists different options considered in this study. Six epochs are selected for their associated nominal MCC-1a DV costs.

Table 1. Launch Epochs and their Associated Nominal MCC-1a DV

Launch Epoch	Nominal MCC-1a DV (m/s)
November 9, 2020, 13:00 UTC	15.07
January 15, 2021, 12:30 UTC	27.71
February 7, 2021, 12:00 UTC	10.15
April 11, 2021, 13:45 UTC	35.27
June 14, 2021, 13:00 UTC	30.54
July 8, 2021, 12:35 UTC	20.19

Error! Reference source not found. and **Error! Reference source not found.** illustrate the Sun-pitch and Sun yaw variation for three of the six different launch epochs in Table 1. A Sun pitch of ï53° always results in the minimum recovery maneuver DV at L+30 days, apparent in Figure 15. For a ballistic transfer period of 20 days, the DV cost reduction is approximately 1.5 m/s between the minimum and maximum Sun pitches across various launch epochs. The Sun-yaw relationship produces a consistent range between minimum and maximum DV cost of approximately 0.4 m/s, but the Sun-yaw value corresponding to the minimum solution is not constant and depends on the launch epoch. The January example requires a Sun yaw of ï120° to produce a minimum DV to recover from an overburn, while the April example requires a Sun yaw of ï60° and the June example requires a Sun yaw of ±50°. Sun-yaw variational changes are the result of seasonal effects that changes the transfer trajectory for JWST and therefore the Sun-to-Observatory vector.

Figure 15. Sun Pitch vs. MCC-2 DV for a 1% Overburn

Figure 16. Sun Yaw vs. MCC-2 DV for a 1% Overburn

Overburn Recovery by Adjusting the Timing and Direction of the Recovery Maneuver

For the recovery maneuver itself (in lieu of or part of the nominally scheduled MCC-2), the FDT can adjust two parameters to help reduce the DV cost: execution time and maneuver direction (i.e., for fixed thrusters, the observatory orientation during the maneuver). Beginning with the parameter of execution time, the impact of performing the recovery maneuver between L+10 days and L+30 days is examined. A lower bound of L+10 days is predicated on the notional completion of the sunshield deployment, while an upper bound of L+30 days aligns with the notional latest MCC-2 execution time. Impacts of performing the recovery maneuver at a variety of observatory attitudes are also examined. The minimum DV cost for station-keeping maneuvers is achieved when the DV is applied along or as close as possible to the stable eigenvector.[1,3] To maneuver "sunward," a Sun pitch of ±53° is required as that orientation places the observatory's station-keeping thruster as close as possible to the stable eigenvector. This configuration leaves Sun yaw as a free parameter to further reduce the DV cost of the recovery maneuver as much as possible (effects from Sun roll are negligible).

In the nominal operations timeline, MCC-2 is planned to occur at approximately L+29 to L+30 days. In the event of an MCC-1a overburn, MCC-1b is cancelled as the observatory is still in the stowed configuration and corresponding attitude, and a maneuver in this attitude only increases the velocity of JWST, adding more energy to already mission-ending trajectory. When the observatory sunshield is fully deployed (after the planned time of MCC-1b), a wider range of allowable maneuver orientations become available. MCC-2 can become the recovery maneuver to reduce the energy of JWST, recover from the overburn, and still maintain the maneuver's primary purpose of placing JWST in orbit around SEMB L2. However, performing the recovery maneuver (a.k.a., MCC-2) earlier than the nominal L+30 days reduces the DV costs to mitigate the effects of the overburn. An example of this relationship for the November 9, 2020, launch case and 1% MCC-1a overburn appears in Figure 17.