LAUNCH WINDOW TRADE ANALYSIS FOR THE JAMES WEBB SPACE TELESCOPE

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Abstract: The James Webb Space Telescope (JWST) is a large-scale space telescope mission designed to study fundamental astrophysical questions ranging from the formation of the universe to the origin of planetary systems and life. JWST's orbit design is a Libration Point Orbit (LPO) around the Sun-Earth/Moon (SEM) L2 point for a planned mission lifetime of 10.5 years. The launch readiness period for JWST is from Oct 1st, 2018 – November 30th, 2018. This paper presents the first launch window analysis for the JWST observatory using multiple maneuver finite-burn modeling; previous analysis assumed a single impulsive maneuver to achieve the mission orbit. The resultant launch window is still primarily dictated by third body forces, providing significant available launch window in the launch readiness period. Future plans are also discussed.

Keywords: James Webb Space Telescope, Launch Window, Libration Point Orbits

1.   Introduction

The James Webb Space Telescope (JWST) is a large-scale space telescope mission designed to study fundamental astrophysical questions. General topics include studying the assembly of galaxies, planetary systems / origin of life, birth of stars / proto-planetary systems and the concept of first light / re-ionization. One of the primary trade analyses for JWST determines when the observatory can successfully launch. This is traditionally called the launch window trade analysis.

This paper presents the first launch window analysis for JWST with the inclusion of higher fidelity propulsion finite-burn modeling. Significant requirements affecting the JWST orbit design are the overall Libration Point Orbit (LPO) size, the avoidance of any Earth/Moon eclipses, and propulsion/other hardware restrictions. This launch window trade analysis focuses on meeting these requirements and finds feasible epochs to launch the JWST observatory under these conditions. The paper first presents an in-depth view of the JWST mission with emphasis on the requirements and constraints affecting the launch window analysis. The full trade study is then described alongside its methodology. Finally, results that observe the overall nature of the launch window with the updated JWST models are presented with final conclusions and future development.

2.   JWST Mission Overview

The JWST observatory will be launched on a European Space Agency (ESA)-supplied dedicated Ariane 5 launch vehicle (LV) from the Guiana Space Centre in Kourou, French Guiana. JWST has a planned launch in the fall of 2018. The LV will inject JWST into a direct transfer orbit away from the Sun and towards L2 approximately 25 minutes after liftoff. By design, the LV injection state will provide less energy than needed for JWST to reach L2. Therefore the JWST observatory will perform propulsive maneuvers to reach a LPO around the Sun-Earth/Moon barycenter L2 point (SEM L2). JWST must perform three mid-course corrections (MCC) maneuvers to attain the LPO; the first maneuver, MCC-1a will provide the majority of the energy needed to achieve the L2 orbit, while the remaining MCC-1b and MCC-2 maneuvers will provide additional corrections to establish the orbit. There is no LPO injection maneuver.

Once at L2, stationkeeping maneuvers will be required as often as every 21 days; the science pointing plan will be extremely dynamic, which reduces the predictability of the solar radiation pressure as well as the propulsive momentum unloads direction and frequency. These factors in turn cause major perturbations on the trajectory. This orbit will be maintained for a minimum of 5 years, with a goal of 10.5 years. See [3] for a more detailed description of the stationkeeping strategy.

2.1.   JWST Observatory Overview

The JWST observatory consists of a spacecraft bus, the $161m^2$ sunshield, and the Integrated Science Instrument Module (ISIM). The ISIM comprises of four instruments: the Mid Infrared Instrument (MIRI), the Near Infrared Camera (NIRCam), the Near-InfraRed Imager and Slitless Spectrograph (NIRISS), and the Near Infrared Spectrograph (NIRSpec).
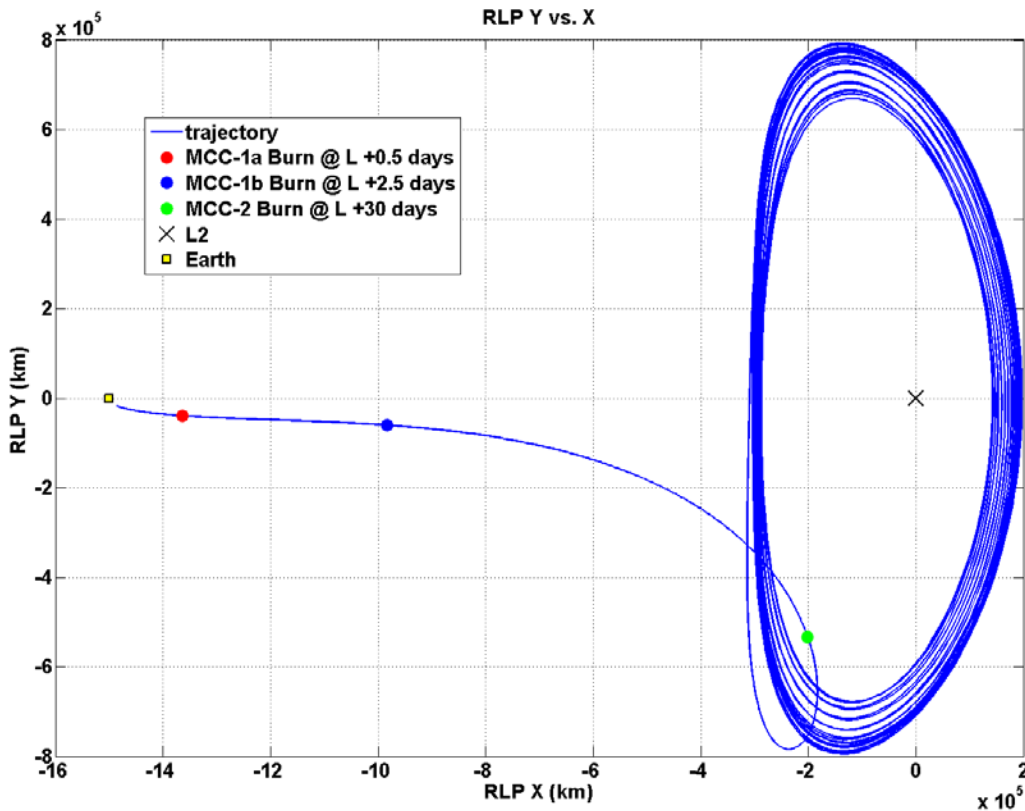
From launch through the first 5.5 days of the mission, the sunshield will be in a stowed configuration shown on the left in Fig. 1; the sunshield will be fully deployed, as shown on the right of Fig.1, 10 days after launch. The center of mass will shift significantly after full sunshield deployment, which drives the need for two Secondary Combustion Augmentation Thrusters, (SCATs), one SCAT for the pre-sunshield deployment trajectory maneuvers (MCC-1a and MCC-1b), and another SCAT for post-deployment trajectory maneuvers (MCC-2 and stationkeeping). In addition to the SCATs, there are 8 primary attitude control thrusters. The attitude thruster on-pulsing during the MCCs are included in the finite burn modeling. All thrusters are located on the spacecraft bus below the sunshield. This protects the instruments both thermally and with respect to plume impingement.

Figure 1: Artist Depiction of the JWST Sunshield Deployment
(image credit:http://www.nasa.gov/images/content/175677main_shield_deploy.jpg)

2.2. Mission Design Overview

JWST will be launched into a direct transfer orbit to the L2 point. MCC-1a will occur 0.5 day after launch injection and will provide the majority of the transfer energy to the L2 LPO. MCC-1b is one of the significant trim maneuvers to correct for any maneuver execution error from MCC-1a and is performed 2.5 days from launch. Finally, MCC-2 is the first stationkeeping maneuver occurring 30 days after launch. Thereafter all trajectory-correcting maneuvers are considered LPO stationkeeping maneuvers. Due to the instability of SEM L2 Lagrange point, stationkeeping maneuvers will continue to be implemented to maintain the orbit for the rest of the mission [3]. Figure 2 shows a representative JWST orbit projected in the Rotating Libration Point frame (RLP) X-Y plane with the three MCC maneuvers.

Figure 2. Representative Trajectory with JWST MCC maneuvers

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The origin of the RLP frame for this analysis is at the SEM L2 libration point with RLP +X direction away from the Sun, the RLP +Z direction towards the Earth orbit ecliptic north, and the RLP + Y direction in the right-handed complement direction. See Fig. 3 for an example.

3.   JWST Launch Window Requirements and Constraints

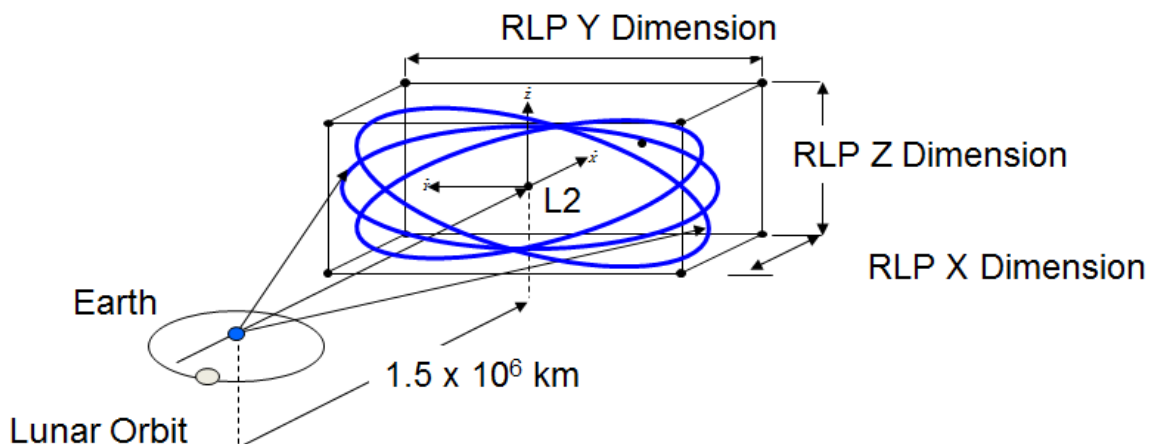### 3.1 Summary of Constraints Affecting the Launch Window

Table 1 summarizes the current requirements and constraints for JWST's launch window and trajectory design.

Table 1. JWST Launch Window Constraints

Constraint	Value	Requirements/ Constraint Driver(s)
LPO Box: Maximum RLP Y	832,000 km	Communications
LPO Box: Maximum RLP Z	520,000 km	Science (Stray light)
Maximum SCAT finite-burn duration	11,425 sec	Propulsion
Minimum precision of SCAT finite- burn duration	0.2 sec	Propulsion
MCC Available ΔV	20.5 - 38 m/s	Mass & Propulsion
Mission Lifetime Goal	10.5 years	Science
Lunar / Earth Eclipse	None allowed	Power and Thermal

The remainder of this section will describe these design drivers in detail.

3.2 LPO Box Requirement

Figure 3. Representation of RLP frame with JWST-specific requirements

The LPO restrictions define a box centered at the L2 point with three dimensions in the RLP X, Y and Z directions. The RLP X requirement was not considered in this analysis as it does not critically constrain the JWST orbit from a flight dynamics perspective [2]. The Y and Z constraints are based on communications and stray light requirements. The stray light requirement protects the JWST instruments from solar, lunar and Earth stray light. As seen in Fig. 3, the LPO requirements can be fulfilled by a general LPO category, which includes tori, quasi-halo, and Lissajous.

3.3 JWST MCC Delta-Velocity (ΔV) Budget and SCAT Hardware Constraints

The MCC maneuvers are defined in this analysis with a finite-burn model. Each maneuver is executed with a finite-burn duration and an associated change in JWST velocity, or ΔV. Overall JWST mass constraints require the minimization of propellant mass in order to carry the instruments and other on board subsystems, translating into a constraint on the ΔV metric.

The total MCC ΔV budget is 66.5 m/s with a maximum of 38.5 m/s available for nominal launch window trajectory design; any launch epoch whose mission trajectory uses more than this upper limit is constrained. Launch dispersions are also not modeled in this analysis so a passive allocation of 20.5 m/s is set as the lower limit to the ΔV budget, detailed below. Table 2 depicts the MCC ΔV budget with a summary explanation of the separate allocations.

Table 2. JWST MCC ΔV Budget

Purpose	ΔV budget
Accommodate low-biased injection state	20.5 m/s
Make up for possible -3 sigma LV dispersion	**20.5 m/s**
Provide more than instantaneous daily launch opportunity	5.0 m/s
Make up for biasing MCC-1a & MCC-1b by -5%	7.5 m/s
Allow for finite burn penalties and propulsion system modeling errors	5.0 m/s
Subtotal available for launch window analysis	**38.5 m/s**
Accommodate up to 6-hour delay in MCC-1a	8.0 m/s
Total ΔV for MCCs	66.5 m/s

The many subdivisions of Table 2 come from JWST system limitations on the thrust direction. Each SCAT's effective thrust direction is through the center of mass of the entire observatory. The attitude pointing constraints related to thermal and stray light requirements result in the limited ability to thrust in the sunward direction. Figure 3 represents the anti-sunward direction in the RLP +X direction; this analysis avoids any trajectories that require an RLP –X (sunward) direction maneuver. With this thruster direction design there is also a concern of overshooting the L2 LPO. The primary factor which could cause JWST to overshoot the target LPO is JWST maneuver execution error. The mission design mitigates the risk from any MCC maneuver execution errors by scaling back finite burn MCC-1a and MCC-1b maneuvers. They are biased to execute only 95% of the optimal energy to reach L2. MCC-1b and MCC-2 make up the residual ΔV needed to achieve the L2 orbit, with MCC-2 also accommodating for any remaining finite-burn penalties. These concerns are reflected in Table 2, with the three MCC maneuvers operating within the budget.

The finite-burn model also puts a limit on the maximum and a precision limit on the SCAT burn duration. The analysis and study to derive these hardware requirements can be seen in [6].

3.4 Launch Vehicle Flight Program Profiles

Because the Moon can provide either a gravity assist or a de-assist to JWST depending on the day of launch, varying injection energies are needed to maximize the number of launch days. The Ariane 5 LV is capable of targeting only a single fixed apogee altitude for any given launch day from day to day. To utilize this capability and increase the launch opportunities, JWST has requested Ariane allow for three different apogee altitude targeted flight programs (FPs), any one of which can be implemented for a specific launch day. The apogee altitudes currently requested are based on the 2009 predicted LV dispersions [2]:

Table 3. JWST Launch Vehicle Flight Program Profiles

Designation	Targeted Apogee Altitude
Flight Program 1(FP1)	1.02×10^6 km
Flight Program 2 (FP2)	1.06×10^6 km
Flight Program 3 (FP3)	1.10×10^6 km

If any of the three achieve launch window requirements at a single launch epoch, the launch epoch is considered successful. As seen in Table 3, each successive flight plan increases the apogee target orbit (and thus orbital energy) that the Ariane 5 will provide in order to guarantee that JWST can reach L2 within ΔV costs.

3.5 Hardware and Other Constraints

Other restrictions on the launch window and trajectory design include meeting the mission lifetime goal and the avoidance of Earth and Moon eclipses during the entire trajectory. While the minimum lifetime of 5 years is an observatory systems requirement, the trajectory must be designed to meet constraints for the full 10.5 year mission lifetime goal. Earth and Moon eclipses pose significant hazards to the power and thermal subsystems. JWST does not include ΔV budget for shadow avoidance, so the trajectories are filtered during the launch window analysis process to exclude any with Earth or Moon eclipses.

4.   Launch Window Methodology and Simulation Implementation

The wide possibility of libration orbit designs coupled with the nonlinear dynamics of L2 LPOs pose a significant implementation challenge. However, the resultant information provides insight to the JWST orbital behavior and accommodates for any hardware requirements.

4.1 Launch Window Trade Space

Previous studies of the JWST launch window detail the feasibility of the JWST L2 libration orbit [2] using a single impulse MCC-1a maneuver. Earlier analyses demonstrated the cyclical monthly effects of lunar gravity on the trajectory design. They also illustrated that a general type

of LPO can either achieve or violate the LPO requirement. This paper's analysis expands on that knowledge base by updating the requirements and mission design, refining the precision of the previous results, and encompassing hardware specifications to perform finite burn maneuvers.

Figure 4 displays RLP Y-Z plots of the JWST trajectory with different launch times for a single launch day. As seen by comparing the different trajectories, a variety of LPOs can be achieved on a given launch day. Figure 4 shows earlier launch times create a Lissajous orbit (11:30 UTC), midday launch times create quasi-halo/smaller torus orbits (12:15 UTC and 12:45 UTC) and late launch times create larger torus orbits (14:00 UTC). Orbits with earlier and later launch times (11:30 UTC and 14:00 UTC) violated LPO constraints in the RLP Y and Z component. The 11:30 UTC launch trajectory also violates Earth/Moon eclipse constraints since the orbit remains close to the plot origin in Fig. 4, the general location of the Earth and Moon shadows. Because JWST does not have the ΔV budget to perform LPO-shaping maneuvers, the trajectory is dictated by the launch date and time.
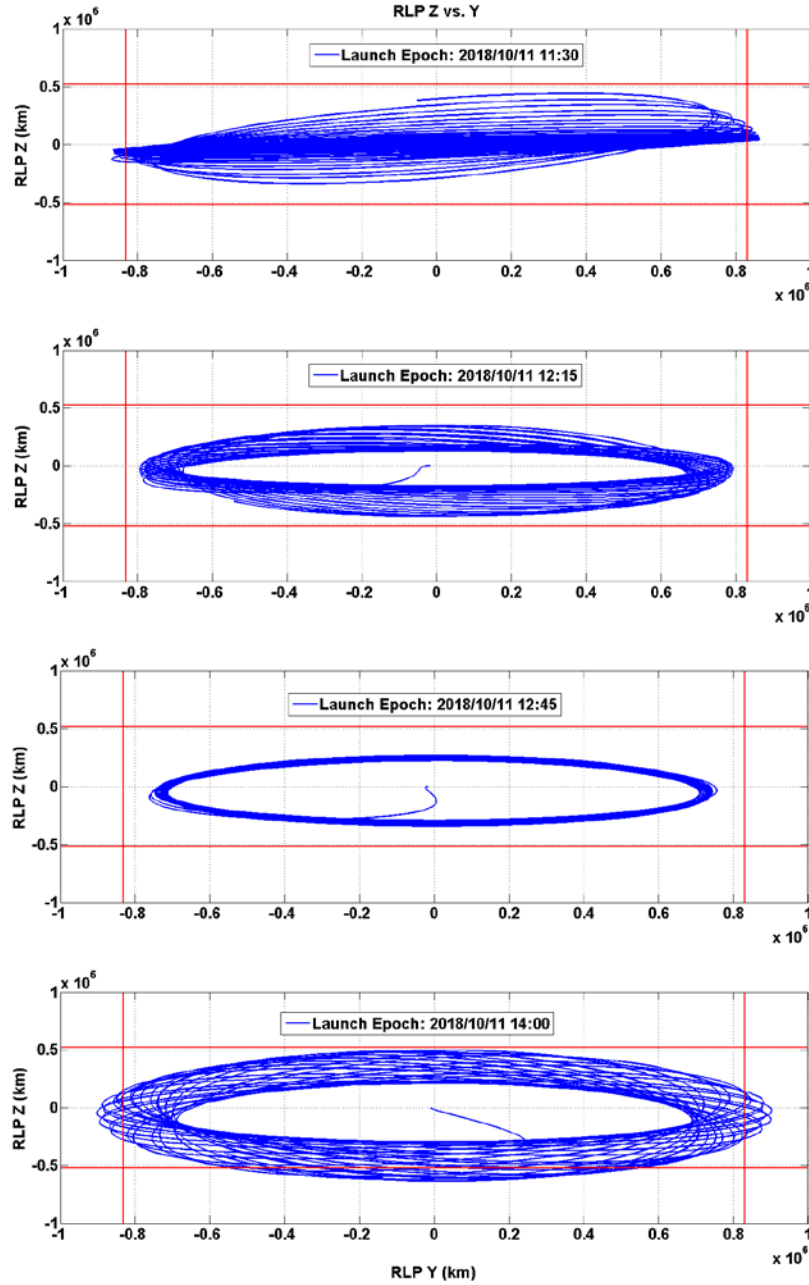
Along with the addition of finite maneuvers, other system design concerns were addressed in the launch window trade analysis. Analysis of launch times outside the Fall 2018 launch readiness period was needed to fully investigate the yearly solar-lunar effect. The analysis also needed to provide information to JWST management regarding the possibilities of launching earlier or later than the readiness period. The LV provider Arianespace prefers 45 minute continuous daily launch windows to perform launch operations. To compensate, a higher granularity of launch times than in Fig. 4 was evaluated. This would clearly define both the beginning and end of the daily launch window and ensure optimal contiguous daily launch windows for each LV FP. Finally, mass trades and requirements refinements drove the necessity to examine a large trade space that could quickly be adjusted to requirement updates.

4.2 Methodology and Simulation Implementation

The fluidity of requirement definitions and the ongoing negotiations with other subsystems required an overall knowledge of the JWST orbit design trade space. This trade analysis explored the July 2018 – December 2019 time frame from 11:30-14:00 UTC in 5-minute increments, or 26,901 separate epochs, each with a goal of producing a 10.5-year JWST trajectory. These trade analyses required not only a large number of trajectories, but also a short turnaround to reproduce and re-evaluate the data for variations in requirements.

The FreeFlyer® software produced by a.i. solutions, Inc. is used to target and propagate the JWST trajectory using a box method similar to that described in [2]. Freeflyer® outputs orbit design parameters and ephemeris data initially. Afterwards, the ephemeris data is scanned to calculate the LPO orbit box size and check if eclipses occur within each trajectory.
The significantly non-linear behavior of propagating the JWST orbit design requires a Runge-Kutta 8/9 numerical integrator for the full mission. The full 10.5-year ephemeris is required in order to evaluate the entire science mission for eclipse periods and RLP Y and Z constraint violations. The complex and lengthy propagation and post-evaluation analysis required extensive time to produce the entire trade space analysis.

Figure 4. Varying JWST LPOs in the RLP Y-Z plane for a single launch day. Each plot from top to bottom varies launch time (11:30, 12:15, 12:45, and 14:00 UTC).

Evolving requirements meant the data had to be re-evaluated frequently so a filtering process was implemented. The filtering process was designed so that the range of any numerically-defined requirement could be varied independently of every other requirement. One can evaluate whether a combination of relaxed requirements would produce significant increases in launch opportunities. A successful launch epoch met every requirement as set by the filters. This filtering process enabled a consistent up-front production time for the trajectory generation and a shorter response time for future requirement changes or trade studies. Once a set of successful

launch epochs was found the longest continuous successful launch window for each day was compiled. Measuring these continuous daily launch window periods provided the metric to determine JWST's launch window.

The large trade space caused a production bottleneck in the trade analysis and post processing. To mitigate the computation-intensive analysis required, the trade space launch epochs were broken into 16 independent FreeFlyer® background processes. Each process ran its data set in parallel with the others using multithreading software libraries. The information was stored in separate text files and then concatenated into the final output products. The system is orchestrated by a NASA Goddard in-house Java program, Pavo. Pavo was the master program that starts all the processes, collects output statements from these processes and then combines all the processes' outputs into the final products. This automated, parallelized implementation reduced the processing time from two months of time with a human operator to less than two weeks. Post processing was then performed by a GSFC-developed MATLAB® GUI utility for filtering and displaying results.

5.   Results / Analysis

Other analysis evaluated a trajectory design using a single impulsive maneuver, as compared to three finite maneuvers for the JWST mission design [8]. The results of the launch window trade focused on how the latest requirements, including hardware and propulsion finite burn limitations, provide the end result launch window periods.

5.1.   Overall Launch Window Behavior

Figure 5 shows the results for the entire 18-month period using the latest launch window trajectory design: The histogram indicates in minutes the longest continuous launch window per launch day for any of the three FPs, with all launch times occurring between 11:45 and 14:00 UTC. The blue area indicates the launch readiness period, October 1st, 2018 – November 30th, 2018. This period provides 40 possible launch days within the 61-day launch readiness period. Within those 40 valid launch dates, 17 days provide over 45 minutes of continuous launch window using a single FP. These results are consistent with the impulsive trajectory launch window results [2]. Subsequent sections describe monthly and annual launch window patterns.

5.2.   Launch Window during the Launch Readiness Period

The monthly results for the October 1st – November 30th, 2018 readiness period are addressed separately, as seen in the MATLAB® generated Fig. 6 and Fig. **7**.
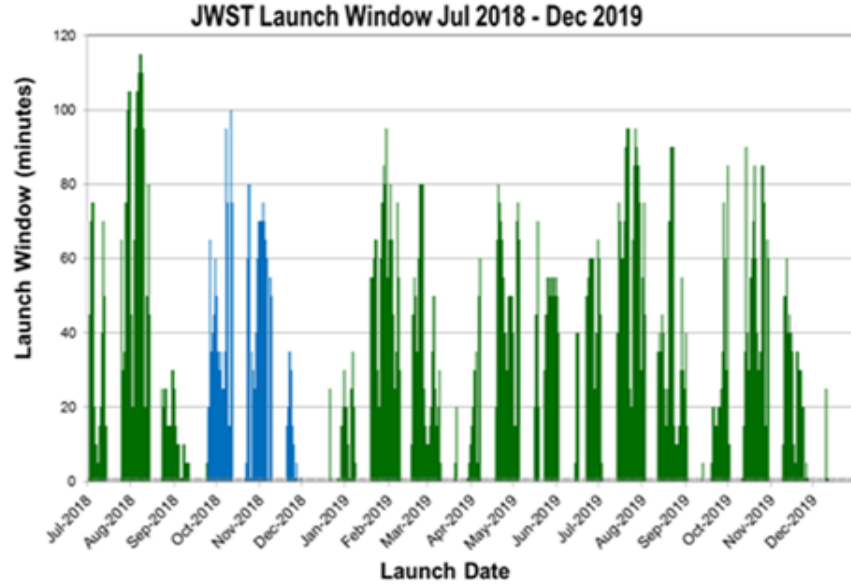
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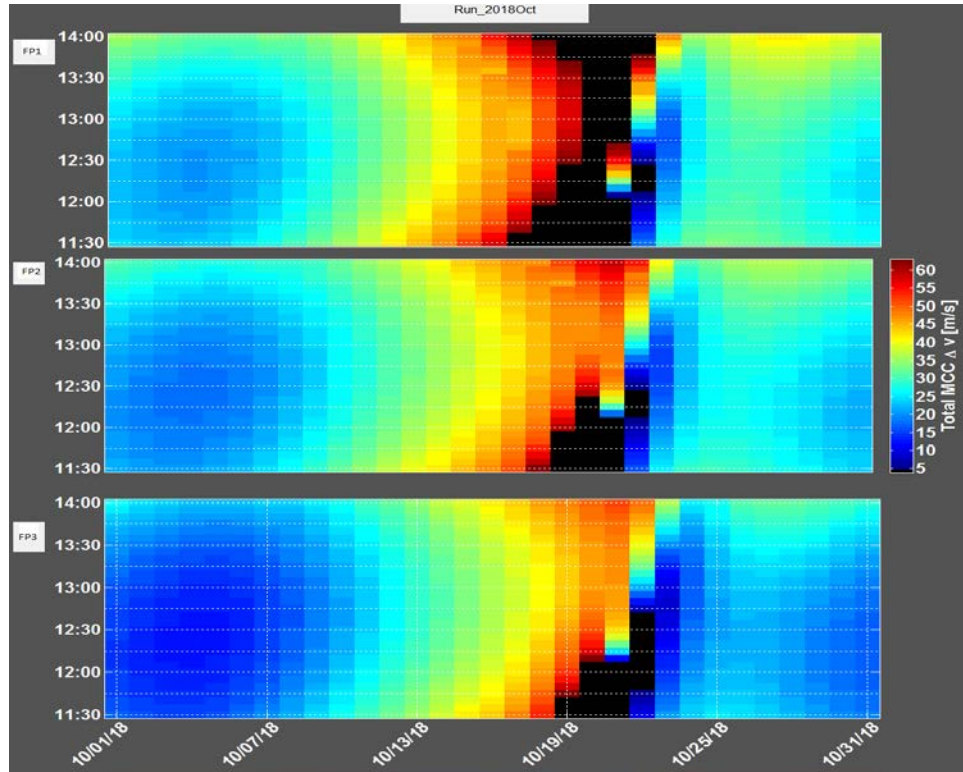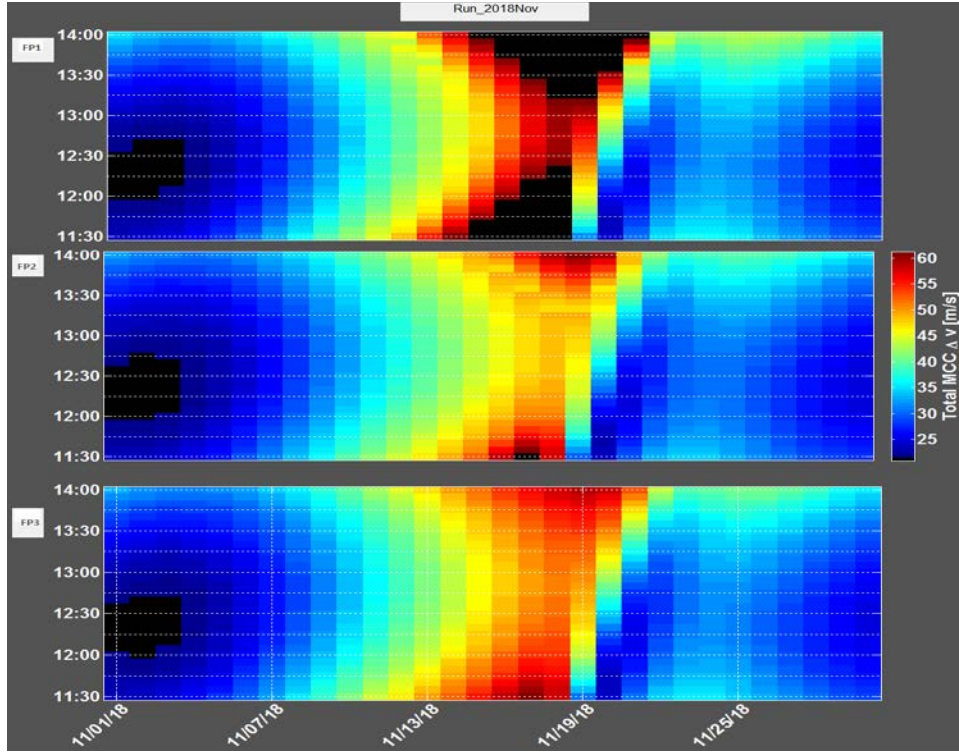**Figure 5. Fully Constrained, Longest Continuous Launch Windows vs. Launch Epoch**

Figure 6. October 2018 Launch Period with No Constraints
x axis: launch date, y axis: launch time. Total MCC ΔV costs represented by color gradient. The 3 FPs are displayed in three separate plots. Black shows failed epochs.

Figure 7. November 2018 Launch Period with No Constraints

Each figure displays the data for the three FPs specified in in Table 3 in three separate rows. The X and Y axes of each FP plot show the launch epoch day and UTC launch time in one day and 5 minute increments, respectively. The color gradient maps the cumulative ΔV costs for the MCC maneuvers. Blue represents the lowest ΔV cost and red represents the highest cost (though not necessarily exceeding the JWST MCC ΔV budget). Black areas on the plot indicate that the mission design failed to target a successful LPO orbit. The two most common failures occur due to a lack or an excess of orbital energy. A lack of orbital energy occurs when the maximum finite maneuver duration is reached from Table 1, preventing the maneuver from targeting a longer duration. An excess of energy occurs when the Freeflyer® targeter achieves the L2 LPO with a maneuver in the negative RLP -X direction, which is not possible with JWST's propulsion design. An example of such a scenario can be seen on Nov 1st, 2018 around 12:15 UTC for all three flight plans. The progression from the top row of FP1 to the bottom row of FP3 flight plans show a decrease in ΔV costs. This pattern directly corresponds to the increase in apogee height (and thus specific energy) shown in Table 3.

Another trend clearly seen in Fig. 6 and Fig. **7** are the significant increases in ΔV costs mid-month. This monthly behavior coincides with the Moon's position with respect to the Sun-Earth line, and occurs approximately between the full moon and first quarter. During this time, the Moon's gravity forces the JWST spacecraft to apply increasingly more ΔV to reach the L2 LPO.

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5.3.   Launch Window Pattern due to LPO Box Constraints

The overall JWST orbit launch window hinges on the orientation of the large third body effects (Sun, Earth, and Moon) relative to the transfer trajectory and the LPO itself. In contrast to Fig. 6 and Fig. **7** where no constraints are enforced, Fig. 9 and Fig. 10 depict the launch periods when the RLP Y and Z constraints are applied. The possible launch window has been significantly reduced. In each launch date, earlier launch times near 11:30 UTC and later launch times near 14:00 UTC result in violations of the LPO size constraints. Launch times in the middle of the trade study between 11:30 to 14:00 UTC have the highest likelihood of success.

Figure 8 illustrates LPO size violations by plotting trajectories from a single FP in the RLP X & Y plane. With the two dotted red lines in Fig. 8 reflecting the RLP Y constraint stated in Table 1, the blue 11:30 UTC trajectory and the black 14:00 UTC trajectory both violate that constraint. In contrast, the green 12:45 UTC trajectory does not violate the RLP Y constraint. One observation comes from the beginning of the JWST trajectory to the location of MCC-1b, specified in Fig. 2. Since the JWST launch site at Kourou is close to the Earth's equator, it is always launched into a near-equatorial orbit with its apogee towards the L2 point. One can then observe the angle of the RLP X axis with the Earth equatorial plane as a metric for LPO box violations. Observing Fig. 8, a JWST launch on the 12:45 launch time maintains its transfer trajectory to the SEM L2 orbit with a small offset to the RLP X axis. This results in a tighter LPO in the RLP Y dimension. Launch times that appear earlier or later in the launch day increase the transfer trajectory's maximum offset to the RLP X axis and result in an increased orbit box size.
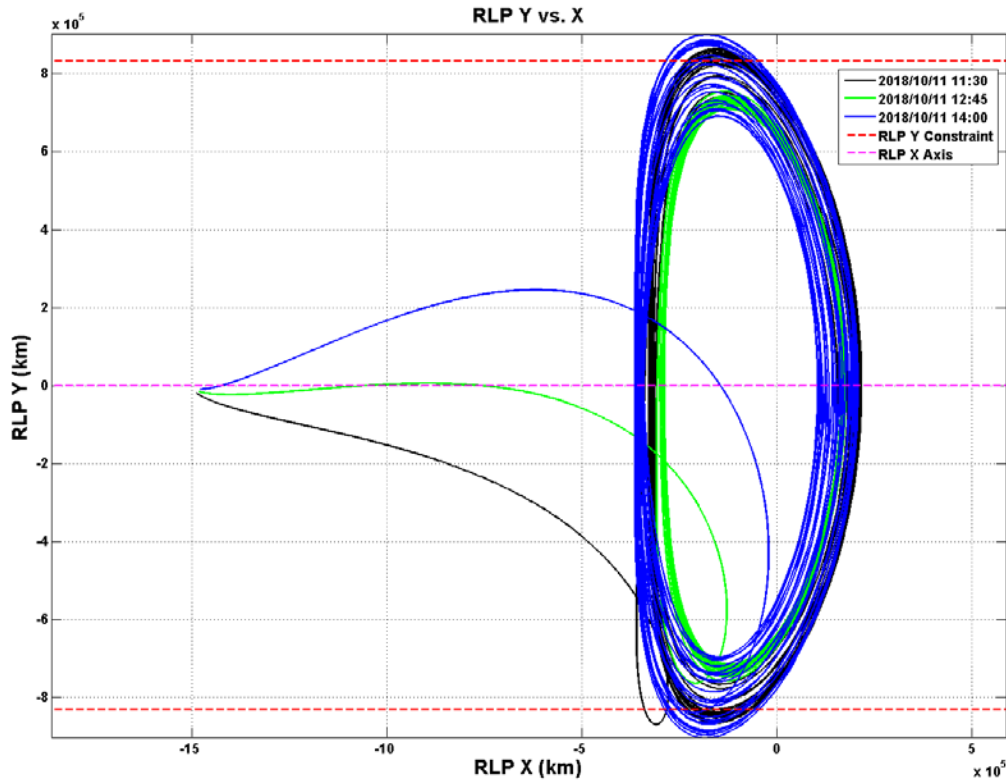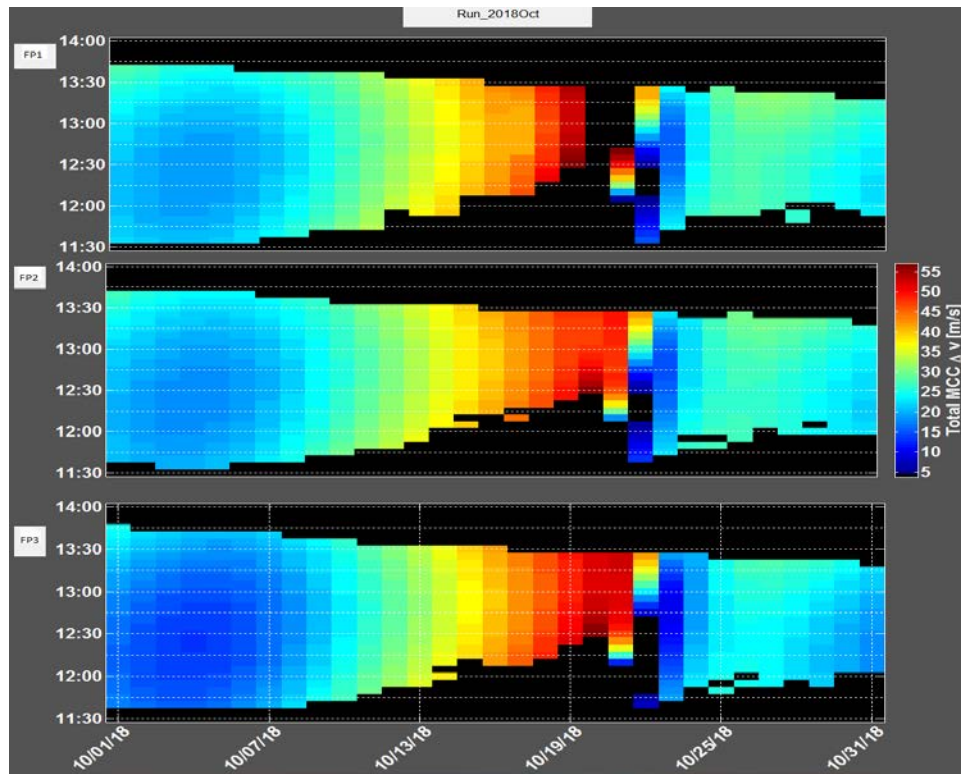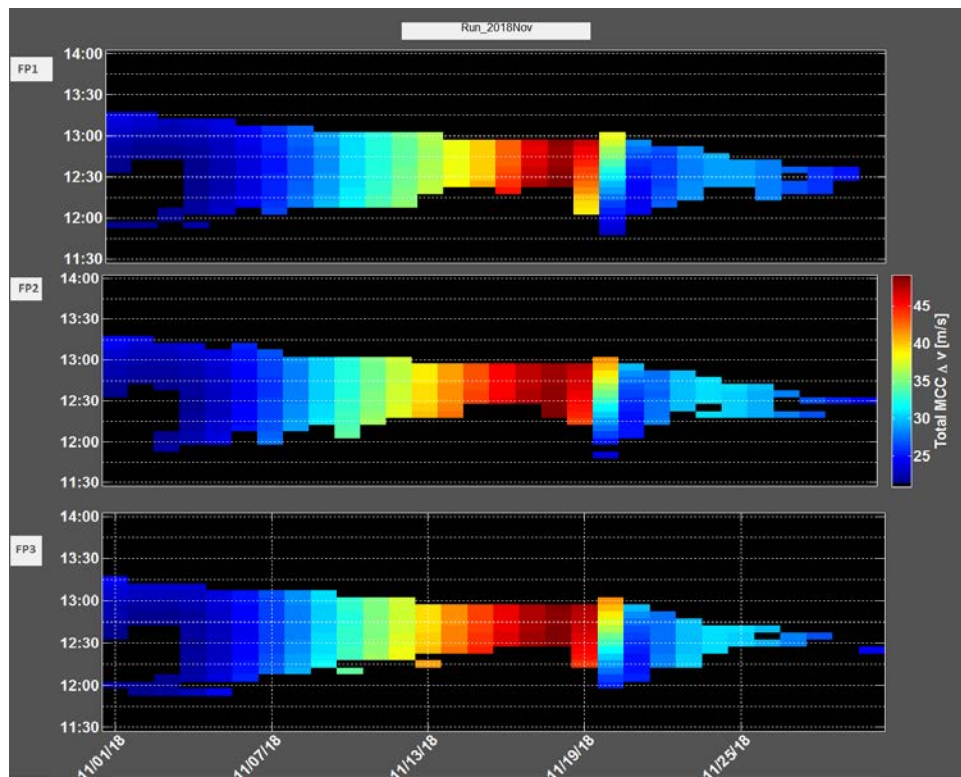

Figure 8. JWST trajectories resulting from early, midday and late launch times.
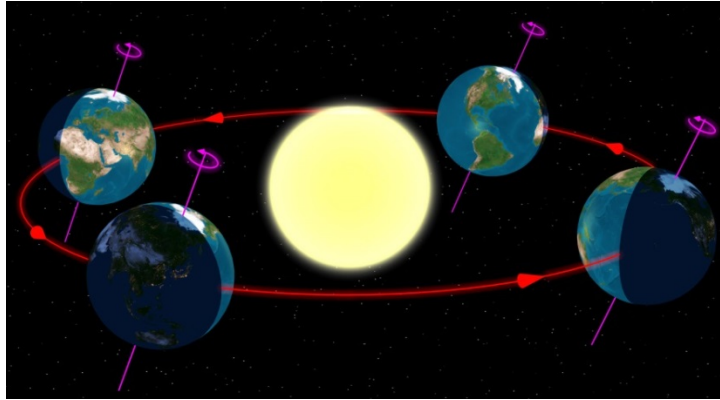
Figure 9. October 2018 Launch Period with RLP Y & Z constraints

Figure 10. November 2018 Launch Period with RLP Y & Z constraints

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This pattern is also reflected in Fig. 4. The quasi-halo orbits that exist in the midday of the UTC launch day seen in Fig. 4 manage to keep within constraints, a pattern which coincides with other authors [2].

Note also that in Fig. 10, the 2018 November continuous launch window period decreases each day to the end of the launch month. Over this time Earth is approaching its winter solstice, seen below in Fig. 11:
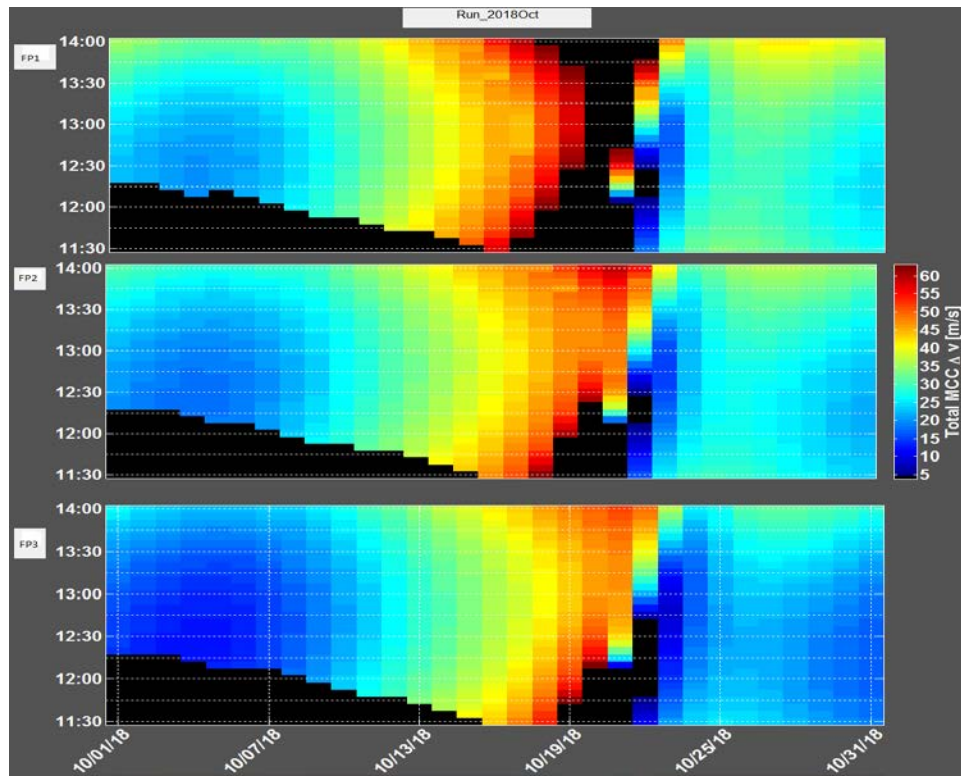

Figure 11. The Earth Seasons. Note that +RLP X axis projects away from the Sun to the Earth. The Northern Winter Solstice appears in the image at the far right.
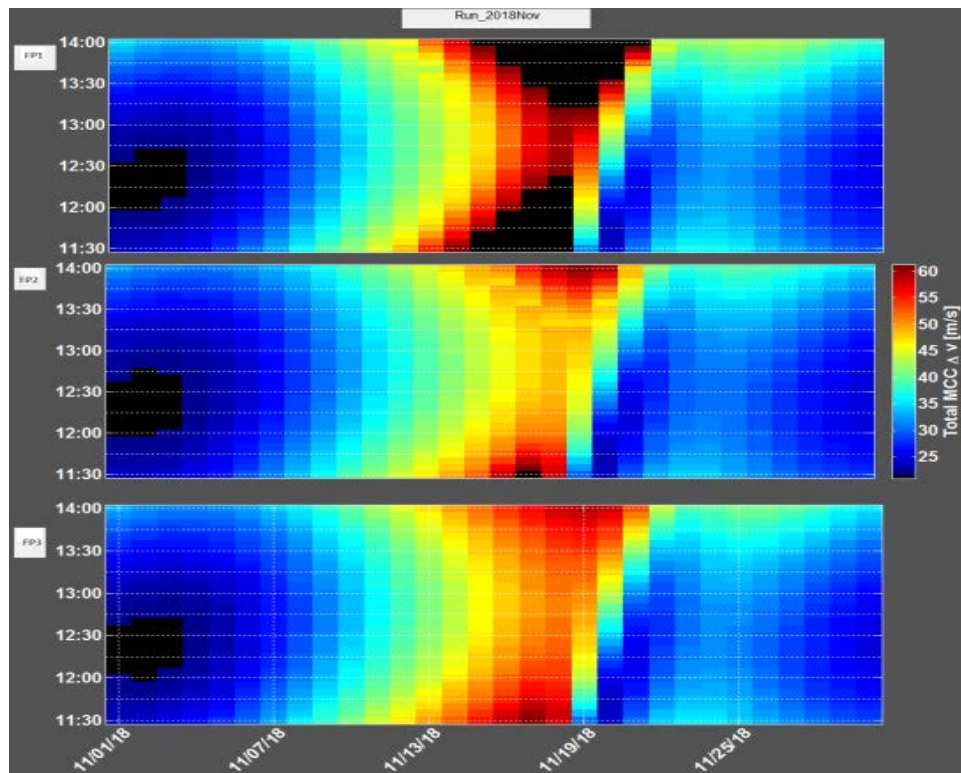**(image credit http://en.wikipedia.org/wiki/File:North_season.jpg)**

The Earth equatorial (and thus JWST orbit plane) is increasingly offset to the RLP X axis through November 2018 and towards the northern winter solstice slated to be in December 21, 2018. Fig. 11 visually demonstrates the Earth's equatorial plane during the northern winter solstice, seen on the far right image of Earth. With this behavior, JWST arrives into the L2 LPO with a significant angular offset from the RLP X axis. This causes the final LPO orbit box to be larger. This pattern throughout the November 2018 launch month decreases the overall continuous daily launch periods seen in Fig. 10.

5.4.   Launch Window Pattern due to Earth/Moon Eclipse Constraints

The Earth/Moon eclipse constraint can be interpreted as a minimum RLP Y and RLP Z constraint. From Fig. 3, the RLP X axis is defined by lining up the Sun with the Earth/Moon barycenter. Since the barycenter exists within Earth, any orbit trajectories that approach the RLP X axis (or similarly have smaller and smaller RLP Y and Z components) will increase the likelihood of Earth/Moon eclipses. The 11:30 launch time trajectory from Fig. 4 (specifically known as a Lissajous orbit) demonstrates a clear eclipse violation. Figure 12 shows that this early launch time violation appears through early October 2018. As seen in other papers [2], orbits that occur early in the launch window period induce a folding effect on the orbit trajectory. The orbit's natural progression eventually decreased the RLP Y and Z components until the Earth or Moon can cause an eclipse on the JWST observatory. Earth/Moon eclipse constraints also do not appear in November 2018 with Fig. 13, an effect demonstrated by other sources [5]. The large amount of LPO box violations seen before in November 2018 indicate that these JWST trajectories had RLP Y and Z components that approached the maximum value. This actively avoids the RLP Y and RLP Z minimum that increases Earth/Moon eclipses.

Figure 12. October 2018 Launch Period with Earth/Moon Eclipse Constraints

Figure 13. November 2018 Launch with Earth/Moon Eclipse Constraints

5.5. Launch Window Pattern due to ΔV Budget Constraints

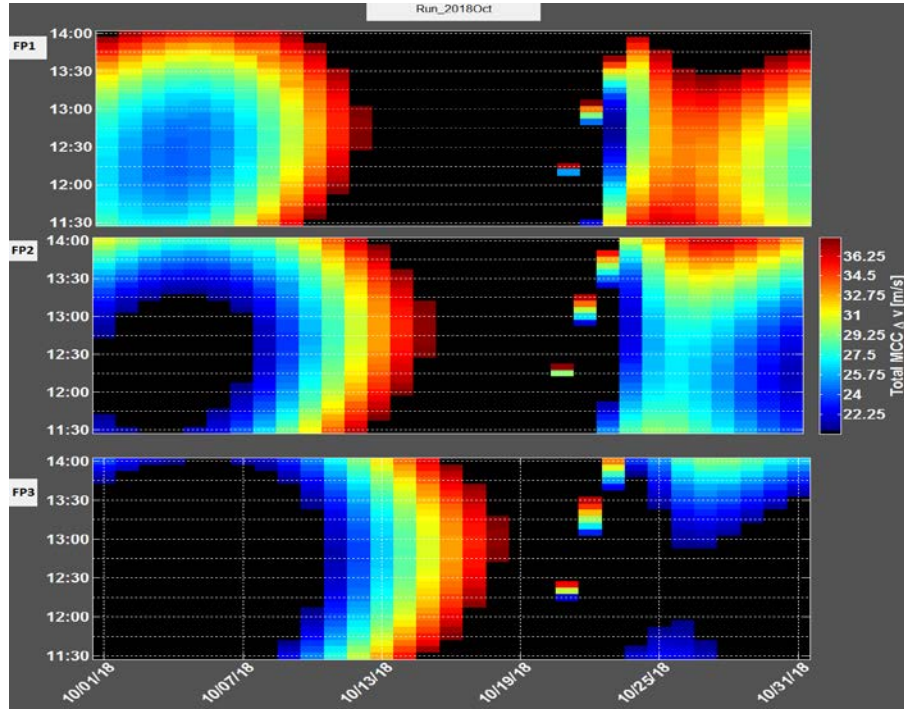Figure 14 and Figure 15 show that the ΔV constraints as they currently stand between 20.5-38 m/s.

Figure 14. October 2018 Launch with ΔV constraints.

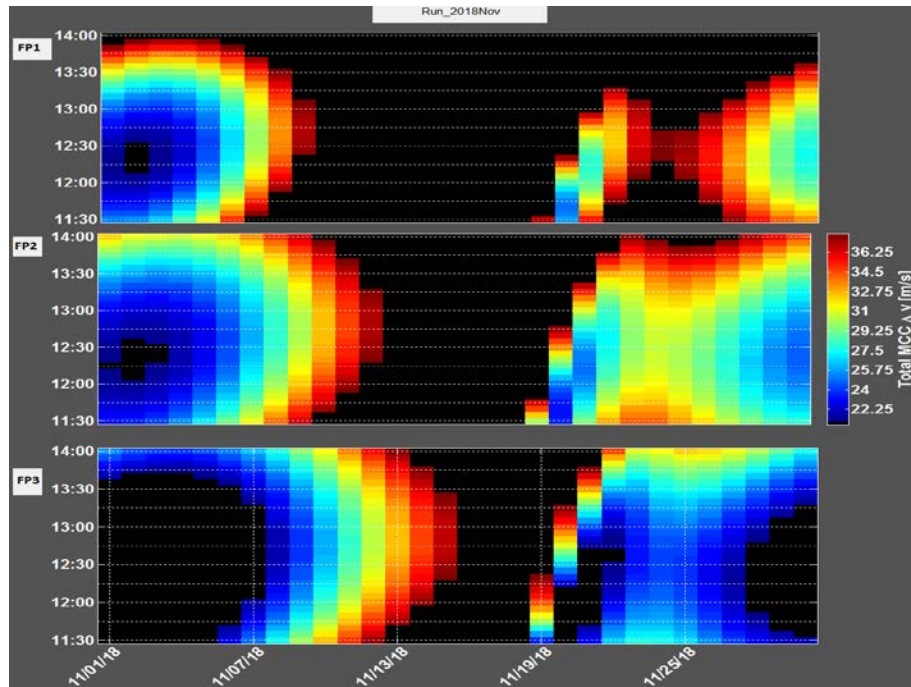**Figure 15. November 2018 Launch Window with ΔV constraints.**

The ΔV ranged constraint was also designed to avoid any launch dispersions without modeling them, so thus a middle ground of launch epochs appear in the launch readiness period. The upper limit of the ΔV range filtered launch epochs from the peak ΔV behavior in the middle of each month. The filtered epochs in the middle of each month were filtered because of monthly lunar effects on the JWST orbit. The moon will slowly assist or de-assist the JWST observatory depending on its relative location at launch. The lower limit removes any of the low ΔV cost launch epochs in order to avoid any JWST propulsion hardware issues.

Note however that the results reflect a conservative estimate on the current launch window budget in order to compensate for unmodeled launch dispersions and other factors. These unmodeled factors are scheduled to be added in the future and are further explained in the future work section.

5.6.   Overall Launch Window during the Launch Readiness Period

Figure 16 and Figure 17 display the entire launch readiness period with all constraints enforced. As seen in both figures, the LPO box and ΔV constraints are the most aggressive constraints as seen in previous figures. This heavily decreased the viability of 2018 November but still provides a significant number of 50-minute continuous daily launch windows early in 2018 November. The Earth/Moon eclipses only decreased the continuous launch window in October 2018, but is still the more beneficial period for continuous launch window in the launch readiness period.

Figure 5 displays the largest continuous launch window from Fig. 16 and Fig. 17 for the entire trade space analysis. This is done by first summing up the largest continuous launch window in a single launch date from Fig. 16 and Fig. 17 for each FP. The largest value between FPs is then chosen and binned into the histogram seen in Fig. 5. The peaks and troughs seen in Fig. 5 reflect the visual patterns seen in Fig. 16 and Fig. 17 for the full trade study.
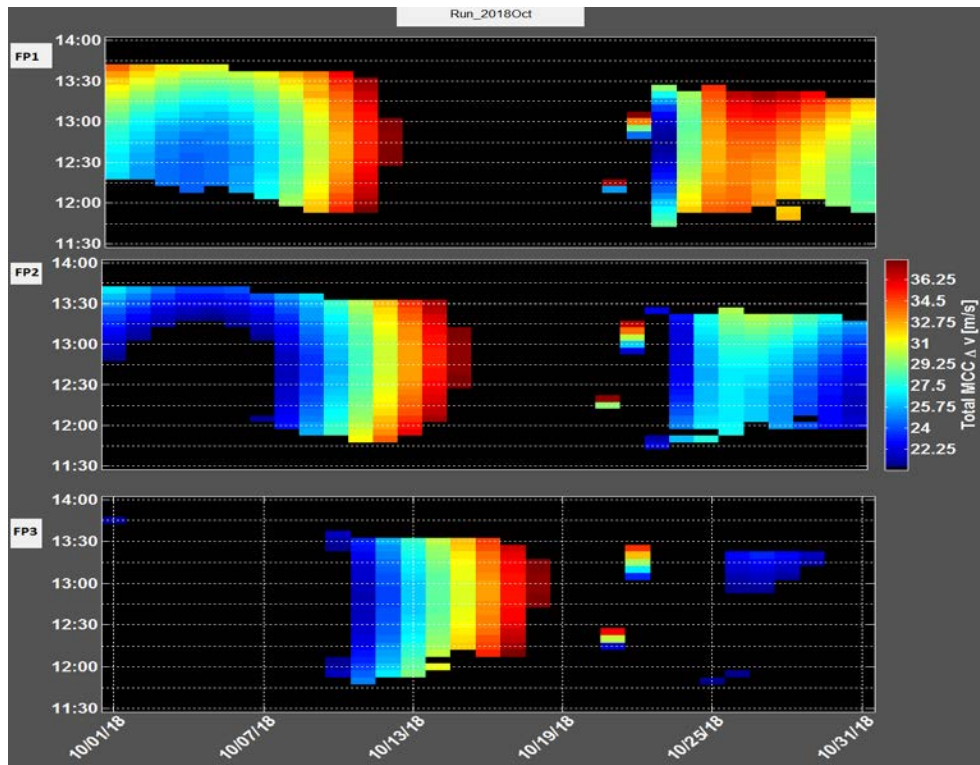
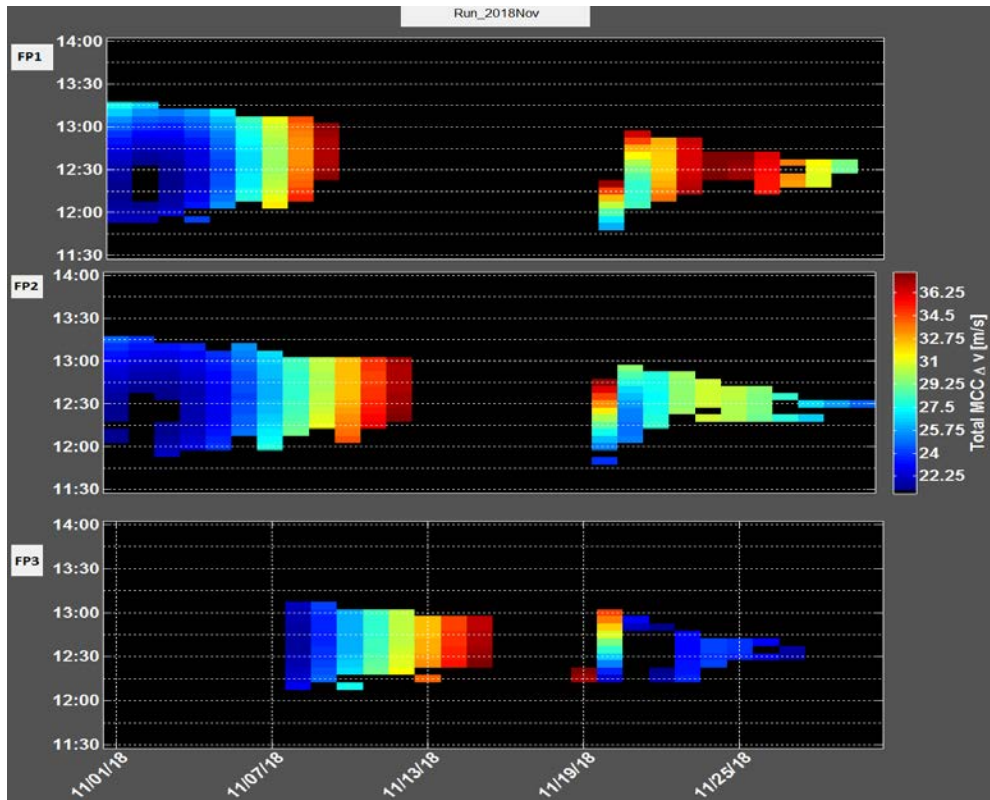**Figure 16. October 2018 Launch with all constraints.**

Figure 17. November 2018 Launch Window with all constraints.

6. Conclusions and Future Work

The finite maneuver JWST orbit design was explained with its current launch window requirements. The implementation of physical hardware parameters significantly changed the overall mission design and thus resultant launch window. To accommodate for rapidly changing requirements, the launch window trade study implemented the finite burn mission design over a large launch epoch period. This allowed the analysis to observe launch window constraints as accurately as possible and accommodate quickly for any constraint variations. The launch window results demonstrate consistent behavior with other trade studies for L2 LPO missions [2] [5]. The LPO box constraints bounded an upper RLP Y and Z box size on the LPO orbit. The LPO box constraints limit the launch times within a single launch day, with launch epochs earlier in the day and later in the day violating constraints. In contrast, Earth/Moon eclipses lower bounded the RLP Y and Z LPO box size. The alignment of the RLP X axis with the Sun and Earth means that smaller RLP Y and Z components increased the chance of Earth/Moon eclipses. Earth/Moon eclipses violations also decreased with the increase of LPO box constraint violations due the same contrast in constraint definitions. Finally, the overall ΔV constraints decrease the launch windows to avoid any monthly cycle lunar perturbations and minimally filter the launch window for the current ΔV budget. Within the launch readiness period, there are 56 days available out of the total 61 day launch readiness period. Within those 56 valid launch dates, 36 days provide over 45 minutes of continuous launch window using a single FP. The results are productive for the success of the JWST mission.

Further work primarily focuses on modeling launch vehicle dispersions of the Ariane 5 vehicle. A planned full +/- 3 σ C3 launch dispersion analysis will fully evaluate the launch window opportunities which will be performed by running each launch epoch trajectory with a +/- 3 σ C3 hot and cold injection state. The requirements on the ΔV budget do not accommodate for this constraint and alongside other concerns can vary the ΔV in the future. Other hardware considerations such as the High-Gain Antenna mechanical pointing restrictions, development of a higher fidelity propulsion model, and development of communication contact times will further update the launch window to hardware design specifications.

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