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SPACE LAUNCH SYSTEM LAUNCH WINDOWS AND DAY OF LAUNCH PROCESSES

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Lunar missions benefit from varying the launch azimuth as a function of launch time to allow longer launch windows with minimum performance impacts. This variable azimuth approach allows the vehicle to track the Moon's apparent motion due to Earth's rotation. The Space Launch System (SLS) Block 1 vehicle design requires the mission to launch into an elliptical parking orbit to provide sufficient energy to insert Orion into a Trans-Lunar Injection (TLI) orbit. The primary benefit of varying the launch azimuth, and as a result the achieved orbit inclination, allows the SLS Interim Cryogenic Propulsion Stage (ICPS) to perform its TLI burn closer to perigee and take advantage of performing a burn in a location where the burn will optimally raise apogee.

INTRODUCTION

The Space Launch System (SLS) is the launch vehicle that will be taking Crew and eventually cargo to the Moon for the Artemis program. Some of the early challenges of the Block 1 variant were determining the best way to fly the ascent to maximize launch opportunities, especially with regard to the daily launch window and launch periods for every lunar month. The parking orbit line of apsides for an optimal mission geometry should be pointed where the Moon will be when Orion performs its flyby maneuver. As the Moon's declination varies from day to day, the most optimal way of achieving the optimal line of apsides is to adjust the parking orbit inclination. Mission targets are generated using combination of two Three Degree of Freedom (3-DOF) trajectory optimization tools; The Program to Optimize Simulated Trajectories (POST)[1] for ascent to the parking orbit, and Copernicus[2] for the trajectory from orbit insertion, through TLI, and past lunar flyby for the Interim Cryogenic Propulsion Stage (ICPS) disposal in a heliocentric orbit.

The SLS guidance team is responsible for processing all of the 3-DOF optimized trajectories for every day in a launch period and for every launch period. This process is used to provide the original flight software initialization inputs, called I-Loads. Later, during the prelaunch countdown, this process is exercised again to provide Day of Launch I-Loads Update (DOLILU) parameters for the Boost Stage (BS) and Core Stage (CS) segments of SLS ascent flight. For the Boost Stage segment of the flight, SLS Guidance is open loop, and optimized 3-DOF trajectories are used to derive the desired azimuth target for the Chi Angle Optimizer (CHANGO) program. CHANGO, a standalone in-house developed tool, uses the processed azimuth target at the end of BS Flight to generate a Chi Table, which consists of an optimal set of attitude commands (yaw, pitch, and roll) and engine throttle commands as a function of altitude. Even though CHANGO can generate a table

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that corresponds to every minute of launch, this would add an excessive burden on Flight Operations and increase risks for potential mistakes in the process. To alleviate these concerns, SLS Guidance team generates only one Chi Table for every single day that corresponds to the middle of the Launch Opportunity for that day. To launch at a different time than planned, SLS Guidance uses a spherical trigonometry methodology to compute a Yaw bias that is added to the precomputed Chi Table in order to account for launch slips. At the end of BS flight, when CS Guidance is activated, similar adjustments to plane targets are performed such that both targeted right ascension of ascending node (RAAN) and Inclination are biased to account for launch slips. Inclination, RAAN and Yaw biases are curve fitted to fifth order polynomial in order to utilize up to +/- 2 hour of launch capability.

SLS LAUNCH WINDOWS

Early in the SLS program, during Design Analysis Cycle 2 (DAC-2), the SLS trajectory team participated in a launch window study to define how long the launch windows should be and how much performance should be set aside to protect for the launch windows. This trade was heavily influenced by a NASA webpage that gives a comprehensive discussion on the Apollo launch windows*. The biggest complication with the SLS Block 1 vehicle, when compared to Apollo, is the delta-V split of the stages. In order to maximize the usage of heritage components, the SLS Core and Solid Rocket Boosters (SRB's) are derived from Shuttle hardware and the upper stage of the SLS Block 1 is a stretched variant of the Delta IV Cryogenic Second Stage (DCSS), or Interim Cryogenic Propulsion Stage (ICPS). The ICPS does not have the capability to throw an Orion massed vehicle to lunar vicinity from a low Earth circular parking orbit, so the SLS CS assists the ICPS/Orion stack with insertion into an elliptical parking orbit. The apogee of that parking orbit is a dial that can be used to transfer performance from the Core Stage to the ICPS or vice versa and is discussed in several papers on the Artemis I and II missions.[3–5]

The SLS launch site will be at Kennedy Space Center at a latitude of approximately 28.5 degrees north. After ascent, the injection target is closer to perigee than apogee with a true anomaly on the order of 33 degrees. This ascent profile puts the apogee in the southern hemisphere. The optimal way to increase the apogee is to optimally place the Trans Lunar Injection (TLI) burn shortly before perigee. This will push the apogee further out to lunar distance, but will require the Moon to have a negative declination. However, if we restrict the launch to just coincide with the Moon's minimum declination, then SLS will have greatly limited its launch opportunities. In order to improve the launch opportunities, the trajectory optimization tool Copernicus is used to find when SLS is capable of sending spacecraft to the Moon while not restricting the TLI burn to occur near perigee. As an aside, the SLS Block 1B and Block 2 vehicles do not have this limitation as the delta-V splits between the stages are specifically designed for lunar missions, allowing the use of a circular Earth parking orbit. The circular parking orbit allows the future configurations of SLS to send spacecraft to the Moon on virtually any day of the month. This is necessary as other mission constraints, like rendezvous in lunar vicinity, may restrict the launch availability.

There are several ways to adjust the line of apsides to improve overall vehicle performance, allowing TLI burns closer to perigee, including varying the target orbit apogee, perigee, inclination, or RAAN. Apogee is used primarily as a performance exchange from the SLS Core to ICPS, so it is eliminated immediately. Perigee and orbit insertion altitude are used to control the SLS Core disposal in the Pacific Ocean, and yaw-steering to target RAAN can be very expensive performance wise, so they, too, are not used. This leaves adjusting the parking orbit inclination, which directly

*`https://history.nasa.gov/afj/launchwindow/lw1.html`

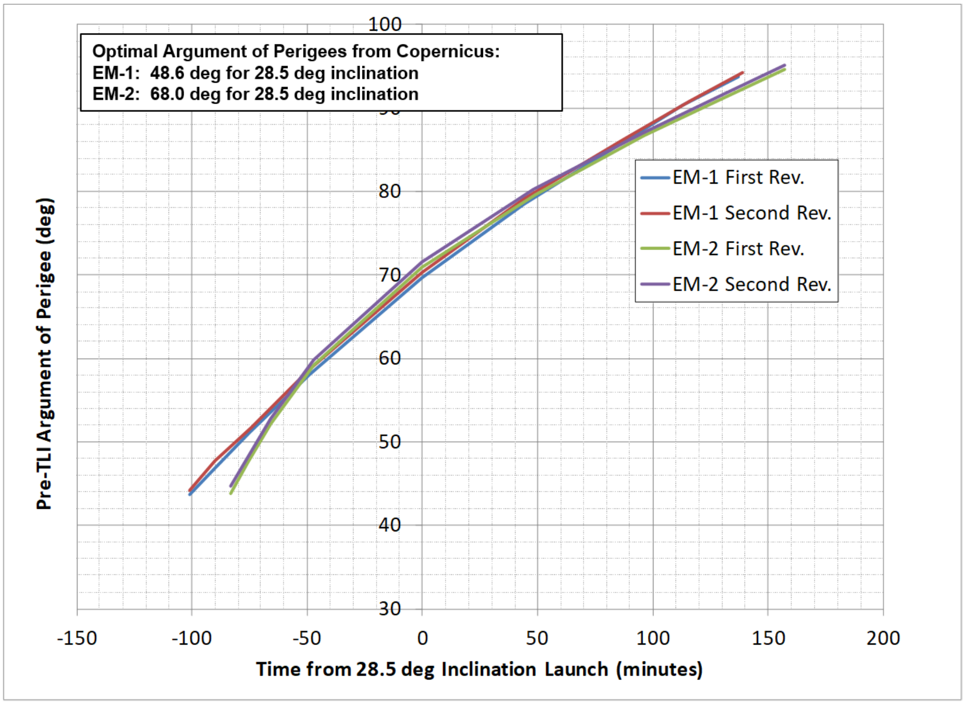

Figure 1. Optimal Argument of Perigee for a Launch Day

changes the argument of perigee, to optimally align with the line of apsides. Figure 1 shows the resultant TLI argument of perigees as a function of launch time from a due east launch for a TLI on the first or second revolution using an early version of the End to End Mission Optimization described.[5] This analysis is from DAC-2 and reflects the original planned launch dates for Artemis 1 and Artemis II * in 2017 and 2021, respectively. The 2017 launch date is closer to the minimum lunar inclination of the Moon's 18.6 year cycle than the maximum, but even then, the analysts were able to solve for launch windows, despite the less than favorable geometry.

Changing the launch azimuth and the resultant parking orbit apogee is relatively inexpensive for small changes as launch windows, on the order of 2 hours or more, can be obtained by spending less than 1,000 lbm of the total Core injected mass capability of the Block 1 configuration. As noted earlier, the launch geometry forces the ICPS to perform the TLI burn significantly prior to perigee in many instances as seen in figure 2. To accomplish this, the launch azimuth must shift further north to maximize the ICPS TLI performance for Artemis I where Artemis II's optimal launch azimuth is closer to due east. Unfortunately, as the launch shifts north, the SLS CS must spend more performance to reach the desired orbit inclination due to losing some of the benefit of the Earth's rotation. In the end, it becomes a balancing act between the SLS Core and ICPS. This can be seen in figures 3 and 4 for Artemis I and II, respectively. The final recommendation of the trade study was to hold back 1,000 lbm of SLS Core performance to protect for the launch azimuth variation during the design phase, however, once flight analysis started in the Flight Readiness Analysis Cycle (FRAC), this was increased significantly to allow for more launch opportunities.

* formerly called Exporation Mission 1 (EM-1) and Exploration Mission 2 (EM-2)

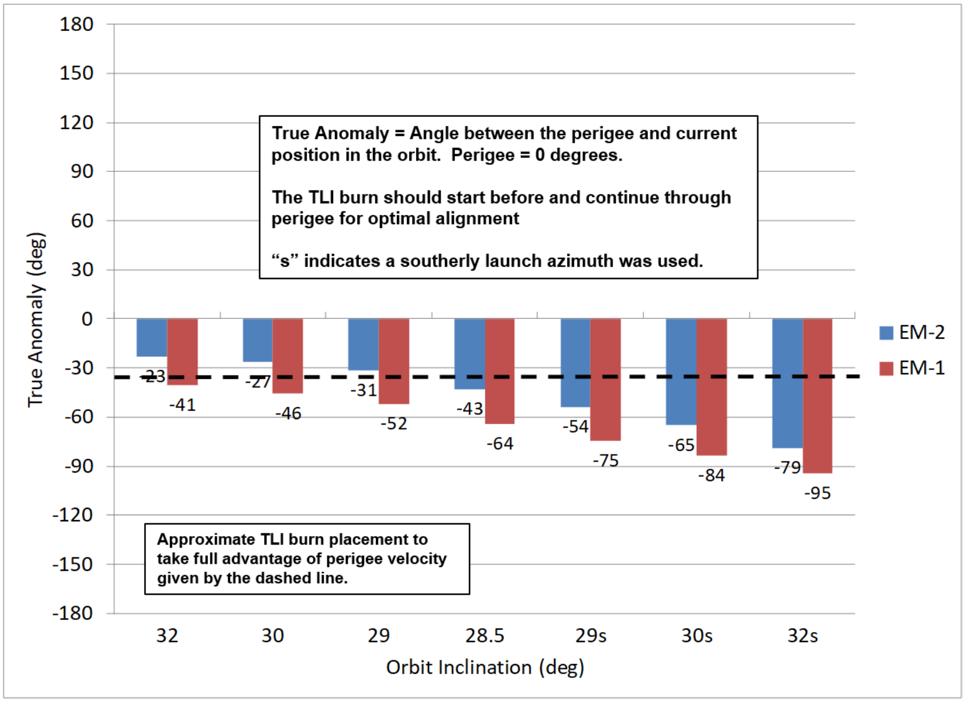

Figure 2. Example pre-TLI True Anomalies for Artemis I and II

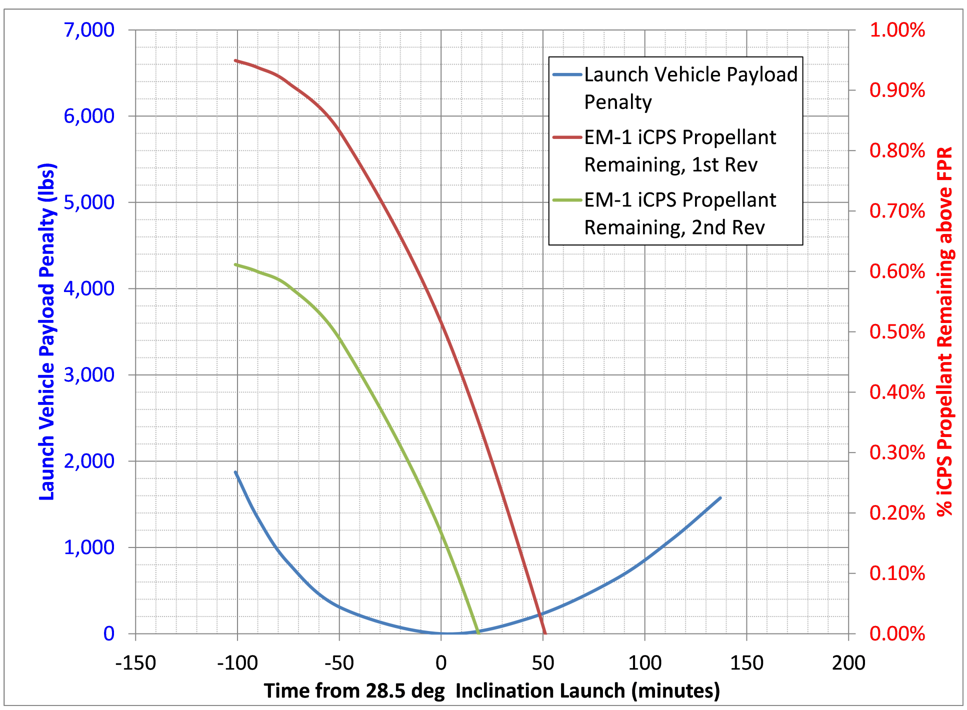

Figure 3. Artemis I (EM-1) launch window example

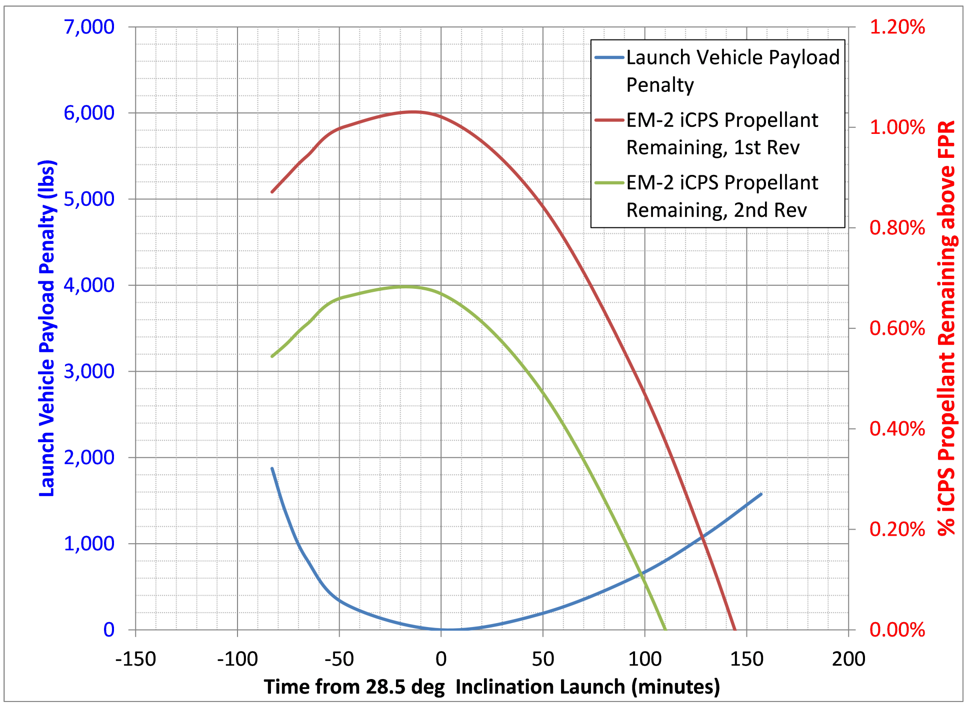

Figure 4. Artemis II (EM-2) launch window example

Another complication is that the analysis, so far, as been focused at the optimal launch date for a given month, or when the lunar flyby will be near the minimum lunar declination. If SLS launches earlier or later, then the Moon will not be at the minimum declination at the flyby. This causes the launch azimuth to shift even further north, so the Artemis II launch windows will end up looking more similar to an Artemis I launch window and drifts even further from perigee until the ICPS no longer has sufficient performance to complete the TLI burn.

GUIDANCE TARGET GENERATION

Now fast forward to FRAC-0, the first of two planned FRAC's for Artemis I. All the previous analysis and research was done with the focus on design. While planning for the actual flight, the SLS trajectory team had a better idea of how much margin was available for launch windows and direction from SLS Program on how to spend that margin on flight day. First, an analysis on the performance impacts of an RS-25 unplanned shutdown indicated there was at most 5200 lbm of margin on the vehicle.[6] This set aside protected for an unplanned RS-25 shutdown off the pad and allowed SLS to achieve an abort to orbit. The only other constraint to defining the performance based launch windows was a minimum coast time between the ICPS Perigee Raise Maneuver and TLI burns.

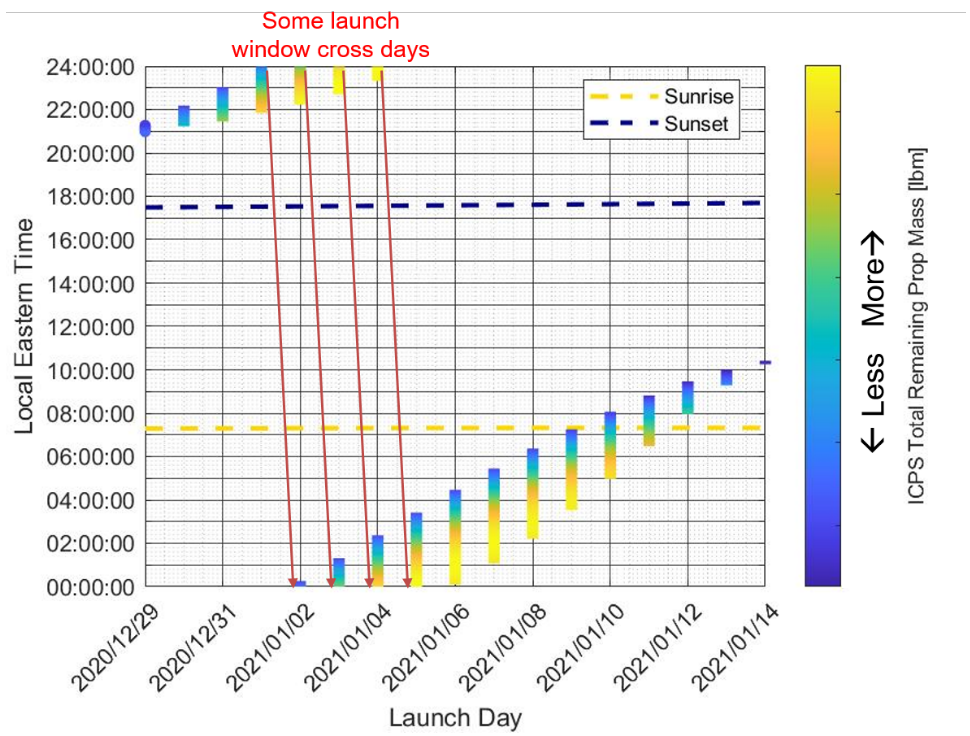

Figure 5. Artemis I Late December 2020/Early January 2021 Performance Based Launch Windows

The actual generation of the trajectories was automated and scanned through an entire year of launch opportunities from November 2020 through October 2021. The Copernicus input deck used the hypergrid methodology to model the SLS Core trajectory as described in Ref. 5, but each launch month had its own hypergrid as the monthly seasonal effects required different throttle profiles to control maximum dynamic pressure. Two sets of outputs were generated from that scan, one for

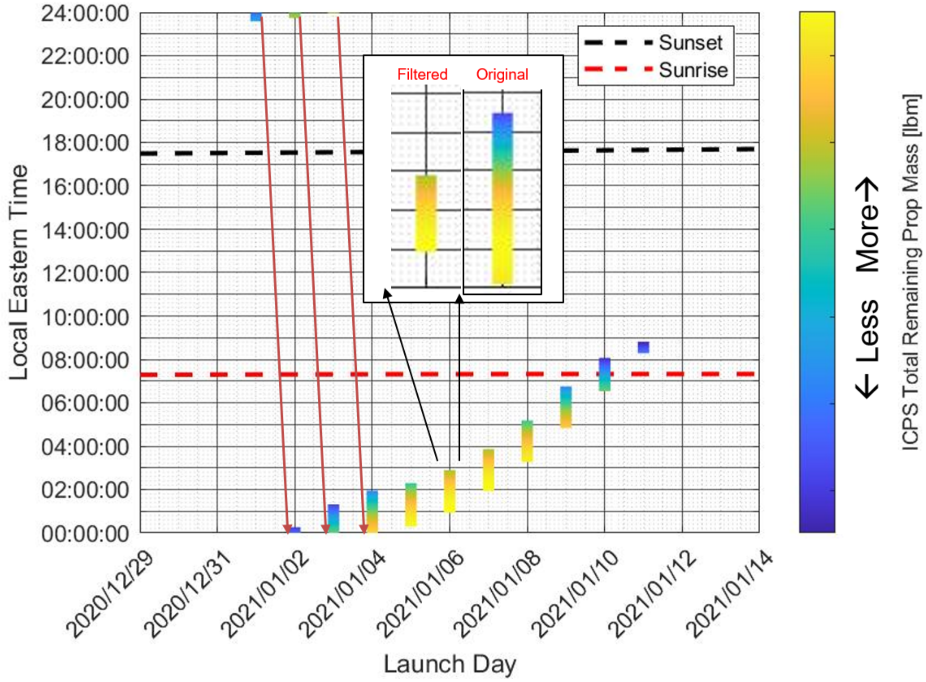

Figure 6. Artemis I Late December 2020/Early January 2021 Reduced Performance Based Launch Windows

the SLS Core guidance targets and another for the ICPS TLI guidance targets. With the increase in ascent launch window reserve, the resulting daily performance based windows ended up being significantly longer than 2 hours in many instances as can be seen in figure 5 for the late December 2020 to early January 2021 launch period. Some aspects of the SLS vehicle were only designed to accomodate up to a 2 hour launch window, but having launch windows that exceed that time limit will allow NASA to pick what 2 hours of each of those 2+ hour launch windows to fly for the given day.

To show the sensitivity to the ascent launch window reserve, the SLS trajectory team was tracking a threat to preserve engine out capability off the pad. The worst case scenario reduced the ascent launch window reserve to 615 lbm, which resulted in the launch windows shown in figure 6, losing both minutes in the day and full launch days in the previously defined launch period. By the end of FRAC-0, this performance threat was diminishing and the final launch windows on the day of flight will be more similar to what was seen in figure 5.

DAY OF LAUNCH INITIALIZATION LOADS UPDATE

Launch Opportunity is defined as a period of the year during which SLS is capable of completing Orion's primary test objective. For the Artemis I mission, this period of opportunity is divided into multiple periods with each period consisting up to seventeen consecutive days. For each day, there is a feasible span of time during which launch has to occur in order to satisfy the primary test objective. This span of time varies from twenty minutes to over four hours. The SLS Guidance system is responsible for designing the inputs for the Launch Window Algorithm which vary on a day to day basis, spanning all of the launch opportunities. Part of the inputs are I-Loads and part of them are designated as the Day of Launch (DOL). I-Loads are used to drive 6-DOF simulation and Hardware in Loop (HWIL) testing and verifications. DOL inputs are fed to DOLILU system. The DOLILU system is the means by which the SLS trajectory is designed, verified to ensure flight safety and then uploaded to the flight computer on day of launch. Launch vehicles are designed to fly down a narrow angle of attack and angle of sideslip corridor in order to keep them within structural load limits. The responses of the launch vehicle to these alpha and beta angles respectively can vary significantly based on actual DOL winds. Vehicle structural loads due to aerodynamic forces and moments can be minimized by maintaining zero total angle of attack during the high dynamic pressure phase of flight. For a specific measured wind, the vehicle attitude angles that result in zero total angle of attack can be computed. Since the measured wind is not identical to the actual wind experienced during ascent, there will be some expected divergence from zero total angle of attack using the attitude angles determined from the measured wind. As was the case with the Space Shuttle, SLS launch availability has been determined to be unacceptable if mean monthly winds are used as the "measured" wind due to the large variation in wind causing corresponding large divergence from zero total angle of attack and, consequently, unacceptable structural loads. The SLS launch availability requirement demands the use of launch-day wind measurements taken shortly before launch to design a table consisting of throttle and attitude command, which is uploaded via the DOLILU process. Once the DOL inputs are verified, these are uploaded on BS followed by I-Loads update on Core Stage.

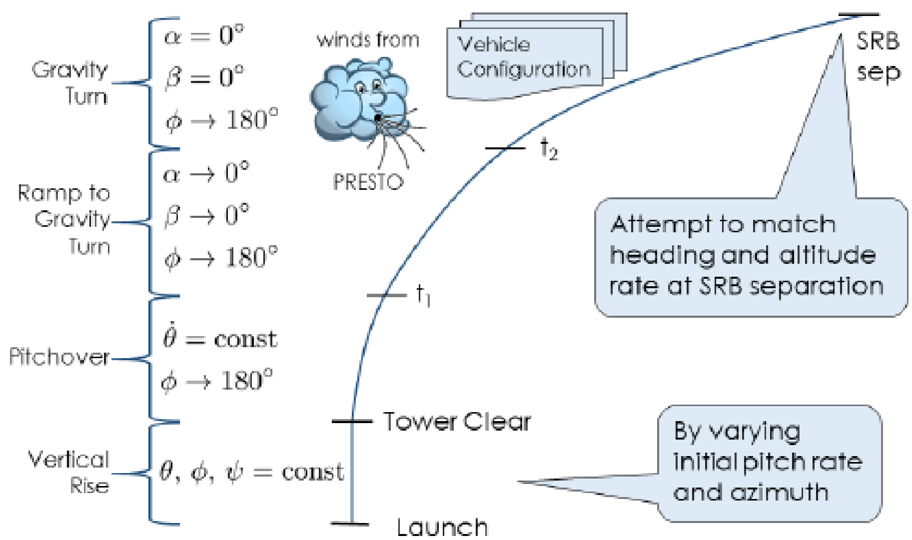

Figure 7. High Level CHANGO Simulation Details

The CHANGO designs the Chi Table which is uploaded to the vehicle's flight computer and used during ascent by the flight software. The CHANGO process is depicted in Figure 7 as it tends to drive vehicle angle of attack and side slip angle to zero for load reduction as it targets specified heading and altitude rate at the termination of BS Flight. The wind and atmosphere conditions are measured prior to launch and pre-processed to become inputs to the CHANGO software along with the DOL estimated Propellant Mean Bulk Temperature (PMBT) and other fixed-value inputs determined from pre-DOL evaluations. Execution of the CHANGO software determines the subset of I-Loads that prescribe the vehicle attitude and throttle from liftoff to SRB jettison. The data is formatted as a table with an independent variable of delta-altitude from liftoff and is referred to as the Chi Table. Figure 7 shows how CHANGO attempts to match targets (heading and altitude rate) generated by 3DOF optimization tool, POST.[1]

GUIDANCE, NAVIGATION, AND CONTROL

The launch window is the span of time within a given day when the vehicle can launch and achieve its objective: reaching a target orbit within an acceptable mass penalty. The planned ascent trajectory for the boost phase is designed for liftoff at a single point in time. To accommodate launching before or after the planned time, the Launch Window Adjustment algorithm computes needed adjustment to the RAAN and Inclination target at insertion and Chi Table Yaw profile. These adjustments ensure that the vehicle reaches an acceptable orbit, including alignment for Earth-Moon missions or rendezvous missions, while maximizing the payload delivered. Analysis of trajectories generated from Copernicus and POST (3-DOF trajectory optimization tools) show that as the launch time is varied across the launch window, the ascent RAAN and Inclination targets change in order to preserve optimality for the entire mission. Examination of the change in target data shows that data can be curve fitted by a polynomial function. Data examination revealed that Launch Azimuth range varies day to day.

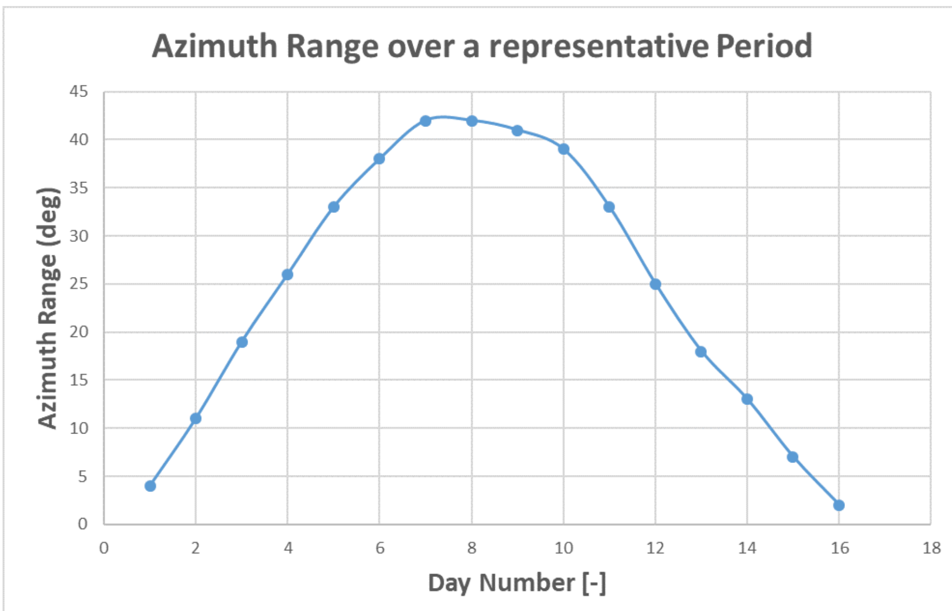

Figure 8. Variation in Azimuth Range in Launch Period

Launch Azimuth is the flight direction at launch, measured clockwise from north on the local meridian. Range of Launch Azimuth vary from two degrees to over 40 degrees as shown in Figure 8. These ranges are directly proportional to launch time, which varies as low as 20 minutes to as high as approximately five hours. Further data analysis and lessons learned have shown that at least a fifth order polynomial is required to estimate data. Moreover, the reference point for the polynomial needs to be at a reference Launch Azimuth which is approximately at the middle of the azimuth range. This reference azimuth is also used as CHANGO's heading target. Lastly, to further reduce the polynomial estimation error, two sets of fifth order polynomials were used,

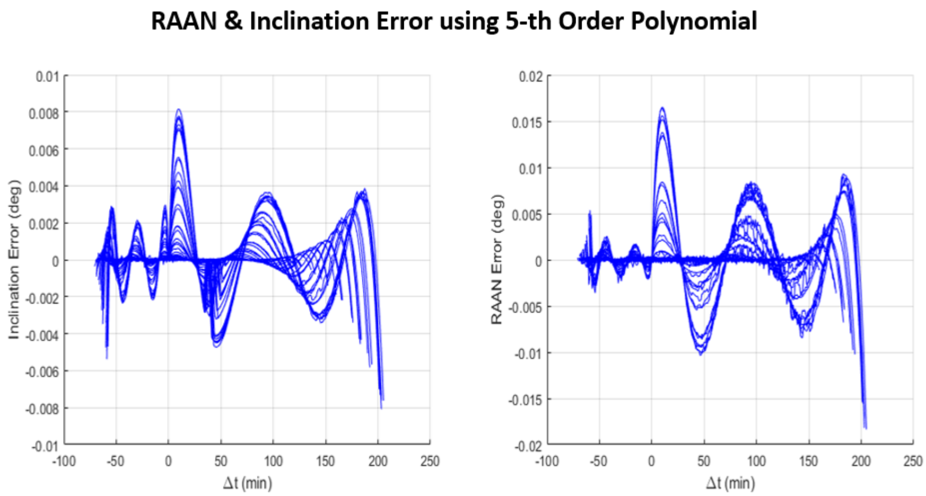

Figure 9. Polynomial Curve Fit Errors corresponding to first 4 periods of launch opportunity

each referenced to the same azimuth. Polynomial curve fitting azimuth lower than the reference launch azimuth are designated as "Northerly" curves and azimuths higher than the reference launch azimuths are designated as "Southerly" curves. Figure 9 shows polynomial error for the first four periods of launch opportunity that spans more than four hours

On the launch day, at liftoff, Flight Software will receive the current GPS time, which will be used along with the time corresponding to reference launch azimuth time, to update the closed loop guidance RAAN and Inclination targets to maximize the payload delivery and achieve the proper orbit geometry for Earth-Moon alignment at that launch time. To reach the new inclination and RAAN targets, the Chi Table yaw command is adjusted with a yaw bias. From a performance standpoint, it is better to yaw the vehicle early in the flight since less control authority will be required as the vehicle has not gained high momentum. If the Chi Table is not adjusted, all the yaw adjustment will be completed by onboard guidance after BS flight, significantly impacting performance. A constant yaw bias is sufficient to improve performance. A spherical trigonometric algorithm is employed to determine the optimal yaw bias at any given launch time. Inputs to this algorithm are the target orbital plane and launch time for both the reference launch time and actual launch time. This algorithm has tunable parameters, which have been tuned for the SLS Block-1 configuration, and have demonstrated near-optimal performance over a wide range of possible SLS target trajectories as shown in Figure 10. Figure 10 is generated using two sets. One method, labeled as performance optimal, uses a brute force method to determine the value that actually results in optimal performance in 6DOF simulation, whereas as the spherical trigonometric algorithm is used to estimate the optimal value. From this figure, as expected, as the delay in launch exceeds two hours, spherical trig estimation starts to diverge from its optimal value. Sometime prior to the DOL and even though capable of launching at any time during the window up to four hours, the cross-programs will select the two hour block in which they will launch. The spherical trigonometric algorithm is used to determine the optimal yaw bias for several launch times throughout the launch window and is also modeled as 5th-order polynomial.

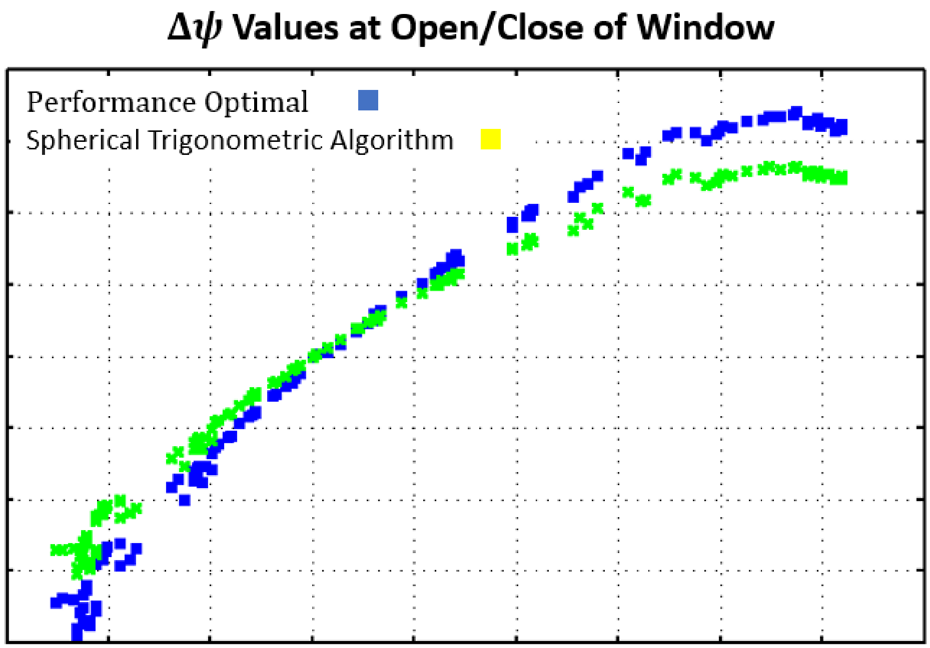

Figure 10. Yaw Bias estimate using Spherical Trig and Optimal Yaw bias comparison

RESULTS

As stated earlier, updated inputs are used to drive the 6-DOF Monte Carlo simulation of 2000 cases. Initially a 5 point check is used which simulates launch times consisting of launching at open and close of the window along with reference launch and two intermediate points. Figure 11 shows sideslip angle, total angle of attack and Guidance convergence behavior. These results show that overall launch window algorithm works as expected.

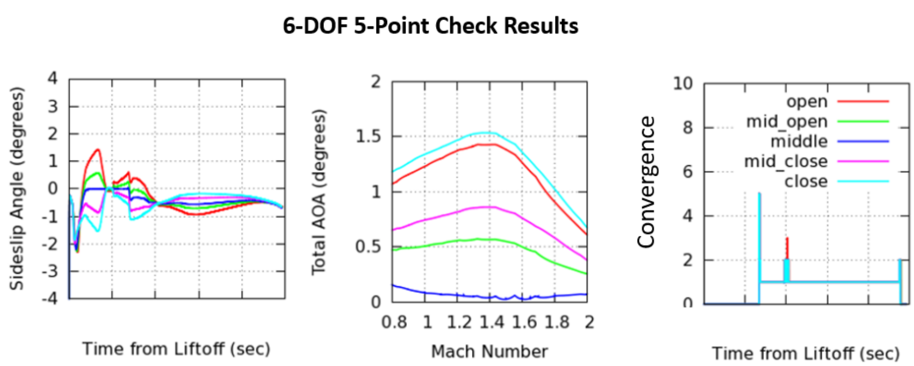

Figure 11. (Left) Side Slip Angle, (Middle) Total Angle of Attack, (Right) Guidance Convergence

Figure 11 demonstrates that, as planned, both side slip and angle of attack are minimized and kept near zero. Most stressing case corresponds to the case that has the greatest time difference between reference launch and actual launch. Furthermore, the 6-DOF 2000 case Monte Carlo simulation is run with the most stressing case and are used to verify the performance and target accuracy.

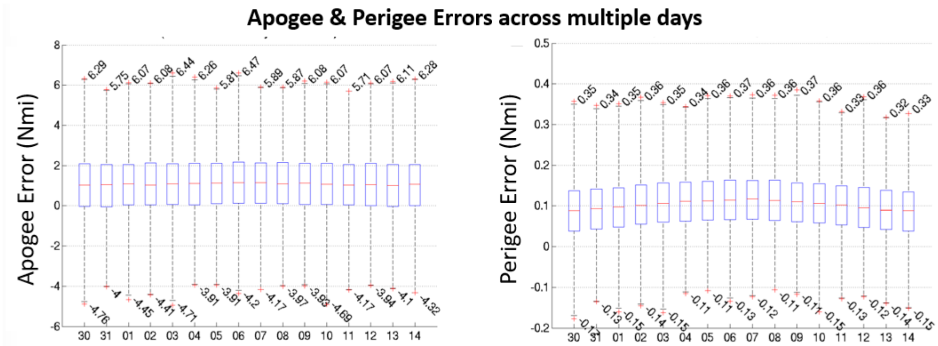

Figure 12. Apogee and Perigee Errors Monte Carlo statistics across Launch Period

Figure 12 shows the 2000 MC results for Apogee and Perigee error if launched between the dates of December 30, 2020 and January 14, 2021, confirming that SLS achieves desired apogee/perigee target within acceptable error margin

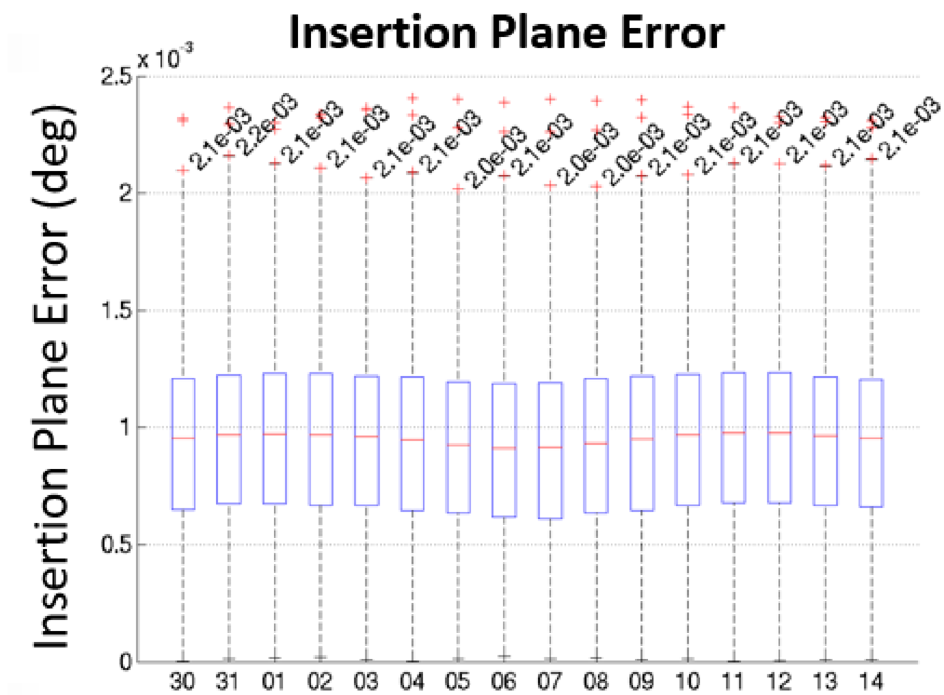

Figure 13. Insertion Plane Error Monte Carlo statistics across Launch Period

Figure 13 shows that the SLS successfully inserts into the desired orbital plane (within acceptable error margin), if launched between the dates of December 30, 2020 and January 14, 2021.

And lastly, figure 14 shows positive propellant margin at orbital insertion, which ensures that design inputs produce near optimal trajectory.

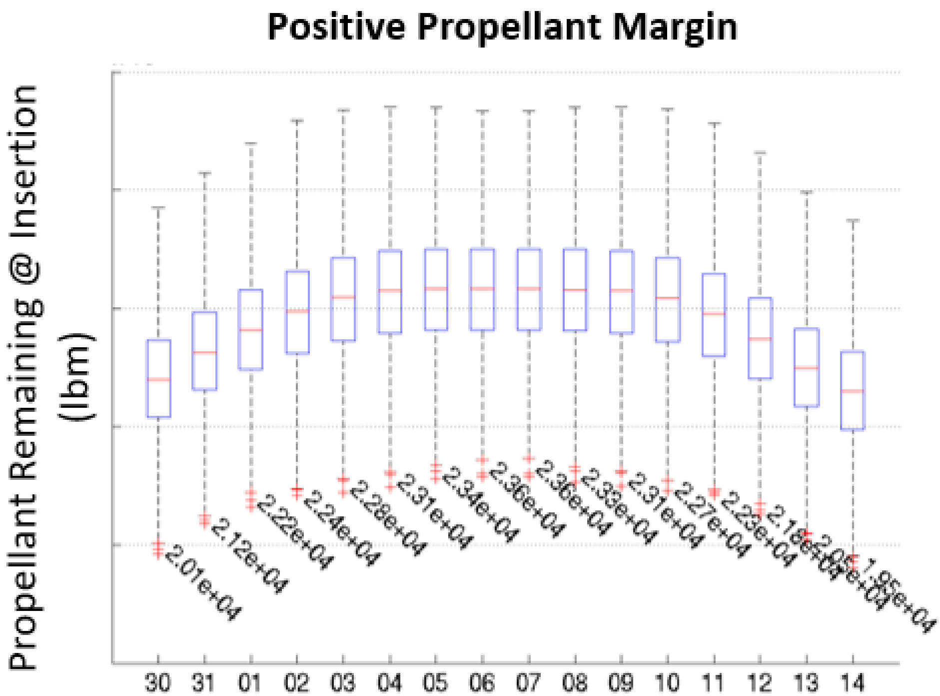

Figure 14. Propellant Margin statistics across Launch Period

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