Launch Availability Analysis for the Artemis Program

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***Abstract*—On March 26, 2019, Vice President Pence stated that the policy of the Trump administration and the United States of America is to return American astronauts to the Moon within the next five years i.e., by 2024. Since that time, NASA has begun the process of developing concepts of operations and launch campaign options to achieve that goal as well as to provide a sustainable human presence on the Moon. Whereas the Apollo program utilized one Saturn V rocket to carry out a single lunar landing mission of short duration, NASA's preliminary plans for the Artemis Program call for a combination of medium lift class rockets along with the heavy lift Space Launch System (SLS) to achieve a lunar landing by 2024 as well as subsequent missions. This paper describes how discrete event simulation is used to model the launch campaigns and provide metrics on launch availability and mission duration for each element being launched. Possible methods for improving launch availability are presented.**

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1. INTRODUCTION

The Artemis Program has a bold initiative to return humans to the lunar surface by 2024. To achieve this goal NASA and its partners are planning on launching multiple spacecraft and have them join up in lunar orbit to form an integrated lunar lander. The Space Launch System (SLS) will then be used to launch the Orion spacecraft and a crew of four to rendezvous and dock with the lander in lunar orbit. Once NASA commits to launching the first element of the lunar lander, the focus will be on achieving all of the launches in a timely fashion. NASA and the commercial partners need quantitative estimates for launch delay risks as they develop the lunar lander design and refine the concept of operations. Of particular importance will be understanding how long each lunar lander element will be in space and how long the integrated lander will have to wait in lunar orbit prior to the arrival of Orion and the crew.

2. THE HUMAN LANDING SYSTEM

NASA's Human Landing System (HLS) for the Artemis Program is described in a NASA Broad Agency Announcement (BAA) solicitation number NNH19ZCQ001K, Appendix-H-HLS. Attachment A01 describes a nominal concept of operations for the HLS. "The nominal HLS mission will be to pick up the crew and mission materials at the Gateway, transport them to the lunar surface, provide surface and EVA support, then return the crew and surface samples to the Gateway." The Gateway will be in a near rectilinear halo orbit (NRHO) around the Moon and will consist of a Power & Propulsion Element (PPE), a habitat element, and a logistics module.

Figure 1 is the generic concept of operation figure from Attachment A01 and, as stated, is meant to be minimally prescriptive. While the figure shows a multi-launch solution to get elements of the HLS to the Gateway in lunar orbit, NASA explicitly states that the number of launches required will be based upon the offerors design solutions for the HLS. Additionally, while it is expected that offerors will likely choose commercially available rockets to get the HLS to lunar orbit, they are also allowed to consider use of the Space Launch System (SLS). Following launch, the integrated HLS, or separate elements of the HLS depending upon the offerors approach, will travel to the Gateway orbit either via fast transit (~6 days) or slow transit (>~100 days). After the HLS is confirmed to be in a state of readiness at the Gateway, an SLS will launch an Orion with a crew of four to lunar orbit. Orion will dock with the Gateway and two crewmembers will

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transfer into the HLS for the sortie mission from the Gateway down to the lunar surface.

Figure 2 provides a Gantt chart of the launches and operations between launch and crew return to earth for our illustrative campaign. The assumed earth to lunar orbit transit time is 120 days for each of the HLS elements. The planned launch-to-launch spacing is 30 days. The planned in-space durations for each of the HLS elements as well as the Artemis III Orion capsule and crew are shown in the figure. Launch delays may cause the actual in-space durations to be significantly greater.

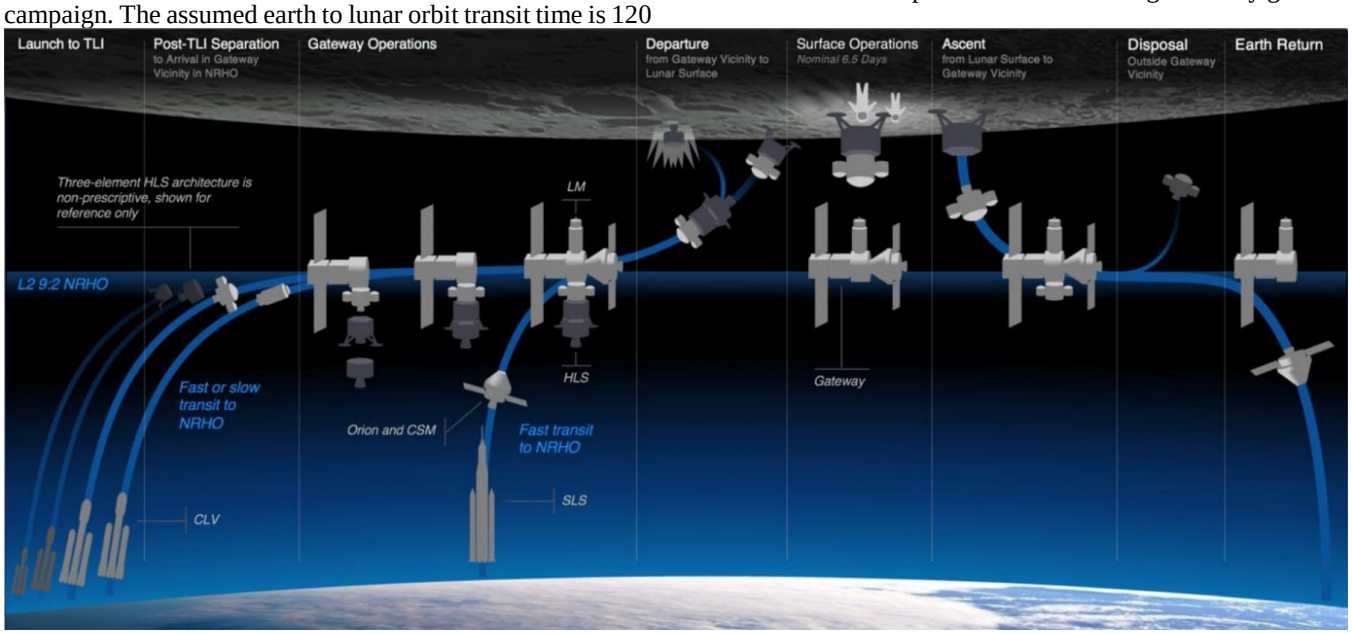


Figure 1. NASA's generic concept of operations for the HLS

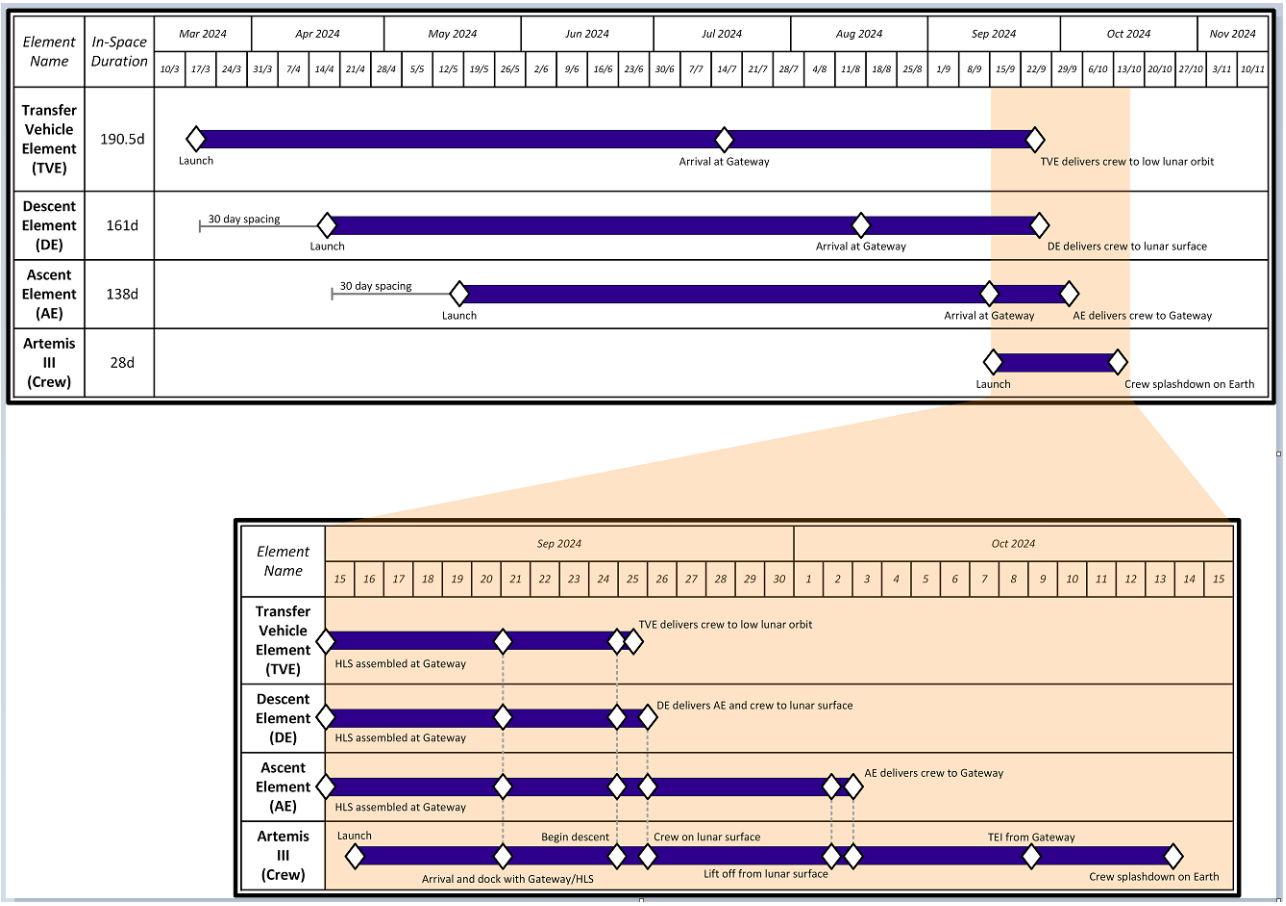


Figure 2. Illustrative Launch and In-Space Operations Campaign

Requirement HLS-R-0322, "Quiescent Lunar Orbit Operations," in the HLS system requirements document (SRD), states that, "The HLS shall be capable of maintaining quiescent operations for no less than 60 days (threshold) and 90 days (goal) at Lunar Orbit." Quiescent operations is defined in the SRD glossary as, "a passive phase with no dynamic operations (e.g., RPODU, robotics, propulsion, dockings, or space walks, etc…)." RPODU stands for Rendezvous, Proximity Operations, Docking, and Undocking. The rationale for this requirement reads as follows. "The Crew will not launch until HLS is confirmed operational in Lunar Orbit. The HLS may need to remain in Lunar Orbit for 90 days after the HLS is confirmed operational, to await crew and cargo delivery, including potential launch scrubs and mission delays." This requirement will drive the lifetime of the HLS elements prior to execution of the lunar sortie mission.

3. Campaign Launch Opportunities

Launch opportunities for the HLS elements and the SLS-Orion will be based upon launch vehicle performance, payload (each HLS element and Orion), the planned lunar orbit as well as other factors such as the need for lighted conditions for the surface stay time on the Moon. The actual set of opportunities will not be known with certainty until after the offerors proposals have been evaluated and NASA has made a selection.

For this analysis, a preliminary set of opportunities was developed by NASA's Johnson Space Center based upon estimates for launch vehicle performance and payload mass constraints. These opportunities may be optimistic given that not all the launch opportunity constraints are known at this time. The provided assumed launch opportunities for the HLS elements by commercial launch vehicles (CLV) and the Artemis III (SLS – Orion) are shown in Figure 3 and Figure 4 respectively. The figures reflect there being either none, one or two launch opportunities, on any given day. The provided data set for the HLS element launch opportunities only covered the time period of April through July of 2024 rather than the entire fiscal year. It should not be concluded that no opportunities exist in the first half of FY2024, nor after August of 2024. These other periods were simply not analyzed at this point in time.

The defined launch opportunities for SLS are constrained only by the ability of Orion to reach NRHO and are therefore likely to be conservative. There will be additional constraints related to required operations and opportunities for the HLS to land on the Moon. Therefore, it is likely that the actual SLS launch opportunities will be more restricted than those depicted in Figure 4. For that reason the actual SLS launch opportunities are treated as a sensitivity variable in this analysis.

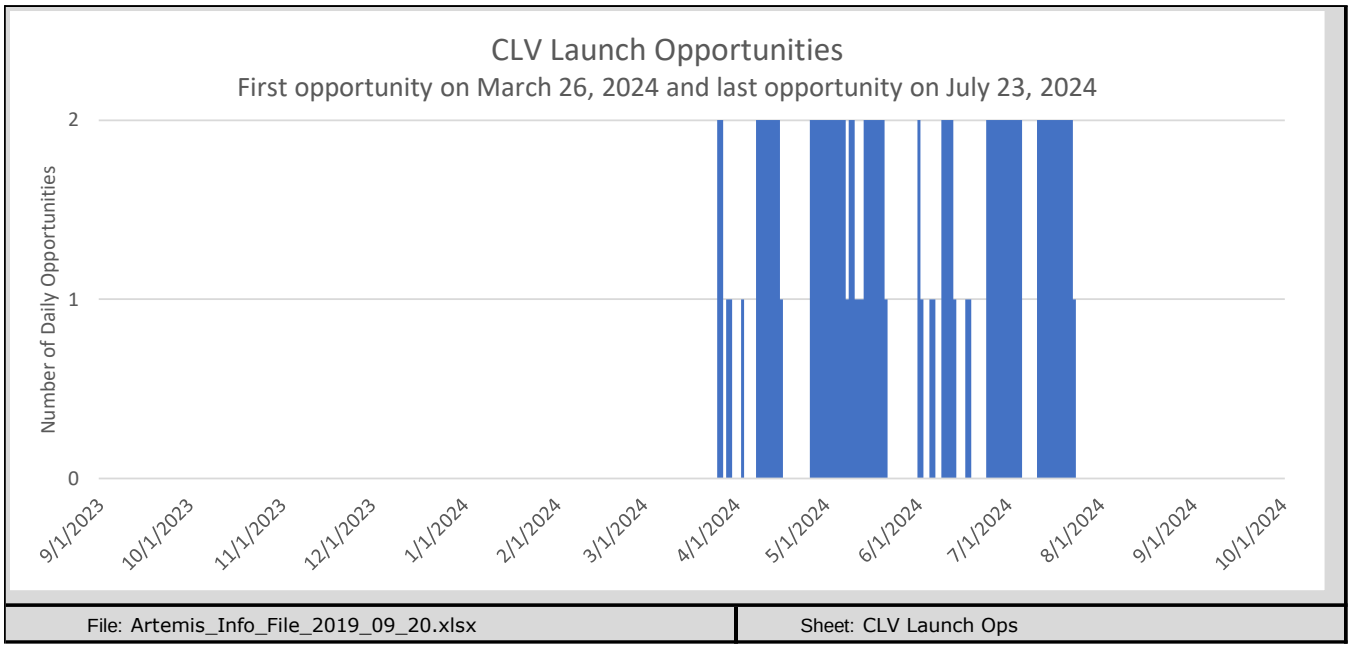


Figure 3. Launch Opportunities for Human Lander System Elements

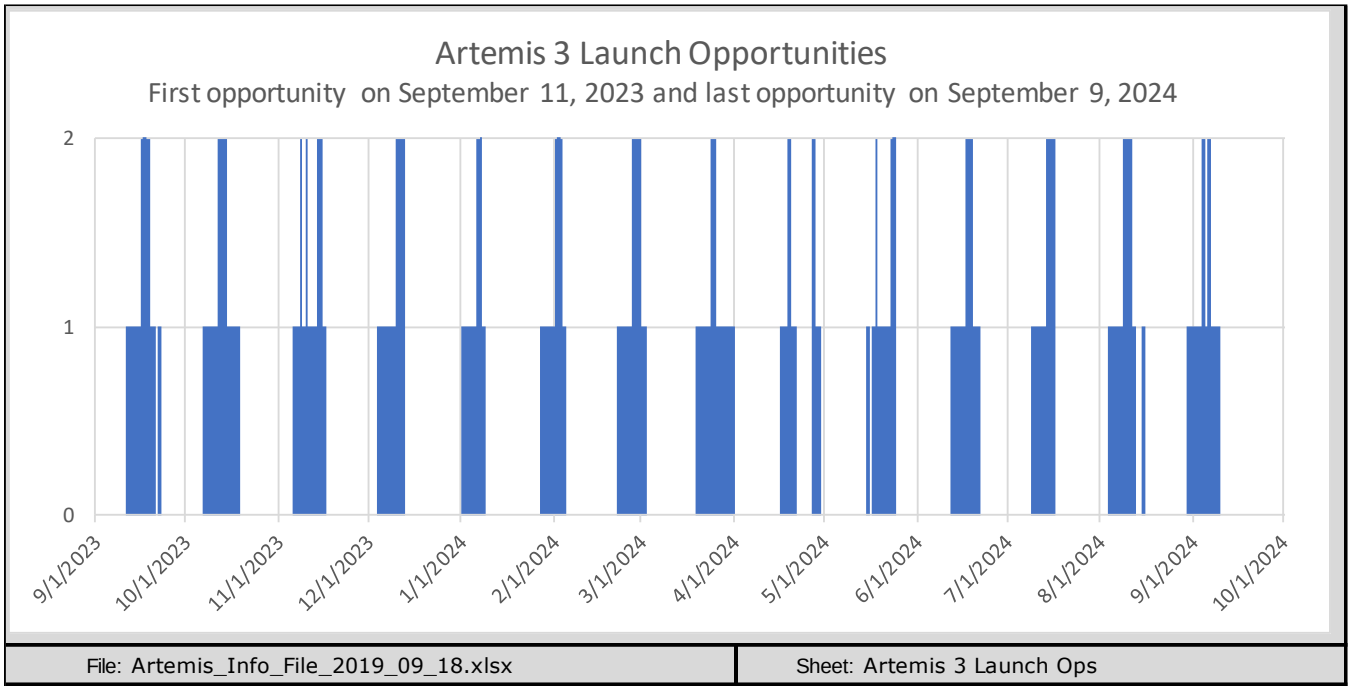


Figure 4. Launch Opportunities for Artemis III (SLS – Orion)

4. MODELS AND ASSUMPTIONS

With a focus on Artemis III, the assumed concept of operations for this paper is a three-launch solution for three single-use HLS elements, those being a transfer vehicle element (TVE), a descent element (DE), and an ascent element (AE). Each element would launch separately on a Commercial Launch Vehicle (CLV), in that launch order. Planned minimum launch-to-launch separation was assumed to be 30 days. A relatively slow low-energy transit of 90 to 120 days from trans-lunar injection to arrival at the Gateway orbit was assumed for each of the HLS elements. Orion is assumed to travel to the Gateway on a fast transit of approximately 5 days. It is important to note that the final HLS design and concept of operations may significantly differ from these assumptions.

To model the availability of the multiple launches required for each Artemis mission, the authors utilized two different discrete event simulation models: the Assured Space Access Model and the SLS Launch Availability Model. Both models were developed using Rockwell Automation's Arena software, a commercially available discrete event simulation (DES) suite that is widely taught in academia and used in many domains [1]. Textbooks on discrete event simulation and simulation modeling and analysis methods include those by Nicol et al [2] and Law [3]. DES has been used for many years in support of human space exploration, dating back to the early Space Shuttle days [4][5], midway through the Space Shuttle program [6][7], during the ISS assembly era [8][9], for the Constellation program [10][11], and for prior NASA studies on lunar, asteroid, and Mars exploration [13][14][15].

The Assured Space Access Model (ASAM)

ASAM simulates all launch service provider operations on both the Eastern and Western Ranges (as well as other U.S. and international launch sites) making it ideal for capturing the scheduling effects of the multiple launches required for each Artemis mission. Within the model, each monolithic launch vehicle (Falcon Heavy, Atlas V, SLS, etc.) and their payloads are initiated based upon a planned launch date and the vehicle-specific operations from launch site arrival to launch. Each entity flows through their ground infrastructure subject to facility availability and delay risks. Risk factors are derived from historical data where possible or based on analog data. Each entity is subjected to interactions between launch sites and the resources required to support a launch. Typically, the ASAM simulates a complete manifest of all scheduled launches based upon the day the simulation is executed. Consequently, all future launches and their payloads are subject to availability, processing, integration, and launch scrub delays prorated for how close they are to launch and what delays risks have been retired.

For the analysis of the integrated launch campaign of HLS and the Artemis III mission, the assumption was made to initialize ASAM two weeks prior to the launch of the first HLS element, the TVE. This decision was based upon NASA conducting a Flight Readiness Review (FRR) two weeks before launch as described in the HLS BAA Appendix H, Attachment G Statement of Work section 5.4.5. This modeling analysis decision retires a majority of the risk associated with the availability of each element, assuming that the first element would not proceed with its launch without the subsequent elements being on schedule for launch.

The SLS Launch Availability Model (SLS-LAM)

The SLS-LAM produces estimates for SLS launch availability through a detailed simulation of an SLS launch countdown [16]. It is currently used to estimate the integrated EGS-SLS-Orion launch probability. It heavily relies upon Space Transport System (STS) launch attempts history [17] that has been factored to account for the differences between the STS and SLS systems. The model has been reviewed by the NASA Engineering and Safety Center (NESC), who found the model to be sound overall and provided recommendations for model enhancements that are currently being addressed. It is important to note that estimating SLS launch availability is difficult due primarily to the fact that the SLS has no flight history and behavior is extrapolated based on launch history of other similar vehicles. Consequently, the results from this model are considered estimates at best.

The SLS launch availability assessment produced by the SLS-LAM has many inputs including, but not limited to, launch vehicle version, planned launch date, daily launch window duration, launch opportunities, the payload, and number of crew members if applicable. For this analysis, it was assumed that the version would be the Block 1 SLS and that the payload is an Orion spacecraft with a crew of four. For this analysis, it was also assumed that there is a two-hour launch window in each day for which there is a launch opportunity. In reality, launch window duration can vary substantially from day to day. Additional analysis will be completed in the future to evaluate the impact of variable launch window duration.

SLS-LAM additionally has the capability to analyze launch probability from the perspective of many different starting points. For example, the model can be started coinciding with the start of the two-day SLS launch countdown, or many days prior to launch when the SLS in the vehicle assembly building (VAB). For this analysis the starting point was 14 days prior to the planned launch date, a.k.a. launch minus 14 days (L-14). L-14 was chosen because that is approximately when the last significant amount of schedule reserve can be held. From that point forward there is essentially 14-days of continuous activity including final testing in the VAB, closeouts, rollout, and launch pad pre-launch operations to get to launch including the last two days of formal launch countdown.

A launch sensitivity analysis was performed because of the likelihood that the actual Artemis III launch opportunities will be less than shown in Figure 3 once all mission constraints are accounted for. The approximate pattern of Figure 3 is 10 days with opportunities to launch followed by 17 days with no opportunities, driven by an approximate 27-day lunar cycle. The sensitivity analysis conducted using the SLS-LAM considered 10-days, 8-days, 6-days, 4-dasy, and 2-days of launch opportunities per 27-day cycle.

5. RESULTS

The results for SLS launch availability from the SLS-LAM are presented first in standalone fashion, without any propagating delays from CLV launches. As the final (and most constrained) launch in an Artemis mission, the availability of the SLS directly drives the amount of time the HLS will have to be in quiescent mode at the Gateway. The output of the SLS-LAM then became one of the many inputs to the ASAM, which was used to produce the integrated launch campaign analysis that considered launch delay risk to the HLS element launches as well as to the Artemis III launch. The results of the integrated assessment using ASAM are presented after the SLS-LAM results.

SLS Launch Availability Results

Figure 5 shows the Artemis III expected launch date cumulative distribution functions (CDF) with respect to a planned launch date of June 15. Within the SLS-LAM this date was the assumed first opportunity of the 10-days (or 8-days, or 6-days, or 4-days or 2-days) of launch opportunities per cycle. The CDFs and their stair step pattern are reflective of the number of days of the launch opportunity. The horizontal portion of the CDF reflects the days in which launch opportunities are not available. The probability of launch is also driven by all the delay risks from L-14, when the simulation was started, through whenever launch ultimately occurs. The planned launch date will also influence the probability of launch.

Figure 6 demonstrates the variability of launch probability with planned initial launch date for SLS. This plot includes CDFs for planned June, September and December launch dates under the assumption that the launch opportunity pattern is 10 days on – 17 days off. Because of potential weather and sea state delays, December is a less favorable time to launch.

Of considerable significance is the cumulative probability of launch at the 60 and 90-day points. These coincide with the 60-day (threshold) and 90-day (goal) quiescent dwell time requirement on the HLS. Ideally, one would want the cumulative probability of launching the SLS to be very high for these milestones. If SLS cannot launch within these timeframes, the HLS elements may reach the end of their planned lifetimes before the mission can be completed.

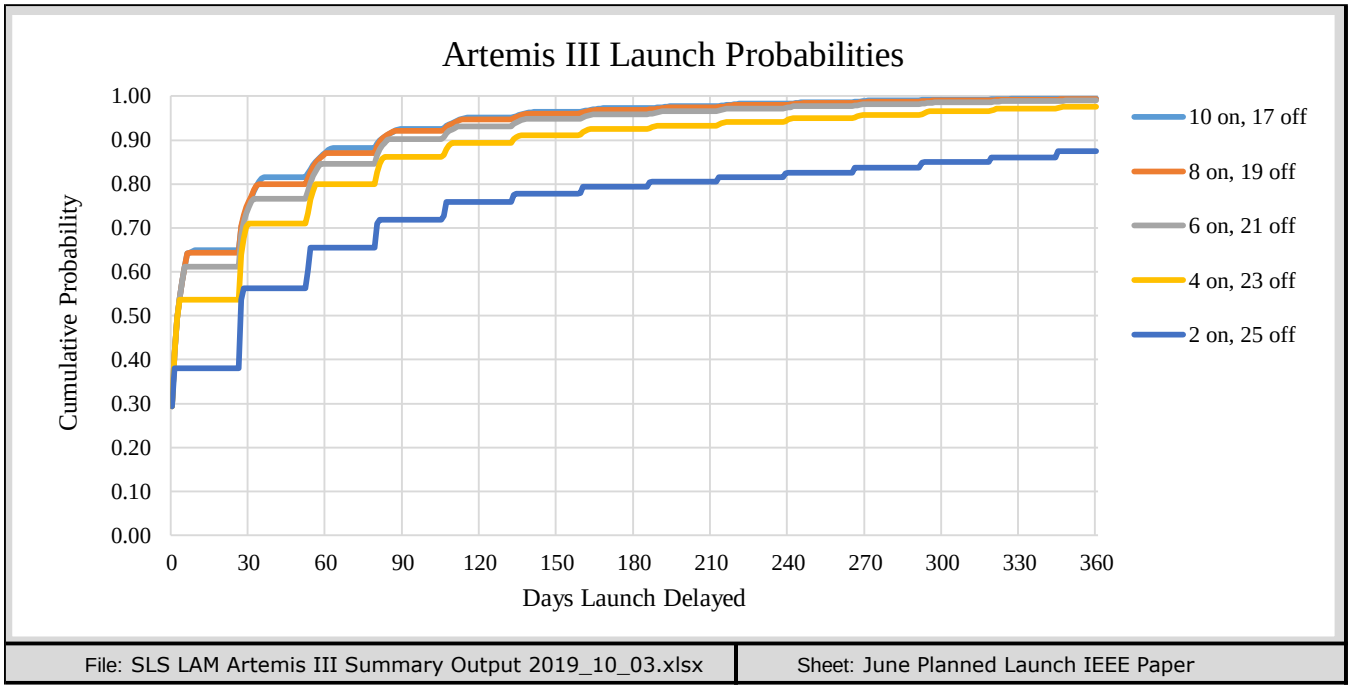


Figure 5. Artemis III Cumulative Launch Probabilities versus Launch Opportunties

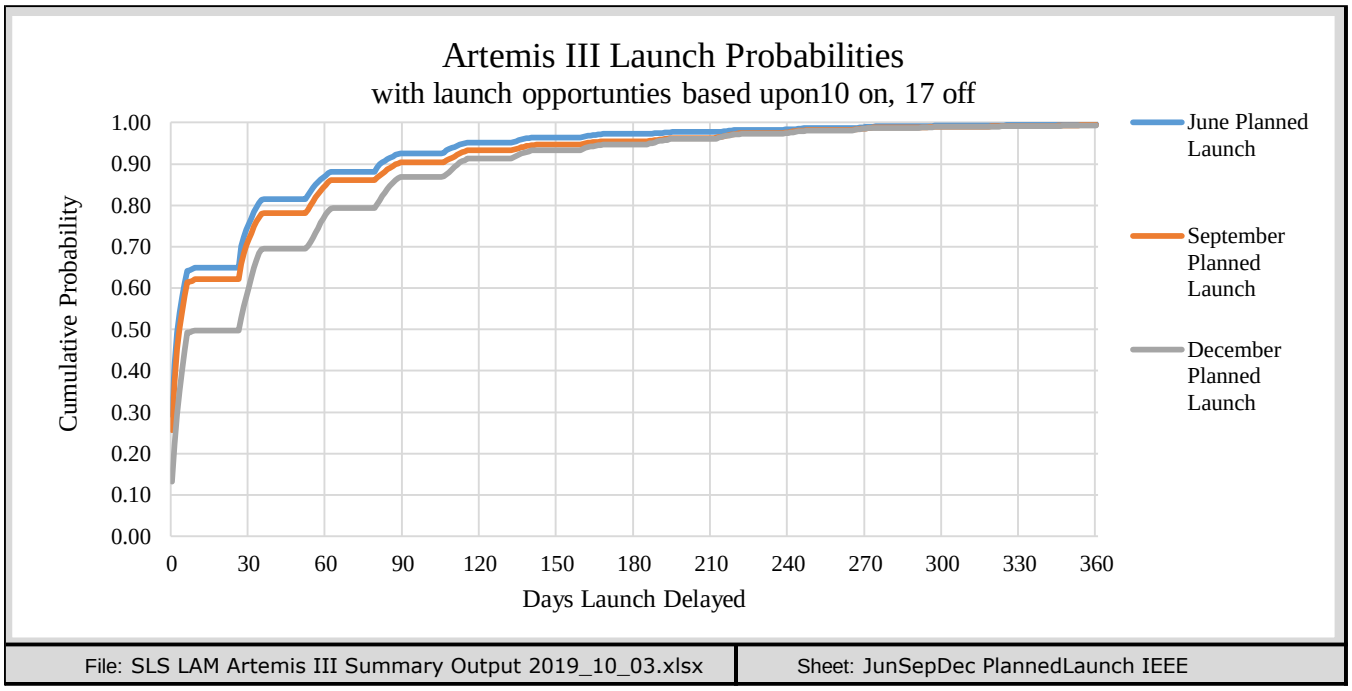


Figure 6. Artemis III Cumulative Launch Probabilities versus Planned Launch Month

Results for Integrated Launch Campaign

An evaluation was then completed for launch availability for the integrated campaign of four launches, including propagating delays across launches. Figure 7 shows the time in space for the HLS elements as measured from the point in time in which each element is launched to the time in which all the HLS elements are integrated in lunar orbit. Recalling Figure 2, the nominally planned in-space durations for the TE, DE, and AE launch to an integrated HLS are 180, 150 and 120 days respectively, based on launch spacing and transit time. Once the TE launches there is considerable risk that the subsequent DE and AE launches will be delayed. Consequently, there is a risk that the TE and DE will spend longer in space than planned prior to the HLS being fully integrated.

Figure 8 shows the time in space for the HLS elements as measured from the point in time in which the HLS element is launched to the time during the Artemis III mission when that

element completes its function. This figure thus integrates both HLS element launch delay risk and SLS launch delay risk. The TE is assumed to complete its portion of the mission after the TE transfers the DE and AE from the Gateway to low lunar orbit. The DE completes its portion of the mission upon lunar landing. The AE completes its potion when the AE has returned to the Gateway after the lunar sortie.

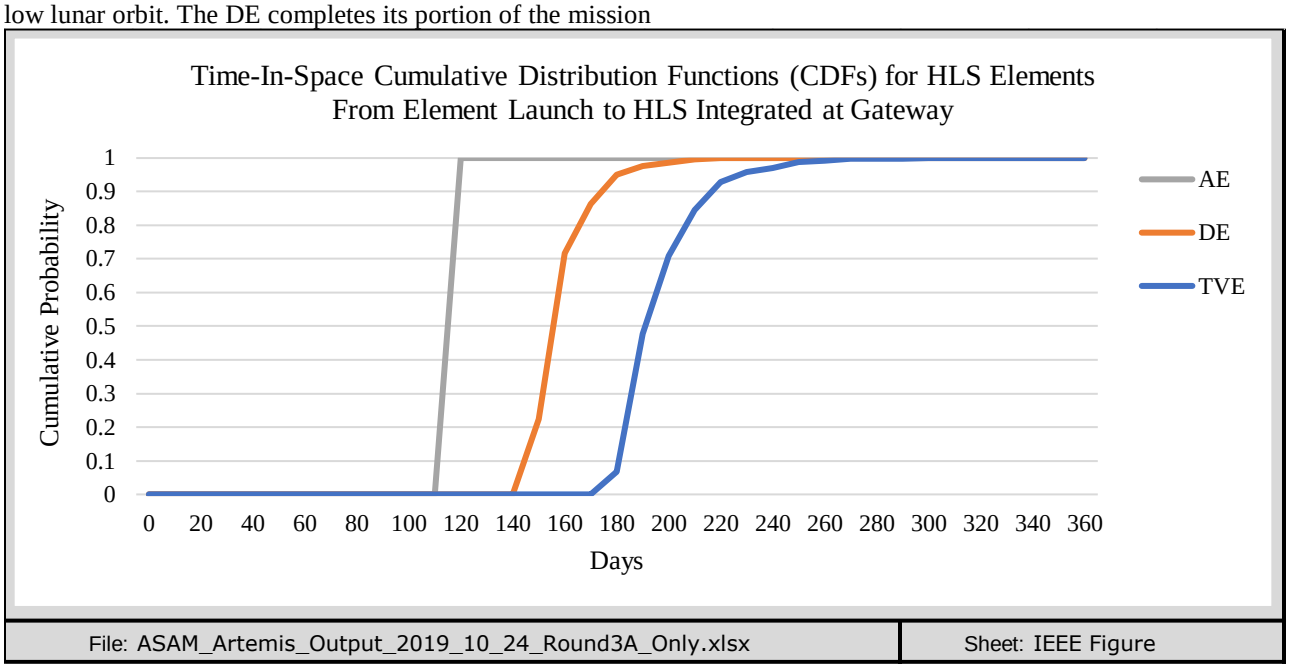


Figure 7. Human Lander System Element Time In Space (element launch to integration)

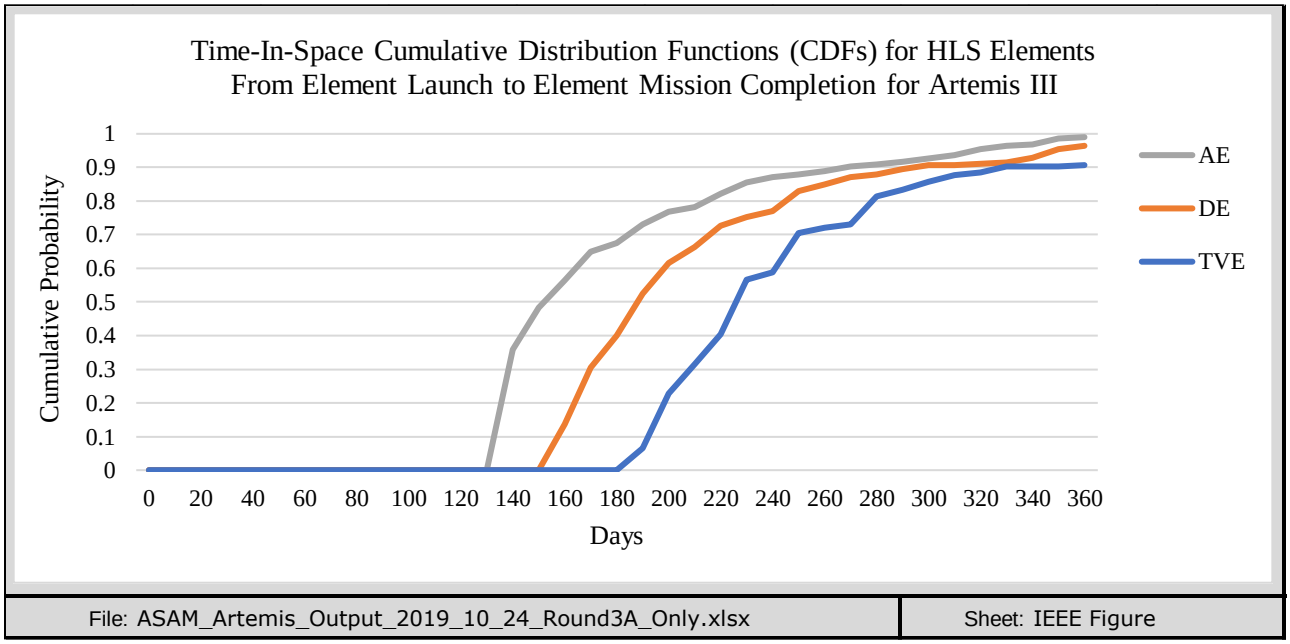


Figure 8. Human Lander System Element Time In Space (element launch to mission completion)

Figure 2 shows that the total in-space durations (from launch to element mission completion) for the TE, DE and AE are 190.5, 161 and 138 days respectively. The results shown in Figure 8 demonstrate that there is considerable risk that the actual total durations in space could exceed the nominally planned durations by a large amount.

6. Opportunities for Improvement

There are many opportunities to be explored for improving upon both the SLS launch delay risk and the HLS element time in space. The SLS results point directly to the benefit of having extended opportunities for launch and for planning for launches to occur during favorable months. While not analyzed for this example study, other factors can be

evaluated to see if SLS launch availability can be further improved. For example, having additional margin in the launch campaign and having that margin as close as possible to the opening of a launch opportunity will likely improve launch availability. Improvements in SLS performance and/or mass could also potentially improve the availability of launch opportunities.

The first driver to HLS element time in space is the transit time between Earth and lunar orbit. Faster transits will reduce time in space. The second driver is the launch-to-launch spacing. Spacing launches closer together will reduce time in space. This could be done by launching each element from separate launch pads. By 2024, the U.S. launch market should be served by multiple providers with launch vehicles capable of getting the HLS elements to lunar orbit.

7. CONCLUSIONS

The results developed as part of this analysis are preliminary in nature and are not intended to represent what the final launch availability of the HLS-SLS system may be. This analysis is intended to explore potential issues with launch availability and HLS duration that should be addressed during the design phase. It is possible that HLS elements will need to have considerable capability, beyond the currently planned 60 to 90 days, to remain in space while awaiting the arrival of Orion. The analysis will need to be revised and updated as the Artemis Program matures.

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BIOGRAPHY



Grant Cates *is a Senior Engineering Specialist at The Aerospace Corporation. Prior to joining Aerospace in 2014, he was a Chief Scientist at SAIC. He retired from NASA in 2006 after 25 combined years in federal service, including 7 years on active duty in the Air Force. At NASA he served in varying capacities on the Space Shuttle Program, including Space Shuttle Columbia Vehicle Manager and Flow Director. He received a Ph.D. in Industrial Engineering from the University of Central Florida in 2004.*



Chel Stromgren *currently serves as the Chief Scientist of Binera, Inc. Risk Analytics Division. In this role, Mr. Stromgren leads the development of probability and risk-based strategic models and strategic analysis of complex system development. Mr. Stromgren has supported NASA in the analysis of Space Shuttle and International Space Station operations in the post-Columbia environment and has led the development of strategic campaign models for the lunar exploration initiatives. He holds a Bachelor of Science degree in Marine Engineering and Naval Architecture from the Webb Institute and a Master of Science degree in Systems Management from the Massachusetts Institute of Technology.*



Doug Coley *has been an aerospace engineer in the Space Architecture Department since joining The Aerospace Corporation in 2017. In this role, he has worked to decompose complex problems and perform architecture-level trade studies in many different domains. He has a Bachelor of Science in Engineering Physics from Abilene Christian University and a Ph.D. in Aerospace Engineering from the University of Texas at Arlington.*



William Cirillo *currently serves as a Senior Researcher at NASA Langley Research Center in Hampton, Virginia, where he has worked for the past 30 years in the area of Human Space Flight Systems Analysis. This has included studies of Space Shuttle, International Space Station, and Human Exploration beyond low Earth orbit. In 2005, Mr. Cirillo served at NASA Headquarters as a core member of the Exploration Systems Architecture Study (ESAS) team, where he was responsible for studying the use of Ares I/Orion in meeting future ISS crew and logistics transportation needs. Mr. Cirillo currently leads a team of analysts in assessing at a strategic and tactical level the manifesting of assembly and logistics flights human exploration beyond low Earth orbit.*



Kandyce Goodliff *is an aerospace engineer at NASA Langley Research Center in Hampton, VA, with the Space Mission Analysis Branch (SMAB). Over the last 20 years, her roles as a systems analyst for SMAB have included conceptual design and sizing of human and robotic spacecraft, mission and spacecraft analysis, and campaign analysis for human exploration. She currently supports NASA's Advanced Exploration Systems as a systems analyst and serves as the International Space Exploration Coordination Group (ISECG) International Architectures Working Group (IAWG) lead. She has a Bachelor of Science in Aerospace Engineering from Embry-Riddle Aeronautical University and a Master of Science in Mechanical Engineering from the George Washington University.*