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NEAR-FIELD SEPARATION AND DYNAMICS ANALYSIS OF NASA'S SPACE LAUNCH SYSTEM BLOCK-1 AND BLOCK-1B SECONDARY PAYLOADS

Jared T. Rucker[*], Carole J. Addona[†], Peter J. McDonough[‡],
Benjamin S. Burger[§], Michael M. Sanders[*], Zachary T. Muscha[*],
Rekesh M. Ali[**], William J. Harlin[††], and Drake A. Ranquist[*]

The NASA Space Launch System (SLS) Program Block-1 and Block-1B missions are expected to carry a number of CubeSat secondary payloads (SPL) to space, where they will be ejected from internal SLS structures to begin their own missions. This near-field ejection process must be closely evaluated to ensure that no SPL contacts the SLS structures, as contacts could result in SPL component damage, mission loss, or aberrant SPL trajectories. To this end, multiple SPL ejection events were analyzed for both Block-1 and Block-1B mission configurations using CLVTOPS, a NASA Marshall Space Flight Center (MSFC) developed multibody dynamics, proximity analysis, and visualization toolchain. This paper details the SPL-to-SLS clearance assessment process, with a focus on simulation setup and results as well as SPL design requirement analysis. Relevant CLVTOPS, statistics, and mission backgrounds are covered; important constraints, difficulties, and assumptions are also documented. Furthermore, the importance of SPL housing geometry on near-field vehicle clearance is highlighted, and examples are shown.

INTRODUCTION

The National Aeronautics and Space Administration (NASA) plans to put people back on the moon as well as transport lunar space station components using the newly developed Space Launch System (SLS). With the successful flight of Artemis I and the upcoming flight of Artemis II, the SLS is well on its way to becoming the Earth-to-Moon transit vehicle. Furthermore — on top of the Block-1 configuration used for Artemis I, II, and III flights — the development of the long term

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[*] Aerospace Engineer; EV42 Guidance, Navigation, and Mission Analysis Branch; Amentum Space Exploration Division (ASED)/Amentum; Huntsville, AL, 35806

[†] SLS Liftoff and Separation Dynamics Technical Lead; EV42 Guidance, Navigation, and Mission Analysis Branch; ASED/Amentum; Huntsville, AL 35806

[‡] EV42 ESSCA Lead; EV42 Guidance, Navigation, and Mission Analysis Branch; ASED/Amentum; Huntsville, AL 35806

[§] SLS Flight Mechanics Co-Lead; EV42 Guidance, Navigation, and Mission Analysis Branch; NASA/MSFC; Huntsville, AL 35812

[**] Aerospace Engineer; EV42 Guidance, Navigation, and Mission Analysis Branch; ASED/McLaurin Aerospace; Knoxville, TN 37929

[††] SLS Flight Mechanics Co-Lead; EV42 Guidance, Navigation, and Mission Analysis Branch; ASED/McLaurin Aerospace; Knoxville, TN 37929

Block-1B and Block-2 SLS configurations further solidifies SLS's role in the expansive future of human spaceflight.

Figure 1. Launch of Artemis I. [*]

However, transport of people and habitat structures like Gateway are not the only missions for which the SLS is designed. As each mission makes use of multiple stages with lengthy in-space flight time, the SLS is expected to carry numerous payloads to space, where they will be launched to serve their own missions. These payloads consist of larger co-manifested payloads and a varying number of smaller secondary payloads. Secondary payloads (SPLs), the focus of this paper, are comparatively small missions, typically comprising of small satellites or sensor packages that transmit data back to the SPL operators.

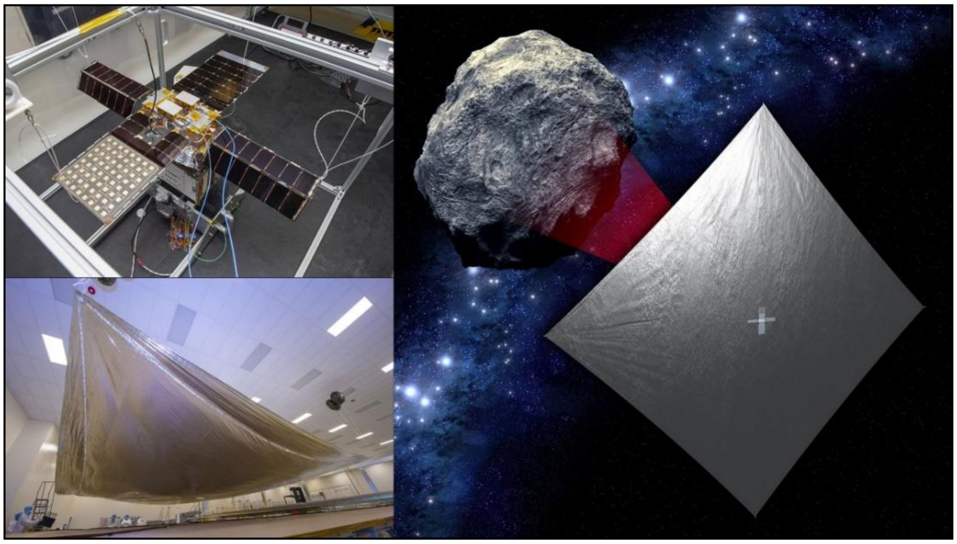

Figure 2. NEA Scout Design, Testing, and Theoretical Operation. [†]

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[*] https://images.nasa.gov/details/NHQ202211160200

[†] https://www.nasa.gov/solar-system/nasa-solar-sail-mission-to-chase-tiny-asteroid-after-artemis-i-launch/

SPLs serve a variety of missions, including technology demonstrations, science exploration, and data gathering. For example, Figure 2 above shows the design and function of NEA Scout, one of the SPLs that flew on Artemis I. NEA Scout was a CubeSat designed to test solar sail technology as well as to accomplish organizational objectives of studying relatively small near-earth asteroids.

To ensure that these SPLs are able to complete their missions, they must first safely and reliably deploy from the parent SLS mission. Successful deployment from the SLS is measured by whether the SPL exits the SLS vicinity without recontacts ("near-field") and remains outside of the designated keep-out zones for any other vehicle the SPL may approach ("far-field"). This analysis focuses on near-field clearance.

The paper begins with an introduction to the CLVTOPS toolchain and relevant post-processing software tools. Then, the SPL ejection event is covered, including an overview of the event as well as implemented models and assumptions necessary to simulate the event. Finally, analysis results are discussed. The discussion contains explanations of useful plots and a method used to help set certain requirements.

TOOLCHAIN BACKGROUND

To measure SPL near-field clearances, the NASA Marshall Space Flight Center Liftoff and Separation Dynamics (LO&Sep) team utilizes the CLVTOPS toolchain to simulate trajectories, measure proximities, process the results, and generate graphics for use in reports.

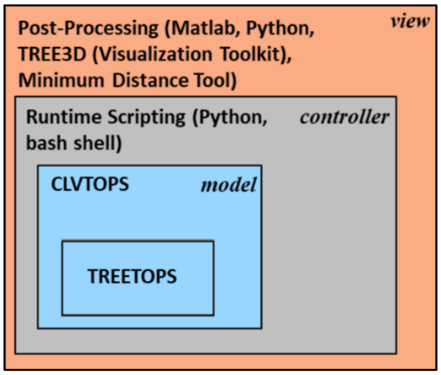

Figure 3. Structure of the CLVTOPS Toolchain. [1]

Figure 3 above shows the composition of the LO&Sep team toolchain. This paper generally refers to the toolchain in its entirety as CLVTOPS, with the exception of specific extension programs such as Tree3D[*] and the MinDist tool.

The CLVTOPS Simulation

CLVTOPS is a wrapper around the NASA-funded TREETOPS flexible multi-body time-domain dynamics and controls simulation software. TREETOPS computes the translations and rotations between connected bodies and elements by automatically creating the equations of motion using Kane's method.[1,2] CLVTOPS provides accommodation for custom FORTRAN modules consisting of system models, forces and moments, plus other computational components, and integrates them into the underlying TREETOPS computational physics engine.[1]

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[*] https://software.nasa.gov/software/MFS-34076-1

Ordered Statistics

While singular nominal simulation runs are useful, CLVTOPS utilizes the Monte Carlo method to explore the effects of random variations of input parameters (dispersions) on simulation outputs to verify requirement compliance. Furthermore, input parameters may not be exactly known, so they can be randomly generated within a reasonably expected or estimated range. Ordered statistics are used to systematically quantify output parameters that result from these varied inputs.[3] This approach seeks to sample a value's distribution to create desired bounds for success probability at a given confidence level, such as the 99.865% highest value with a 90% level of confidence.[4] To ease the analysis and interpretation, these bounds are referred to with σ-level notation. For example, the 99.865% ejection velocity at a 90% confidence level is referred to as the $+3\sigma$ bound and can be interpreted as the largest statistically significant ejection velocity output from the simulation. The bounds are used to filter CLVTOPS outputs into statistically meaningful data, usually to indicate the valid upper and lower extents of a given clearance which can help verify no-recontact requirements. Lower levels such as $\pm1\sigma$ and $\pm2\sigma$ bounds can also be useful metrics for classifying outputs at a lower success probability.

Tree3D

Tree3D[*] is a NASA-developed trajectory visualization tool created to parse and animate CLVTOPS, or general 6-DOF (degrees of freedom), simulation output.[1] The tool utilizes computer-aided design (CAD) models and simulation data to position the models in 3D space through time. The tool can also co-animate clearance plots as well as force vectors acting on the bodies. The full animation as well as individual frames can be recorded for use in presentations and reports. Using Tree3D to animate the trajectories of the SPLs and vehicle is helpful in verifying that the simulation is set up correctly and that any reported contacts are legitimate.

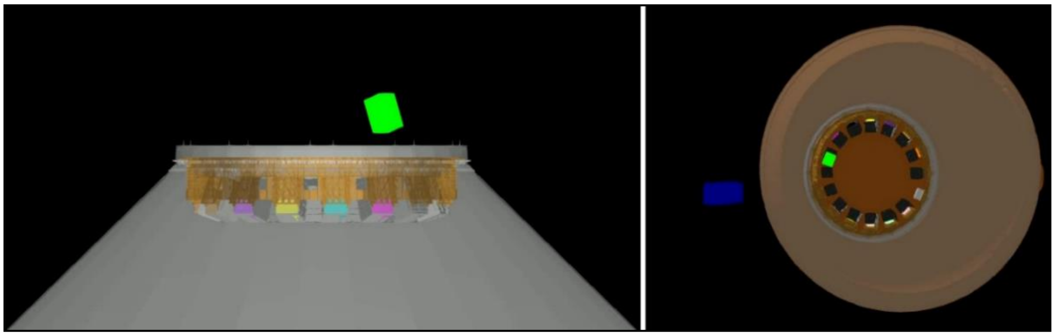

Figure 4. SPL Ejection Modeled in the Tree3D Program.

Figure 4 contains two sample frames from a Tree3D animation of the Block-1B SPL simulation, one showing a side view of an SPL ejection and the other showing a camera attached to a previously ejected SPL tracking the vehicle housing.

MinDist Tool

The MinDist tool, short for Minimum Distance, is a software package wrapped into CLVTOPS that measures the distance between bodies during the simulation.[1] The MinDist tool implements the externally developed Proximity Query Package[†] that computes the proximities between pairs of triangular meshes, which are then filtered into the minimum distances between custom-set pairs.

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[*] https://software.nasa.gov/software/MFS-34076-1

[†] https://gamma.cs.unc.edu/SSV/

These minimum distances, or clearances, are one of the most important parameters with respect to separation dynamics, as they help expose requirement violations, set risk tolerances, and inform vehicle design. SPL mission success is predicated on having positive clearance between concerned bodies at all times after initial separation.

EVENT BACKGROUND AND SIMULATION SETUP

To determine near-field clearances, CLVTOPS must first be set up according to the cases being studied. SPL and dispenser characteristics as well as vehicle housing geometries differ across the Block-1 and Block-1B vehicle configurations. Various assumptions are also made to make the setup simpler, such as neglecting gravitational accelerations and solar pressure that could act on the bodies. Numerical details are sparse in this paper due to limitations on their public release, so some components may only be discussed generically or are outright omitted.

SPL Ejection Event Background

The future Block-1 and Block-1B flights are expected to carry a varying number of SPLs to be ejected at some point during in-space flight. At the time of the analysis, four payloads were manifested for Block-1, and fifteen were manifested for Block-1B. The SPLs will be stored in canisters/dispensers and ejected from internal SLS structures.

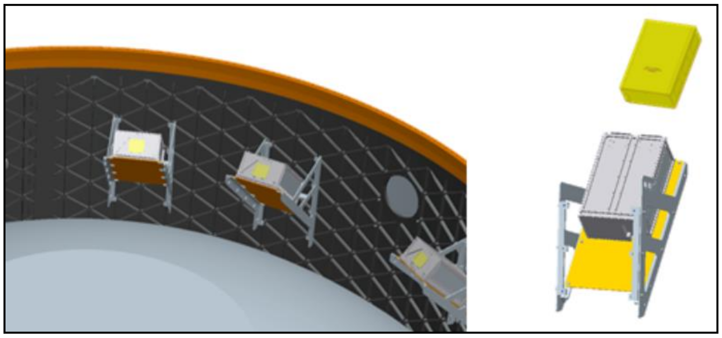

Figure 5. SPL Ejection in the Artemis I Configuration.

For this analysis, SPLs are considered solely to be CubeSats or CubeSat-style payloads, as no specific geometry or SPL design was provided at the time. A CubeSat is a small satellite that fits into a cubic shape of standard incremental dimensions. The basic building block of the incremental dimensioning is the 10cm^3 U, a cube that can be conjoined to form varying structures with standardized dimensions.

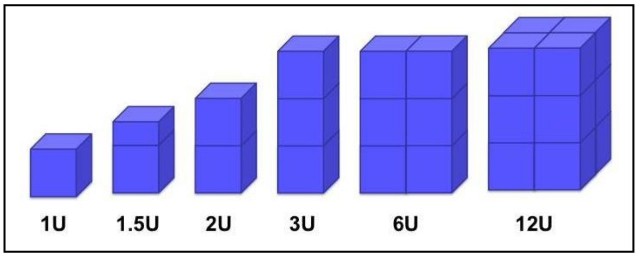

Figure 6. Sample CubeSat Sizes. [*]

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[*] https://science.nasa.gov/solar-system/10-things-cubesats-going-farther/

Figure 6 above shows a variety of standard CubeSat sizes. There are only a few CubeSat sizes considered for the analysis. Previously, Artemis I utilized 6U SPLs; however, Artemis II plans to utilize up to four 12U SPLs, and Block-1B plans to carry up to 27U SPLs. As no 27U mounting hardware models existed at the time of the analysis and 12U SPLs bound smaller CubeSats with regards to near-field clearance, only 12U SPLs are considered. Smaller CubeSats would be ejected faster and would therefore clear the vehicle housing before any recontact concerns manifest, indicating that the 12U SPL bounding the 6U SPL preserves conservatism.

This analysis focuses on the Artemis II mission and an arbitrary Block-1B Artemis mission. A small amount of previous work has been presented on the Artemis I SPL analysis[1], and the analysis presented herein is the original simulation updated to fit the different mission profiles. Models used for both missions are described first, then mission-specific models are introduced.

Mission-Independent Models

Models used across mission profiles are the dispenser and SPL characteristics, such as SPL mass properties and dispenser ejection force profiles. These models are integrated into various CLVTOPS components, such as problem definition mass property files and custom-made FORTRAN modules that interact with and apply the ejection forces.

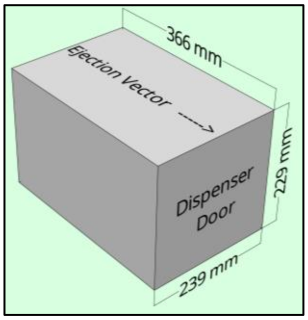

Figure 7. Simplified 12U Canisterized Satellite Dispenser Dimensions.

The dispenser characteristics are taken from the Planetary Systems Corporation[*] Canisterized Satellite Dispenser (CSD) datasheet for 3U, 6U, and 12U CubeSats.[5] The 12U dispenser physical characteristics are shown in Figure 7 above. The datasheet also contains information for determining the SPL ejection velocity based on SPL mass and dispenser configuration.

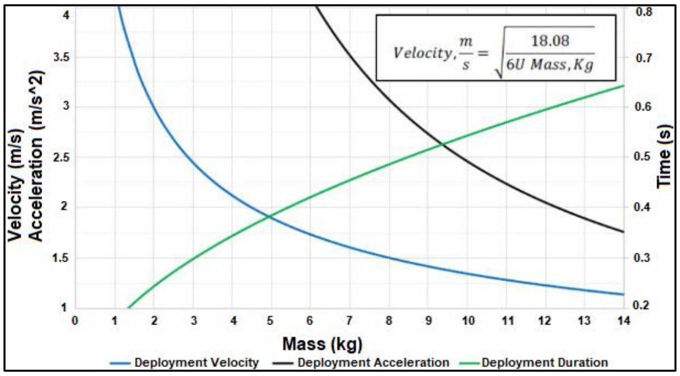

Figure 8. Dispenser Ejection Velocity Curve-fit.[6]

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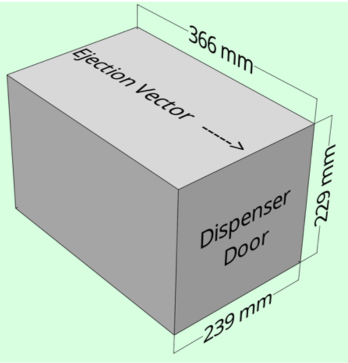
[*] Acquired by Rocket Lab



$$Velocity\left[\frac{m}{s}\right] = \sqrt{\frac{18.08\left[kg\cdot\frac{m^2}{s^2}\right]}{Mass\ [kg]}}$$

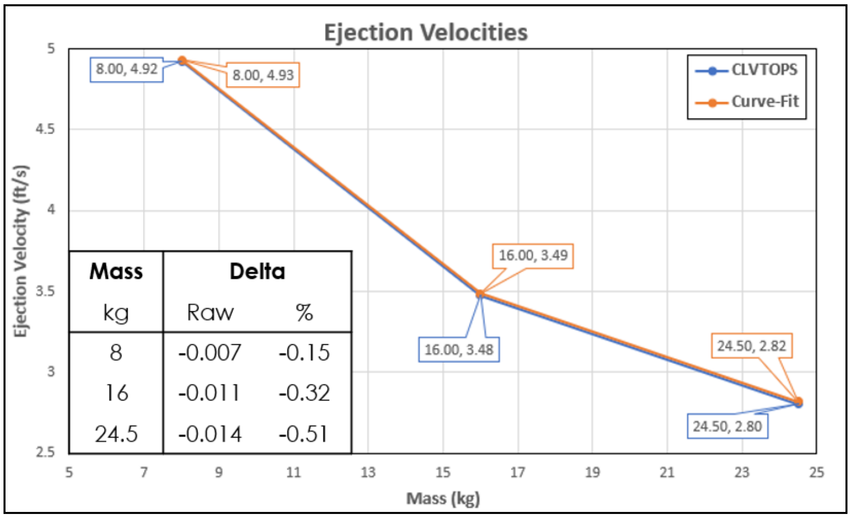
$$Force\ [N] = \frac{1}{2}\left(\frac{Mass\ [kg]}{Distance\ [m]}\right)\left(Velocity^2\left[\frac{m^2}{s^2}\right]\right)$$

$$Force\ [N] = \frac{1}{2}\left(\frac{18.08\left[kg\cdot\frac{m^2}{s^2}\right]}{Distance\ [m]}\right) = \frac{1}{2}\left(\frac{18.08\left[kg\cdot\frac{m^2}{s^2}\right]}{0.366\ [m]}\right)$$

$$Force = 24.7\ [N] \rightarrow 5.553\ [lbf]$$

Figure 9. Calculation of the Dispenser Ejection Force.

Utilizing simplified physics calculations with appropriate assumptions, one can determine the force applied by the dispenser to the SPL and reactively back into the vehicle, which can both then be implemented into CLVTOPS. Figure 8 shows the vendor-provided dispenser ejection velocity curve-fit, and Figure 9 shows the calculation of the ejection force fed into CLVTOPS.



Mass	Delta	
kg	Raw	%
8	-0.007	-0.15
16	-0.011	-0.32
24.5	-0.014	-0.51

Figure 10. V&V Between CLVTOPS and Datasheet Specifications.

Figure 10 shows a verification and validation (V&V) activity performed with the datasheet and CLVTOPS ejection velocities to ensure CLVTOPS was properly modeling the 12U dispensers. Arbitrary SPL masses were tested up to the maximum considered for the analysis. Data was taken the first timestep after full ejection, where unconstrained 6-DOF motion first begins. The data was then compared to what the curve-fit predicted the velocity should be. As seen in Figure 10, CLVTOPS is in very good agreement with the manufacturer provided curve fit.

In addition to ejection forces, ejection moments were also considered. These moments are not intentional dispenser design but rather inescapable effects of an imperfect ejection vector. Any deviation from the intended ejection path will cause non-axial forces between the tip of the dispenser and aft end of the SPL. These non-axial forces create moments on the vehicle and SPL, which are called tipoff moments.

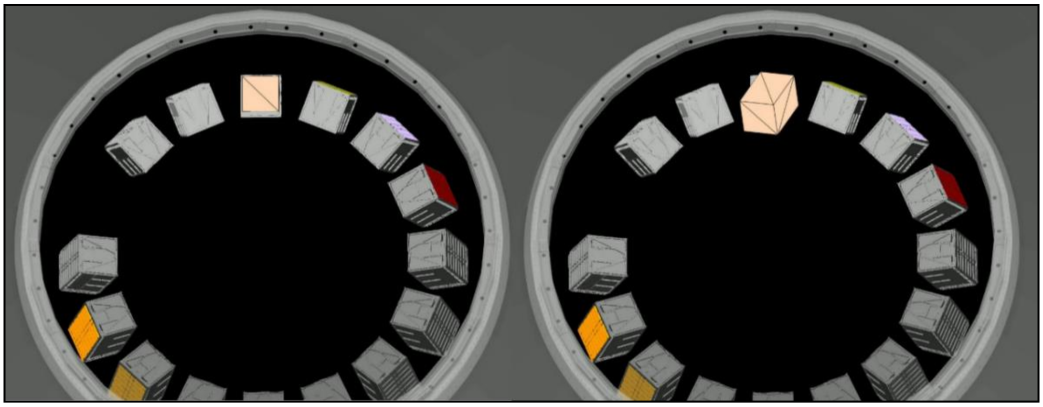


Figure 11. Two Tree3D Frames Highlighting Tipoff Rotation in an SPL, Mid-Ejection (left) and a Few Seconds Later (right).

Due to the mass difference between the vehicle and the SPL, the SPL experiences the full effect of these moments as seen in Figure 11 above. Tipoff moments were included in the simulation using the manufacturer specified limit on dispenser-imparted rotation rate to calculate the torque necessary to induce that rate. Such rotation is imperative to include, as it can reduce clearance by rotating longer sections of the SPL towards the vehicle housing.

The analysis utilizes arbitrary SPLs to generalize setup for any Artemis mission. To accomplish this generalization, a cuboid the size of the 12U dispenser with the mass properties provided in the CSD datasheet was used. Figure 11 shows the cuboid being ejected, and the surface of the SPL shows the triangular mesh that is used in the MinDist tool.

Mission-Specific Models

Models particular to a mission are the vehicle housings and vehicle kinetic states, both of which are highly important for clearance. The kinetic states of the vehicles are controlled information, so only the vehicle housings are detailed here.

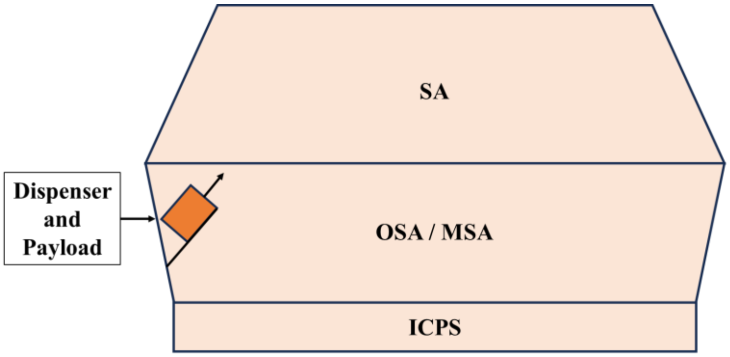


Figure 12. Simplified 2D Drawing of the Block-1 Vehicle Housing.

At the time of the SPL ejection event, the SLS Block-1 vehicle consists of an empty Interim Cryogenic Propulsion Stage (ICPS) beneath the Orion Stage Adapter (OSA), also called the Multipurpose Crew Vehicle (MPCV) Stage Adapter (MSA), which itself sits beneath the Spacecraft Adapter (SA). Dispensers are mounted around the OSA pointed through the opening of the SA. This creates a concave housing, where the structure narrows towards the separation plane opening that the SPL must fly through. The Block-1 configuration is shown in Figure 12 above.

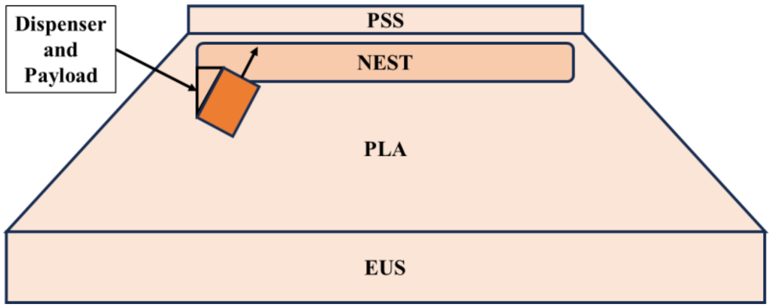


Figure 13. Simplified 2D Drawing of the Block-1B Vehicle Housing.

For the Block-1B SPLs, the vehicle will consist of an Exploration Upper Stage (EUS) beneath a Payload Adapter (PLA) that houses the New Exploration Secondary Transportation (NEST) at the top. Additionally, there is a piece of leftover separation hardware attached to the top of the PLA that the SPL must fly past called the Payload Separation System (PSS). The dispensers are mounted to the NEST ring just below the separation plane. As opposed to the concave Block-1 housing, the Block-1B configuration creates an open housing, with only the hardware surrounding the dispenser posing clearance concerns. The Block-1B configuration can be seen in Figure 13 above.

Major Assumptions

Certain key assumptions have been made for this analysis in order to make the problem palatable to CLVTOPS and keep the workload manageable. These assumptions involve forces with minute effects on SPL trajectory, complex models that would be difficult to integrate, and concerns highlighted by the manufacturer.

Negligible Forces. Due to the relatively close proximity of the SPLs to the vehicles and relatively short timeframe of near-field analysis, all gravitational accelerations acting on the vehicles and SPLs are assumed constant and are therefore not modeled. Furthermore, all SPLs were assumed to be passive for this time duration, meaning that the SPL does not perform any propulsive or control maneuvers. It is also assumed that no other source of force or torque disturbances, such as solar radiation or vehicle venting, act on the vehicle or SPLs. These assumptions simplify the simulation by excluding forces with minute effects on short-term near-field clearance. Fewer forces to program also helps to streamline and hasten the simulation.

Complex Models. All bodies in the simulation are assumed to be rigid. SPLs retain constant mass and inertial properties, meaning that the properties are not updated if the SPL deploys appendages after ejection. The ejection force vector is assumed to act perfectly parallel to the mounting bracket, and no dampening or lateral forces, drag in particular, are imparted to the SPL from the interior dispenser walls, with the exception of generalized tipoff moment and ejection velocity dispersions. These assumptions ease the workload by excluding complex, time-consuming, or externally developed models that may or may not be possible to implement into CLVTOPS.

Manufacturer Concerns. The dispenser manufacturer provided data involving dispenser door settling time, general ejection velocity variability, and temperature effects on ejection velocity. Firstly, the dispenser door has not been modeled and is assumed to be at its full extension. In all cases, the SPLs did not exit the dispenser railings prior to door settling, making this a safe assumption. For another concern, manufacturer data shows that spring forces vary with temperature and eject payloads at varying ejection velocities. Although Monte Carlo dispersions should cover this variability, the dispersions are centered around what is assumed to be the manufacturer reported nominals.

ANALYSIS OF SIMULATION OUTPUTS

With CLVTOPS set up, it is possible to generate meaningful results. Default TREETOPS output records the motion of the vehicles and forces between bodies, and custom CLVTOPS output modules and the other post-processing generate clearance results, animations, and other useful analyses. Each plot is the result of at least 2000 runs for each vehicle as well as for each special study, and post-processing filters these results according to set parameters and ordered statistics.

Trajectory Analysis

Using CLVTOPS output, one can reconstruct the trajectories of the bodies. This is useful for determining if the bodies are behaving as intended and to detect any obvious contacts. For near-field SPL cases, a majority of the possible output parameters are unimportant so long as the SPL clears the vehicle in a reasonable time without recontact.

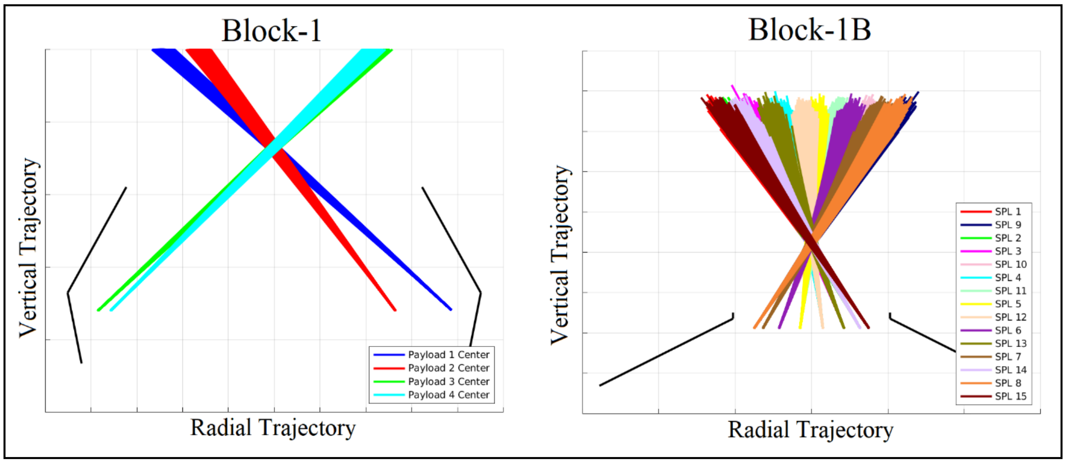


Figure 14. Trajectories for Baseline Block-1 and Block-1B Cases.

Simulation trajectories are shown in Figure 14 above. The figure shows 2000 dispersed centerline trajectories for each SPL for both vehicles, with the outside black bars representing vehicle geometry. By plotting all the runs together, the effects of dispersions can be seen visually. A large spread on any one set of lines can indicate sensitivity to some dispersion, although further correlation analysis is needed to determine the particular sensitivities. Any curvature in the trajectories is due to vehicle attitude rates, as the trajectories are presented in the vehicle-fixed frame with the observer attached to the rotating vehicle while tracking the SPL locations. These cases had fairly low initial attitude rates, which is evidenced by relatively straight SPL trajectories.

Clearance Analysis

Although studying the trajectories is useful, the most significant analyses performed on simulation outputs are the clearance analysis and sensitivity analysis. Clearance is determined using the MinDist Tool along with provided CAD geometries. For separation dynamics, clearance is the main measure by which an event is considered successful, as contact poses many mission risks ranging from generating simple disturbances to damaging hardware to failing missions.

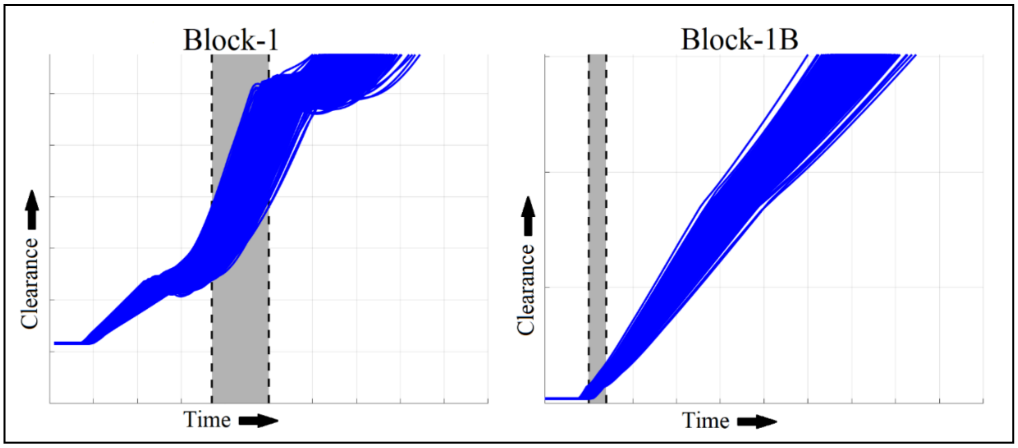


Figure 15. Clearance Results for the Baseline Block-1 and Block-1B Cases.

Figure 15 shows vastly different trajectory clearances prior to the full separation, with post-separation trajectories showing increasingly positive clearance. The gray bar represents the range of separation times, where the SPL fully crosses the top of separation plane, indicating that the pre-separation clearance differences are mostly a result of SPL housing geometry differences. The plot on the left uses the concave Block-1 housing, indicating that the SPL is launched away from the walls but comes in close contact with the upper piece of the housing later. The plot on the right uses the Block-1B open housing with SPLs launched directly at the separation plane, resulting in monotonically increasing clearance albeit with a lower initial clearance.

Sensitivity Studies

Analysis of the nominal is important for understanding the expected dynamics of the case; however, real flights do not always stay within expected parameters. In order to protect for this, additional simulations are run to determine the effects of these extreme cases with a focus on sensitive parameters. These extreme conditions are typically drawn from worst case scenario conditions, or worst case combinations of conditions, in an attempt to create a bounding box that defines the absolute worst conditions, within reason, that an event can undergo. This bounding box helps to determine flight risk under off-nominal scenarios and to determine the need for preventative measures as well as failure protocols.

Correlation studies on the baseline case help reveal the sensitive parameters. For the SPL cases launching axially, there are only a few sensitive variables of concern with respect to near-field clearance: vehicle attitude rates and SPL ejection forces. Vehicle attitude rates impart undesirable velocities to the SPLs, which can cause them to fly into the vehicle housing. Likewise, if the SPL ejection force is too low, then the SPL may not separate completely or may be too slow to separate before the vehicle rotates itself into the SPL.

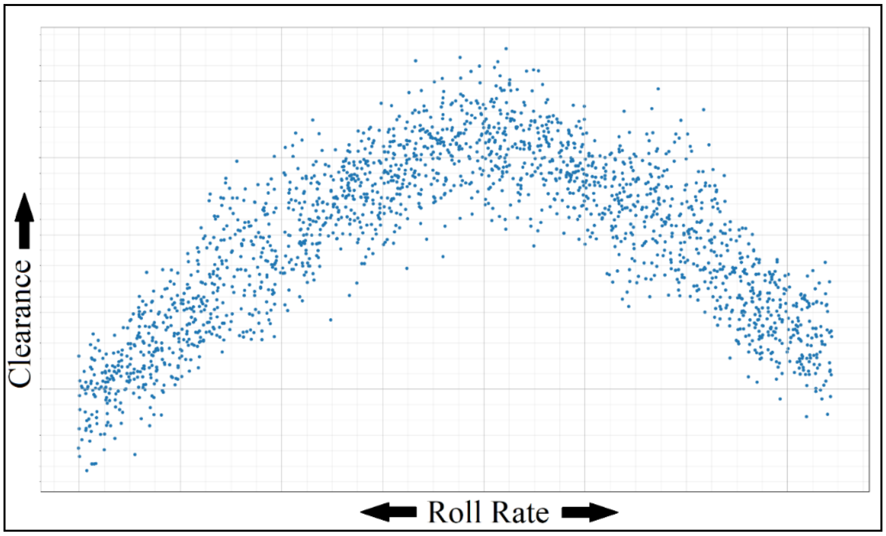


Figure 16. Roll Rate Sensitivity Study for the Block-1 Case.

Roll rate was tested first at varyingly large positive and negative rates. As can be seen in Figure 16, clearance is indeed reduced by higher roll rates. The decrease in clearance as roll rate becomes larger in magnitude is due to roll imparting a proportionally large lateral velocity onto the SPL, which will fling the SPL into the vehicle housing walls before it is able to exit the housing.

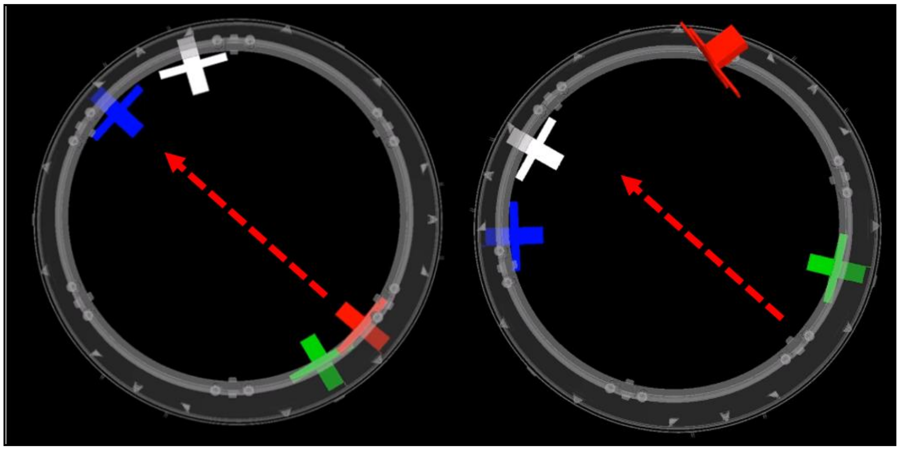


Figure 17. Tree3D Animation Frames Depicting Lateral Motion Imparted to SPL.

Figure 17 above shows the flinging of the SPLs. The figure shows the Block-1 configuration at the time of the red SPL ejection, and the system after 2 seconds have elapsed. The red SPL is ejected under vehicle axial rotation with the red dashed line representing the dispenser ejection force vector. Under non-rotational circumstances, the SPL would fly straight along that line, but due to the rotation-imparted velocity it flies laterally into the walls. It is assumed that roll rate is the most concerning of the standard attitude rates (roll, pitch, and yaw) for SLS secondary payloads as roll rate acts along the main axis of the vehicle and is typically much larger than pitch and yaw. Studies were also performed with generally larger pitch and yaw attitude rates than the baseline, but not to the same extent shown for the roll rate clearance study.

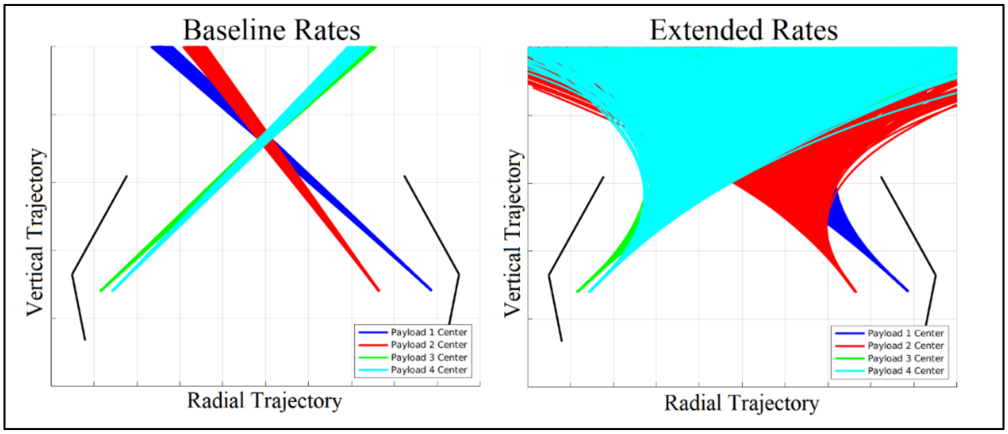


Figure 18. General Attitude Rate Study for the Block-1 Case.

In Figure 18 above, the significant curvature of the trajectories in the right plot is due to the large attitude rates imparting undesired motion onto the SPLs when viewed from the vehicle-fixed frame. From the trajectory plots, it is obvious that clearance is reduced as SPLs curve back towards the vehicle housing. An important note is that the shape of the vehicle housing significantly characterizes the clearance margins, as the concave housing provides ample opportunity for recontact during SPL exodus. To highlight the effect of housing geometry on clearance, a similar study was performed for the more open Block-1B housing.

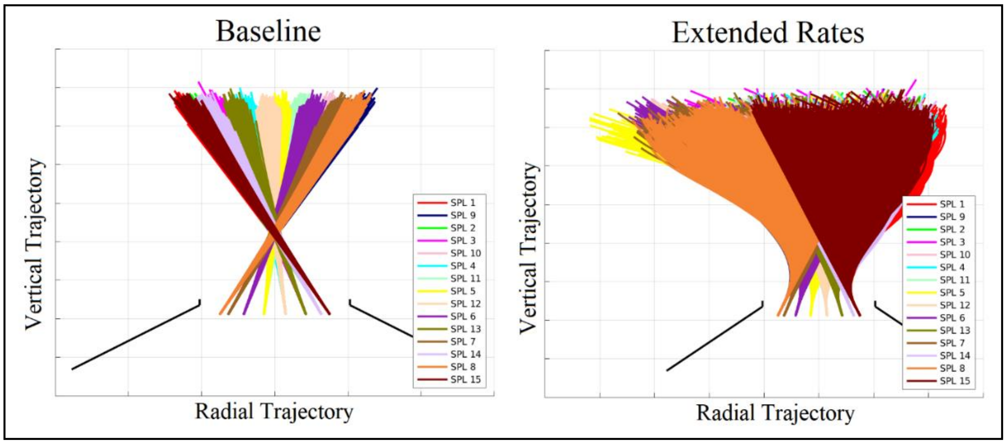


Figure 19. Attitude Rate Sensitivity Study for the Block-1B Case.

As can be seen in Figure 19, the SPLs remain in far less danger of recontacts than in the Block-1 housing, despite the significantly larger attitude rates. There simply is no hardware for the SPL to curve back toward with the open-housing style. The attitude rates affect the SPL trajectories in the same manner, but the vehicle housing itself determines whether or not that is a concern. Less opportunity for recontacts allows for more variation of attitude rate.

There are several configurations for the SPL ejection canisters provided by the manufacturer. A study was performed with the Artemis I simulation to determine the minimum ejection velocity necessary to successfully eject the SPL from the Block-1 housing and place it on its long-term trajectory. The study involved comparing spring configurations: a baseline 4-spring configuration and a reduced velocity 2-spring configuration. This study was not repeated for the Block-1B housing under the assumption that the Block-1 housing is more conservative.

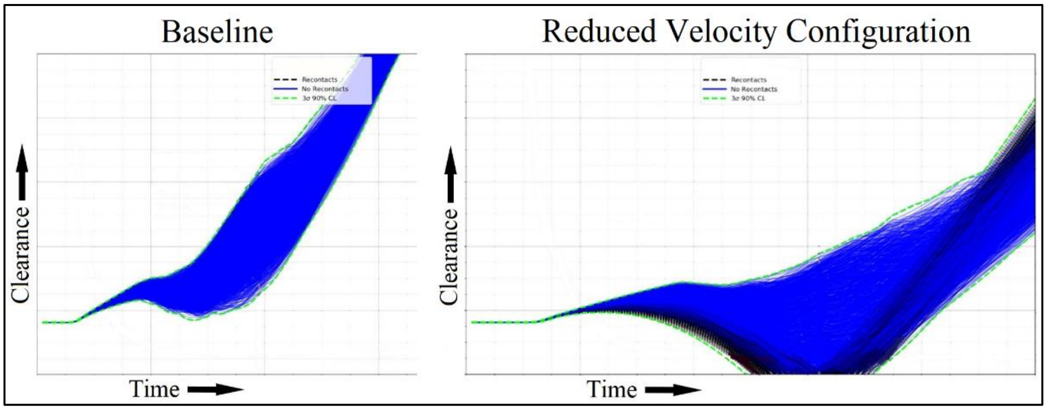


Figure 20. Ejection Velocity Sensitivity Study for the Block-1 Case.

In Figure 20, the plot on the left shows the baseline clearances for all simulated SPLs, and the plot on the right shows the clearances for the reduced ejection velocity. For the same initial conditions, the SPLs with reduced ejection velocities ended up significantly closer to the vehicle housing, even recontacting in some cases. This is largely due to the vehicle rotating into the SPL. As seen when comparing the first sections of the plots, the clearances are similar, albeit with a less rapid increase in clearance in the reduced velocity configuration. After that initial segment, the baseline escapes the housing quickly, but the reduced velocity configuration lags and narrowly avoids the concave housing. To ensure safe and reliable separation, the 4-spring configuration yields the most ejection velocity for an SPL and therefore facilitates good clearance.

Requirement Setting

The purpose of analyzing SPL clearances is not solely to determine recontact risk but also to set limits for canister-constrained deployables, such as solar panels or antennas. These limits are defined as deployment volumes that extend beyond the undeployed SPL with varying dimensions. SPL providers did not have access to detailed information about the geometry of the vehicle and had to rely on these established volumetric limits to determine if their SPLs would successfully exit the vehicle housing without recontacts. Therefore, the analysis included determining the allowable deployment volume for the SPLs. To do this, simple geometries were used in place of the undeployed SPL CAD model. The geometries could then be scaled depending on the results of each simulation to achieve the maximum deployment volume with minimum risk of recontact.

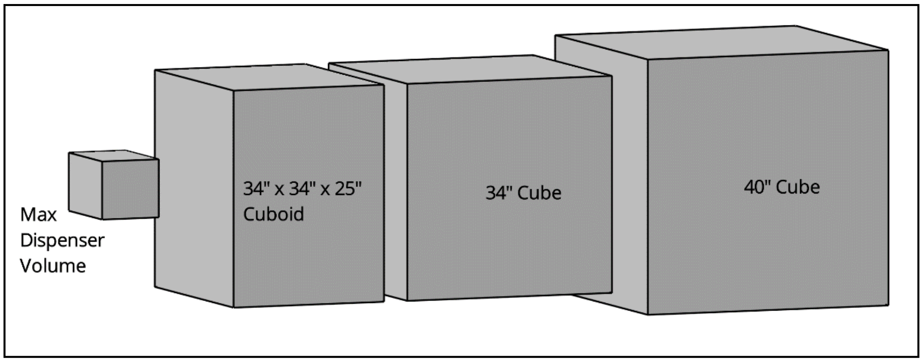


Figure 21. Sample Shapes Used in the Deployment Volume Analysis.

As shown in Figure 21, the shapes utilized in the deployment volume analysis involved cubes and cuboids. The max dispenser volume was used to represent the size of an undeployed 12U, and the other shapes were modeled as extensions beyond that original size. Spheres were considered originally but were not used because cubes are more likely to cover unconventional deployable geometries, especially when considering cube rotation due to tipoff rates.

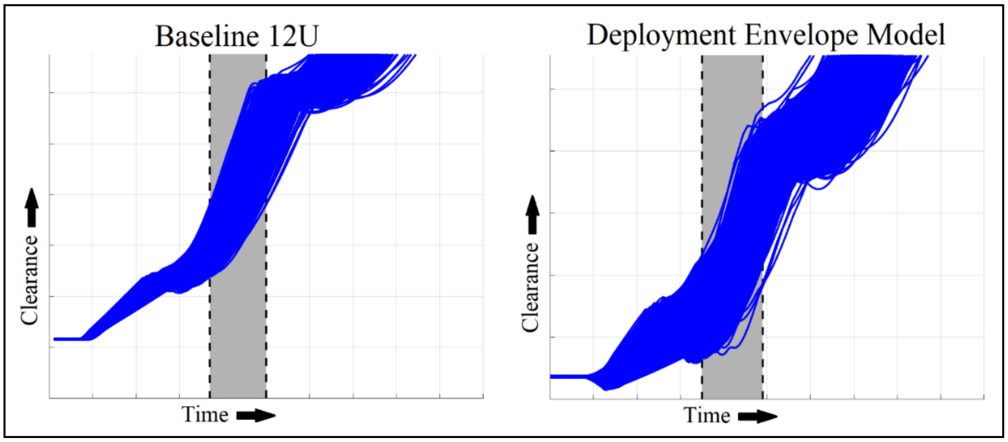


Figure 22. Clearance Results for a 40” Cubic Deployment Volume for the Block-1 Case.

In all cases, the deployment volume decreases clearance. The shape of the volume can be iterated upon until a desirable shape is found, balancing size and risk. The effects of adding a deployment volume on minimum clearance can be seen in Figure 22 above.

In addition to reducing clearance in general, clearance concerns may present themselves in new ways when adding the deployment volume. For example, the deployment volume could be in contact with vehicle housing prior to when the expanded volume is considered valid and active. Furthermore, ignoring the invalid recontacts, the Block-1 SPLs may now be recontacting earlier due to the deployment volume’s proximity to its neighboring dispensers immediately after ejection. Recontacts in this timeframe are difficult to spot using only CLVTOPS and the MinDist tool.

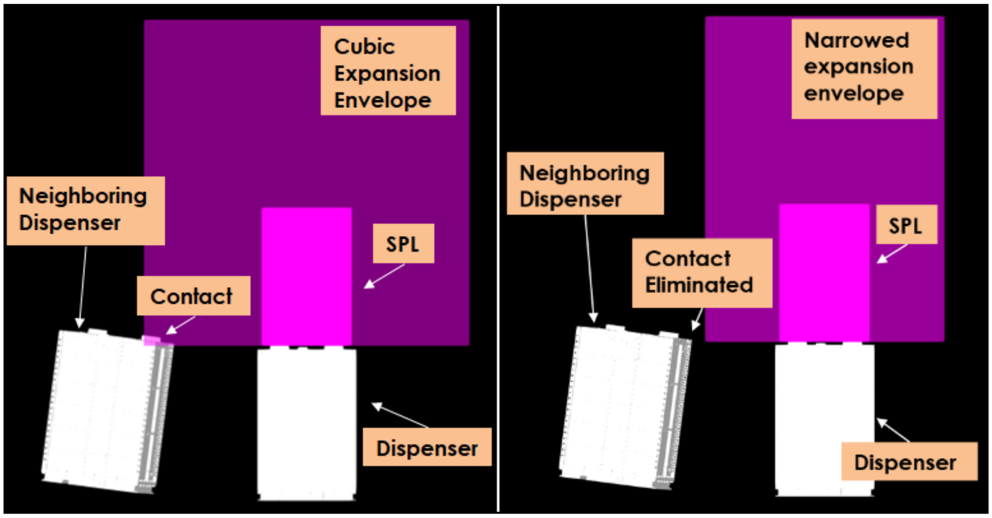


Figure 23. Deployment Volume Narrowing to Eliminate Recontact with the Neighboring Dispenser.

To identify and verify these types of recontacts, Tree3D is easily used to visualize the physical area of concern during the relevant timeframe. Using the information obtained through Tree3D examination, alternate cube configurations were created that involved various shifting and narrowing of the volume. For example, in Figure 23, the deployment volume was narrowed to avoid recontacting the neighboring dispenser immediately after ejection. Iterating upon volume sizes and transformations using the CLVTOPS toolchain allowed for the development of an effective volume requirement for SPL canister-constrained deployables.

CONCLUSION

With rapidly increasing forays into space research, travel, and utilization, small project interest in ridesharing with these new bigger projects has skyrocketed. NASA's Artemis I has carried numerous small projects to space alongside its main payload, and future Artemis missions plan to carry many more secondary payloads in the same way. As more and more vehicles carry SPLs or other separable payloads, reliable simulations are necessary to ensure mission success where full tests are not possible. For Artemis SPLs, the CLVTOPS multiple flexible body time-domain dynamics simulation tool is used. The Liftoff and Separation Dynamics Team analyzes the CLVTOPS outputs using post-processing tools such as Tree3D and the MinDist Tool to generate clearance results, trajectory animations, and report graphics. Using the simulation along with the post-processing tools allows users to influence design by determining risk or validate requirements such as positive clearance through separation.

In the paper, certain aspects of CLVTOPS simulation setup for SPLs riding on Artemis II and future Block-1B Artemis missions were summarized. Particularly, the dispenser ejection forces and moments as well as separate mission specific vehicle housing designs were shown. Furthermore, notable assumptions that likely would not have affected results and the reasoning behind making such assumptions were described. The analysis consisted of processing, animating, and iterating upon CLVTOPS simulations to understand trajectories and clearances as well as to help set requirements. Firstly, the trajectories and the clearances were discussed, showing what CLVTOPS output produces as well as interpreting what the results mean for the SPLs. These initial results were used to identify system sensitivities impacting clearance. The attitude rate sensitivities were iterated upon for both vehicle configurations, identifying that roll rate is the most critical sensitivity for SPLs on the SLS due to the lateral imparted motion and the likelihood of higher magnitude. The other sensitivity of dispenser ejection force was also discussed. Lower dispenser ejection forces were analyzed as these would produce lower ejection velocity. The lower ejection velocities proved to be problematic for the SPLs as the vehicle would have time to rotate itself into the SPL and catch it within the housing. Finally, various elements of requirement setting that this analysis helped with was shown. Particularly, the development of the deployment volume required iterating upon CLVTOPS, the MinDist tool, and Tree3D to determine the maximum volume that dispenser-constrained deployables can utilize whilst minimizing the risk of recontact. Various challenges faced while creating the deployment volume were also discussed.

The analysis did help reveal a key finding that can aid future SLS missions as well as other vehicles that may carry secondary payloads. With regards to SPL clearance, the most important aspect is the vehicle housing. As shown in the Block-1 design, SPLs ejected from deep within a concave housing face a variety of potentially unnecessary challenges whereas, as shown in the Block-1B design, SPLs ejected from near or just below the housing surface face comparatively few challenges with regards to near-field clearance. As per the deployment volume section, volume size is determined by recontact risk. For the concave housing, the high risk of recontact prevents a substantial deployment volume until well after initial ejection. For the open housing, the risk of recontact rapidly decreases, allowing for larger deployment volumes to be employed comparatively sooner. Good vehicle housing design, with respect to near-field clearance, allots SPLs more opportunity to deploy with less recontact risk.

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