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ASSESSMENT AND VERIFICATION OF SLS BLOCK 1-B EXPLORATION UPPER STAGE AND STAGE DISPOSAL PERFORMANCE

Sean Patrick,* T. Emerson Oliver†, Evan J. Anzalone‡

Delta-v allocation to correct for insertion errors caused by state uncertainty is one of the key performance requirements imposed on the SLS Navigation System. Additionally, SLS mission requirements include the need for the Exploration Upper Stage (EUS) to be disposed of successfully. To assess these requirements, the SLS navigation team has developed and implemented a series of analysis methods. Here the authors detail the Delta-Delta-V approach to assessing delta-v allocation as well as the EUS disposal optimization approach.

INTRODUCTION

One of the SLS Navigation System's key performance requirements is a constraint on the payload system's delta-v allocation to correct for insertion errors due to vehicle state uncertainty at payload separation. The SLS navigation team has developed a Delta-Delta-V analysis approach to assess the effect on trajectory correction maneuver (TCM) design needed to correct for navigation errors. This approach differs from traditional covariance analysis based methods and makes no assumptions with regard to the propagation of the state dynamics. This allows for consideration of non-linearity in the propagation of state uncertainties[1].

This paper will discuss the application of the Delta-Delta-V analysis approach for performance evaluation as well as trajectory re-optimization so as to demonstrate the system's capability in meeting performance constraints. Additionally, further discussion of the implementation of assessing disposal analysis will be provided.

For SLS mission performance, a model based design approach was implemented to develop and refine requirements[2]. A series of analysis methods are necessary to sufficiently assess mission performance and develop requirements as the model based design matures. For the SLS navigation system in particular, this manifests in the form of insertion error on the Orion crew vehicle due to state uncertainty. These state errors have a direct impact on mission design post insertion. To correct for this, a TCM is designed and with a requirement not to exceed a certain delta-V allocation. For mission design, a constraint was placed on the TCM such that it will not exceed a specified

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* Aerospace Engineer, EV42 Guidance Navigation and Mission Analysis Branch, ESSCA/Jacobs Engineering, Huntsville, AL 35812.
† SLS Navigation Lead, EV42 Guidance Navigation and Mission Analysis Branch, ESSCA/Dynamic Concepts Inc, Huntsville, AL 35812.
‡ PhD, Aerospace Engineer, EV42 Guidance Navigation and Mission Analysis Branch, NASA/MSFC, Huntsville, AL 35812

size. An analysis approach is needed to assess hardware and sensor models as well as to validate and improve guidance targeting inputs to ensure mission success.

The current DDV analysis approach was employed by the SLS Navigation team in EM-1 mission analysis. The EM-1 mission design assumes a Near Rectilinear Orbit (NRO) trajectory and, following separation from the ICPS upper stage, includes three burns[3]. A TCM to correct for state errors following separation and two more burns to insert the craft into the DRO. For the EM-1 mission, a requirement limiting the size of the TCM was developed based on previous analysis using the Fixed-Time-of-Arrival Orbit Corrections method. The DDV Analysis was employed to verify compliance with said requirement as mission design assumptions had changed since the requirement was developed. Results of said analysis are presented later in the paper.

In addition to delta-v allocation constraints on SLS navigation performance, SLS mission requirements dictate successful upper stage disposal. Due to engine and propellant constraints, the SLS Exploration Upper Stage (EUS) must dispose into heliocentric space by means of a lunar fly-by maneuver[4]. As with payload delta-v allocation, upper stage disposal maneuvers must place the EUS on a trajectory that maximizes the probability of achieving a heliocentric orbit post-Lunar fly-by considering all sources of vehicle state uncertainty prior to the maneuver. To ensure disposal, the SLS navigation team has developed an analysis approach to derive optimal disposal guidance targets. This approach maximizes the state error covariance prior to the maneuver to develop and re-optimize a nominal disposal maneuver (DM) target that, if achieved, would maximize the potential for successful upper stage disposal.

Disposal Optimization and Assessment analysis tools were employed for EM-1 and are being applied to EM-2 for SLS Block-1B navigation design. The EM-1 mission assumes the ICPS will perform a trajectory correction maneuver following separation from Orion. For analysis purposes, a series of suggested disposal targets were developed by the SLS navigation team to assist in development of ICPS disposal analysis. Along with Disposal targeting optimization, the SLS navigation team found the need for a tool to assess the probability of successful disposal based off the results of Monte Carlo Analysis. To this end, a third tool was developed to propagate and determine the chance of disposal based on a series of dispersed states.

DELTA-DELTA-V ANALYSIS

The delta-delta-V (DDV) analysis approach re-optimizes perturbed SLS mission trajectories by varying key mission states in accordance with an assumed state error. The state error is developed from detailed vehicle 6-DOF Monte Carlo analysis or generated using covariance analysis. These perturbed trajectories are compared to a nominal trajectory to determine necessary TCM design. To implement this analysis approach, a tool set was developed which combines the functionality of a 3-DOF trajectory optimization tool, Copernicus, and a detailed 6-DOF vehicle simulation tool, Marshall Aerospace Vehicle Representation in C (MAVERIC)[5, 6].

Background

Initially, the SLS navigation team used a method for assessing TCM magnitude derived from Battin's Fixed-Time-of-Arrival Orbit Corrections method[7]. Battin's approach is designed to find the delta-V associated with correcting a position and velocity at a given time for a known offset in position and velocity. Note that this method assumes no deviation in time (hence, fixed-time-of-arrival). The delta-V required to correct for the known offset can then be found using the gradient of the velocity vector with respect to the position (C^*). This is demonstrated below in Equation (1)

$$\Delta \boldsymbol{v}(\mathrm{t}) = \mathbf{C}^{*}\delta \boldsymbol{r}_{-} - \delta \boldsymbol{v}_{-} \tag{1}$$

Here, the – subscript represents the time prior to the application of the delta-V correction. Additionally, the delta-V found is valid for a single TCM. This method is similar to the Figure-of-Merit (FOM) method that is employed by the Jet Propulsion Laboratory in assessing mission requirements[8].

The Fixed-Time-of-Arrival method has two limitations that impact SLS Navigation analysis. First, the method assumes a single fixed TCM. Secondly, this approach assumes a linear problem, or requires linearization of the TCM optimization problem. Early applications of the Fixed-Time-of-Arrival method produced much larger TCM magnitudes than expected due to sub optimal placements of TCM maneuvers.

To address these limitations, the delta-delta-V approach was developed. This approach applies dispersed states from a Monte Carlo analysis and applies these dispersions to a nominal mission trajectory. The trajectory is re-optimized for these state dispersions and the newly developed delta-V maneuvers in the trajectory are compared to the nominal mission trajectory so as to determine the change in delta-V (hence Delta-Delta-V) that can be attributed to navigation state uncertainty. This approach looks at the total mission delta-V of all maneuvers allowing for analysis of state impacts across multiple maneuvers. In addition to the approach of using dispersed states developed via Monte Carlo analysis, a method of seeding new dispersions based of a state covariance matrix was developed.

Algorithm Overview

In addition to verifying mission requirement compliance, the DDV analysis has found use with the SLS navigation team in assessing maximum allowable navigation state uncertainties as a method of assessing error sensitivities as well as refining requirements based on performance. As part of this, a method to generate and expand state errors based on an error covariance was developed. This method starts with the final position and velocity states from the statistical analysis at MPCV separation and defined in a Radial-Tangential-Normal Inertial True-of-Date coordinate frame. The covariance of the vehicle state, providing insight into the dispersions from the Monte Carlo analysis, is given by the Equation (2).

$$\mathrm{d}\mathbf{X}_{Sep.} = COV\left(\begin{bmatrix} t_1 & r_{R,1} & r_{T,1} & r_{N,1} & v_{R,1} & v_{T,1} & v_{T,1} \\ t_2 & r_{R,2} & r_{T,2} & r_{N,2} & v_{R,2} & v_{T,2} & v_{T,2} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ t_n & r_{R,n} & r_{T,n} & r_{N,n} & v_{R,n} & v_{T,n} & v_{T,n} \end{bmatrix}_{MPCV\ Separation}\right) \tag{2}$$

The vehicle covariance at the separation point can then be re-sampled in order to assess overall requirements design. This is enabled by scaling the error states and re-assessing DDV performance. In order to maintain the interrelationships between the error terms which are coupled due to inertial navigation performance, any navigation filter coupling, and error dynamics, an eigenvector approach is utilized to maintain this information when scaling errors terms. From the covariance matrix, d**X**, the eigenvalues and eigenvectors can be calculated to determine the unique base vectors and values that define these statistics. The eigenvectors and eigenvalues of the covariance matrix are solved from Equation (3).

$$(\mathrm{d}\mathbf{X}_{Sep.} - \lambda_i \mathbf{I}) = \boldsymbol{v}_i \tag{3}$$

These eigenvectors and eigenvectors are then scaled by *s* to form a matrix of scaling terms that can be sampled and applied to each state component. This scaling term allows for the newly generated error terms to be individually scaled based on sensitivities. The entire scaling term is then multiplied with a normally distributed random sampling to generate N cases of a seven state position, velocity, and time dispersions that are applied to a nominal state as defined in Equation (4).

$$\begin{bmatrix} t_i \\ \boldsymbol{r}_i \\ \boldsymbol{v}_i \end{bmatrix}_{i=1\ldots N} = \begin{bmatrix} t_{nom} \\ \boldsymbol{r}_{nom} \\ \boldsymbol{v}_{nom} \end{bmatrix} + s * diag([\sqrt{\lambda_1} \quad \ldots \quad \sqrt{\lambda_7}]) \begin{bmatrix} \boldsymbol{v}_1 \\ \vdots \\ \boldsymbol{v}_7 \end{bmatrix} [NORMAL(0,1)_1 \quad \ldots \quad NORMAL(0,1)_7]_{i=1\ldots N} \tag{4}$$

Using either direct Monte Carlo states or the covariance reseeding method, the dispersed states are injected into a nominal trajectory and re-optimized. The optimization is designed to closely mirror assumed inflight targeting logic of the Orion vehicle to better assess the capability of correcting state errors. This assumption matches planned operations of the payload and additional accuracy of the Orion navigation, assuming that the vehicle would re-optimize its state for the entire mission prior to performing any Trajectory Correction Maneuver. Following re-optimization, post processing routines are employed to analyze the resulting trajectories. These two analysis approach allow for both assessment of the vehicle to its requirements as well as scaling the error statistics in order to determine the max allowable error at separation that can stay within the prescribed DV budget to aid in requirements development for the launch vehicle, both ascent and upper stage.

Implementation

The Delta-Delta-V analysis approach was implemented for EM-1 analysis using MATLAB. A script acts as a wrapper to automate the generation and optimization of 3-DOF trajectories using the Copernicus optimization tool. A series of MATLAB functions included with Copernicus were implemented in the tool. These functions act as an interface between the script and Copernicus allowing for manipulation of the Copernicus input trajectories and allowing for the script to initiate Copernicus via command line operation.

This script allowed for the automation of much of the analysis process. The tool implements routines to read in dispersed states, perform covariance reseeding, and statistical post processing. Dispersed Monte Carlo states produced by the MAVERIC 6-DOF vehicle simulation tool were used to initialize the analysis. These states were used to produce the state covariance matrix used in the Covariance reseeding approach.

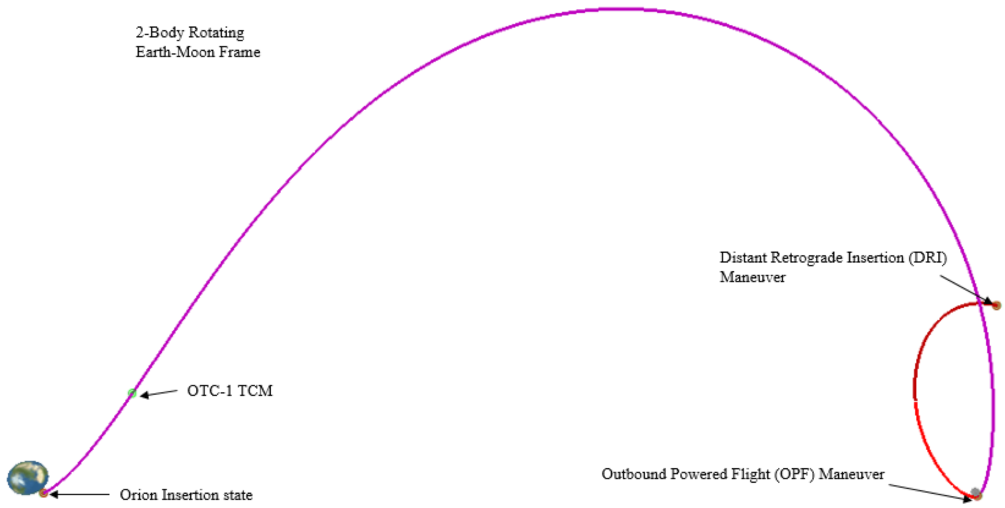

Figure 1. Delta-Delta-V analysis trajectory. Trajectory shown is in a 2-Body Earth-Moon Frame.

Following separation from the ICPS, the Orion spacecraft will perform three maneuvers to place it into a Distant Retrograde Orbit (DRO) around the moon: A single TCM to correct for state errors, a second burn to place the Orion into a lunar flyby trajectory, and a final burn to insert into the DRO. For the analysis, a generic Copernicus trajectory based on the EM-1 mission was designed. This trajectory covers the Orion mission profile from post separation to DRO insertion. The trajectory is designed to emulate Orion guidance retargeting by fixing the assumed insertion state to the nominal mission insertion target as well as fixing the DRI insertion state. Copernicus' optimization routine was set to allow for the three burns to retarget. The TCM is fixed in time relative to the earlier Trans-lunar Injection burn performed by the ICPS. The second and third burns are allowed to vary in start time.

DISPOSAL OPTIMIZATION AND ASSESSMENT ANALYSIS

In addition to placing the payload on a trans-lunar trajectory, the upper must properly be disposed of to meet NASA-STD-8791-14[9]. This inter-agency agreement defines constraints for what to do with spent stages and satellites at their end of life. NASA-STD-8719-14 was developed to address and limit the amount of orbital debris in the Earth-Moon neighborhood to reduce the risks of impacts to future missions and help to reduce the amount of orbital debris. Additionally, this document has been levied to require satellite missions in LEO to have end-of-life plans and de-orbit capabilities for higher altitudes where the orbits are naturally stable with lengthy natural decay periods (100s of years). Several options are laid out, including: controlled breakup, planetary impact (Earth or Lunar surface), and insertion into heliocentric space. Each of these options carries specific criteria for measuring success, constraints for implementation, and unique challenges.

For the SLS missions, the core stage is disposed of through re-entry and eventual splashdown in the Atlantic Ocean. A large amount of Monte Carlo analysis is performed prior to flight to ensure no impact to populated areas with a high degree of confidence. While traditionally Lunar-bound missions have allowed for Lunar impact, this still requires high confidence of avoiding historic sites and active research areas (for example mirrors placed on the Lunar surface by Apollo astronauts). For these purposes, a Lunar impact was shown to be highly undesirable. A direct burn into heliocentric orbit was not considered due to the existing design of the EM-1 trajectory but is being considered baseline for EM-2. Requirements were levied on the upper stage for it to perform a heliocentric burn to enable Lunar Fly-by. The ability to meet this mission is heavily dependent on the GNC system of the vehicle and on the Earth-Moon geometry. This is primarily due to the limited operational lifetime of the upper stage and lacking capability for orbital trajectory maneuvers. As such, the stage must perform a burn placing it on a flyby trajectory for several days of coast after the maneuver. At the Lunar interface, the vehicle must then fly through a pre-defined altitude window in order to gain enough velocity to enter into a heliocentric trajectory[10].

For EUS disposal analysis, a set of two tools was developed. The first considers only the nominal pre-disposal maneuver state, vehicle constraints, and an a priori estimate of the state error covariance. In the analysis, the optimal nominal disposal target is determined. This is performed by re-formulating the trajectory optimization to consider constraints on the eigenvectors of the error ellipse applied to the nominal trajectory. A bisection search methodology is implemented in the tool to refine these dispersions resulting in the maximum dispersion feasible for successful disposal via lunar fly-by. Success is defined based on the probability that the vehicle will not impact the lunar surface and will achieve a characteristic energy (C3) relative to the Earth such that it is no longer in the Earth-Moon system. The second tool propagates post-disposal maneuver states to determine the success of disposal for provided trajectory achieved states. This is performed using the optimized nominal target within the 6-DOF vehicle simulation.

Background

The Disposal Optimization analysis was initially devised for use in EM-1 6-DOF mission analysis. As part of mission design, the EM-1 mission trajectory included a nominal RCS maneuver performed by the ICPS to place the stage into a lunar flyby which would result in heliocentric disposal. This work was performed to provide insight into the upper stage performance and provide a notional disposal trajectory. As part of the 6-DOF analysis, navigation state errors at the end of the disposal burn need to be assessed. To do that, the Disposal Optimization and Assessment algorithms were developed and implemented.

Algorithm Overview

The goal of the Disposal Optimization algorithm is to assess navigation state errors and develop a mission disposal target that will allow for the successful upper stage disposal without requiring guidance retargeting in flight. To do this, the SLS navigation team developed a method to impose an error ellipsoid corresponding to navigation state errors onto a trajectory for re-optimization. These algorithms operate similarly to the DDV analysis, using results from a Monte Carlo as a starting point. As opposed to capturing the state dispersions at the time of payload separation, this analysis starts at the beginning of the disposal maneuver. At this point in the mission, the vehicle has continued on its translunar trajectory. State dispersions as this point have continued to expand past errors at separation due to the propagation of dispersed states at the end of the disposal burn. Similarly the navigation errors have continued to grow due to continued time operating at high altitudes, via accumulation of state integration and sensor errors from inertial navigation. The statistics of the state at the disposal burn are captured in Equation (5). These same individual states are also captured after the disposal burn with final targets and used for assessment of lunar flyby conditions with propagation using Copernicus.

$$\mathrm{d}\mathbf{X}_{Disp.} = COV\left(\begin{bmatrix} t_1 & r_{R,1} & r_{T,1} & r_{N,1} & v_{R,1} & v_{T,1} & v_{T,1} \\ t_2 & r_{R,2} & r_{T,2} & r_{N,2} & v_{R,2} & v_{T,2} & v_{T,2} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ t_n & r_{R,n} & r_{T,n} & r_{N,n} & v_{R,n} & v_{T,n} & v_{T,n} \end{bmatrix}_{Disposal\ Burn\ Start}\right) \quad (5)$$

The covariance provides information about the correlations and coupling between error terms at this point in the mission among the individual simulations. In order to dispose properly, a set of targets needs to be developed that robustly meet lunar flyby conditions. In the previous problem addressed in this paper, the assumption was made that the vehicle can re-optimize its orbital targets in flight to account for any state dispersions. This is due to having a more accurate navigation solution and re-targeting capability. The upper stage, though, must fly with a fixed target, which can typically only change as a function of time through pre-programming. This can be improved through the use of Lambert Targeting as part of the guidance routines, but mean state errors must be considered when developing and analyzing disposal targets. As such, a single target orbit needs to be defined that works across the state dispersions. One approach is to brute force the optimization and optimize target variables with a large number of dispersed cases being tested against for performance and fitness. As opposed to this, the covariance can be used to inform the shape of the dispersions at the start of the burn condition to perform a more informed optimization. This information comes from the eigenvector and eigenvalue pairs, which define the unique vectors within the error space. As such, a series of unique dispersed states can be formed as in Equation (6).

$$\begin{bmatrix} t_i \\ \boldsymbol{r}_i \\ \boldsymbol{v}_i \end{bmatrix} = \begin{bmatrix} t_{nom} \\ \boldsymbol{r}_{nom} \\ \boldsymbol{v}_{nom} \end{bmatrix} + s * \sqrt{\lambda_i} * \boldsymbol{v}_i \quad (6)$$

Along with the nominal dispersed state, these 7 state vectors of time, position, and velocity are then used to determine a single set of targets. This optimization determines a set of targets such that all the trajectories, when propagated, pass within a pre-determined altitude window relative to the Lunar surface to ensure an adequate flyby to gain enough C3 to ensure the stages escapes into heliocentric space. Upon generation of an optimal target, the 6DOF analysis is re-run with the vehicle performing a closed-loop disposal burn. The dispersed states at the end of the disposal burn are captured and propagated forward ten days post Perilune to assess achieved lunar flyby and C3 statistics.

Implementation

In order to perform this analysis, a 3DOF baseline trajectory deck in Copernicus was used that captures the nominal upper stage mission timeline. This includes ascent and in-space maneuvers and forward propagation to the end of mission. The deck served as the baseline scenario and was expanded to include the dispersed trajectories as outlined above and additional events such as the disposal burn and lunar flyby.

An analysis script was developed for Disposal Optimization similarly to the tool developed for the DDV Analysis. As with the DDV analysis tool, the Disposal optimization script acts as a wrapper for the Copernicus optimization to automate the analysis process between Monte Carlo results and target optimization. This tool implements a bisection search algorithm to automatically refine the sizing of the applied state dispersions using the eigenvalue and eigenvector method described above. To do this, an iterative search algorithm was applied. In this approach, an initial 1-D search routine scales the applied state dispersions to find bounding cases in which some or all of the dispersed trajectories fail to dispose. Disposal failure is defined for this search as any trajectory with a C3 value < 0 km^2/s^2. These bounding cases are determined as the largest set of dispersions in which all trajectories dispose as well as the first dispersion set in which one or more trajectories fail to dispose. With the bounding cases found, a second search routine applies the bisection search algorithm to refine the size of the state dispersions between the bounding cases.

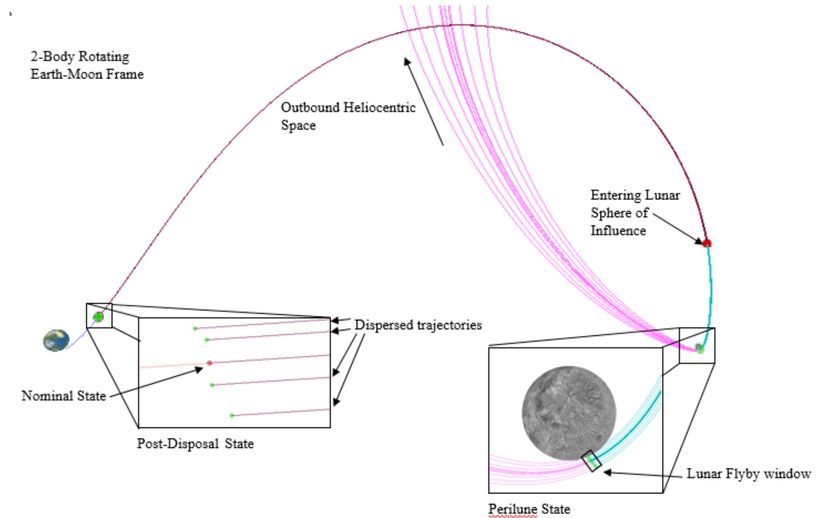

Figure 2. Overview of Disposal Optimization trajectory. Trajectory is in a 2-Body Rotating Earth-Moon frame. The full trajectory represents the Upper Stage trajectory post separation from Orion through Heliocentric Disposal

The bisection search applies simple logic to adjust the size of the dispersions dynamically finding the median dispersions within the range of the boundary cases and re-optimize the dispersed trajectories based on an internal tolerance limit. For the analysis, individual Copernicus trajectories are developed for each mission as described above. These trajectories consist of a series of "child" trajectories that begin with dispersed states off of the nominal mission trajectory. These dispersed states represent the bounds of the error ellipsoid. The Copernicus trajectory was designed such that the dispersed trajectories begin at the post-Disposal state of the ICPS, i.e. immediately following completion of the disposal maneuver. By dispersing each the set of dispersed trajectories and the nominal are propagated to ten days past perilune. The lunar flyby state of each trajectory is constrained to have a minimum flyby altitude of 15 km above the lunar surface to prevent lunar impact.

To assess disposal success of 6DOF analysis, a disposal assessment tool was developed. Disposal assessment tool was developed much like the previous tools using a MATLAB wrapper script to automate Copernicus analysis. The tool inserts a given end of mission state into a generic Copernicus trajectory which is propagated without optimization. Following propagation, a series of post processing routines are performed to determine lunar closest approach and Characteristic energy (C3) values ten days post Perilune. The probability of successful disposal for the set of all EOM states is determined based on a simple set of logic:

Table 1. Success and Failure Criteria for Disposal Assessment

C3 at ten days post Perilune > 0 and Alt > 0	Success
Alt < 0	Impact
C3 < 0	Failure to enter Heliocentric Disposal Path

DELTA-DELTA-V AND DISPOSAL ANALYSIS EXAMPLE

The DDV analysis tool as well as the Disposal Optimization analysis tool have been implemented by the SLS navigation team for assessment of predicted mission performance based on the navigation model based design approach implemented for SLS mission design as well as for requirements verification. Here, example cases were prepared to demonstrate applications of the developed analysis tools. For the DDV analysis, a set of five 200 case analysis sets were produced using covariance reseeding as described above. Each set was increasingly scaled with increasing values for *s*. The reseeding was initialized with 2000 Monte Carlo states derived from MAVERIC EM-1 mission analysis. Each of the five sample cases were processed using the DDV Analysis tool. The dispersed states were inserted into the DDV analysis tool post-Orion separation and retargeted.

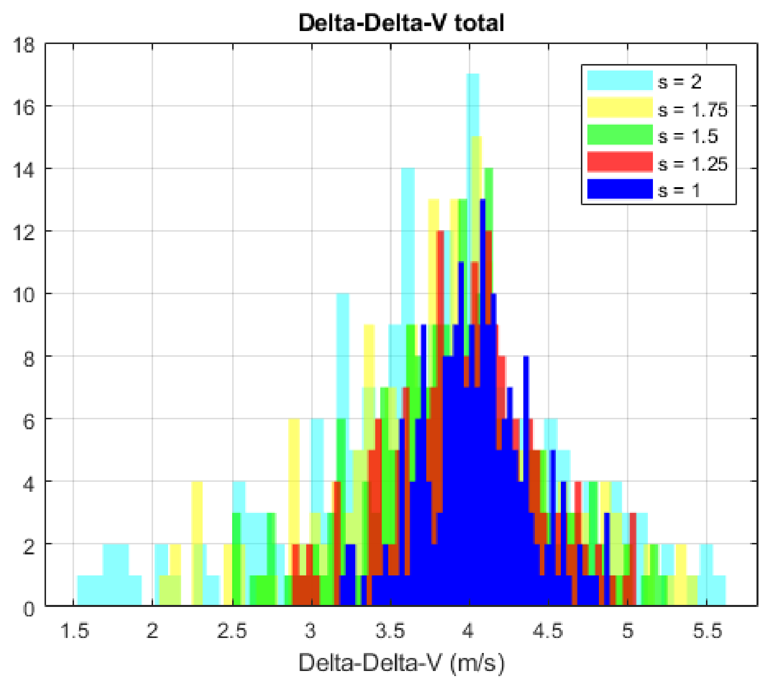

Figure 3. Delta-Delta-V distribution. The magnitude of the scale factor, s, used for dispersed state reseeding impacts the size of the Delta-Delta-V distribution as can be seen above

As part of developing the DDV analysis, the SLS navigation team performed a comparison between two targeting routines. The first was to optimize only the OTC-1 TCM maneuver. Due to the nonlinearity of the problem, as well as the constraints imposed upon the trajectory to emulate

Orion targeting logic, the single burn re-optimization approach was suboptimal compared to retargeting all burns across the full trajectory. This produced much larger delta-delta-V magnitudes than excepted.

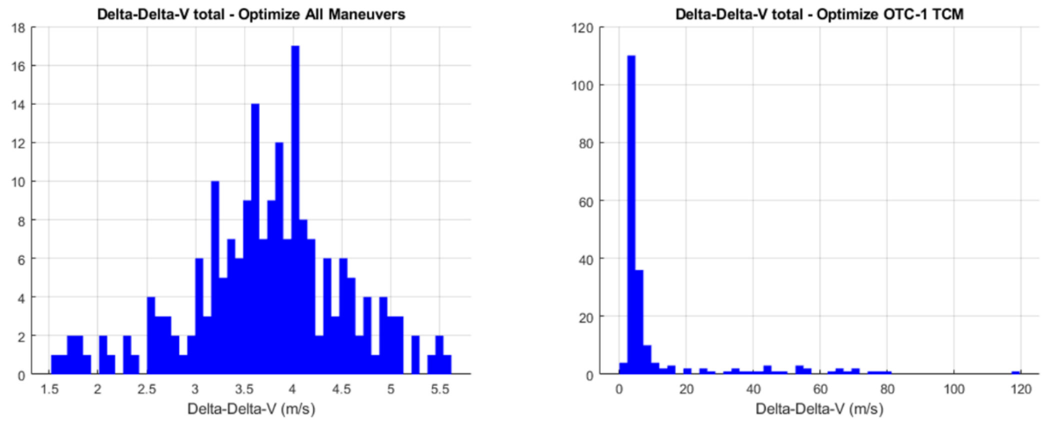

Figure 4. Comparison of total Delta-Delta-V magnitudes between retargeting approaches. By targeting all maneuvers, the analysis is better able to emulate expected Orion targeting logic and increase targeting accuracy

Additionally, the Disposal optimization analysis was performed. The analysis was performed using nominal EM-1 mission analysis for two launch days in October and November of 2019. State dispersions were developed based on EM-1 Monte Carlo data generated with MAVERIC. The mission trajectory is the same for both launch days. The dispersions were inserted into the disposal optimization analysis tool and propagated. Optimized disposal targets were developed from this such that each trajectory had a lunar flyby window as detailed in the table below

Table 2. Optimized Lunar Flyby window and Minimum C3 Values for a set of October and November 2018 launchs

	Minimum Lunar Alt (km)	Maximum Lunar Alt (km)	Minimum C3 (Km^2/s^2)
October 2018	15	543.79	3.90e-05
November 2018	15	612.59	0.0513

Because both trajectories are identical save for launch day, it can be shown that lunar position has an impact on launch window sizing. The November 2018 launch date allows for a larger range of flyby altitudes compared to October 2018. Note that a higher maximum lunar altitude for the November 2018 launch date could be achieved based on final C3 values, however the based on the disposal optimization routine's internal tolerances, the presented values are still optimal, presenting no difficulties in achieving disposal .

For the Disposal Assessment Analysis tool, EUS disposal states were analyzed. These states were analyzed as part of model development for MAVERIC 6DOF analysis for SLS Block-1B. 2000 dispersed Post-Disposal states were assessed by propagating to 10 days post Perilune. Based on the success criteria presented earlier, 98.70% of cases successfully disposed with 1.30% failing to dispose heliocentrically. No cases impacted the Lunar surface.

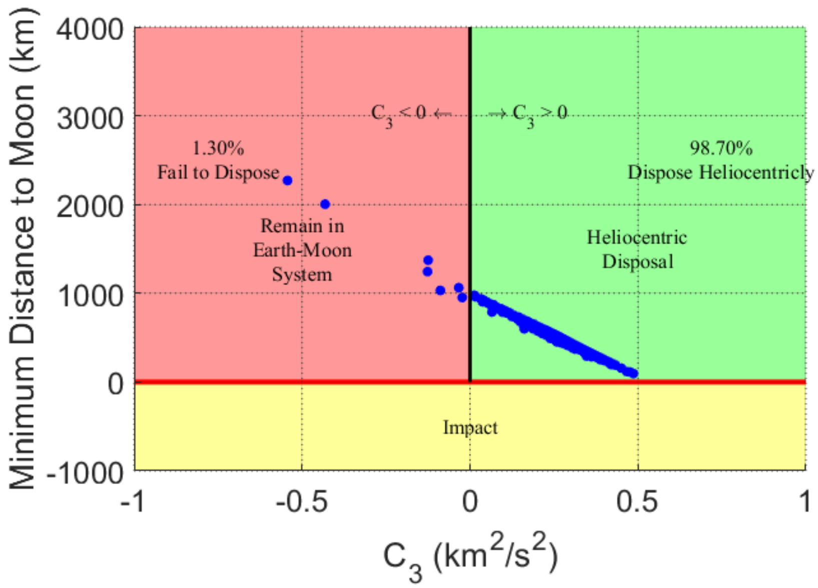

Figure 5. C3 vs minimum distance to the moon.

FUTURE APPLICATIONS

Currently, the SLS Navigation team is in the process of adapting the delta-delta-V analysis tool as well as the Disposal Analysis tool set for future SLS mission analysis. Current efforts are focused on the application of the analysis to EM-2 mission requirements verification and MAVERIC target development. As part of this effort, the MATLAB versions of the tools are being phased out and newer versions have been developed using Python.

Additionally, the SLS navigation team has plans to expand the scope of the applied algorithms with additions of additional dynamics such as boiloff, blowdown, and Collision Avoidance Maneuvers. An expansion of the disposal analysis to include multiple delta-V maneuvers is being considered to expand mission applications.

CONCLUSION

The SLS navigation team has identified a need to assess impact of navigation state errors on SLS mission performance. Additionally, mission requirements are in place to ensure upper stage disposal. Historically, the SLS navigation team has employed TCM assessment approaches similar to the Fixed-Time-of-Flight method as presented by Battin. These approaches were found to have shortcomings related to mission design and linearization assumptions. The SLS navigation team found traditional assessment approaches insufficient for requirements analysis.

To better assess state error impacts, the SLS navigation team developed the delta-delta-V analysis approach. This approach is designed to be applicable to multiple mission types, does not assume linearity, and through the application of Monte Carlo analysis and covariance reseeding can capture the full effects of navigation state errors. Further, to assess disposal, a series of analysis tools were developed that are designed to implement a full error dispersion upon a disposal trajectory and maximize the dispersion ellipsoid such that it will all for a successful disposal.

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