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SPACE LAUNCH SYSTEM

Assessment and Verification of SLS Block 1B Exploration Upper Stage and Stage Disposal Performance

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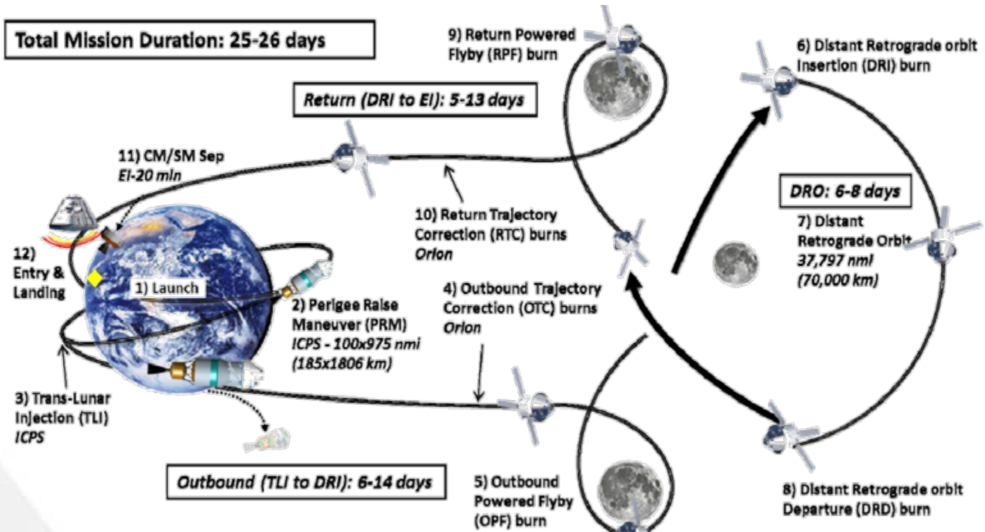
2018 AAS GNC Conference

Upper Stage Mission Needs/ Requirements

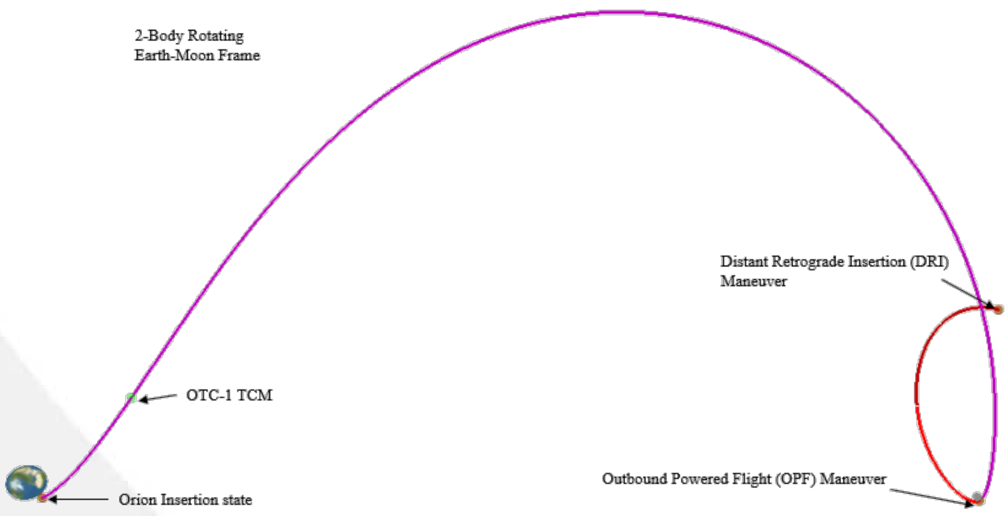
- **Insert Payload into desired orbit**
  - Assessed as Delta-V allocation to correct for state errors
- **Disposal of upper stage into heliocentric orbit**
  - NASA-STD-8719-14 imposes constraints on disposal of the spent SLS and EUS stages
  - SLS core stage disposes via reentry into the Atlantic Ocean
  - EUS/ICPS dispose via Lunar flyby into Heliocentric Space
- **Tools developed to assess verification of performance requirements**
  - Impact to payload (Delta-Delta-V)
  - Upper Stage Disposal capability
  - Applied to EM-1 mission



EM-1 Mission Profile Considerations
- **Demonstrates initial SLS vehicle performance**
- **Provides for challenging, extended (3 week) test of uncrewed Orion systems in the deep space environment**
- **Demonstrates ability to enter, operate in, and exit DRO**

Delta-Delta-V Approach

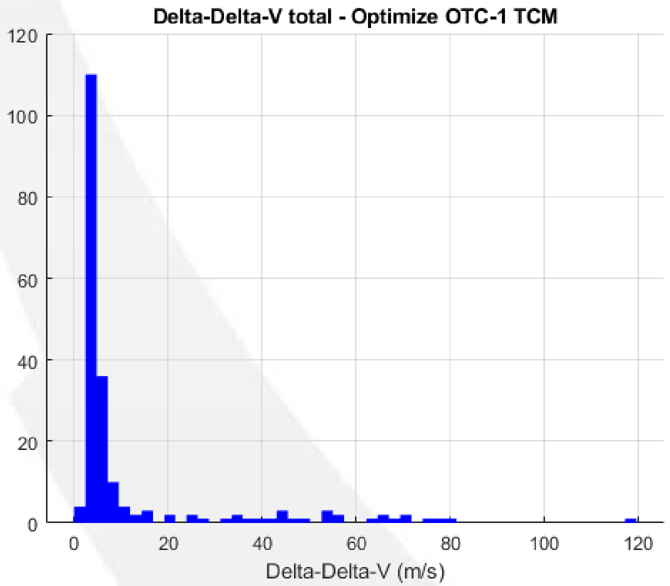
- **Determine impacts to payload mission performance caused by state dispersions on insertion conditions from an integrated vehicle**
- **Originally employed Fixed-Time-of-Arrival trajectory correction method (Battin)**
  - Assumes linear dynamics for estimate of correction maneuver – ***long-time dynamics in Earth-Moon system highly non-linear***
  - Calculates ΔV for a single TCM – ***ignores sensitivities to when TCM applied***
  - Very conservative – ***limited allocation for correction maneuver in Program***
- **Stochastic approach**
  - Re-optimize payload trajectory with dispersed initial conditions
  - Assumes accurate knowledge of payload state at insertion
  - Assess differences in Delta-V in order to meet payload mission requirements
  - Utilizes state propagation with nonlinear dynamic models

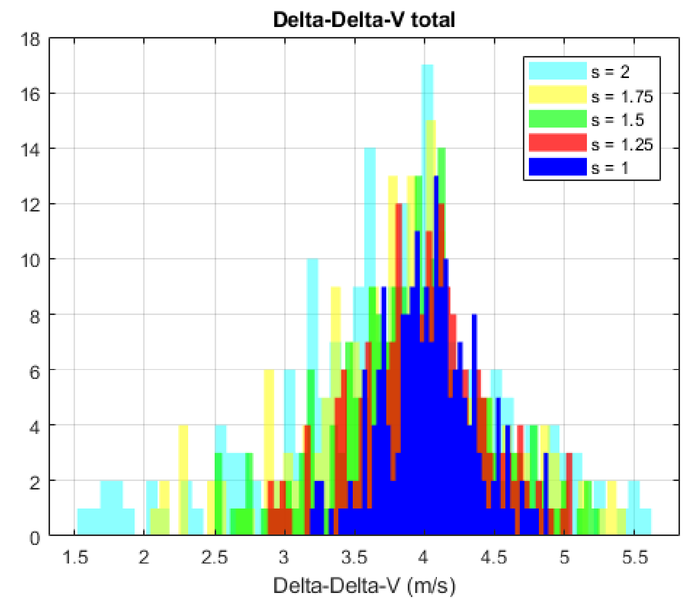


Implementation and Results

- **Method initializes with dispersed states**
  - Derived from Monte Carlo 6DOF analysis – ***assessment of performance***
  - Generated states from covariance reseeding – ***supports requirements design***
- **Perturbed trajectories are re-optimized using Copernicus**
  - Emulates assumed Orion onboard guidance targeting logic
- **Delta-V for all maneuvers in perturbed trajectories are compared to nominal**
- **Optimized single TCM as well as entire mission (3 maneuvers)**
  - Single maneuver requires large delta-V to correct for out-of-plane motion
- **Scaling state errors used to determine allowable insertion errors to Delta-V allocation**

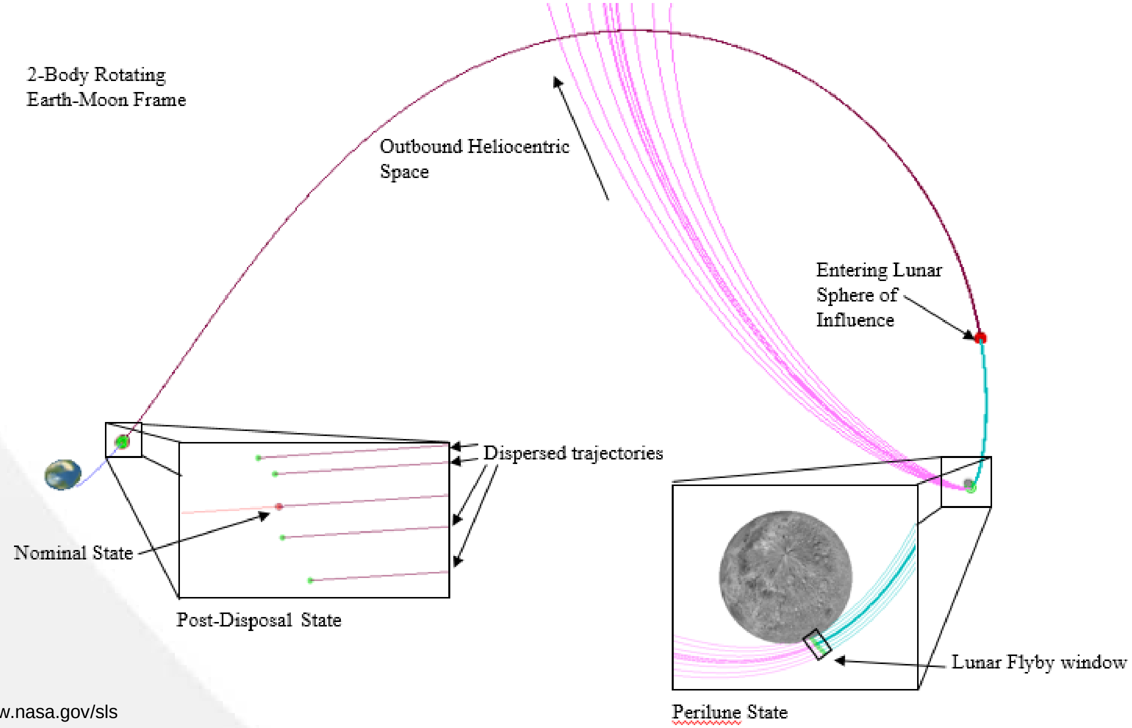
$$\begin{bmatrix} t_i \\ \boldsymbol{r}_i \\ \boldsymbol{v}_i \end{bmatrix}_{i=1\ldots N} = \begin{bmatrix} t_{nom} \\ \boldsymbol{r}_{nom} \\ \boldsymbol{v}_{nom} \end{bmatrix} + s * diag([\sqrt{\lambda_1} \quad \ldots \quad \sqrt{\lambda_7}]) \begin{bmatrix} \boldsymbol{v}_1 \\ \vdots \\ \boldsymbol{v}_7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





Disposal Target Generation

- **Development of disposal targets that are robust to dispersions**
- **Analysis approach**
  - 6DOF Monte Carlo results provide statistics on time, position, velocity dispersions post-disposal maneuver
  - Covariance used to generate 7 unique trajectories that capture bounds of error ellipsoid
  - Maneuver optimized to maximize window at lunar flyby that ensures disposal across all trajectories with minimization of Delta-V

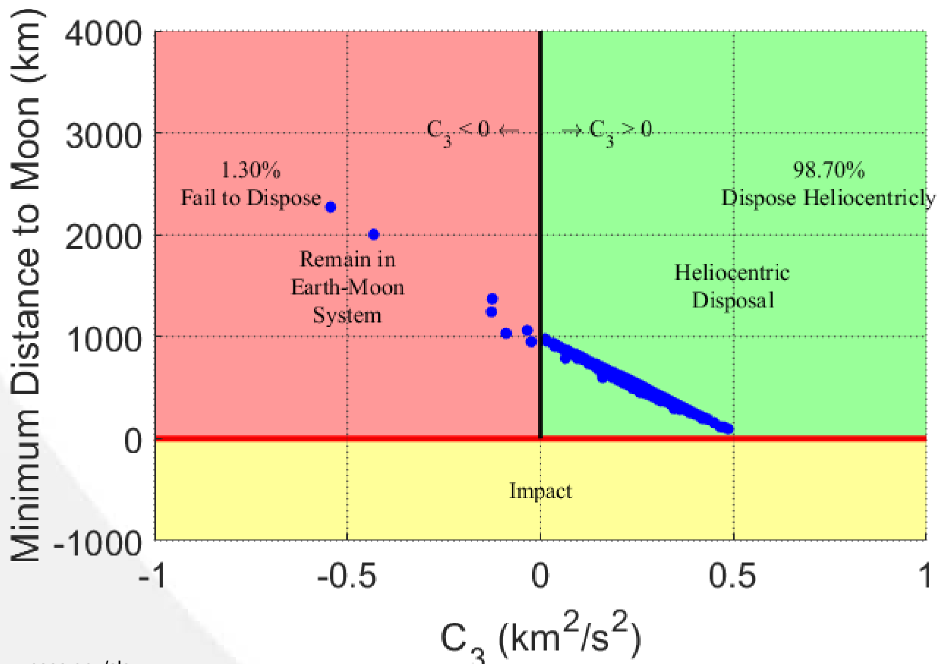


Disposal Capability Assessment

- **Optimization to determine largest bound of dispersions that dispose**
  - Coarse 1-D iterative search to increase the scaling on the applied errors
    - Determine upper and lower bounds to the optimal ellipsoid that ensures disposal
  - Bisection search fine-tunes optimal state targets
    - Captures median dispersions within the range of the bounding dispersions
    - Re-optimizes based on internal tolerance limits

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

- **Performance assessment to determine probability of disposal**
  - Utilizes Monte Carlo results of integrated vehicle with optimized targets
  - Forward propagates end of mission states using Copernicus
  - Assesses success based on C3 10 days post-Perilune



Conclusion

- **Supports requirements development and performance assessment**
- **Develop and assess performance metrics for upper stage**
  - Impact to payload from dispersed insertion states
  - Capability to dispose of stage into heliocentric stage
- **Utilization of a nonlinear analysis approach**
  - Utilize trajectory optimization tools and nonlinear propagation techniques
  - Applied to a wide variety of mission trajectories
- **Future Work**
  - Continued tool refinement and integration with standard Monte Carlo inline processing
  - Expand Disposal Optimization to include additional forces and maneuvers
  - Adaptation to EM-2 mission design and implementation of direct disposal