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OVERVIEW OF THE NASA SPACECRAFT TRADE MODELING SYSTEM (NSTRDMS), A RAPID MISSION ANALYSIS TOOL

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A rapid mission analysis tool is developed to support the ongoing design of the Lunar Transit trajectory of the Power and Propulsion Element (PPE). A 50-kW class electric propulsion system is envisioned to transit a massive vehicle between a Medium Earth Orbit (MEO) parking orbit and a lunar L2 southern Near Rectilinear Halo Orbit (NRHO). A parameterization is developed by which the Lunar Transit can be analyzed in the context of varying vehicle mass, solar electric propulsion (SEP) configurations, and solar array power output. A rapid and novel mission analysis tool enables a wide array of these trade analyses to be completed without the need for extensive computing resources or time. This tool is shown to be useful in the analysis of a reference trajectory, where changes to the baseline vehicle architecture or off-nominal operational scenarios (such as electric thruster failures) can be rapidly assessed by the mission designer.

INTRODUCTION

As part of NASA's Artemis program, Gateway will serve as a habitable outpost in cislunar orbit to enable sustainable exploration of the Moon. The Power and Propulsion Element (PPE) and the Habitation and Logistics Outpost (HALO) will launch and transit together from the Earth to the Moon as the Co-Manifested Vehicle (CMV). The CMV will be propelled by the PPE's 50-kW class solar electric Ion Propulsion System (IPS) to a lunar Near Rectilinear Halo Orbit (NRHO). The selected L2 southern NRHO will serve as the baseline orbit for Gateway throughout its mission lifespan (a full description of the NRHO is available publicly[1]). The CMV will be injected into a highly elliptic medium Earth orbit (MEO), after which the IPS will be used to fly a low-thrust Lunar Transit trajectory, the details of which have been published previously[2]. High-fidelity trajectory design tools, such as Copernicus[3] or the General Mission Analysis Tool (GMAT)[4], are instrumental in the development of reference trajectories for this Lunar Transit. These tools, however, are severely limited by the computing resources and time required to compute an optimized solution.

The development of an optimized low-thrust trajectory is additionally complicated by continuously evolving vehicle configurations as the design of the CMV matures. Analysis is regularly

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required to understand the impacts of various architecture decisions on mission and trajectory performance. Large trade analyses provide valuable results to program leadership as well as mission designers. The computational effort required to run these types of analyses in existing tools such as Copernicus or GMAT often proves infeasible for large trade spaces and short turnaround times.

To enable rapid trade analysis of this complex low-thrust trajectory, the PPE Mission Design (MD) Team has developed a rapid mission analysis tool, the NASA Spacecraft TRaDe Modeling System (NSTRDMS). NSTRDMS allows the effects of variations in key mission parameters such as mass, power, propulsion system performance, launch vehicle performance, and launch date to be analyzed in an integrated environment without the need for significant computing resources.

BACKGROUND

The CMV, in its current configuration, exceeds the direct mass-to-NRHO delivery capability of any existing commercial launch vehicle. The highly efficient solar electric propulsion (SEP) system onboard PPE functionally can be compared to the third stage of the launch vehicle, delivering CMV to the NRHO on a low-thrust spiral trajectory (Figure 1). The baseline Lunar Transit begins in a highly elliptic Medium Earth Orbit parking orbit with an inclination of 28.5°. The trajectory itself is broken into four primary phases (Spiral, Alignment, Ballistic, and Insertion), each one unique in its design, optimization, or operational strategy.

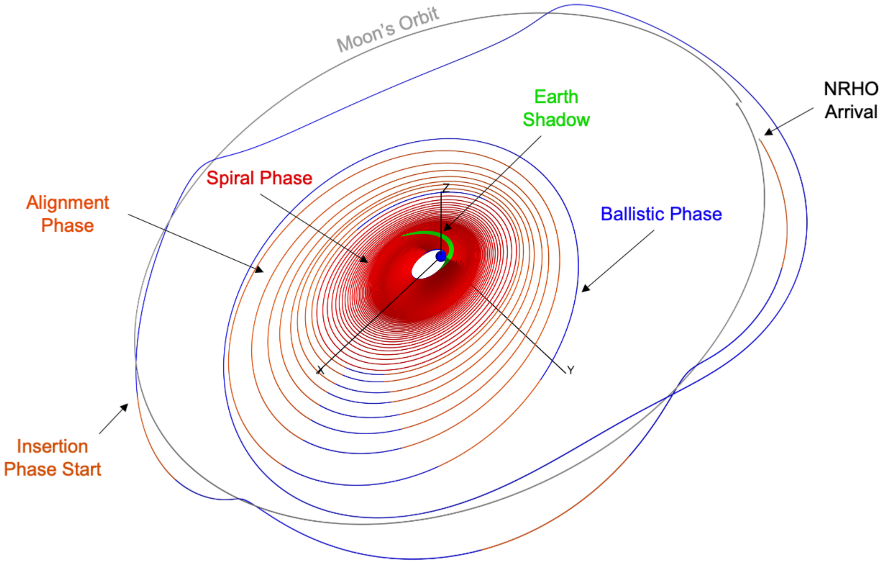

Figure 1: CMV Lunar Transit trajectory[2]

The Spiral Phase consists of nearly constant tangential thrusting, designed to raise the CMV's orbit as rapidly as possible. Coasting is inserted as required by planned operational shutdowns or by eclipse occurrences. The Alignment Phase is primarily designed around optimized coasting and steered thrust arcs. These thrust events encompass any plane change maneuvers that are required to target the later NRHO insertion state. The Alignment Phase also utilizes a different IPS configuration than the Spiral Phase, with the electric thrusters switching to a higher efficiency, lower thrust operating mode. During the Ballistic Phase, the vehicle coasts towards its rendezvous with the Moon. Trajectory correction maneuvers may occur during this phase to ensure the desired approach path to the NRHO is maintained. Finally, the Insertion Phase consists of the final optimized thrust arcs that complete the insertion maneuver to enter Gateway's planned baseline NRHO.

At current design and performance assumptions, the Lunar Transit trajectory requires a transit time in excess of one year to complete from launch vehicle separation to arrival in the NRHO. More than two thirds of this time is spent under thrust, with the SEP system outputting more than 3 km/s of Δv (a more complete overview of the Lunar Transit has been published previously by the PPE MD Team[2]). Starting from its MEO parking orbit, the CMV embarks on a long, complex, and in many ways unprecedented journey.

METHODOLOGY

Like any low-thrust trajectory, the CMV Lunar Transit is a complex, multi-variate problem. In the development of a reference trajectory, the PPE MD Team relies on high-fidelity tools such as Copernicus to solve for, and optimize, the hundreds of variables that make-up the Lunar Transit. This complexity is precisely what makes completing trade analyses using these tools difficult, and what spurred the need for a rapid mission analysis tool.

To create a rapid analysis tool, a methodology must be developed to model a complex low-thrust trajectory within a comparatively simple framework. This is accomplished by distilling the Lunar Transit into a rocket equation calculation (Equation 1). In this manner, the complexities of analyzing a multidimentional trajectory are reduced to a straightforward calculation consisting of Δv, vehicle initial (m_0) and final (m_f) mass, and the specific impulse of the IPS (I_{sp}).

$$\Delta v = I_{sp} g_0 \ln\left(\frac{m_0}{m_f}\right) \tag{1}$$

With a rocket equation based methodology, the trajectory itself and the performance of individual spacecraft subsystems can be contained within just three variables (Δv, mass, and IPS performance). Each of these variables, however, contain within them integrated models of the subsystems themselves. NSTRDMS incorporates each of these models along with a parameterization of the Lunar Transit trajectory into a single integrated rapid analysis environment (Figure 2).

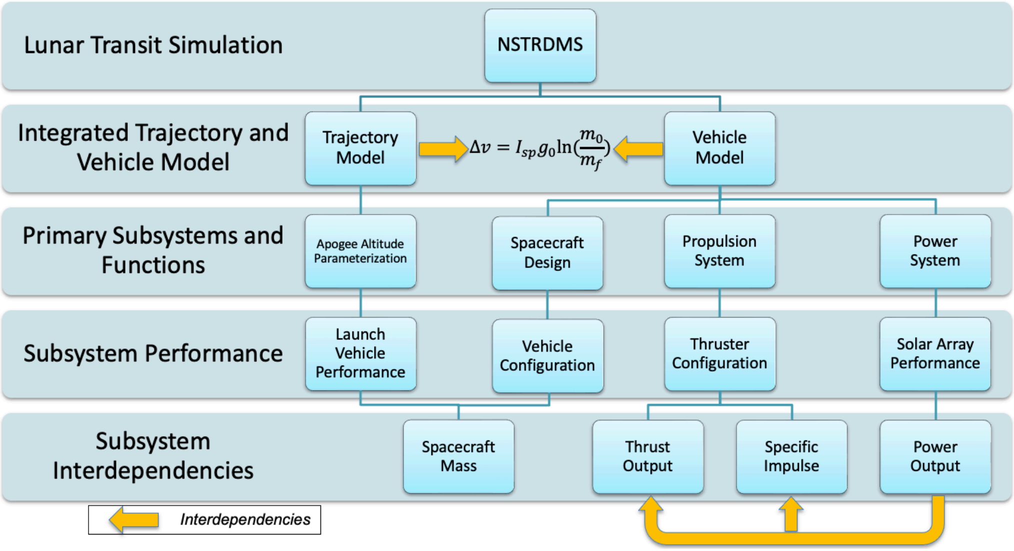

Figure 2: NSTRDMS integrated analysis environment

Lunar Transit Parameterization

To enable a rocket equation based methodology, a reliable method for calculating Δv must be developed. Defining Δv in terms of a single independent variable will decouple the trajectory from the performance of the spacecraft itself, but that independent variable must always be known to the mission designer. For the CMV Lunar Transit, the apogee altitude of the initial vehicle parking orbit provides the ideal parameter with which to define Δv.

As mentioned above, the CMV is deposited into a highly elliptic parking orbit by the selected launch vehicle. As the design of the CMV and its Lunar Transit have continued to mature over time, this 200 km perigee altitude has been held constant. The apogee altitude, however, varies along with spacecraft mass (as described in the following section *Launch Vehicle Performance*). With a fixed perigee altitude, this means that the Δv required to reach the NRHO can be parameterized as a straightforward function of initial parking orbit apogee altitude (Figure 3). This parameterization is a polynomial curve fit of data generated using Copernicus and GMAT, both high-fidelity trajectory design tools with uses across multiple heritage NASA missions. Previous work has shown that the parameterization is insensitve to changes in vehicle performance in the range of interest to CMV[5].

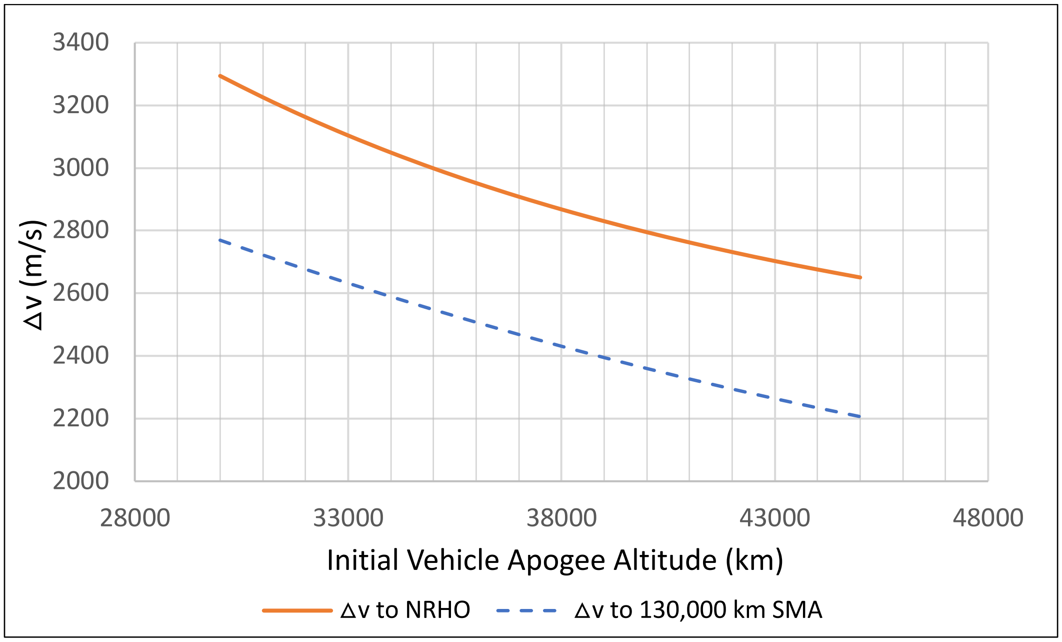

Figure 3: Parameterization of Δv as a function of apogee altitude

The same methodology can also be applied to any orbital state of interest throughout the trajectory, enabling the modeling of all subphases of the Lunar Transit. Precise modeling of the transition from Spiral to Alignment phases is critical to any analysis of the Lunar Transit, as this represents a change in both the construction of the trajectory and in the configuration of the SEP system (as discussed above). This transition occurs when the CMV trajectory reaches a semi-major axis (SMA) of 130,000 km. The Δv required to reach this SMA can be easily calculated as a function of initial apogee altitude, meaning that the Spiral and Alignment phases can be easily incorporated into the same rocket equation based framework.

Launch Vehicle Performance

The Lunar Transit itself, via the methodology above, is parameterized as a function of the initial spacecraft parking orbit. The CMV is deposited into this parking orbit by a launch vehicle, which is limited in the mass it can deliver to any given orbital altitude. The performance capability of this launch vehicle is the singular parameter which couples the NSTRDMS trajectory parameterization to the modeling of the spacecraft itself.

While the *Δv* required to reach the NRHO is parameterized as a function of initial apogee altitude, the initial apogee altitude itself is a function of spacecraft wet mass. The apogee to which a given mass can be delivered (given a fixed 200 km perigee) is dependent on launch vehicle performance. The higher performing the rocket, the higher the apogee and the less *Δv* that the CMV SEP system needs to expend to complete the Lunar Transit. Conversely, a higher CMV mass means a lower apogee altitude for a given launch vehicle, and more time and propellant needed to complete the mission.

In 2021, NASA announced the selection of SpaceX as the launch provider for the CMV, with a Falcon Heavy rocket serving as the launch vehicle. SpaceX, along with NASA's Launch Services Program (LSP), provides the PPE MD team with expected launch vehicle performance in the form of mass delivery to a range of apogee altitudes (similar to Figure 4). A curve fit is applied to the available performance data to form a continuous model of the launch vehicle.

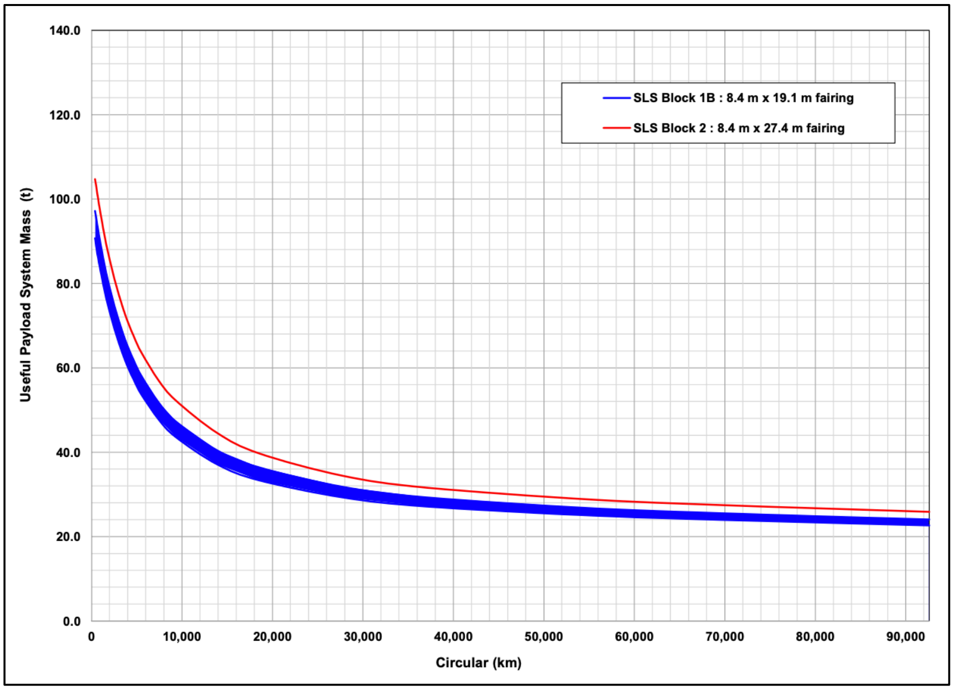

Figure 4: Representative launch vehicle performance (data provided from SLS)[6]

With *Δv* and the spacecraft coupled via the launch vehicle performance curve, the rocket equation based NSTRDMS methodology is further simplified. The number of variables is reduced from three to two (IPS performance and mass), with *Δv* becoming a function of the spacecraft wet mass (Equation 2).

$$f(m_0) = I_{sp} g_0 \ln\left(\frac{m_0}{m_f}\right) \tag{2}$$

Power System Modeling

Critical to any electric propulsion based mission is a sufficient power generation capability. The Roll Out Solar Arrays (ROSA's) onboard PPE produce enough electrical power to meet the demands of both the spacecraft itself and the 50-kW class SEP system. The instantaneous output of the ROSA's is not a constant, however, and varies over the duration of the mission. Variances in solar flux due to range to the Sun and degradation of the arrays themselves both contribute to a time varying power output, which must be calculated accurately to produce a valid model of the Lunar Transit.

NSRTRDMS implements the same power modeling methodology employed by Copernicus[3] (Equation 3), calculated as a function of mission elapsed time (MET, represented as *t*), and range to the Sun (*r*). Power to the IPS (P_{IPS}) is calculated as a function of the solar array output (P_{input}) at MET +0 days and a solar range of 1 AU, the spacecraft power loads from all non-SEP systems ($P_{spacecraft}$), and a decay factor (κ). The decay factor itself (Equation 4), consists of two terms, one to govern how array output varies with distance to the sun and one to model array degradation as a function of time. The coefficients g_1, $g_2 \ldots g_6$ and t_1, $t_2 \ldots t_4$ are user defined and mission/solar array specific. For instance, a simple $1/r^2$ power model with no time dependent degradation would hold g_1 and t_1 equal to one, with all other coefficients equal to zero.

$$P_{IPS} = (\kappa \cdot P_{input} - P_{spacecraft}) \tag{3}$$

$$\kappa = [\frac{g_1 + \frac{g_2}{r} + \frac{g_3}{r^2}}{1 + g_4 \cdot r + g_5 \cdot r^2} \frac{1}{r^2} + g_6] \cdot (t_1 + t_2 \cdot e^{t_3 \cdot t} + t_4 \cdot t) \tag{4}$$

To model the PPE power system, both terms of κ are utilized to account for $1/r^2$ variation in the output of the arrays and MET dependent degradation. The ROSA degradation model accounts for photovoltaic cell failures due to manufacturing defects, impacts from micrometeorites and orbital debris (MMOD), and from the effects of ionizing radiation as the CMV transits the Van Allen Belts.

Ion Propulsion System Modeling

The IPS carried onboard PPE is itself a multivariable system, consisting of seven individual thrusters of two types, three 13-kW class and four 6-kW class. All seven thrusters are assumed to be continuously throttleable within their range of power input. Additionally, the 6-kW class thrusters can operate in either a High Thrust or High Isp mode (functionally controlled by changing the input potential to the thruster). Performance curves for both thruster types (and both 6-kW operating modes) (Figure 5) are functions of power into the power processing unit (PPU) for each thruster. Thruster performance curves are generated using available flight qualification testing data, with statistical uncertainty in thruster performance and PPU efficiency accounted for in the linear fit.

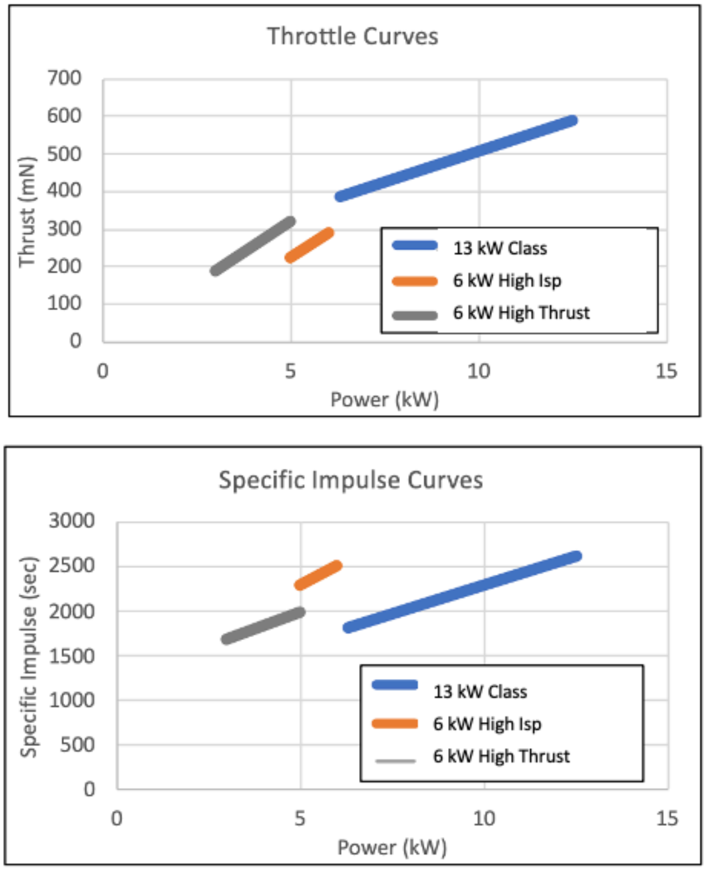

Figure 5: Performance curves (thrust, top and *Isp*, bottom), for 13-kW and 6-kW class thrusters[7]

Integrated Ion Propulsion System Management

Critical to the modeling of the Lunar Transit is the time dependent management of a mutli-variable IPS configuration. With seven individually throttleable thrusters, two thruster types, two operating modes, and a varying power available to the IPS, the management of the propulsion system is a complex problem with multiple viable solutions. The implementation of these solutions makes NSTRDMS unique among the tools utilized by the PPE MD Team.

In high-fidelity trajectory design and analysis tools, IPS management can be both cumbersome in application and limited in functionality. In Copernicus, for instance, individual thruster strings cannot be modeled, instead the entire IPS is represented by a single “engine”. This makes it difficult (if not impossible) to track the performance and usage of individual strings. For PPE, where all seven thrusters are life limited in the amount of throughput they can provide, this type of propulsion system modeling requires the mission designer to perform additional post processing on a solution to ensure that thruster implementation complies with system requirements. Additionally, major changes to the IPS, such as the change from High Thrust to High Isp operating modes or a failure in one or more thruster strings, requires a completely new “engine” model. This implementation further complicates an already complex solution space.

Other high-fidelity tools do allow for the modeling of individual thruster strings, but are limited in their capabilities. Attentive user input is often required to fully model an IPS across an end-to-end trajectory. Many tools allow a user to input a polynomial thruster throttle curve as a function of available electrical power, allowing for $1/r^2$ variations to be accounted for in the design of a trajectory. These polynomials allow for continuous throttling of a thruster or propulsion model within a minimum and maximum power. The 50-kW class PPE SEP system, however, is not continuously throttleable across all power levels. As the power output of the solar panels decreases, it may drop below the minimum power required to run the baseline number of thrusters. In these cases, at least one thruster must be shut off. But with multiple thruster strings spread across two thruster types, which string should be powered off? Conversely, if the array output increases again, which string should be powered on as power becomes available? This kind of discontinuous IPS management is often difficult, if not impossible, to implement in a high-fidelity analysis environment.

NSTRDMS manages this complex propulsion environment by modeling all seven thrusters as distinct, individual strings throughout the entirety of the trajectory (Figure 6). All seven thrusters are modeled for the entirety of the transit, allowing results for each string to be easily tracked across a mission. Results are tracked when a thruster is operating and when a thruster is shut off, providing a complete time history for each string. At each individual time step, NSTRDMS assesses the state of the vehicle, the phase of the mission, and the health of each thruster string before building an IPS configuration. This allows NSTRDMS to select an appropriate combination of 13-kW and 6-kW class thrusters based on how much power is available, how much lifetime individual strings have remaining, and whether or not any of the strings have experienced a failure.

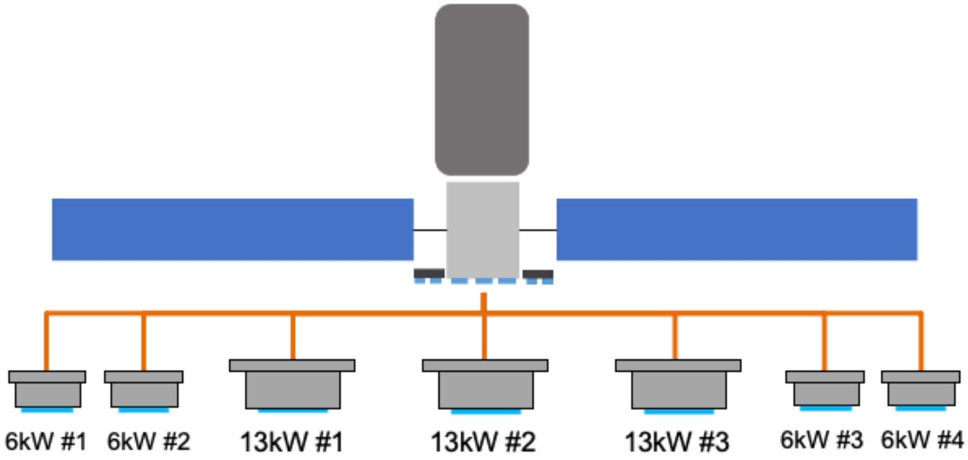

Figure 6: NSTRDMS PPE IPS model

To handle discontinuities in the operation of the thrusters (such as shutdowns or failures), NSTRDMS also implements a management algorithm on the SEP system. A user defined thruster priority is used to automate the micromanaging of the thrusters, with NSTRDMS then dynamically throttling individual thrusters according to this pre-defined strategy. The baseline strategy employed by PPE MD holds the 13-kW class thrusters as the top priority, with the 6-kW strings being used in a complementary role. NSTRDMS uses this input to bias power towards the 13-kW strings, attempting to run all three 13-kW thrusters at full power at all times. The 6-kW strings are throttled back or shut down to maintain power priority to the larger thrusters (in practice this typically results in running a 3x 13-kW + 2x 6-kW configuration, with the remaining two 6-kW strings held in reserve).

The native thruster priority algorithm is also combined with a simulated annealing[8] optimization wrapper to enable a more capable analysis of thruster failure scenarios. In the case of a thruster string failure, the user can define a set of constraints within which NSTRDMS must find a viable solution to reach the NRHO. Constraints can be placed on the required transit time, propellant consumption, and remaining lifetime on a given thruster string. Likewise, one of transit time, propellant consumption, or thruster lifetime can be designated as the objective function. The optimizer is then free to iterate on the chosen thruster priority until an optimal solution is found which fits within the designated constraints. This simulated annealing approach allows for desirable failure recovery strategies to be quickly identified without the need to run large, time consuming test matrices.

This dynamic management of the propulsion system (Figure 7) allows for a mission solution to be computed without extensive input from the mission designer. Using the pre-defined thruster priority, NSTRDMS is able to apply a varying solar array output, incorporate thruster string failures, and handle changes to thruster operating modes automatically. Tracking of results for individual strings also allows for easy post processing of analysis results such as throughput, total impulse, hours of operation, and Δv per thruster.

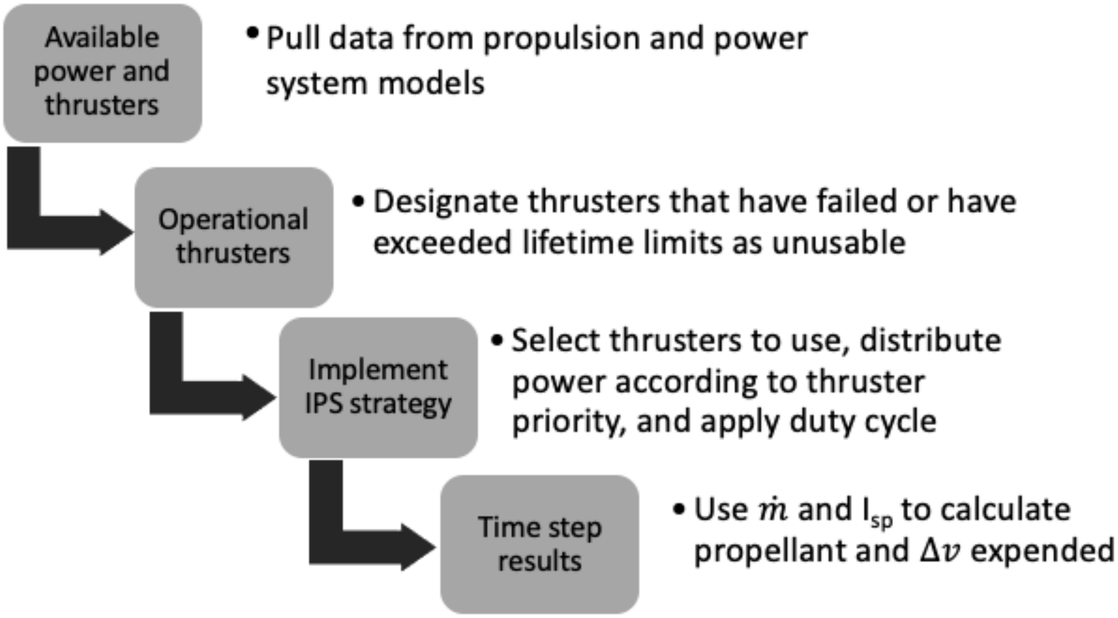

Figure 7: NSTRDMS IPS management flow

Modeling the Mission

With the relevant subsystems modeled, a solution must be calculated for a given set of user inputs. The user must supply six values in order to fully define all three variables in the modified rocket equation in Equation 2 (

Table 1). These six parameters supply NSTRDMS with the initial conditions necessary to run the models of the associated subsystems. Spacecraft wet mass defines the initial parking orbit via the launch vehicle performance model. Launch date determines the MET +0 days output of the solar arrays as a function of $1/r^2$, serving as a starting point for the array degradation model. The baseline IPS configuration (typically 3+2) gives the NSTRDMS IPS management algorithm a reference with which to apply the available power to SEP. The electric thruster duty cycle is then applied universally to all operating thrusters in the IPS and is modeled as a decrement to the thrust and mass flow rate of a thruster string. Finally, the spacecraft power load determines how much of the solar array output will be made available for use by the SEP system.

Table 1: NSTRDMS user inputs

Parameter	Description	Related Rocket Equation Variable
Wet Mass	CMV wet mass at time of launch vehicle separation.	m_0 Δv
Launch Date	Day/Month/Year of launch. Determines range to Sun at the beginning of the transfer.	I_{sp} m_f
Baseline # of Hot 13 kW Thrusters	Baseline number of 13-kW class thrusters in use simultaneously (between 0 and 3).	I_{sp} m_f
Baseline # of Hot 6 kW Thrusters	Baseline number of 6-kW class thrusters in use simultaneously (between 0 and 4).	I_{sp} m_f
Duty Cycle	Duty cycle of the operating thrusters in the IPS (between 0% and 100%).	m_f
Spacecraft Power Load	Power subtracted from solar array output for all non-SEP functions of the spacecraft.	I_{sp} m_f

Utilizing the described methodology, NSTRDMS is able to distill a complex low-thrust mission into a relatively simple series of calculations. With complete models of the relevant spacecraft subsystems (IPS and power), a parameterization of the Lunar Transit, and a launch vehicle performance curve defined, the final step is to “fly” the trajectory itself. NSTRDMS computes a solution by creating a virtual CMV, and then “flying” that CMV through the mission in discrete time steps. For each of these time steps, the performance of the vehicle subsystems are modeled, and then applied to the vehicle’s progress along the trajectory.

For a given time step (the default Δt is one day), NSTRDMS first calculates the power output of the solar arrays utilizing Equations 3 and 4. The power available to SEP is then passed to the IPS modeling algorithm, which selects an appropriate combination of 13-kW and 6-kW strings and throttle settings according to the priority described previously in *Integrated Ion Propulsion System Management*. The total mass flow rate and thrust of the combined IPS configuration are then calculated and used to determine the amount of propellant expended at a given time step, *i* (Equation 5). This propellant, along with the IPS configuration specific impulse (Equation 6) are then used to determine the Δv expended for the time step (Equation 7).

$$m_{propellant,i} = \dot{m}_i \cdot \Delta t \tag{5}$$

$$I_{sp,i} = \frac{F_i}{\dot{m}_i \cdot g_0} \tag{6}$$

$$\Delta v_i = I_{sp,i} \cdot g_0 \cdot \ln\left(\frac{m_{0,i}}{m_{0,i} - \dot{m}_i \cdot \Delta t}\right) \tag{7}$$

Once the results for a given time step are calculated, the model is marched forward in time, iterating through the Lunar Transit parameterization (Figure 8). When the Δv required to reach the NRHO is met, the final time step is truncated to the appropriate duration and the trajectory is considered complete. Mission results can then be calculated, collected, and organized for delivery to the user.

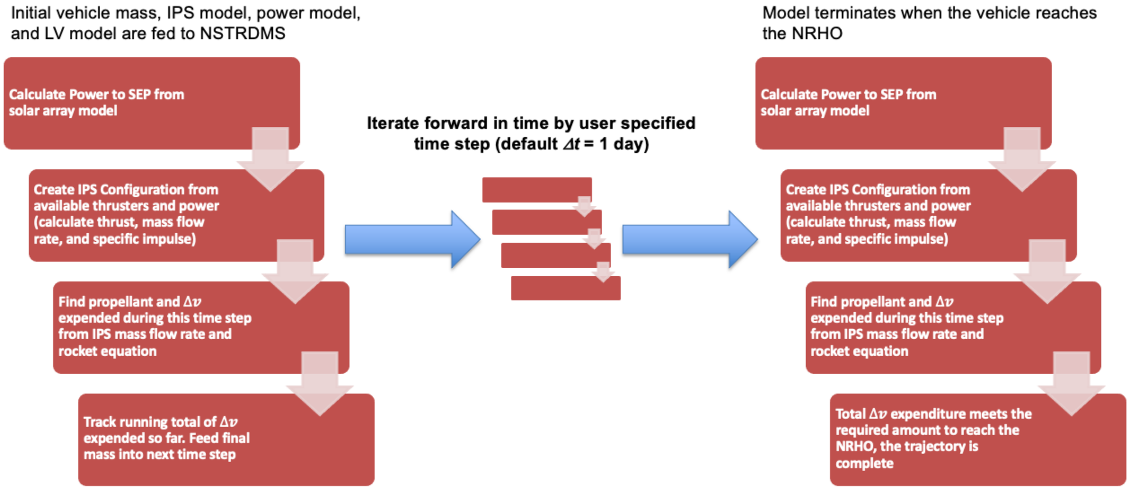

Figure 8: NSTRDMS iterative solution cycle

Utilizing the Δv based parameterization methodology outlined in Figure 3, major mission events can be easily incorporated into the mission model. This includes the transition from the Spiral to Alignment phases, as discussed previously, planned operational shutdowns and coasts, and significant trajectory events such as the MET at which the spacecraft completely exits the altitude bands associated with the Van Allen Belts. The described methodology allows NSTRDMS to maintain a rapid analysis environment while also providing a valuable level of fidelity that goes far beyond that associated with quick back-of-the-envelope calculations. Additionally, the novel IPS management method affords insights into propulsion system operation that is not possible with other tools currently in use by the PPE MD Team.

NSTRDMS combines models of the Lunar Transit trajectory, the launch vehicle, the power system, and the IPS into a singular package. The CMV is modeled as an integrated system of systems within a simple parameterization based framework. This framework allows NSTRDMS to compute solutions far more rapidly than high-fidelity trajectory analysis tools (Table 2) while still providing valuable results to the spacecraft engineering teams.

Table 2: Comparison of approximate Copernicus and NSTRDMS run times on a typical personal computer

Number of Solutions	Estimated Copernicus Run Time	Estimated NSTRDMS Run Time
1	~minutes	~1 s
12	~hours	~5 s
>100	~hours to days	~10 s

Limitations

While enabling a valuable class of analysis capabilities, NSTRDMS does suffer from a number of limitations associated with the assumptions within the methodology. These assumptions are associated with the base design philosophy of NSTRDMS as a mission analysis tool, not a trajectory design tool. NSTRDMS can complete a wide range of rapid analyses on existing trajectories but it cannot develop a new trajectory independently. This means that NSTRDMS neglects many of the higher order variables that affect a fully optimized low-thrust trajectory. Effects due to factors such as shadowing and orientation (such as the argument of perigee or right ascension of the ascending node of the initial parking orbit) are neglected in NSTRDMS. As a result, NSTRDMS results are often optimal floors. Design Reference Missions (DRM's), however, are often deliberately chosen to be sub-optimal solutions to provide a conservative reference to inform analysis conducted by engineering teams. A brief overview of the simplifying assumptions that enable NSTRDMS is presented in Table 3.

Table 3: Major NSTRDMS limitations

Limitation	**Notes**
Shadowing	NSTRDMS does not implement a shadow model or account for eclipse related thruster shutdowns, meaning that time of flight is always lower than a high-fidelity solution for the same trajectory.
Geometry	NSTRDMS is a rocket equation based analysis tool, it does not model a three dimensional multi-body environment. Neglecting the effects of orbit geometries leads to lower propellant consumption in NSTRDMS analyses.
Trajectory Construction	NSTRDMS does not model individual thrust and coast arcs, and so events such as optimal coasts are not represented. Instead, NSTRDMS models all thrusting that occurs during the Lunar Transit as a single continuous event, interrupted only by planned operational shutdowns. All coasting (which is assumed to be a fixed number of days across different iterations of the Lunar Transit) is appended to the end of the thrusting period to form the complete mission. This introduces error relative to high-fidelity results.
Power Modeling	NSTRDMS does not model the real-time state of the spacecraft. Meaning that $1/r^2$ variations in power generation are calculated with respect to Earth-Sun range, not spacecraft-Sun range.

RESULTS

As the design of both elements of the CMV mature, trade analyses are in constant demand. The results of these studies are regularly used by spacecraft engineering teams and managers to inform ongoing work. The PPE MD Team often uses NSTRDMS results to inform ground rules and assumptions for the next iteration of high-fidelity reference trajectory development. Mission leadership, both at the PPE and CMV levels, rely on analysis from Mission Design to inform risk postures and decisions about vehicle design and mission concept of operations (CONOPS). These analyses include work from both high-fidelity tools and NSTRDMS, with both environments complimenting each other to form a complete data package. NSTRDMS results have driven CMV level decisions on spacecraft mass and power allocations, as well as Mission Design level decisions on thrusting strategy and IPS management.

Validation

As NSTRDMS is used across the CMV program to inform decision making and direct future analyses, a thorough verification and validation of results is critical to the efficacy of the tool. NSTRDMS results are regularly validated against high-fidelity reference trajectories of the Lunar Transit. The PPE MD Team has developed four reference trajectories for the Lunar Transit at the time of writing. NSTRDMS development began after the release of DRM-2 and has been validated against each subsequent DRM (Table 4). Relative errors to DRM's (which are developed primarily in Copernicus) historically have been under 2% for the major figures of merit (time of flight and propellant consumption). As the development of NSTRDMS has continued over time, the methodology has been refined and subsequent errors have been minimized.

Table 4: NSTRDMS error compared to Lunar Transit Design Reference Missions

Parameter	NSTRDMS vs DRM-2	NSTRDMS vs DRM-3	NSTRDMS vs DRM-4
Time of Flight Error	0.8%	0.8%	0.07%
Propellant Consumption Error	0.15%	0.04%	0.066%
Total Impulse Error	1.1%	0.006%	0.43%
Mass Delivery to NRHO Error	0.08%	0.006%	0.009%

In addition to validating results against trajectory figures of merit, the time-based methodology of NSTRDMS allows for results to be verified across the duration of a mission. Perhaps the most novel, and critical, aspect of the NSTRDMS methodology is the native management of the SEP system. The developed algorithm that governs thruster priority is critical to the accurate modeling of the CMV mission. Figure 9 shows a comparison between the power utilized by SEP across the Lunar Transit between NSTRDMS and Copernicus. The dotted line indicates the power being consumed by the SEP thrusters as calculated by NSTRDMS, the solid line indicates the same as calculated by Copernicus. The variation between the two results is driven by the innate differences in the two tools. NSTRDMS, as is discussed above, does not account for shadowing and makes several simplifying assumptions about the construction of a trajectory. As discussed in Table 3, NSTRDMS models all thrusting as a single continuous event. Copernicus, however, directly models events such as optimal coasting and shadow driven thruster shut downs. The difference in the two methods is clearly seen in Figure 9, with Copernicus results demonstrating thrust arcs broken up by coasting, while NSTRDMS results show a continuous thrusting period with coasting appended to the end of the trajectory. Despite the inherent differences in analysis philosophy, the results presented in Figure 9 show strong agreement between NSTRDMS and Copernicus. The power to SEP differs by less than 1% between the two tools across the duration of the mission, even with the inclusion of the solar array degradation model. Additionally, a 7-day planned shutdown at MET +162 days is accurately represented.

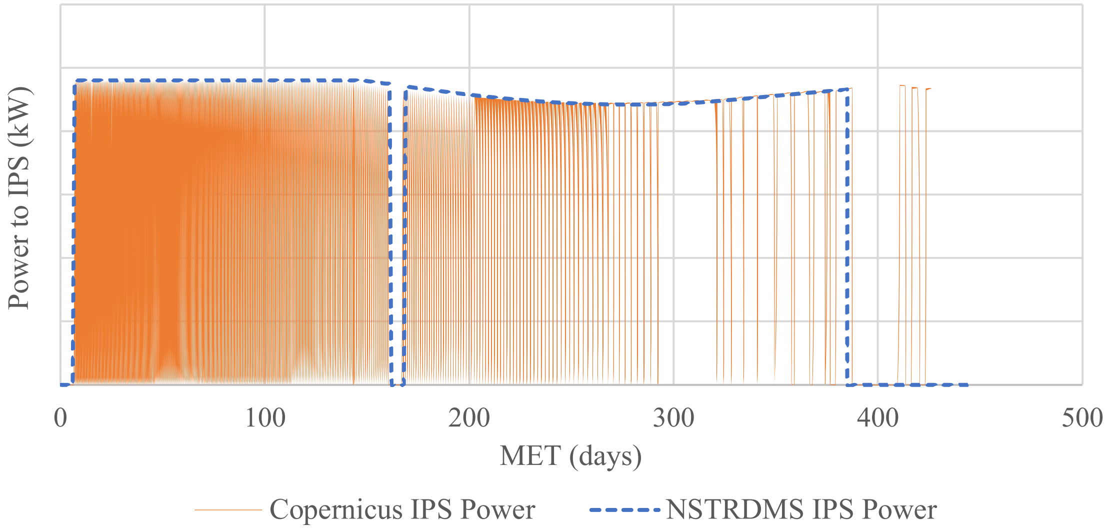

Figure 9: Validation of NSTRDMS IPS management

Continuous verification of results means that NSTRDMS represents a low-fidelity but not low-accuracy mission analysis tool. NSTRDMS has proven to be dependable and resilient across multiple CMV design cycles and continues to make valuable contributions to PPE MD and the CMV program.

Trade Results

NSTRDMS has been utilized extensively to explore trades into spacecraft mass, power allocations, thruster configurations, thruster failures, and launch dates. The ability to rapidly perform a wide array of trades on vehicle configurations or operation strategies has proven invaluable to the PPE MD Team. NSTRDMS results have been used to provide useful context to the results of high-fidelity analyses, identify cases of interest to be studied further in Copernicus, and to inform program level decisions.

With the ability to run a large number of cases in a short period of time, NSTRDMS is ideal for exploring vast trade spaces. One such trade space, and its bounds, is presented in a mission flight envelope (Figure 10), which provides a visual reference of feasible CMV trajectories as a function of wet mass. Each flight envelope represents an array of possible trajectories on a given launch date, using a given baseline IPS configuration. The portion of the graphic shaded in green represents wet mass and initial parking orbit apogee altitudes that exceed the capabilities of the chosen launch vehicle, as determined by the SpaceX Falcon Heavy performance curve. The upper left hand portion of the plot, shaded in grey, represents mass and altitude combinations that would require more propellant than is available onboard PPE to reach the NRHO. All combinations below the red lines thus represent feasible trajectories in terms of propellant consumption and launch vehicle delivery capabilities. All mass and apogee combinations that would result in a transit time greater than one year have been shaded in pink to provide a useful benchmark for the duration of the trajectories.

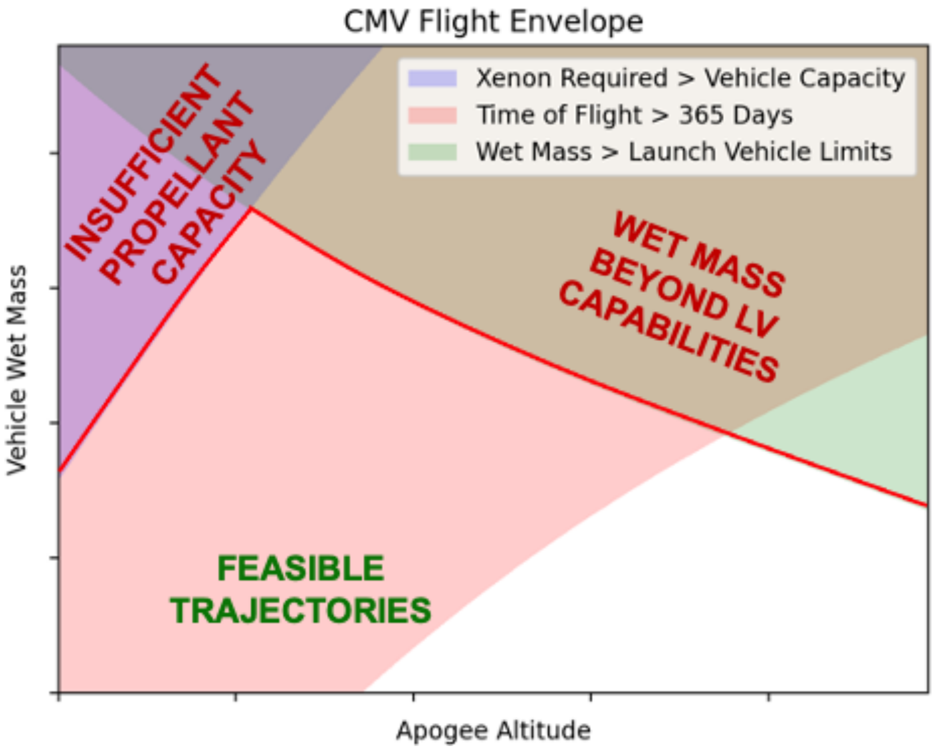

Figure 10: CMV flight envelope

The flight envelope in Figure 10 contains within it a matrix of mass and apogee altitude combinations, resulting in a total of 1,250 solutions. NSTRDMS computed all 1,250 combinations in 20.6 seconds. Attempting to generate the same flight envelope utilizing a tool such as Copernicus would be a massive undertaking in terms of manhours and computing time. The PPE MD Team is regularly asked to turn around analyses in a matter of days, meaning that utilizing a high-fidelity tool for this type of analysis is often infeasible. NSTRDMS enables Mission Design to assess a large trade space rapidly and efficiently communicate the results to audiences that may or may not have a working understanding of trajectory design.

As the development of the CMV continues, it is often useful to assess a spread of potential launch dates in terms of the major figures of merit (time of flight and propellant consumption). As described above, the PPE solar array model includes both $1/r^2$ variation and a time-driven array output degradation. This combination means that the Earth-Sun range at the beginning of the trajectory plays a large role in determining how much power, on average, will be delivered to the IPS over the duration of a mission. This behavior is clearly seen in Figure 11, with time of flight, propellant consumption, and average power to SEP plotted as a function of launch date from December through November of a given one-year time frame. Propellant consumption remains relatively constant across a full year of launch dates, varying by roughly 0.25%. Time of flight displays a greater sensitivity to departure epoch, with roughly a 1.5% variation across a given year. Transit time also displays mirror opposite behavior to average power to SEP. This is to be expected as higher power to the thrusters will directly translate into more thrust from the propulsion system.

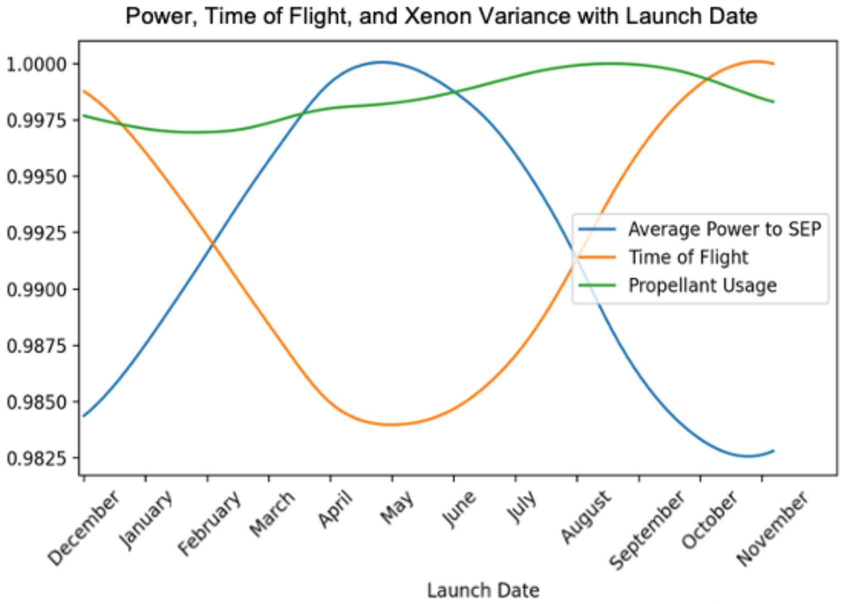

Figure 11: Time of flight and propellant consumption variation across one year of launch dates (results normalized by their maximum values)

Perhaps the most novel capability of NSTRDMS (of the tools in use by PPE MD) is its ability to analyze thruster string failures during the Lunar Transit. The native IPS management algorithm allows for any of the seven individual thruster strings to be designated to fail at a given point in the mission. The failure event can be determined using MET, hours of operation, or thruster throughput. Strategies for how to recover from one or more failure events can then be imposed by the user through a contingency thruster priority or strategies can be determined through the simulated annealing wrapper. Compounding variables such as thruster lifetime (as increased loads on the remaining thrusters may cause multiple strings to reach their effective lifetimes earlier than expected), launch date, and thruster operating modes are all accounted for automatically within the NSTRDMS framework.

These failure analyses help inform program risk posture and operational strategies. The failure of a 13-kW thruster string, for instance, may lead to an insufficient propellant margin remaining at the completion of the Lunar Transit without a change to the baseline IPS management strategy. The ability of NSTRDMS to run large analysis matrices can be combined with this failure analysis capability to generate results across a trade space. Figure 12 presents a heat map of propellant (xenon) margin remaining at the completion of the Lunar Transit as a function of CMV wet mass and the MET at which a single 13-kW string fails. Contours of constant propellant margin have been layered over the trade space. In this manner, it is easy to identify cases where the baseline IPS management strategy would exhaust the available propellant, leading to negative margins at the end of the Lunar Transit.

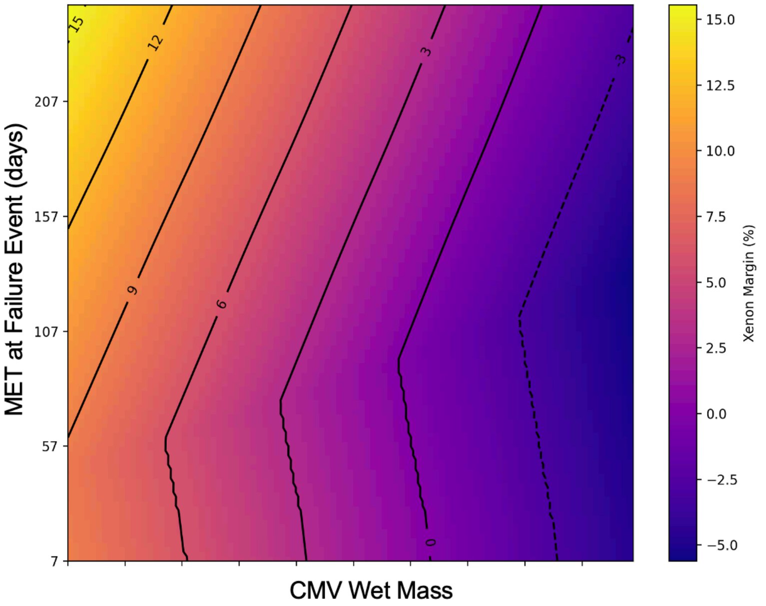

Figure 12: Heat map of propellant (xenon) margin remaining at mission completion as a function of CMV wet mass and the MET at which a single 13-kW string fails

FUTURE WORK

NSTRDMS is designed to be a modular analysis tool, capable of rapidly incorporating new models and functionality. This has proven to be the case, as the capabilities of the tool have expanded significantly since initial development in the Fall of 2020. Over the past two years NSTRDMS has been expanded to include capabilities such as time dependent modeling of the Lunar Transit, a time variable power model, and an automated IPS management algorithm. Moving forward into 2023, several improvements and functionality expansions are envisioned.

First is the inclusion of a guidance, navigation, and control (GN&C) model. Inclusion of CMV moments of inertia, locations of reaction wheels, reaction control system jet locations and performance, and SEP thruster gimbal capabilities will allow NSTRDMS to provide an assessment of GN&C system performance. This can be combined with the current modeling of individual thruster strings to provide analysis of vehicle controllabillity in the context of remaining thruster lifetime and potential string failures. This will be valuable in determining the feasibility of maneuvers such as thrust arcs during Lunar Transit and orbit maintenance once in the NRHO.

Second is the expansion of NSTRDMS to missions outside of CMV. While the tool has been purpose built for CMV's mission, the modular design allows models to be rapidly updated or replaced. The current parameterization of the Lunar Transit can be replaced with any Δv based parameterization for any low-thrust or high-thrust trajectory. PPE IPS throttle curves can be swapped out for performance models of any propulsion system and the current solar array models can be quickly adjusted to fit different arrays or other power systems entirely (such as nuclear reactors). The compartmentalized nature of NSTRDMS affords the mission designer a high degree of freedom in what can be added into the framework.

NSTRDMS has already seen limited usage by the Compass Lab[9] at NASA's Glenn Research Center. Compass is a concurrent engineering team which develops rapid mission and vehicle conceptual designs for various customers within NASA, the government, academia, and private industry. The rapid analysis environment of NSTRDMS is a natural fit for Compass, which typically produces mission studies over a two-week period. During a 2022 study, NSTRDMS was modified to run trade analyses on a nuclear electric propulsion system, demonstrating the ‘plug and play’ capabilities of the tool. The results produced during this three week study informed decisions on mission architecture, propulsion system configuration, and propellant storage sizing. For future studies, NSTRDMS could be easily expanded to include models of subsystems not currently included such as propellant storage and management, thermal control systems, power distribution, etc. In this manner, NSTRDMS would become an integrated mission analysis and vehicle sizing tool, simplifying the design process for a mission study.

CONCLUSION

A rapid mission analysis tool has been developed to support the co-manifested first elements of NASA’s Gateway. A rocket equation based methodology allows for the complex low-thrust CMV Lunar Transit trajectory to be modeled through a relatively simple series of parameterizations. The Lunar Transit itself is represented through a parameterization based on high-fidelity analysis results, ensuring the accuracy of the low-fidelity analysis tool. The direct modeling of spacecraft power generation and propulsion systems allows for the performance of the vehicle to be quickly analyzed across the mission, giving insight into system behaviors and their responses to compounding variables such as vehicle mass and launch date. The resulting mission analysis tool enables the PPE MD Team to perform large trade analyses without the need for extensive computing resources or time. The results of these analyses have been validated against high-fidelity reference trajectories and have proven invaluable to the ongoing design and development of the CMV spacecraft.

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