NASA Spacecraft TRaDe Modeling System (NSTRDMS)

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NSTRDMS Overview

The NASA Spacecraft TRaDe Modeling System (NSTRDMS) is spacecraft mission analysis tool developed to enable the rapid assessment of a wide array of vehicle trades

NSTRDMS is specifically targeted at low-thrust trajectories, using a relatively simple methodology to analyze missions without the need for extensive computing resources

Capabilities of NSTRDMS include:

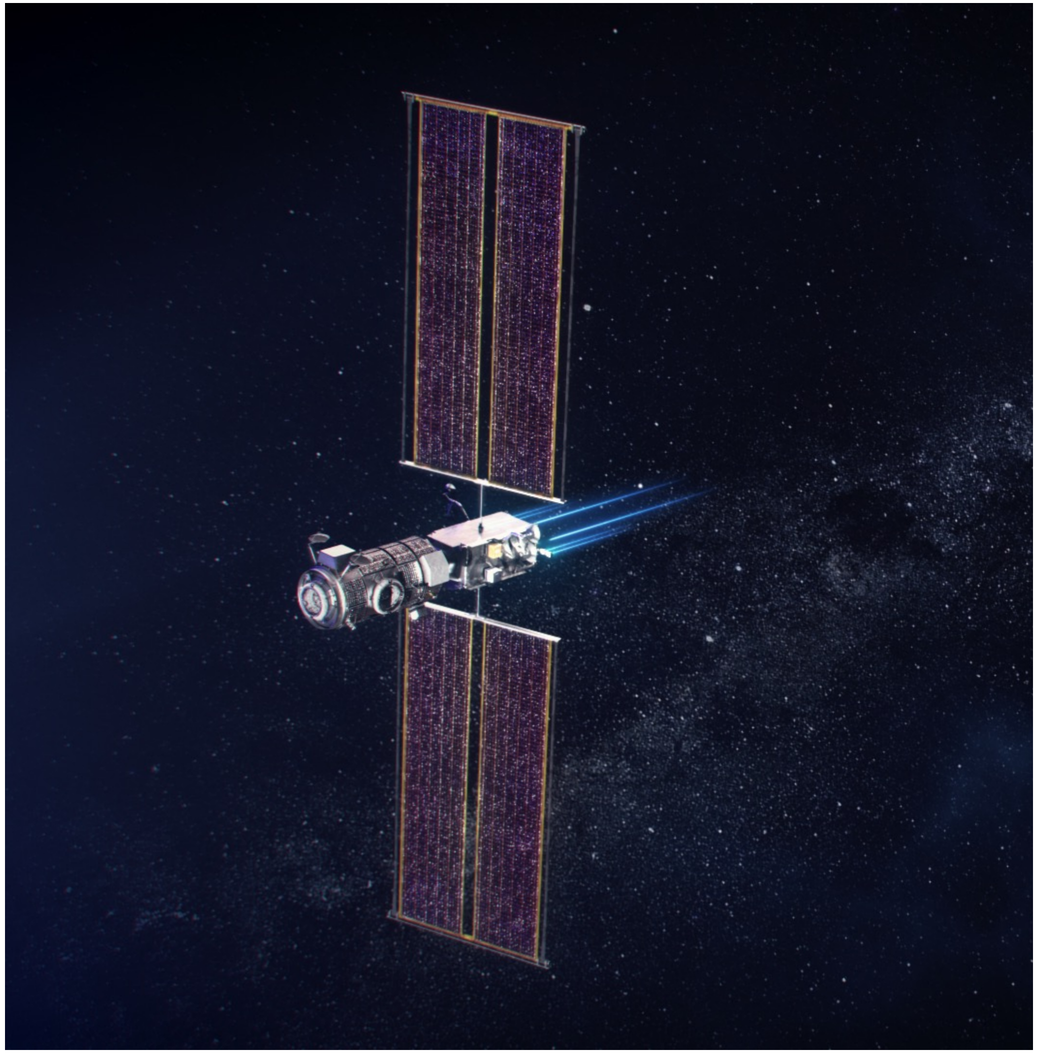
- Assessing the impact of changes to vehicle configuration and design as it pertains to mass, power, and propulsion systems
- Model the effects of launch vehicle performance and launch date on mission viability
- Rapidly incorporate updates and additions to the base methodology thanks to a modular tool design

Background

- Officially named in 2019, NASA’s Artemis program aims to establish a sustainable architecture to enable long term human explorations of the Moon and later Mars
- As a part of this sustainable framework, a Gateway is envisioned as a habitable orbital outpost in cislunar space
- Gateway will support human landings on the surface of the moon, serve as a communications hub for cislunar space, and support the development and maturation of technologies needed to continue human exploration on to Mars

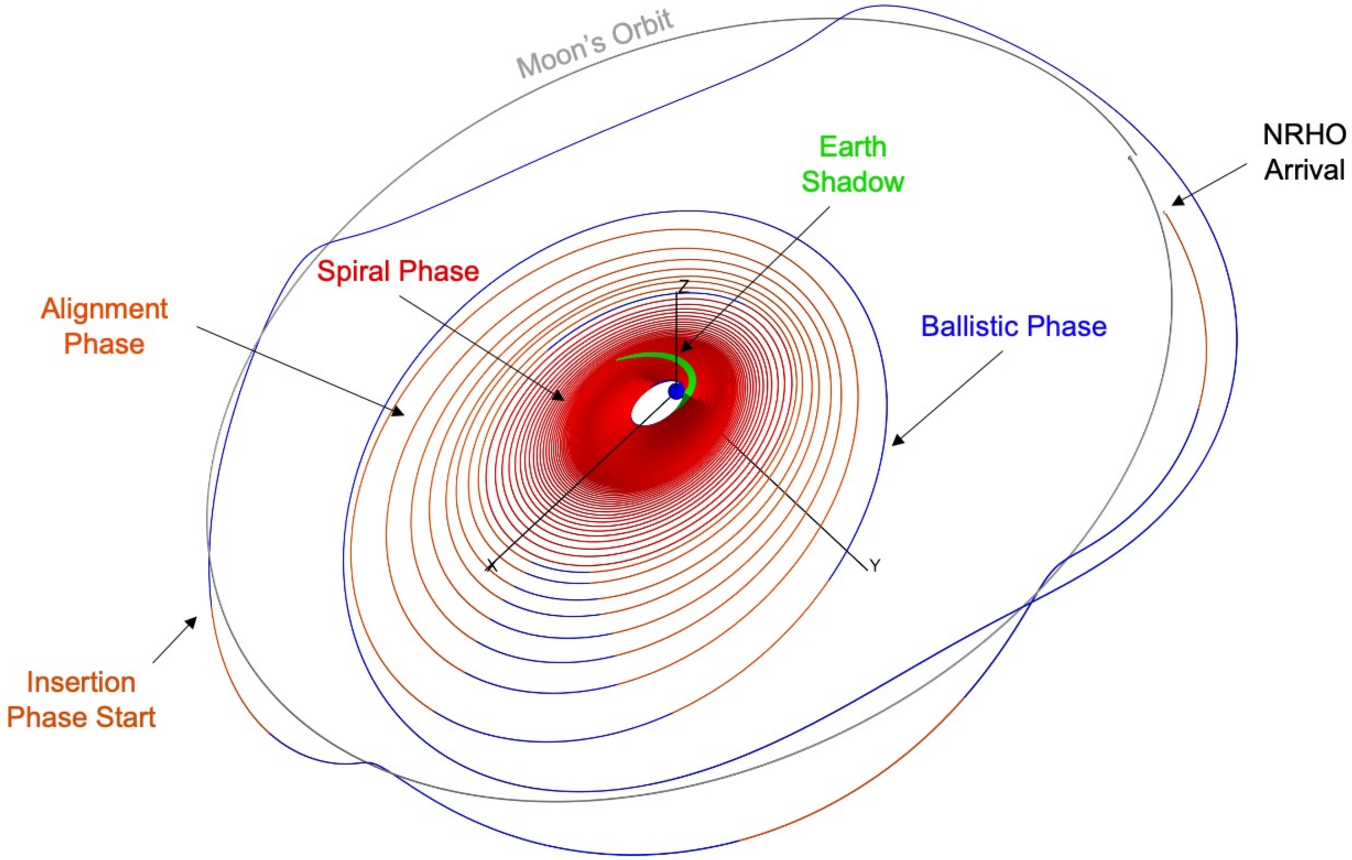
Background (continued)

- The first elements of Gateway to be delivered will be the Power and Propulsion Element (PPE) and the Habitation and Logistics Outpost (HALO)
- PPE and HALO will be launched and together as the Co-Manifested Vehicle (CMV) and complete their transfer to the Moon as a single stack
- The Ion Propulsion System (IPS) aboard PPE will be used to push the CMV stack to Gateway's chosen baseline orbit, an Earth-Moon L2 Southern (L2S) Near Rectilinear Halo Orbit (NRHO)



CMV Lunar Transit

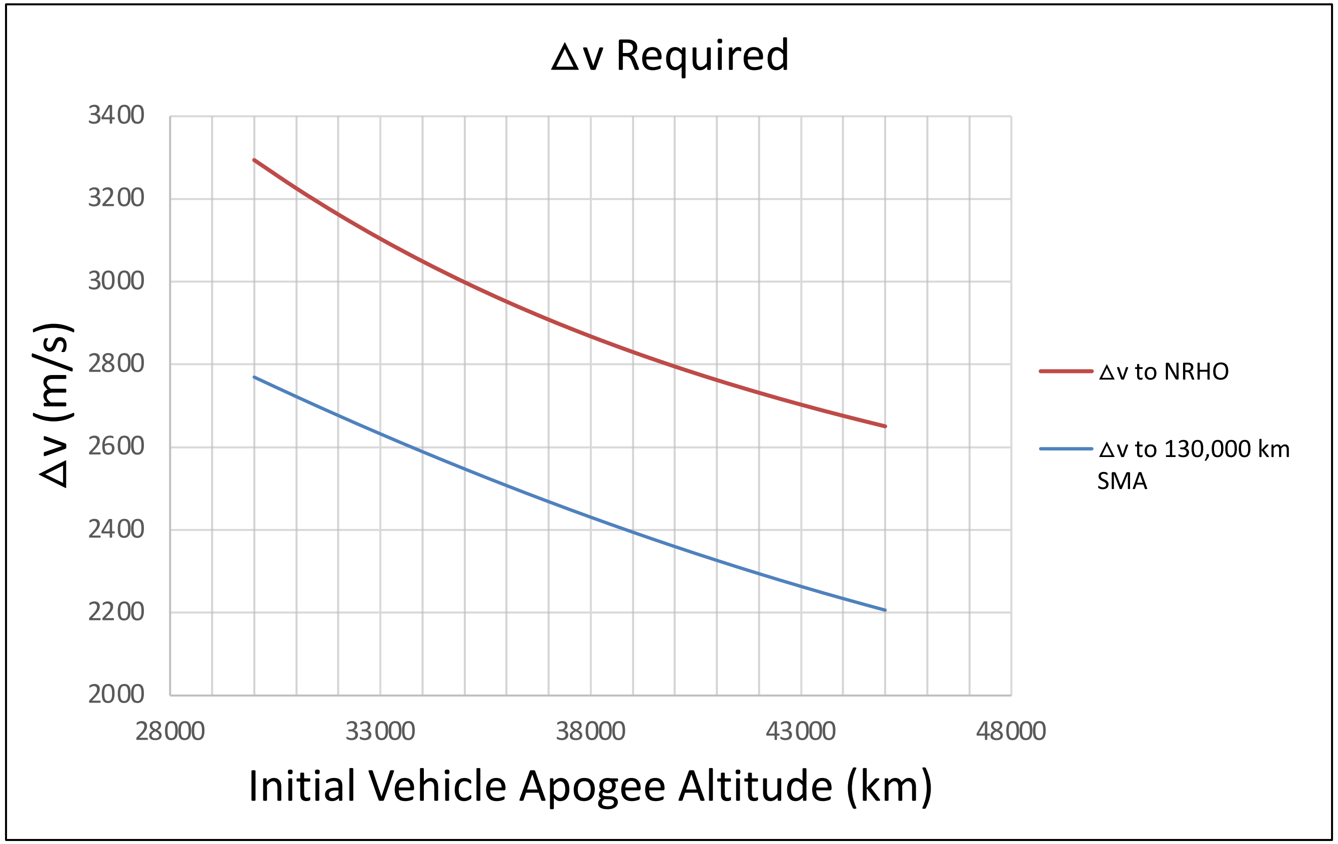
- **CMV Lunar Transit trajectory is broken into 4 primary phases[1]**
    1. Spiral Phase
    2. Alignment Phase
    3. Ballistic Phase
    4. Insertion Phase



- **An end-to-end optimized trajectory may take hours or even days to construct and solve in a program such as Copernicus[2]**
    - Copernicus is a trajectory design and optimization tool developed at Johnson Space Center
    - Copernicus is the primary trajectory design tool utilized by the PPE Mission Design (MD) Team
- **Trade analyses typically require that a model be modified (potentially to an extensive degree), then re-converged and re-optimized**
- **Even with a resource such as a large multi-machine cluster or server, running a large trade matrix may be infeasible**

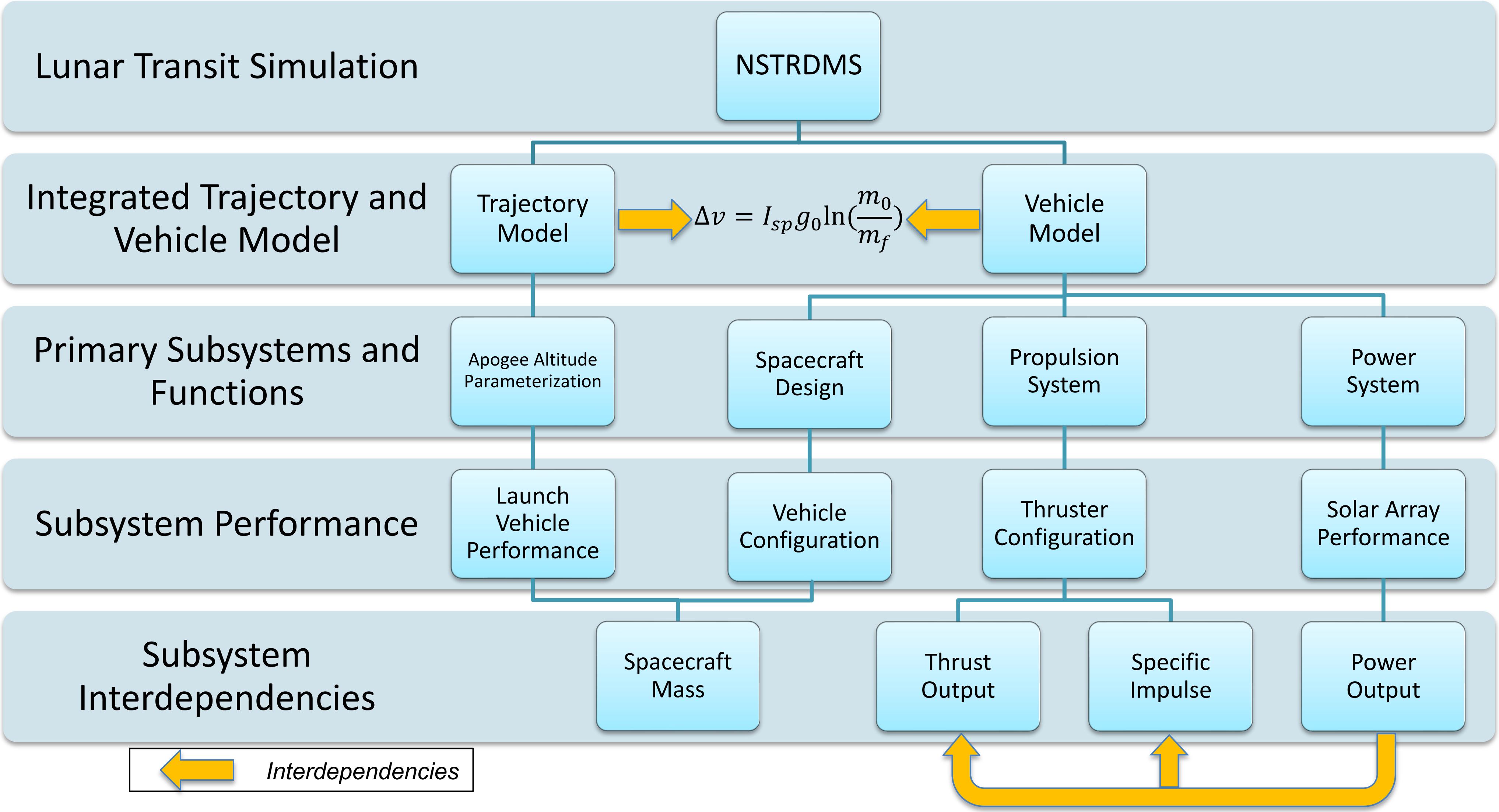
Methodology: Parameterization

- **Our goal is to distill a complex low-thrust trajectory into a relatively simple series of calculations**
- **Work previously completed by the PPE Mission Design Team has shown that Δv maintains a strong correlation to initial apogee altitude of the vehicle[3]**
- **The Δv required to reach the NRHO from some initial defined parking orbit can be parameterized as a function of initial parking orbit apogee altitude**
  - *This parameterization is possible because the initial perigee altitude of the parking orbit has been held to a constant value of 200 km throughout PPE/CMV development*
  - *Parameterizations developed from data generated using Copernicus[3] and GMAT[4]*
- **This same methodology can be applied to any orbital state of interest throughout the trajectory**
  - A semi-major axis of 130,000 km represents the demarcation between the spiral and alignment phases



Methodology: Integrated Analysis Environment

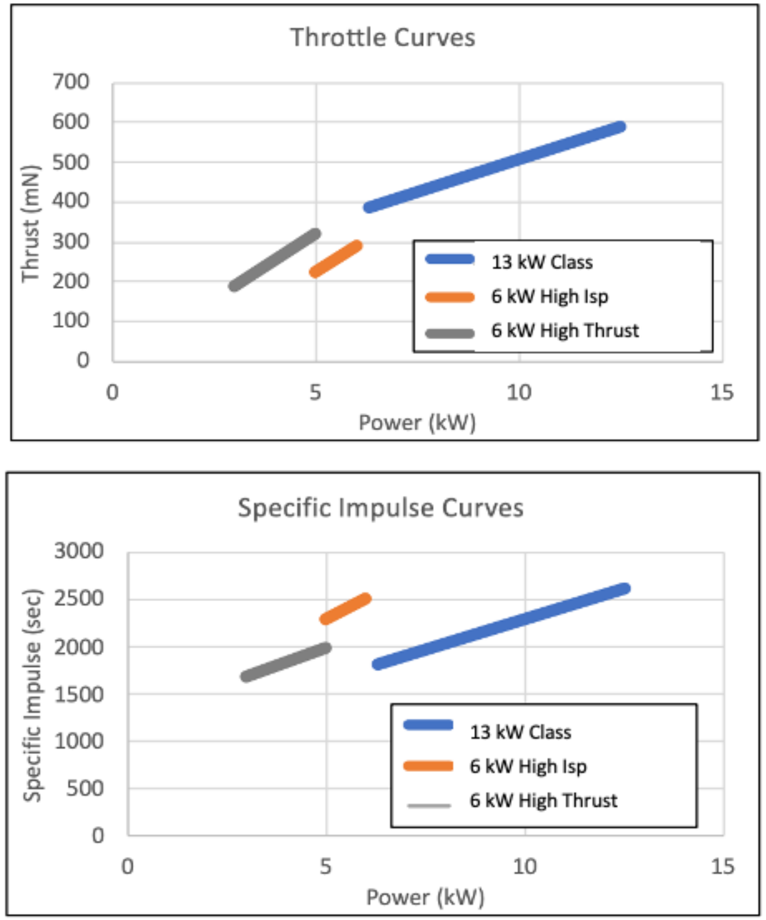
Δv defines our trajectory, NSTRDMS combines this Δv vs altitude parameterization with an integrated model of the spacecraft and its relevant subsystems



Methodology: Propulsion Subsystem Modeling

NSTRDMS has been designed around the PPE 50-kW class ion propulsion system (IPS)

- **The PPE IPS consists of 7 individual thruster strings of two types[5]:**
  - 3x 13-kW class thrusters
  - 4x 6-kW class thrusters
  - 6-kW thrusters have a High Thrust and a High Isp operating mode
- **Each thruster type has a distinct throttle curve where thrust, mass flow rate, and specific impulse can be calculated as a function of power into the Power Processing Unit (PPU)**
  - Thruster performance data accounts for PPU efficiency
  - Duty cycles can be applied to individual strings
- **Thruster lifetime and performance degradation can be incorporated into NSTRDMS as a function of propellant throughput, impulse, or operating time**
- **Modular tool design means that thruster throttle curves can be quickly switched out for updated data based on latest available qualification testing results**



IPS Throttle Curves[5]

Methodology: Power Subsystem Modeling

- **Power output from the solar arrays is modelled as a function of mission elapsed time (MET) and launch date**
  - Model accounts for non-SEP load demands from the vehicle, solar flux as a $1/r^2$ function, and array degradation as a function of time
  - Array degradation models provided by PPE Power team
    - Models account for MMOD impacts as well as ionizing radiation (primarily from Van Allen Belts)
  - Modeling follows the methodology outlined in Copernicus[2]

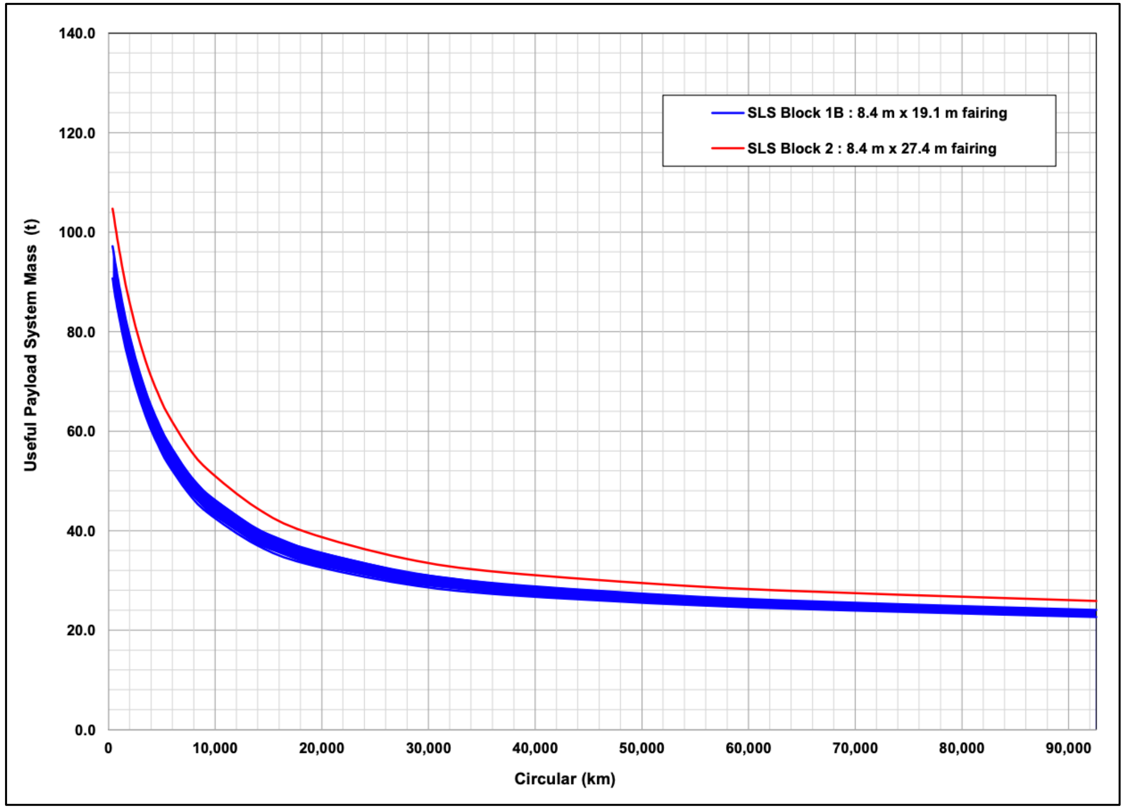
$$P_{thruster} = (\phi \cdot \kappa \cdot P_{input} - P_{reserved}) \cdot P_{factor}$$

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

Where $P_{thruster}$ is defined as the power into the PPU,
P_{input} is the power output of the solar arrays at MET + 0 days and a distance of 1AU,
$P_{reserved}$ represents the power loads from all non − SEP functions of the vehicle,
P_{factor} represents an engine efficiency (set to 1 as NSTRDMS handles PPU effiency within the thruster throtle curves),
ϕ is the Sun view factor (set to 1 for NSTRDMS calculations),
and g and r coefficients are used to model solar array degradation

Methodology: Launch Vehicle Modeling

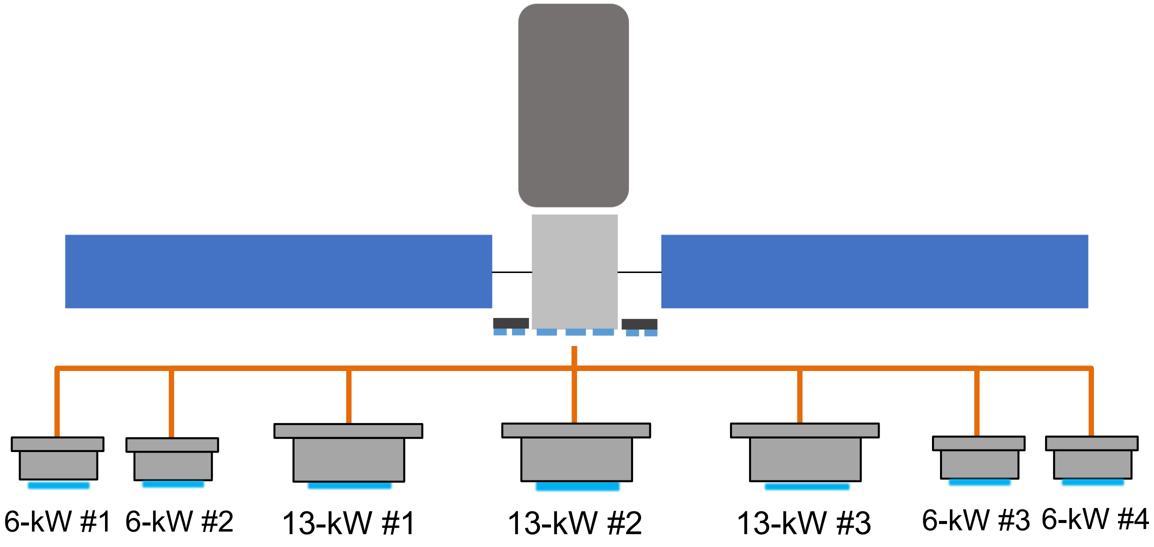
- **Launch vehicle (LV) performance is the singular parameter that couples our trajectory parameterization to our vehicle model**
  - Trajectory parameterization determines Δv from an initial parking orbit apogee altitude
  - LV performance determines parking orbit apogee from an initial vehicle wet mass
  - Wet mass thus drives both Δv and propellant mass (via the rocket equation)
- **SpaceX is on contract to launch CMV onboard a Falcon Heavy launch vehicle**
  - SpaceX and NASA's Launch Service Program provide the PPE MD team with expected Falcon Heavy mass to altitude capabilities based on a fixed perigee of 200 km
  - High fidelity models account for restrictions to elements such as RAAN and AoP due to operational considerations, these are not considered in NSTRDMS



Example LV Mass to Altitude Curve (SLS)[6]

Methodology: IPS Management

- **NSTRDMS models all thrusters as distinct, individual strings**
  - Each string is modelled throughout the entirety of the trajectory, not just when it is in operation
  - Opposed to a ‘configuration’ based approach where the thrusters are modelled as a single monolithic propulsion system
- **An IPS configuration is built at every time step from the pool of available thrusters dependent on constraints such as:**
  - Power available to SEP
  - Lifetime remaining on each individual string
- **Individual strings are dynamically throttled according to available power and thruster priority**
  - Power distribution by default is biased towards the 13-kW class thrusters
  - 6-kW thrusters are shut down if power availability drops too low to operate multiple thrusters concurrently
- **Thruster duty cycles, lifetime availability, and even string failures can be quickly modified to complete trades on various IPS configurations and thrusting strategies**
- **String based approach (instead of configuration) allows NSTRDMS to track results for individual thrusters such as throughput, hours of operation, etc**



Available power and thrusters
- Pull data from propulsion and power system models

Operational thrusters
- Designate thrusters that have failed or have exceeded lifetime limits as unusable

Implement IPS strategy
- Select thrusters to use, distribute power according to thruster priority, and apply duty cycle

Time step results
- Use $\dot{m}$ and I_{sp} to calculate propellant and Δv expended

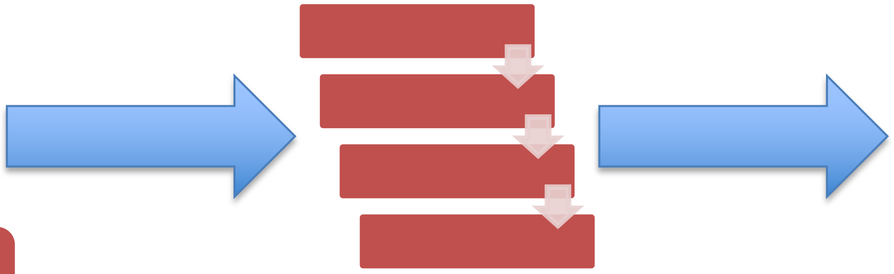
Methodology: Solving the Trajectory

NSTRDMS creates a virtual integrated CMV model, then marches that model forward in time to solve the trajectory

Initial vehicle mass, IPS model, power model, and LV model are fed to NSTRDMS

- Calculate Power to SEP from solar array model
- Create IPS Configuration from available thrusters and power (calculate thrust, mass flow rate, and specific impulse)
- Find propellant and Δv expended during this time step from IPS mass rate and rocket equation
- Track running total of Δv expended so far. Feed final mass into next time step

Iterate forward in time by user specified time step (default Δt = 1 day)



Model terminates when the vehicle reaches the NRHO

- Calculate Power to SEP from solar array model
- Create IPS Configuration from available thrusters and power (calculate thrust, mass flow rate, and specific impulse)
- Find propellant and Δv expended during this time step from IPS mass flow rate and rocket equation
- Total Δv expenditure meets the required amount to reach the NRHO, the trajectory is complete

Validation: Figures of Merit

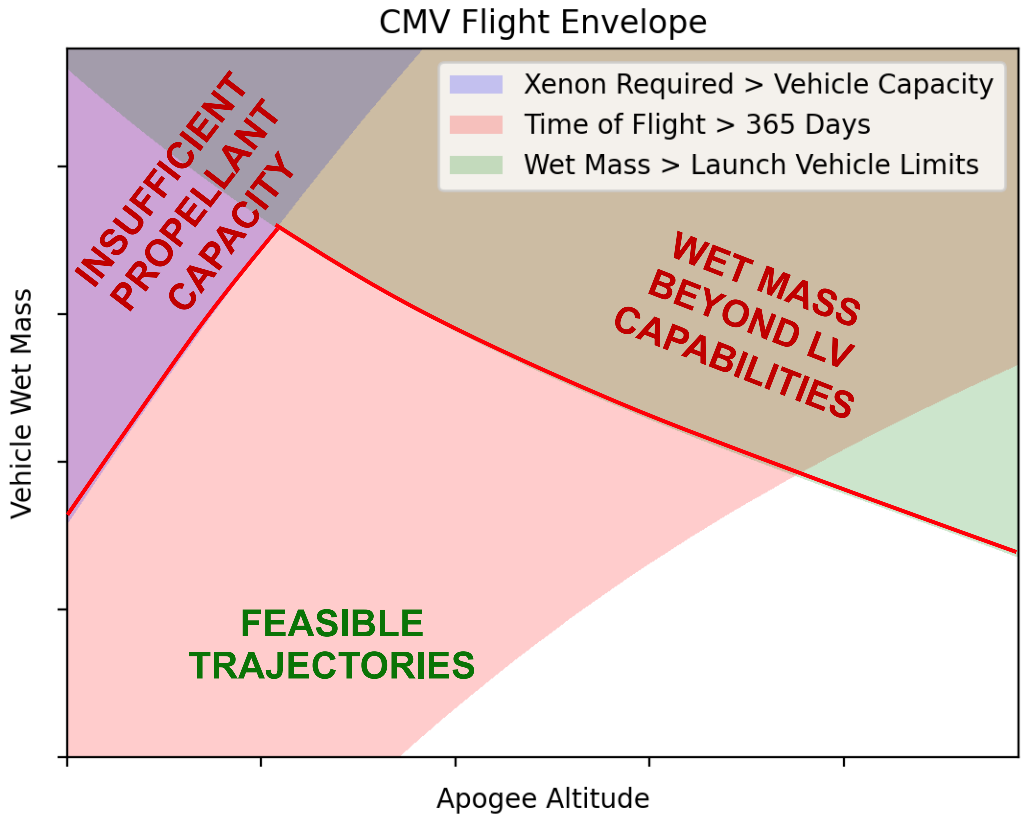
NSTRDMS is used as a low-fidelity but not low accuracy tool for the PPE MD Team

- **Nature of low thrust trajectories make optimized solutions difficult to predict as key parameters such as vehicle mass or launch date change**
- **NSTRDMS, by design, represents a near-optimal solution for the Lunar Transit**
- **DRM trajectories are often chosen to be non-optimal, increasing variation across development cycles**
- **NSTRDMS has proven to be dependable and resilient across multiple CMV design cycles**
- **Trade results are regularly validated against high-fidelity results**

Parameter	NSTRDMS Beta against DRM-2 Copernicus Results	NSTRDMS 1.0 against DRM-3 Copernicus Results	NSTRDMS 2.0 against DRM-4 Copernicus Results
Time of Flight Error	0.8%	0.8%	0.07%
Xenon Usage Error	0.15%	0.04%	0.07%
Total Impulse Error	1.1%	0.01%	0.43%
Mass to NRHO Error	0.08%	0.01%	0.01%

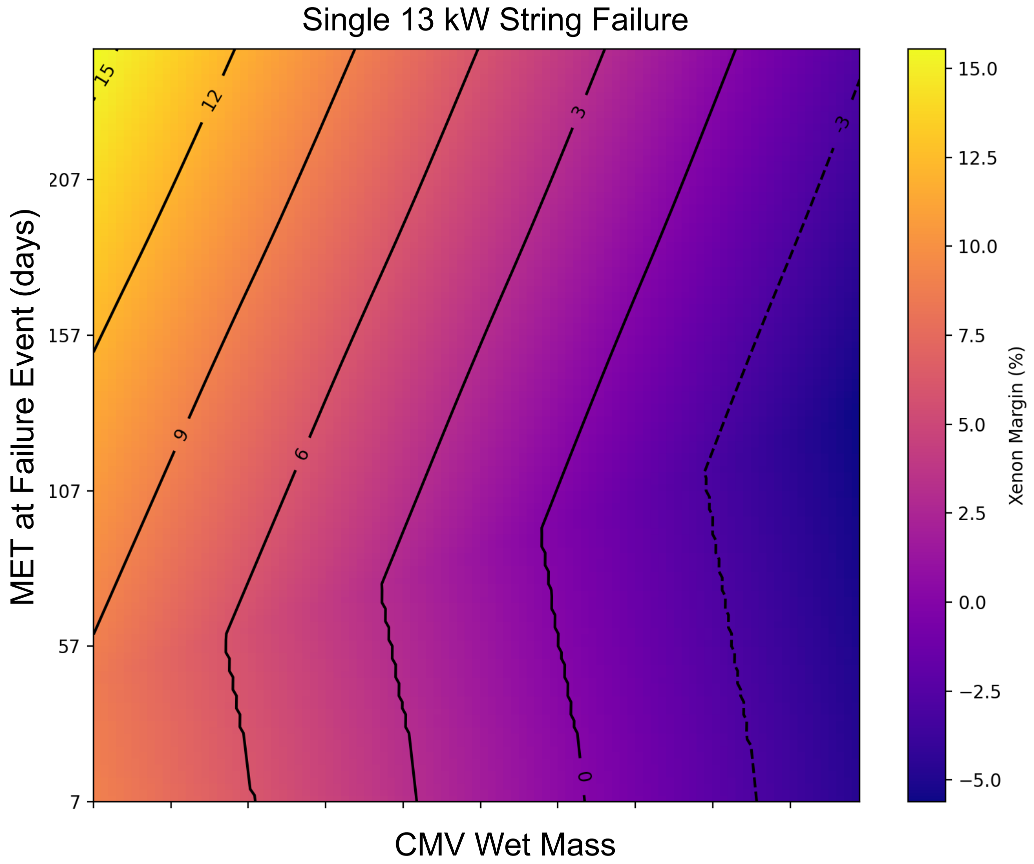
Results: Flight Envelope

- **NSTRDMS has been used since Fall 2020 to provide trade analysis for the CMV Lunar Transit trajectory**
- **Flight Envelopes provide useful visualizations of the CMV trade space and differences between DRM trajectories as the CMV design continues to evolve**
  - Flight envelope is bounded by LV mass to altitude performance and CMV propellant capacity
  - Flight envelopes can be quickly generated for varying launch dates, IPS configurations, and power models
  - >1,000 runs go into a typical envelope
    - Envelope to the right incudes 1,250 trajectory results
      - NSTRDMS execution time: 20.6 seconds
    - Building an equivalent set of trajectories in Copernicus would be a massive undertaking in terms of manhours and computation time
- **NSTRDMS enables the PPE MD team to assess a large trade space in a fraction of the time that would be required with existing trajectory analysis tools**



Results: Thruster String Failures

- **Modeling of distinct thruster strings allows NSTRDMS to assess the impact of individual EP string failures on the CMV Lunar Transit**
  - Any of the 7 individual thrusters can be designated to fail at any point in the mission
    - Event can be triggered by MET, thruster throughput, impulse, or Δv
  - Recovery strategies and throttling profiles can then be imposed to build out the trade space
  - Compounding variables such as thruster lifetime, launch date, and thruster operation modes are all accounted for



Summary

CAPABILITIES

- **NSTRDMS can rapidly perform trades that would be difficult or infeasible in high-fidelity analysis tools**
  - NSTRDMS can run millions of set points in a matter of minutes
- **Highly modular design allows for analysis capabilities to be easily expanded over time**
- **Integrated trajectory/vehicle modeling assesses subsystem interdependencies throughout a trajectory**

LIMITATIONS

- **NSTRDMS is a mission analysis tool, not a trajectory design tool**
- **NSTRDMS can not natively develop trajectories on its own, it can only perform analysis on trajectories that already exist**
- **The tool requires multiple outputs from high-fidelity tools to operate**
  - At a minimum, some estimate of transit Δv must be provided
  - For version 2.0, multiple Δv parameterizations feed the analysis
- **The effects of many variables such as atmospheric drag, solar radiation pressure, AoP, RAAN, etc can not be modelled in the NSTRDMS environment**

Future Development

Several updates are already planned for the near future

Guidance, Navigation, and Control

- Modeling of individual thruster strings allows for the capability to analyze spacecraft controllability as a function of remaining propellant and thruster lifetime
- Add GN&C subsystem modeling to allow for thruster gimballing, momentum wheel, and reaction control system contributions to spacecraft control analysis
  - Primarily will be applied to Gateway orbit maintenance while in the NRHO

Expansion beyond CMV

- The 'plug and play' framework and methodology of NSTRDMS means that the tool can be easily modified to support a wide range of work beyond the confines of CMV/Gateway
- Any trajectory, low- or high-thrust, can be modelled as long as a Δv estimate can be determined
- New propulsion, power, and launch vehicle models can be integrated to model different solar arrays, nuclear power systems, chemical or nuclear thermal propulsion systems, etc
- Vehicle parameters can be made trade outputs, where NSTRDMS would size propulsion systems, propellant storage, solar arrays, etc
  - More detailed subsystem models and cycle analyses can be included with little adjustment to the base framework
  - Potential usage in rapid spacecraft design and conceptualization environments such as the NASA GRC Compass Lab

References

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[2] Ocampo, C. and Senet J., "The Design and Development of COPERNICUS: A Comprehensive Trajectory Design and Optimization System", 57th International Astronautical Congress, 2006

[3] McCarty, S., Sjauw, W., Burke, L., and McGuire, M., "Analysis of Near Rectlinear Halo Orbit Insertion with a 40-kW Solar Electric Propulsion System", *AAS/AIAA Astrodynamics Specialist Conference*, 2018

[4] Hughes, S. and Grubb, T., "General Mission Analysis Tool (GMAT)", GSFC-E-DAA-TN29897, NASA Goddard Space Flight Center, 2016

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[6] "Space Launch System (SLS) Mission Planner's Guide", M17-6014, NASA Marshall Space Flight Center, 2018

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