Mission Design Considerations for a Low-Thrust Spacecraft

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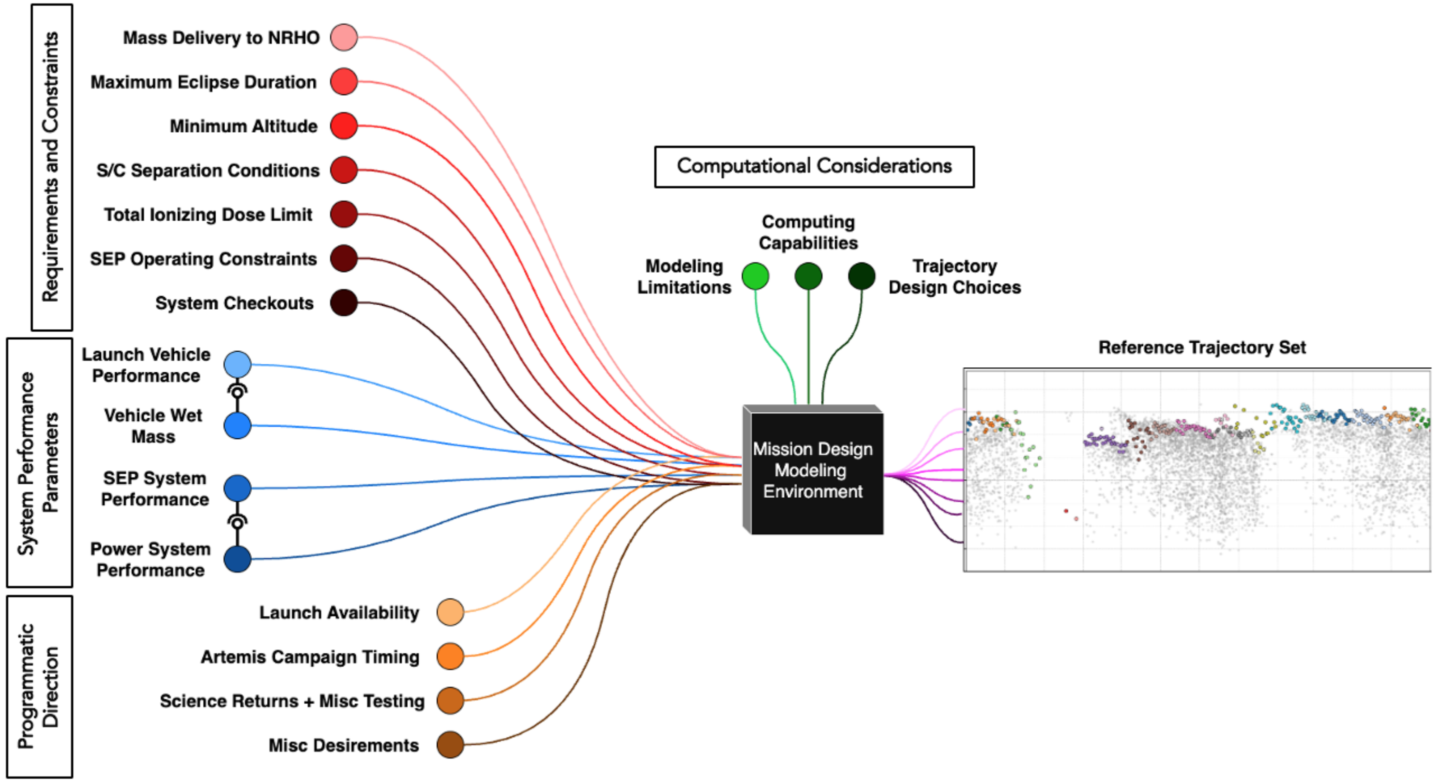
Background and Introduction

- **Electric propulsion has matured from a bespoke technology with relatively niche applications to a workhorse of low-Earth orbit and exploration missions over the last 30 years[1]**
  - First electrostatic thruster – 1960 (NASA Lewis Research Center)
  - First on-orbit demonstration of EP – 1964 (SERT-1, NASA LRC/MSFC)
  - Deep Space 1 – 1998 (JPL)
  - Dawn – 2007 (JPL)
  - Psyche, PPE, BepiColumbo, Starlink, all-EP geostationary comsats, etc – Today
- **The field of low-thrust trajectory design has matured alongside these spacecraft, although its heavy reliance on optimization techniques and sensitivity to path constraints make it lag behind high-thrust counterparts**
- **Robust low-thrust trajectory design remains an emerging and under-represented topic in literature due to the small number of missions (and thus personnel) that have required it**
- **Validation of low-thrust trajectories against requirements, constraints, uncertainties, and risks is critical to the development of executable missions**
  - One-off nature of these missions often means each spacecraft presents its own unique challenges
- **Risk-aware, error-tolerant, flyable trajectories may represent a significant departure from feasibility or conceptual level analysis**

Integrated Optimization Problem

- Executable spacecraft trajectories do not just represent feasible paths through space
- Trajectories represent the implementation of a mission architecture and spacecraft design
- Some requirements and constraints are applied a-priori
- Many constraints and risks are considered and validated a-posteriori

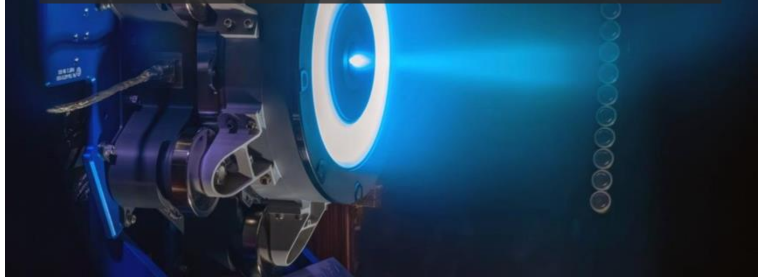


- While it is desirable to include as many boundary and path constraints directly into the optimization problem, it is not always feasible or advantageous to do so within available modeling and computational resources
- These considerations make executable trajectories inherently less-performant than lower fidelity optimized solutions

General Uncertainties

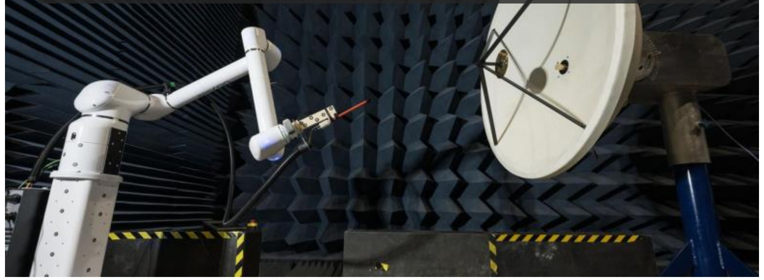
Hardware = Constraints

- Operating constraints
- Qualification limits
- Hardware cannot perfectly execute commands
- TRL impacts risk posture



Pre-flight knowledge is imperfect

- Ground facilities imperfectly replicate space
- Impossible to exactly predict on-orbit environment
- All models are wrong

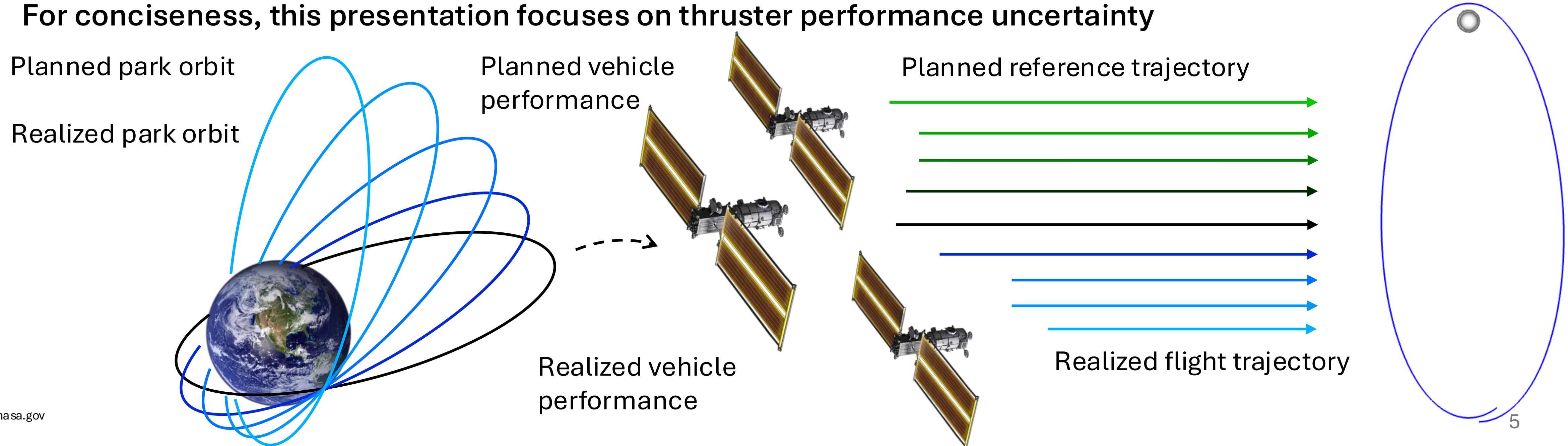


In-flight knowledge is imperfect

- Spacecraft knowledge is always incomplete and only as good as sensors/telemetry allow
- Ground will always have uncertainty in:
  - State (position/velocity)
  - Mass
  - System performance (thruster output, pointing accuracy, clock drift, onboard state, etc)

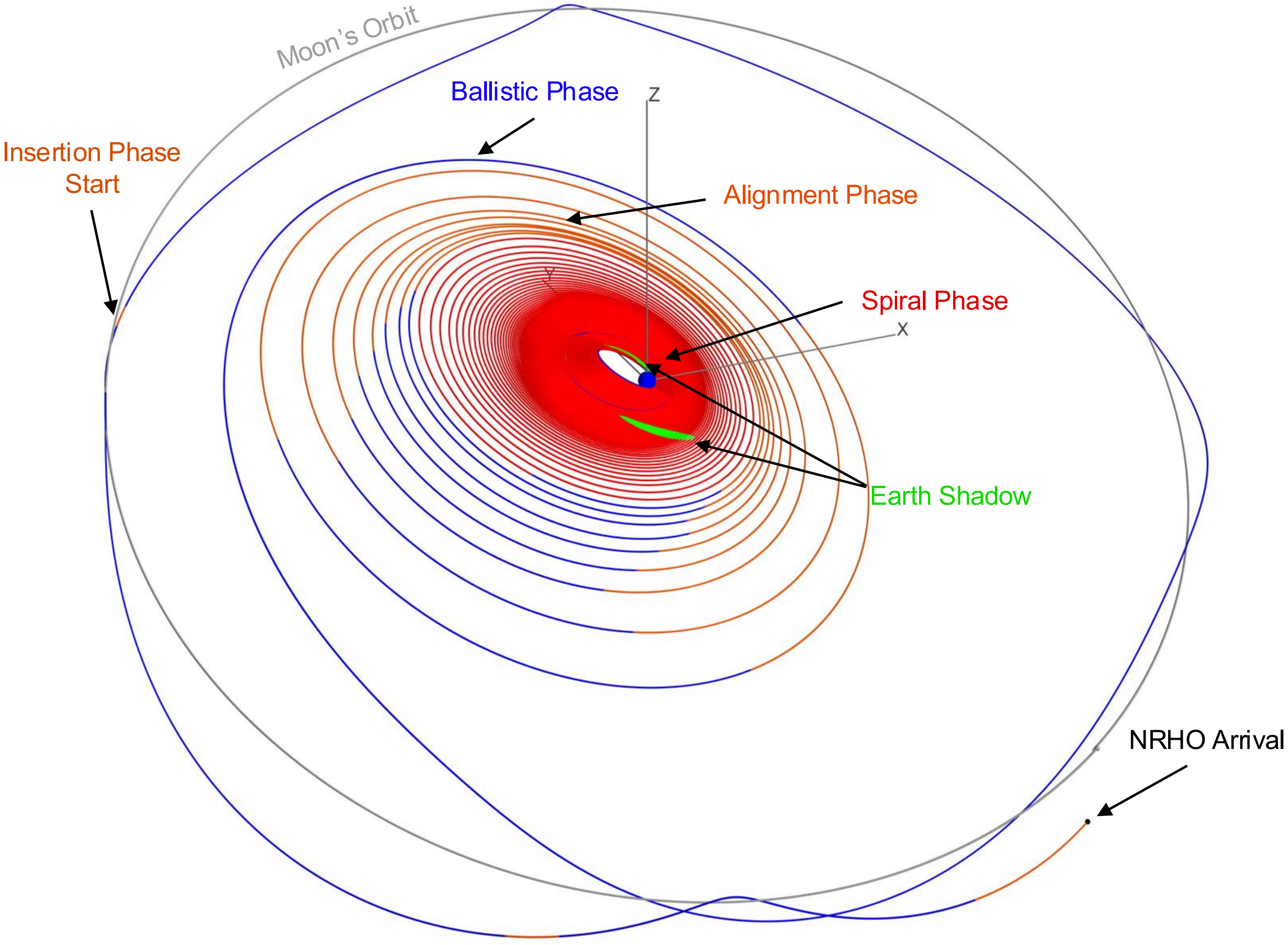
Mission Uncertainties

- **Low-thrust missions are made more challenging than high-thrust equivalents by sensitivities to thruster performance uncertainty, missed thrust events, etc**
- **Methodologies by which the PPE MD team assessed many uncertainties has been discussed previously[2]**
- **Paper presents analysis of:**
  - Launch vehicle insertion error
  - Thruster performance and power availability uncertainty
  - Missed thrust events (a more thorough discussion was published in Feb 2026[3])
  - Thruster string failures
- **For conciseness, this presentation focuses on thruster performance uncertainty**



Gateway Lunar Transit

- Lunar Transit was envisioned to be a >365-day low-thrust spiral[4]
- Launch on SpaceX Falcon Heavy to ~GTO
- Use 48kW Solar Electric Propulsion (SEP) system to spiral out to NRHO
- >2t xenon used at an Isp ~2,600s (>3 km/s Δv)[5]
- >300-days of deterministic thrusting



Earth-Centered J2000 Inertial Frame

Risk Mitigation

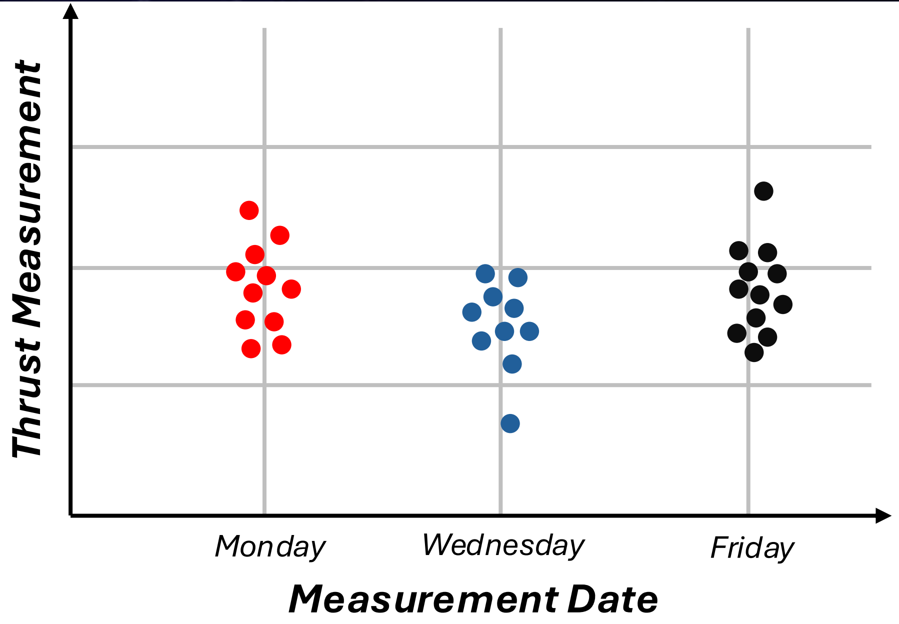
- Uncertainties are accounted for with a combination of margins and reserves applied to time and propellant mass

Reserves	Margins
Covers the "known unknowns" • Uncertainties that ***will be realized*** but do not know to what extent • ***Time reserves built into trajectories*** as a duty cycle or as an explicit period of coasting • Xenon reserves are used to ***correct errors via additional thrusting*** • ***Often informed by monte carlo analysis***	**Covers the "unknown unknowns"** • Off-nominals and contingencies that ***may or may not occur*** • Errors/uncertainties/risks that are ***not being tracked pre-flight*** • Beyond-3σ scenarios that are ***not reasonable to protect for*** with reserves • ***May be informed by case-specific or monte carlo analyses***
• Protected for in the selection of nominal missions	**• Formed by whatever is left unaccounted for in prop tank capacity / time of flight**

Thruster Performance Uncertainties

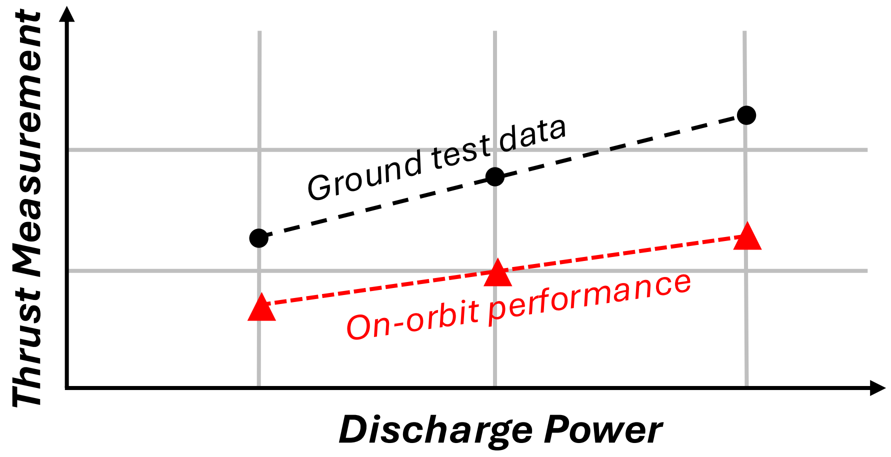
Thrust Measurement Uncertainty

- **Precisely measuring the thrust output of a hall effect thruster (HET) is difficult (and well documented)**
  - AEPS weighs ~46 kg[6] and produces 586mN thrust at 12kW discharge[7] (T:W ratio of 0.001)
- **NASA GRC's VF6 facility is among the most well-characterized test chambers in the world**
- **VF6 test stand has been characterized at: +/- 6.9 mN at a 95% confidence interval[8]**
  - **At AEPS maximum output, this is still 1.2%!**



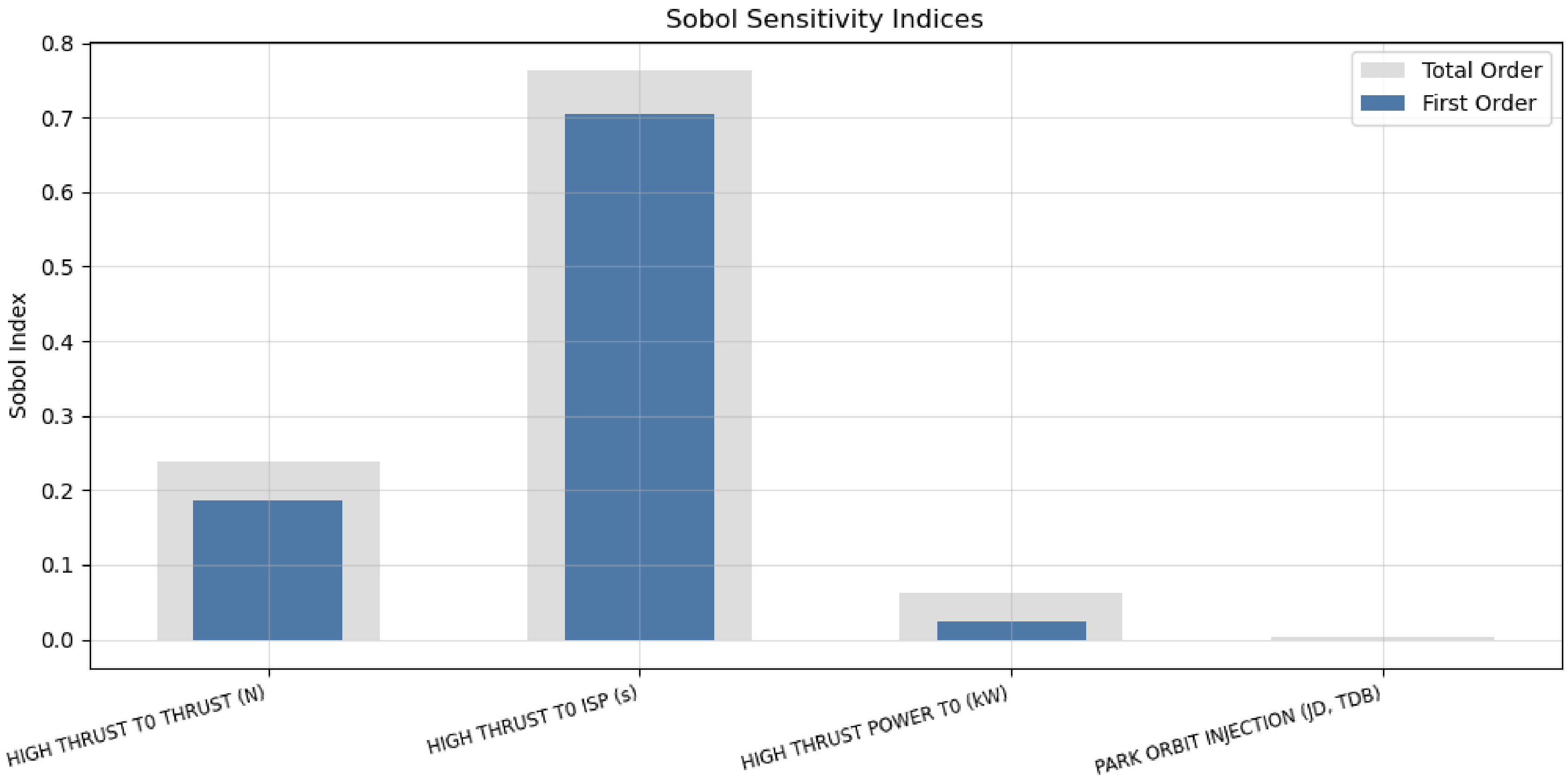
Facility Pressure Effects

- **Historical experience has shown that HET performance is sensitive to facility back-pressure[9]**
  - Thrust performance increases with back-pressure due to stabilizing effects on plume divergence
- **Lack of quality & widely available on-orbit performance reconstructions of HETs means there is no standard accepted method to extrapolate ground test data to on-orbit performance**



Results

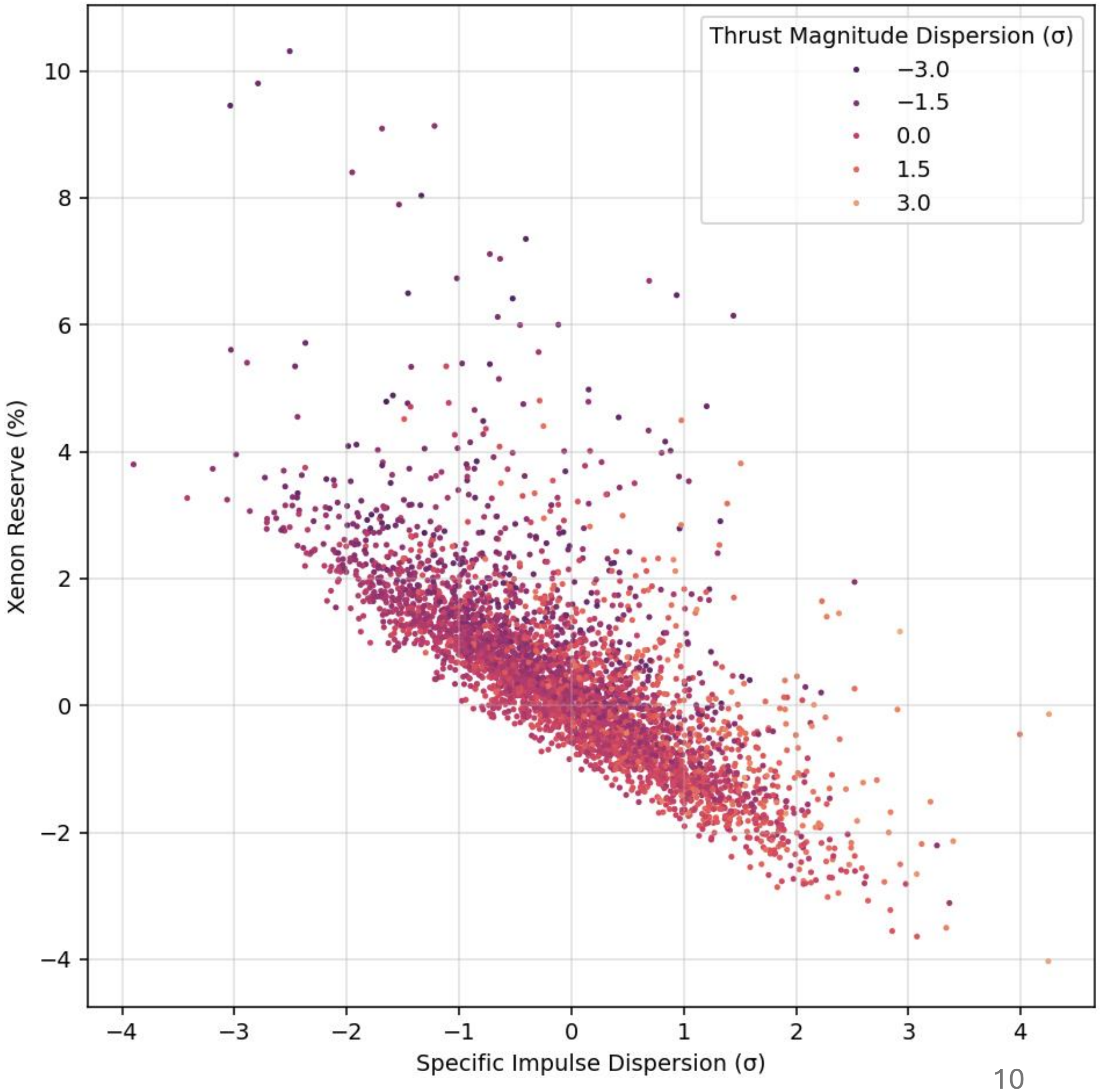
- Analysis was conducted against 3σ uncertainties in:
  - Thrust magnitude
  - Specific Impulse
  - Power available to SEP
- Monte carlos included variations in expected launch date to capture solar array generation variation wrt range to Sun
- Results encompass ~4,000 samples across 21 launch dates (~190 samples / ld)
- Sobol sensitivity analysis shows that variations in Isp dominate propellant use results
- Secondary effects from thrust magnitude due to eclipse seasons



- Minor impacts from power to SEP and launch date (variations in expected power to SEP were much smaller than measurement uncertainty in thruster performance)

Results

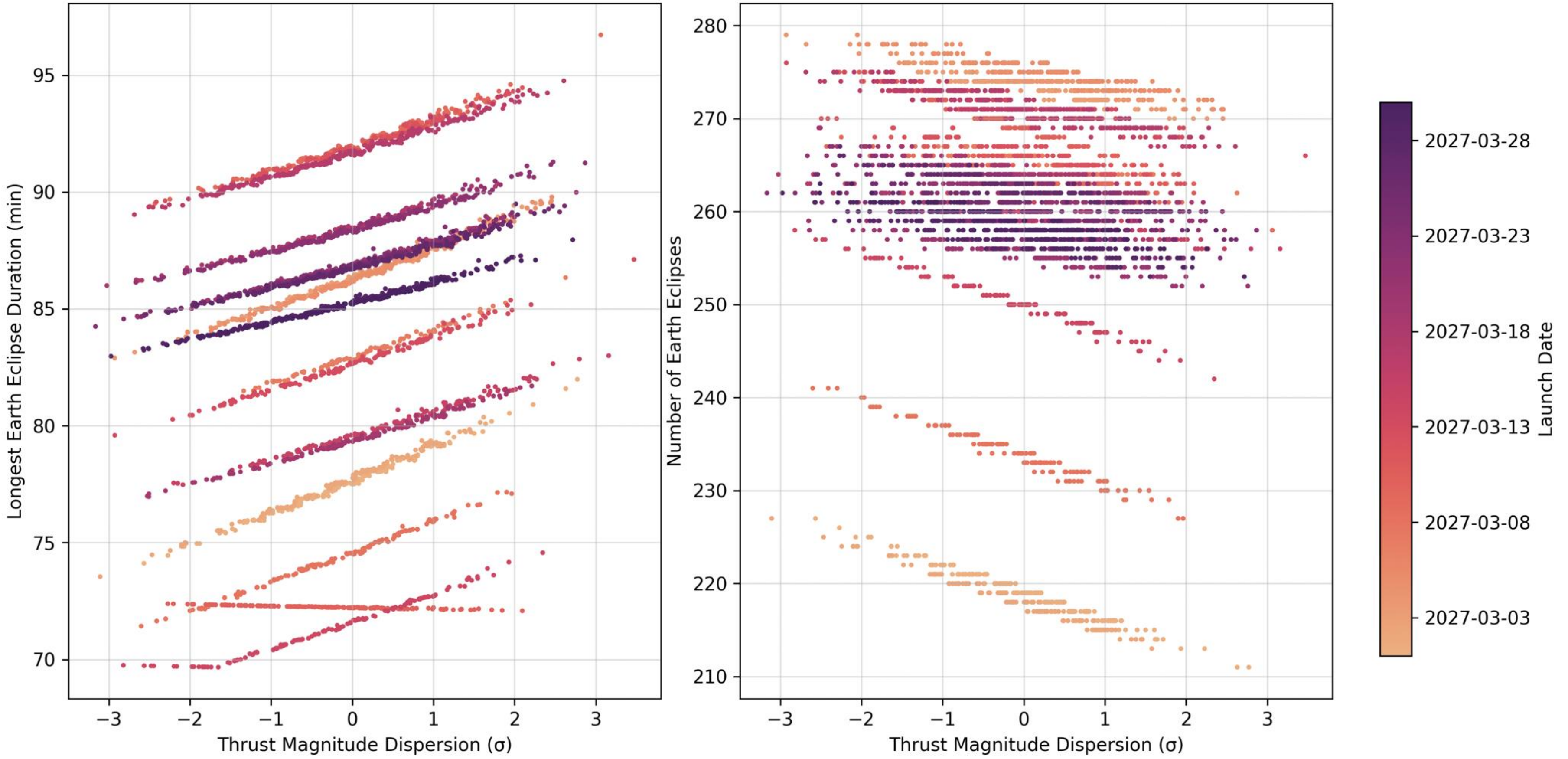
- Specific impulse variation has a near 1:1 correlation with propellant consumption
- Results are presented in terms of xenon reserve required to protect against variations in Isp
- Assumes Isp uncertainty follows gaussian distribution
- Mean + 3σ variation in Isp requires ~4.6% mean + 3σ xenon reserve to correct
- Secondary impacts from thrust magnitude due to eclipse impacts and thrust/Isp coupling behavior



Results

- Thrust magnitude variations directly impacted eclipse profiles across a transit, with higher thrust resulting in, on average, a smaller number of longer eclipses than nominal

- Lunar Transit was required to avoid eclipse durations of >90 minutes
- 3σ variations in thrust magnitude resulted in +/- 3 minutes max eclipse duration
- +/- 5 in the total number of eclipses experienced
- This behavior exemplified the need to build in adequate margin to all path constraints, not just transit time and propellant consumption



- Additional conservatism in designing for 85-minute eclipses instead of 90-minutes further drives executable trajectories away from optimal solutions

Margins and Reserves Impacts

- Paper covers similar monte carlo analysis for launch vehicle insertion errors, end-to-end missed thrust analysis, and a loss-of-AEPS contingency scenario
- 3σ uncertainties in selected known unknowns require a total of 9% xenon reserve to protect against
- Thruster failure contingency requires 9.9% xenon margin
- Together these account for 19% of the deterministic xenon utilization, which well exceeds recommendations in literature of 8-12%[12]
- Risk posture to protect against a failure of a single AEPS alone accounts for 10% margin

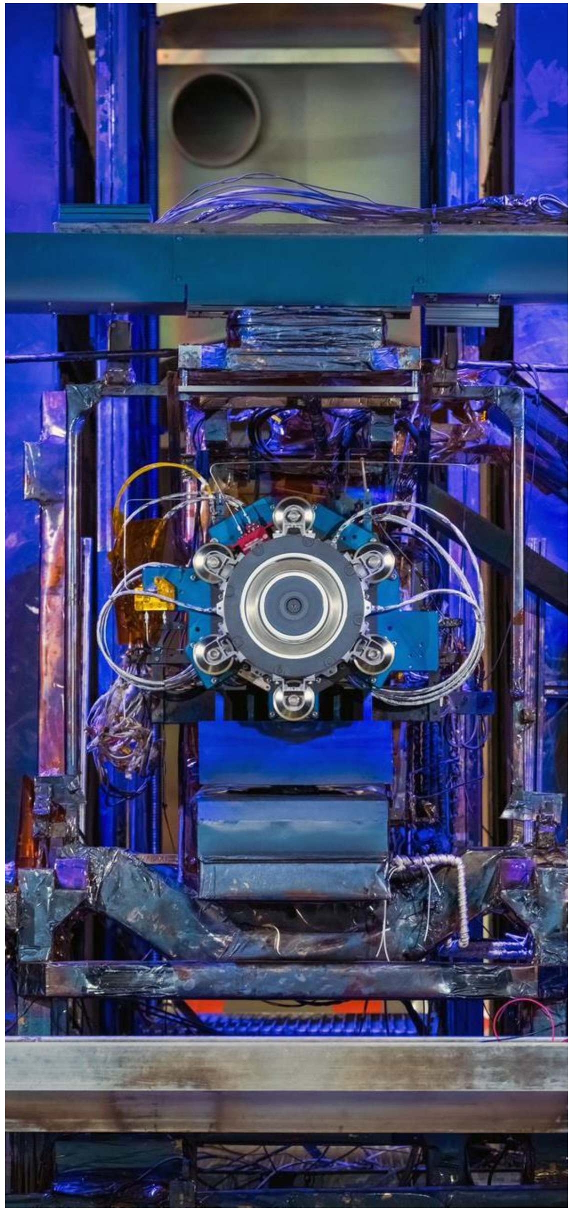
	Mean + 3σ Xenon Reserve	Xenon Margin
LV Injection Error	1.7%	0%
SEP Uncertainty	4.6%	0%
Missed Thrust (21-days)	2.7%	0%
AEPS Failure	0%	9.9%
Total	9%	9.9%

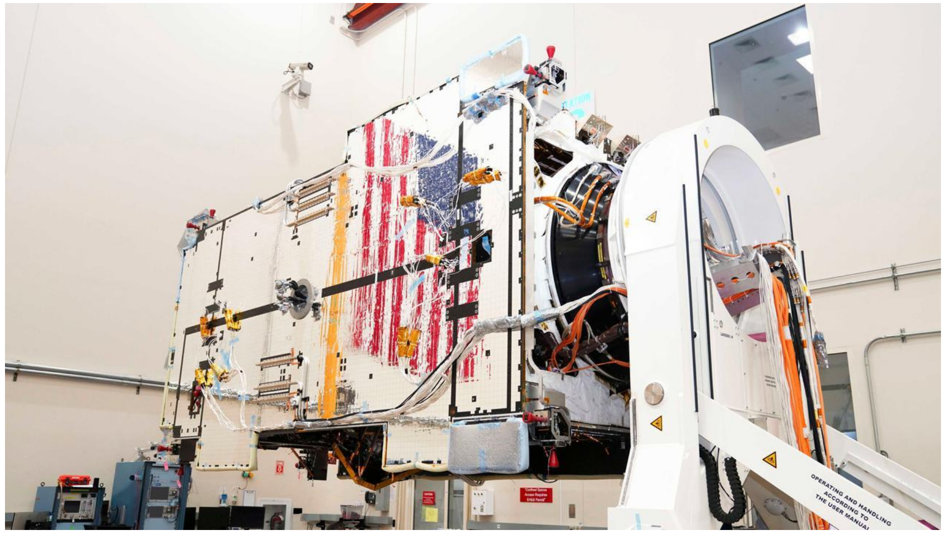
What level of conservatism is harmful to the mission?

Conclusions

- It is tempting to design a mission to the limits of spacecraft capabilities
- Executable missions must be designed to the limits of knowledge
- For Gateway, three of these limits (on-orbit thruster performance, launch vehicle insertion accuracy, missed thrust) manifested in 9% xenon reserve
- Risk posture surrounding implementation of a first-of-its-kind technology (AEPS) drove a further 10% xenon margin
- Nature of technology development meant that many uncertainties were not incorporated until relatively late in the mission lifecycle
  - Flight-like thrusters needed to be designed before measurement uncertainty could be characterized
  - Weakness of new-dev vs heritage technologies
- Incorporating informed-conservatism as early as possible reduces churn, mitigates risks before they become critical, and can head-off costly and time-consuming mass reduction efforts

The PPE Journey





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