

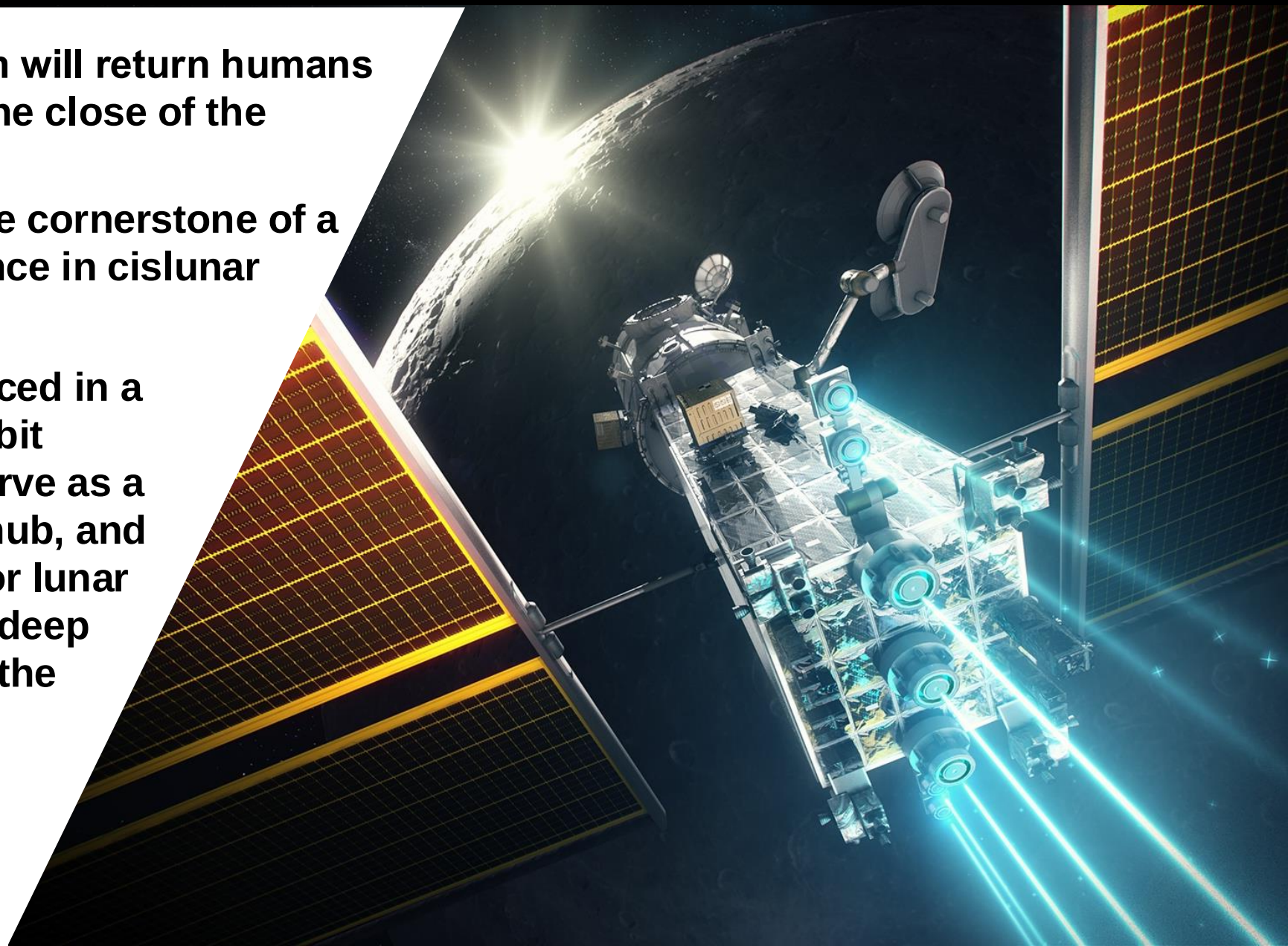
Recovery From Missed Thrust During Gateway's NRHO Insertion Using Auxiliary Propulsion

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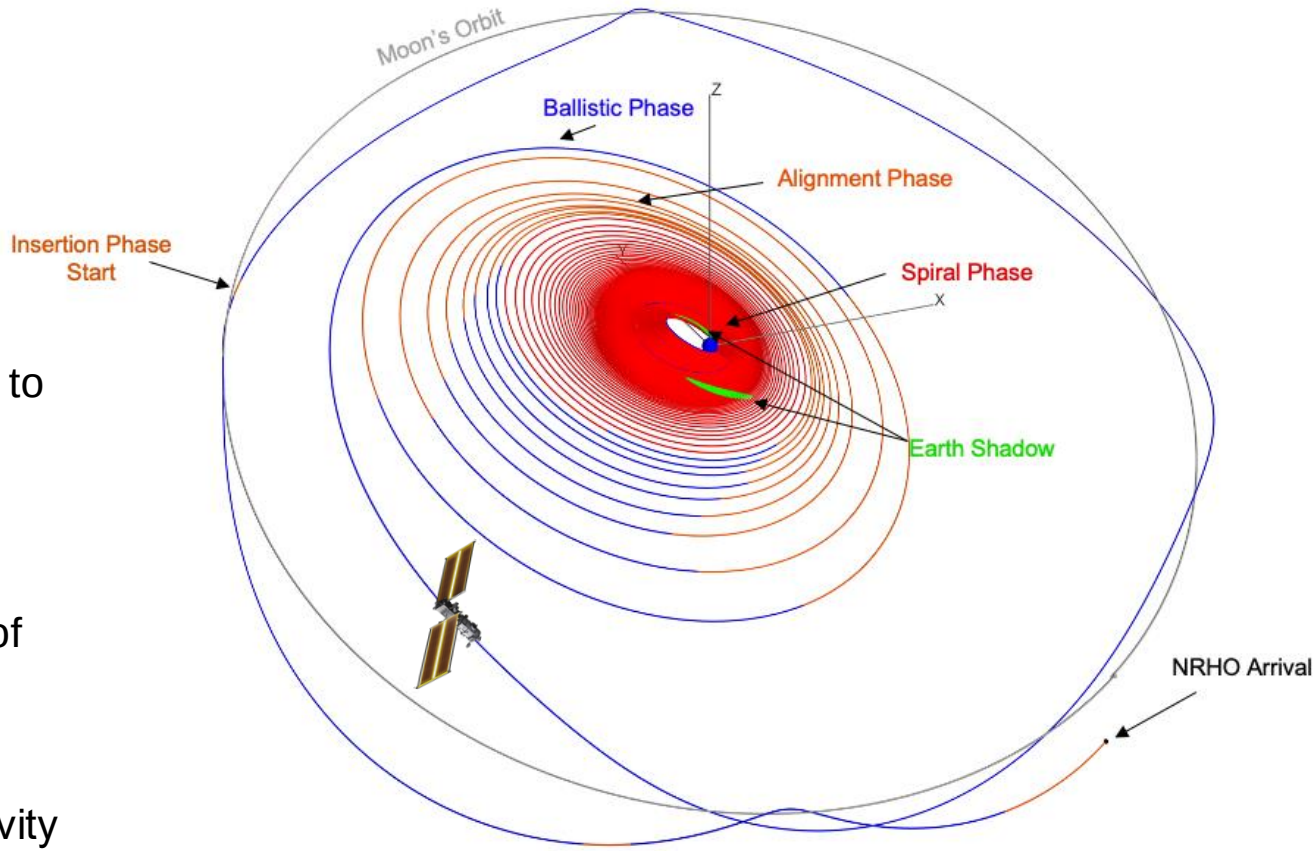
Background

- NASA's Artemis program will return humans to the lunar surface by the close of the decade
- Gateway will serve as the cornerstone of a sustained human presence in cislunar space
- As a crewed outpost placed in a Near Rectilinear Halo Orbit (NRHO), Gateway will serve as a staging point, logistics hub, and communications relay for lunar surface exploration and deep space missions beyond the Earth-Moon system



Gateway Lunar Transit

- **The first elements of Gateway to be delivered will be the Power and Propulsion Element (PPE) and the Habitation and Logistics Outpost (HALO)**
  - These two will transit to the NRHO together as a single integrated spacecraft
- **CMV will fly a low-thrust Lunar Transit trajectory[1]**
  - Launch vehicle will deliver Gateway to an elliptical Earth parking orbit
  - 50 kW class PPE SEP system will transit Gateway to the NRHO
- **Lunar Transit will be more than 365 days in duration**
  - SEP system will be operating for more than 2/3^{rds} of transit
- **PPE is responsible for > 3 km/s Δv**
  - PPE will raise the spacecraft out of the Earth's gravity well over >300 days of nearly continuous thrusting[1]



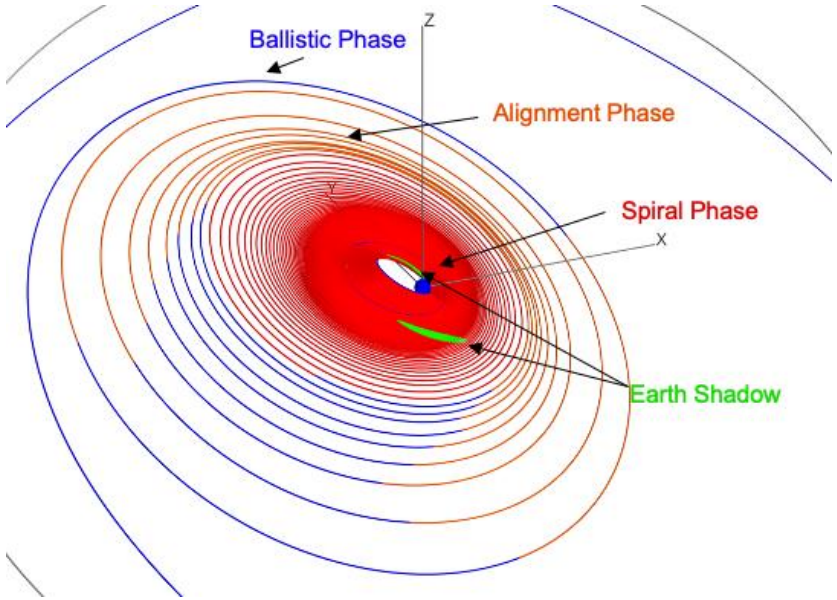
Lunar Transit Design Reference Mission 5

Missed Thrust Events

- **A Missed Thrust Event (MTE) is any time where a low-thrust maneuver cannot be completely executed as planned**
  - Less power available than expected (BepiColumbo[2])
  - Departure from commanded attitude
  - Thruster fault
- **Spacecraft safe events are not uncommon and empirical analysis[3] suggests Gateway will likely experience more than one during the Lunar Transit**
- **Gateway needs to be robust to MTEs during all phases of the mission, but recovery strategies and methodologies will be tailored to the dynamical environments of each mission phase**

Mission Phases

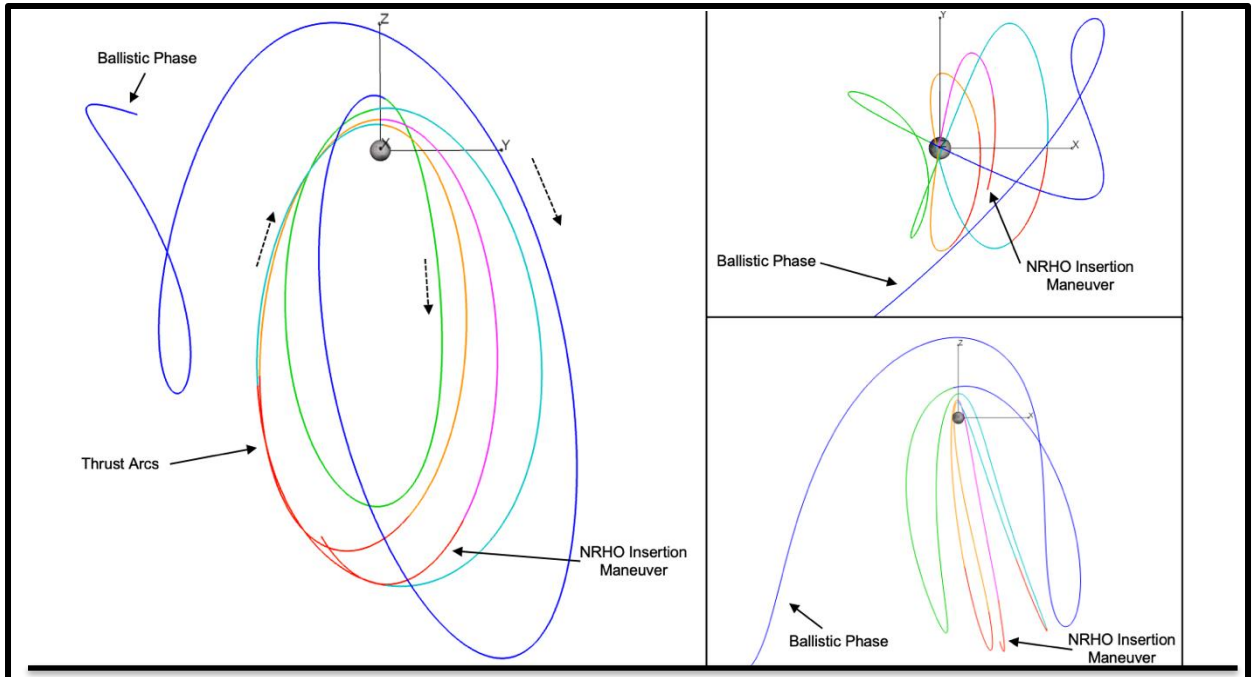
Spiral and Alignment Phases



Characteristics

- Stable and slow dynamics in Earth's gravity well
- Thrusting (mostly) along the velocity vector
- Days to weeks of continuous thrusting
- > 3,000 m/s Δv
- >12 months duration
- ***Indefinite time to assess contingencies, replan reference trajectories, and execute recoveries***

Insertion Phase

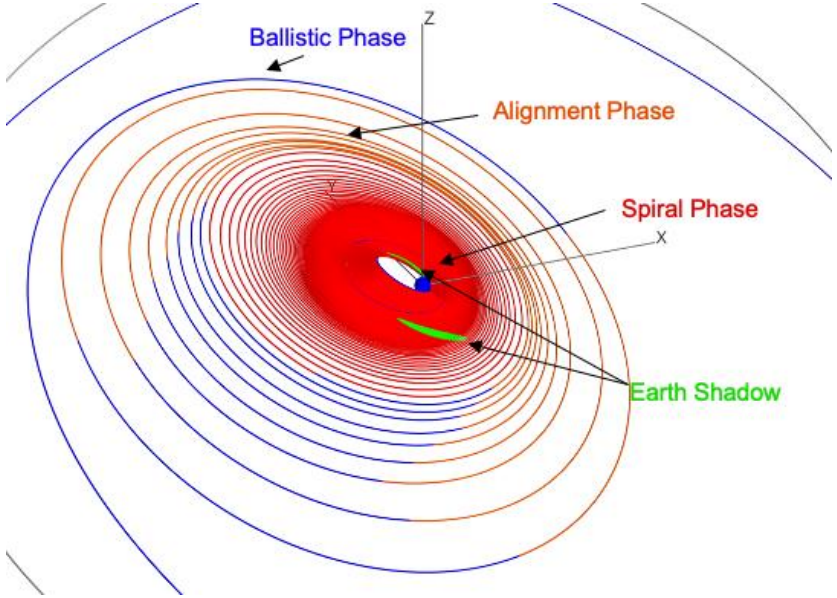


Characteristics

- 3-body gravitational interactions in cislunar space
- Unstable and chaotic dynamics
- < ~2 day thrust arcs
- < ~50 m/s Δv
- ~ 30 days duration
- ***Limited response time before Gateway departs Lunar sphere of influence***

Mission Phases – Missed Thrust Strategy

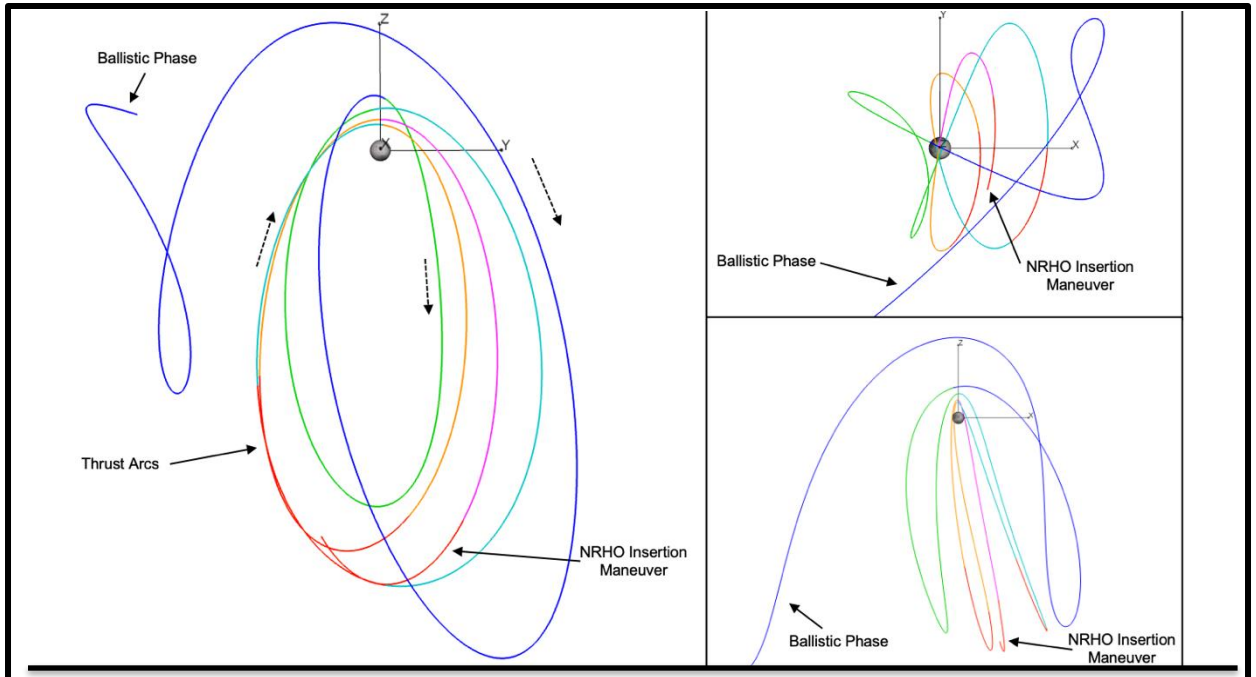
Spiral and Alignment Phases



MTE Recovery

- **Replan reference trajectory**
  - Develop new spiral, alignment, ballistic and insertion phases to reach NRHO
- **Intensive mission design & operator involvement**
- **Long duration process (multiple days)**

Insertion Phase



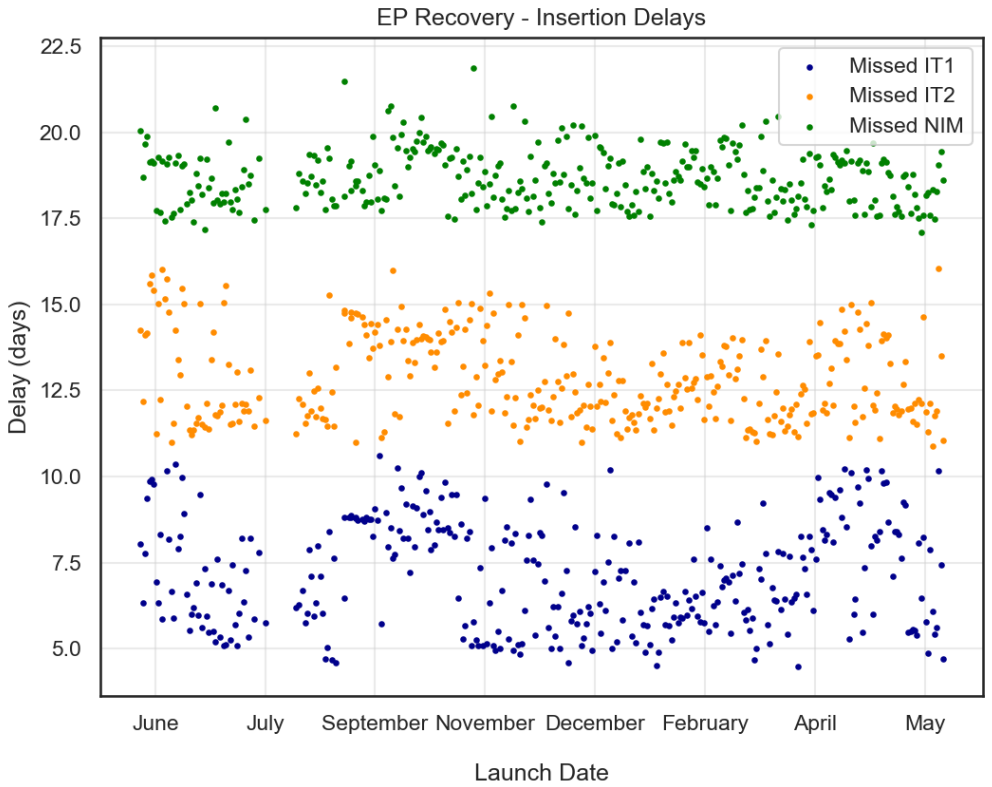
MTE Recovery

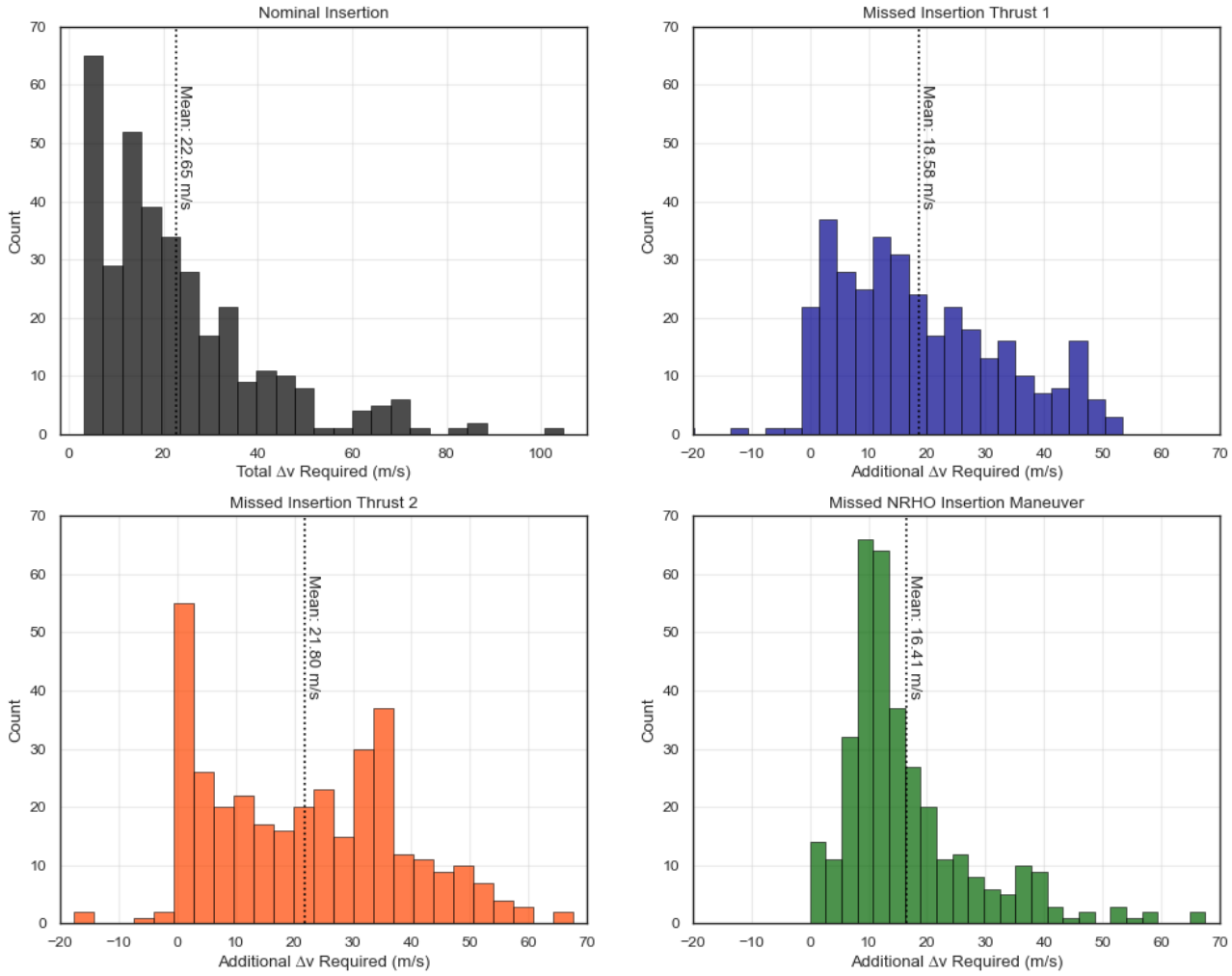
- **Pre-canned solutions in a contingency "playbook"**
  - Solutions can be quickly tailored to real-time specifics
- **Streamlined operations implementation**
- **Quick-response focused**

Subject of this paper

Recovery Options – Electric Propulsion

- **AAS 24-158 (2024, Broomfield)[4] covered Insertion Phase MTE recovery strategies using the PPE electric propulsion system**
- **SEP enables robust, low cost MTE recoveries (16-22 m/s Δv on average) over multiple revolutions (2% Δv reserve)**
- **Low Δv is traded for delayed NRHO arrival**

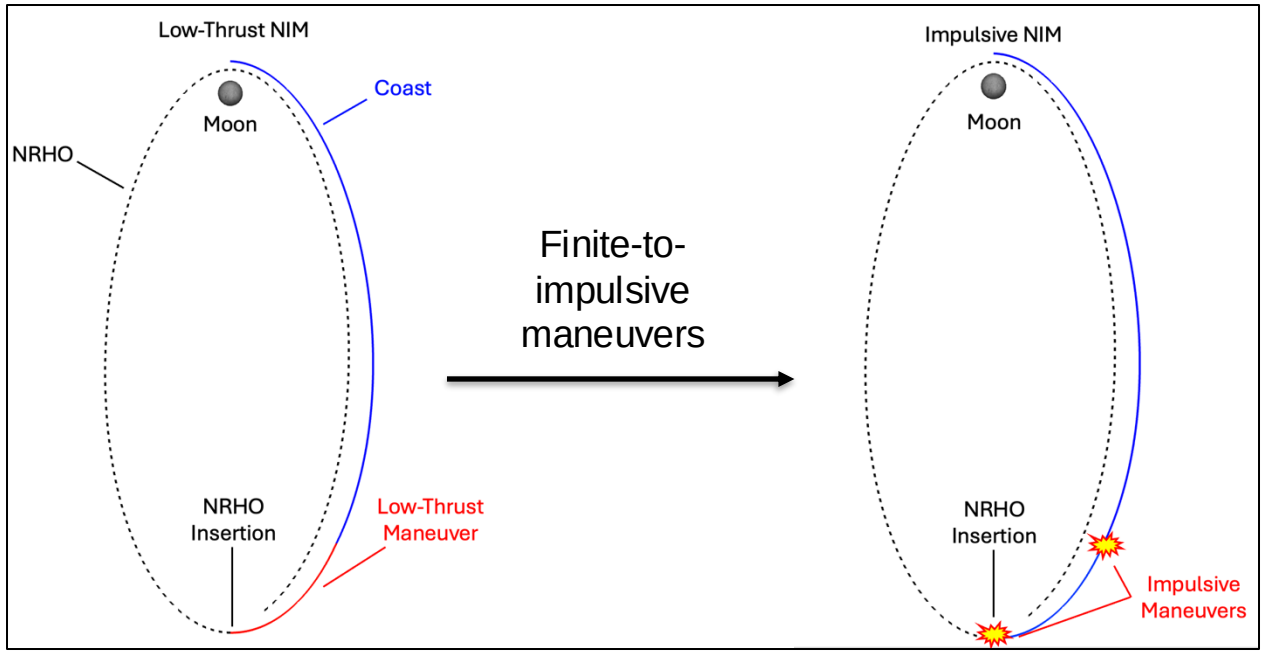


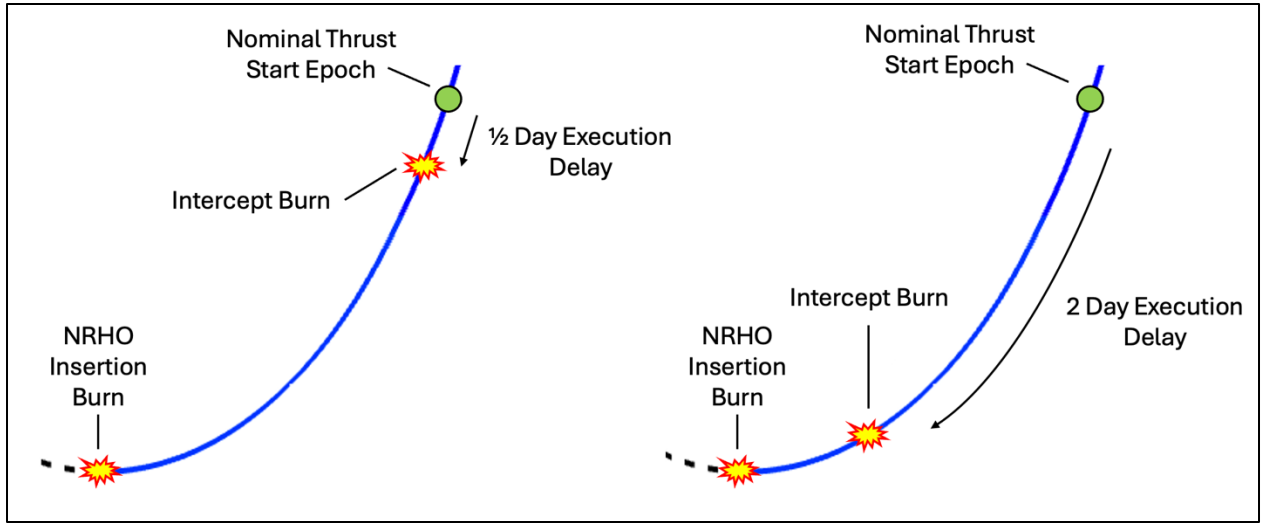


Taken from AAS 24-158

Recovery Options – Chemical Propulsion

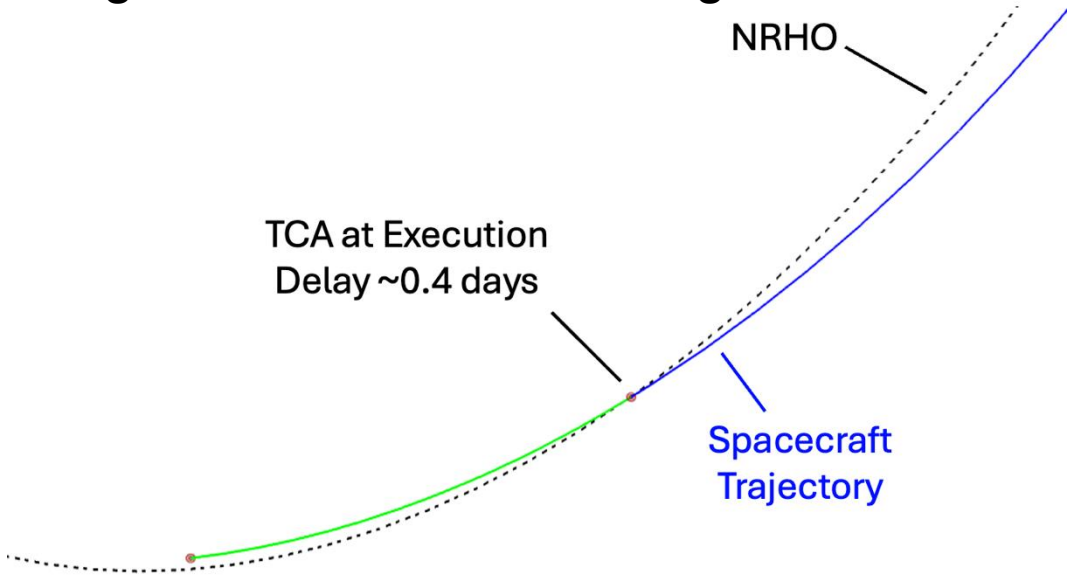
- **This work (a companion paper to AAS 24-158) presents how the PPE chemical Reaction Control System (RCS) can be used for Insertion Phase MTE recovery**
- **RCS is a high-thrust system (higher than SEP, at least) and affords increased control authority and lower time to effect**
- **Modeling involves converting established finite, low-thrust maneuvers into impulsive burns**
- **One low-thrust NRHO insertion maneuver becomes two impulses**
    1. Intercept the NRHO in position
    2. Rendezvous with the NRHO in velocity
- **Assuming that an MTE occurs at the start of the nominal low-thrust maneuver, ground recovery operations can be simulated by delaying the intercept impulse by some period of time**
- **The longer this delay can be without incurring significant Δv (propellant) costs, the more robust a low-thrust maneuver is to MTEs**

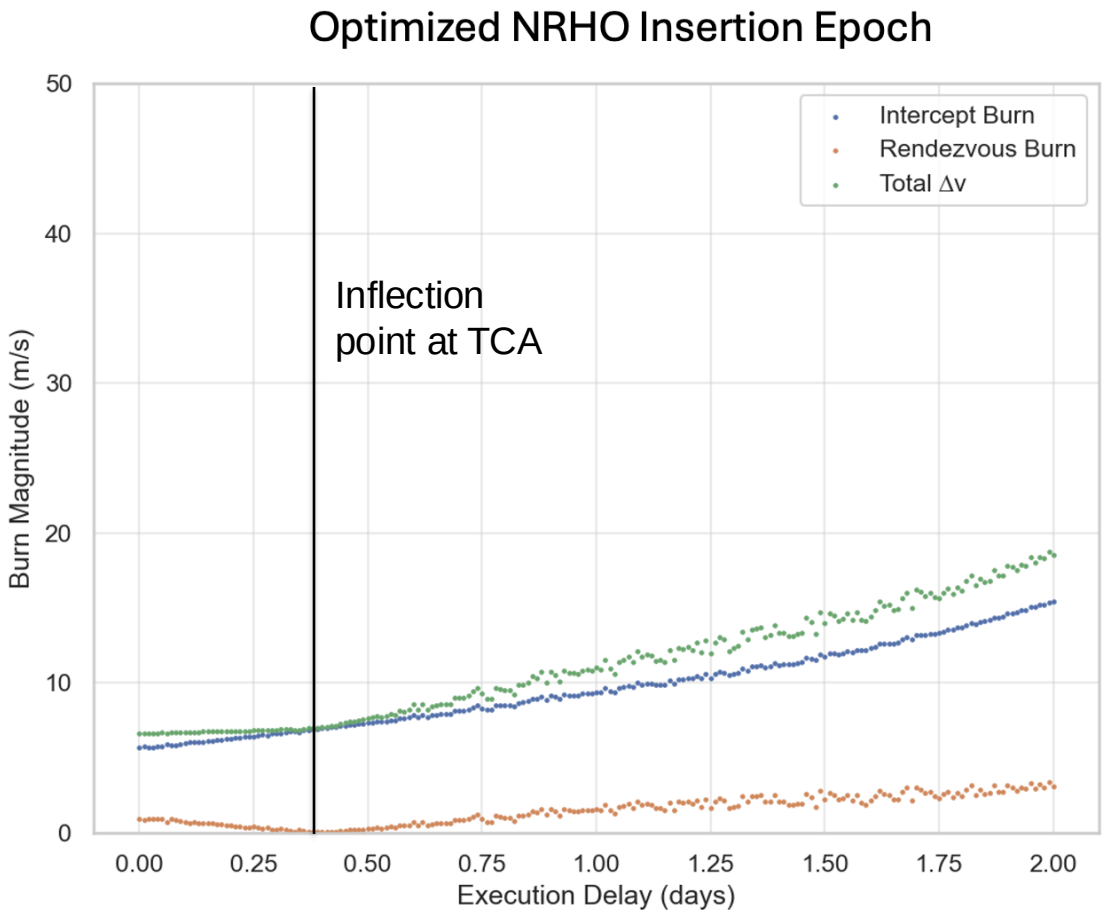




RCS Recovery – Behavior

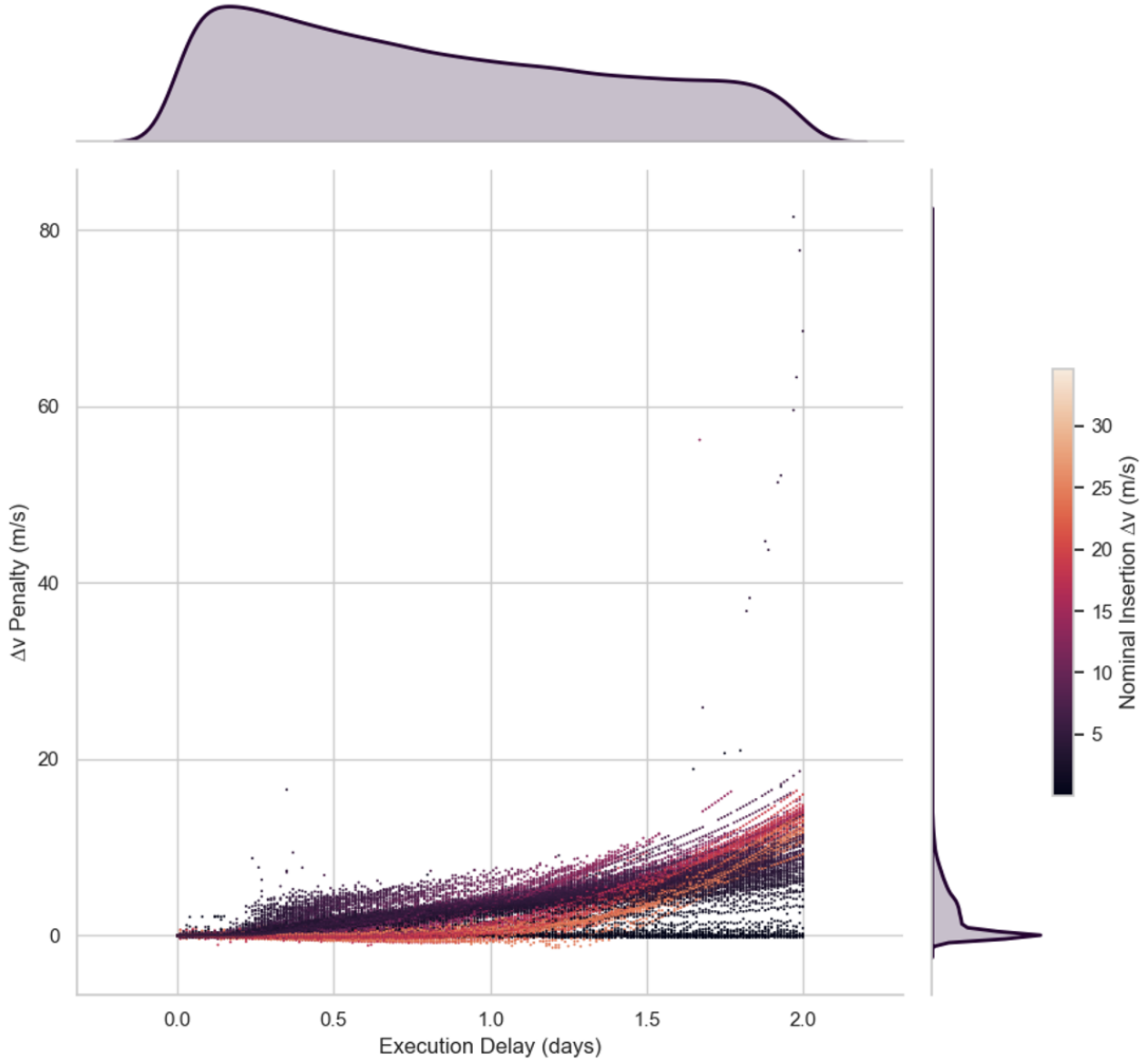
- **NRHO insertion on RCS follows consistent behavior as a function of nominal geometry**
- **Nominal trajectories naturally drift towards the NRHO, resulting in a TCA if the low-thrust maneuver is missed entirely**
- **If an RCS maneuver can be executed prior to this TCA, total ∆v costs remain flat**
  - Intercept and rendezvous burn magnitudes differ
- **If the intercept burn is executed after TCA, the magnitudes of both burns begin to increase**





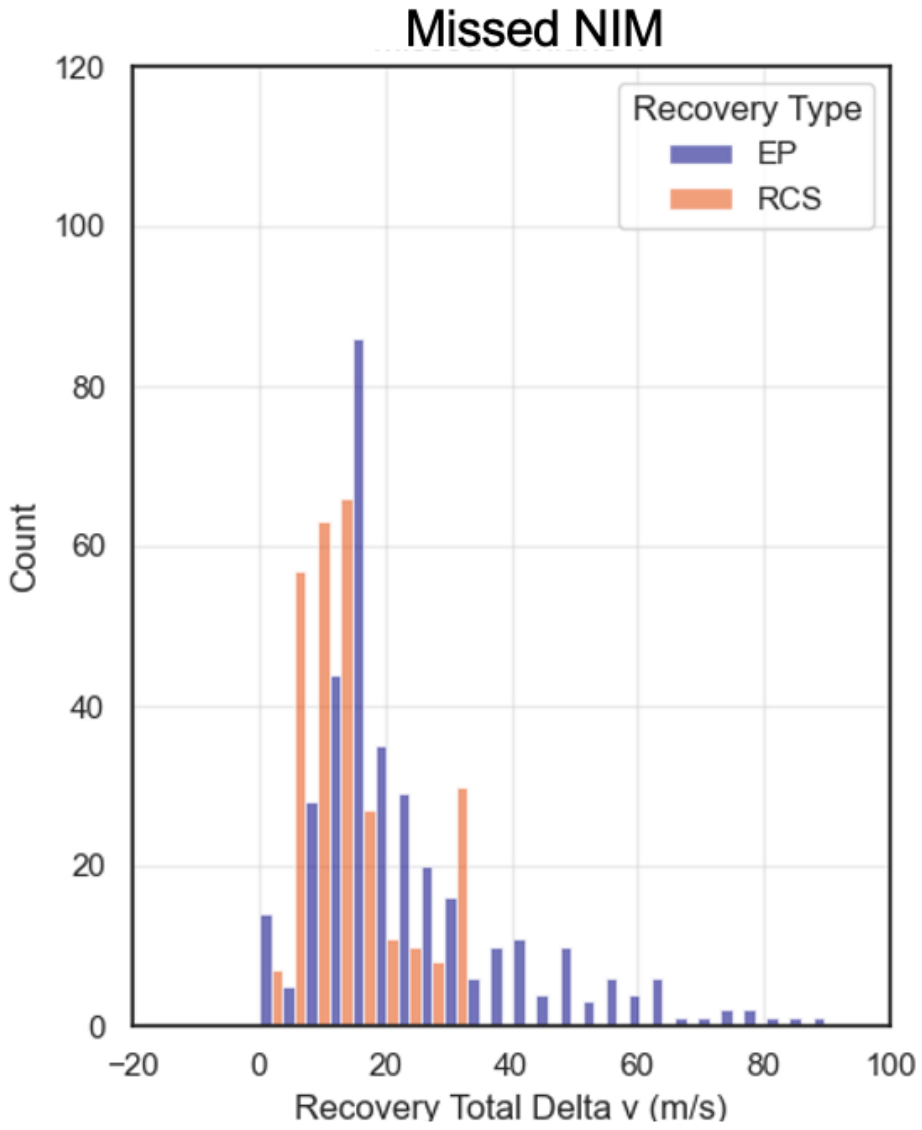
RCS Recovery – Bulk Results

- **Same methodology is run against 346 nominal reference trajectories**
- **RCS is shown to be an effective MTE recovery option across all 346 references**
- **Increasing execution delays do result in higher Δv penalties for NRHO insertion**
  - 2-day delays can be up to ~20 m/s Δv more expensive than 0 delay solutions
- **2-day execution delays result in NRHO insertion ~2 days later than the nominal epoch**
  - Converts to < ½ revolution (insertion occurs prior to perilune passage)
- **48 hours of ground response time can be enabled for all 346 references, within a 20 m/s penalty, before NRHO insertion must be delayed a full revolution (~6.5 days)**



Comparison to SEP Recoveries

- **We can compare RCS results against the SEP results discussed in AAS 24-158 in terms of total ∆v required to recover from an MTE during the NRHO Insertion Maneuver**
- **SEP and RCS MTE recovery solutions exhibit similar ∆v costs**
  - Suggests that low-thrust solutions experience little in the way of gravity losses
- **As discussed earlier, the SEP results shown in AAS 24-158 arrive to the NRHO three revolutions later than planned**
- **RCS recovery solutions arrive within half a revolution of planned epoch**
- **EP specific impulse is ~10x higher than RCS**
- **While ∆v costs may be < 50 m/s, for a vehicle as massive as PPE+HALO, 50 m/s requires a significant mass of chemical propellant**



Conclusions and Forward Work

SEP Recovery

- **Low Δv costs (2% reserve covers all solutions)**
- **Follows established methodology used to design nominal NRHO insertion sequences**
- **Results in delayed NRHO insertion**
  - Delays are necessary to reduce Δv costs
- **EP system may not be available within 1 revolution (6 days) of an MTE**

RCS Recovery

- **Use of RCS adds a layer of redundancy and affords operations team flexibility in how to respond to MTEs**
- **Analysis shows Δv costs are similar to SEP recovery solutions**
- **Limited NRHO arrival delays (< 3 days) can enable up to 2 days of ground response time**
- **RCS is ~10x less efficient than SEP and even low Δv maneuvers require significant propellant**

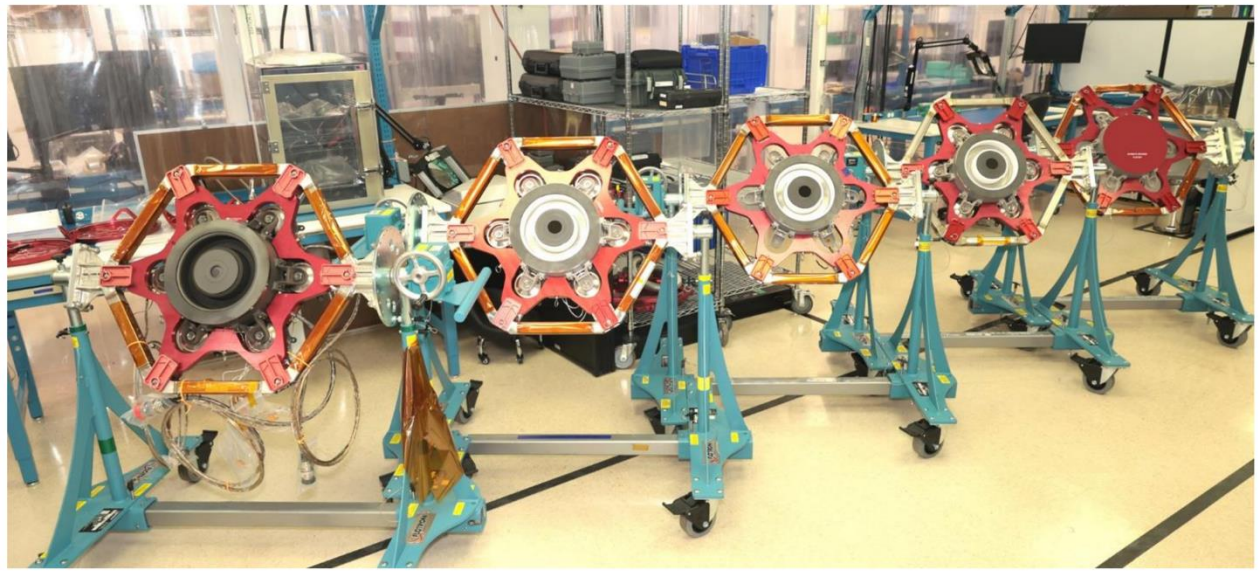
Forward Work & Discussion

- **Methodology shown today is a work in progress**
  - Meant to serve as a basis and bounding analysis for future work
- **AAS 24-158 and AAS 25-160 only cover MTEs during the Insertion Phase**
  - An end-to-end Missed Thrust strategy covering the entire Lunar Transit is current area of work
- **The combined engineering + operator team will work to mature the flight implementation (flight rules) of MTE recovery**

But Wait There's More!

Four other Gateway/PPE related papers here at SFM:

- **AAS 25-230: Mission Scan Approach for the Gateway Low Thrust Spiral to a Near Rectilinear Halo Orbit**
- **AAS 25-251: The Effects of the Solar Beta Angle on Low Thrust Spirals for Solar Electric Propulsion Vehicles**
- **AAS 25-225: Monte Carlo Analysis of Low-Thrust Many-Revolution Spiral Out Trajectories with Statistical Errors for NASA's Gateway**
- **AAS 25-290: Q-Law for Rapid Assessment of Low Thrust Cislunar Trajectories via Automatic Differentiation**



PPE and HALO are taking shape and progressing towards flight!





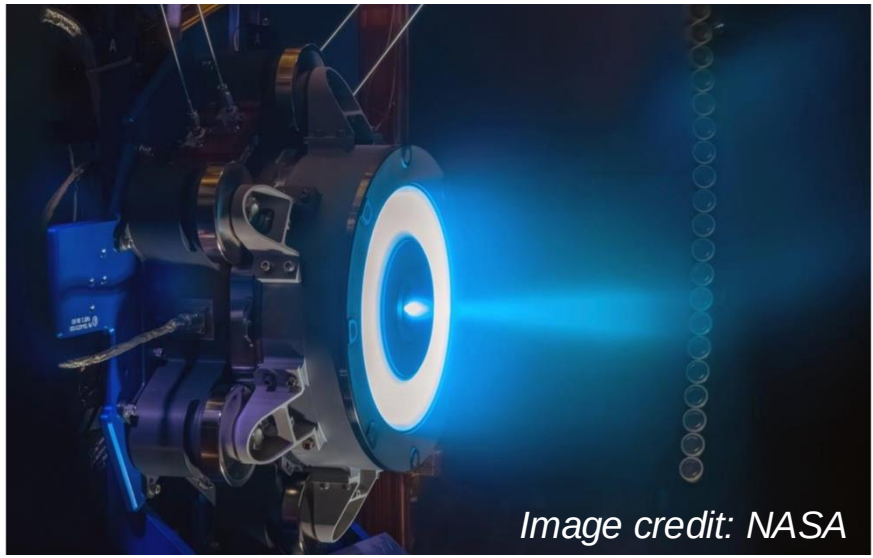


Image credit: NASA


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References

1. M. McGuire S. McCarty, et all, "Overview of the Lunar Transfer Trajectory of the Co-Manifested First Elements of NASA's Gateway", *AAS/AIAA Astrodynamics Specialist Conference*, 2021.
2. Press Release, "Glitch on BepiColumbo, work ongoing to restore spacecraft to full thrust", *European Space Agency*, 2024.
3. Imken, T., Randolph, T., DiNicola, M., and Nicholas, A., "Modeling spacecraft safe mode events," 2018 IEEE Aerospace Conference, Big Sky, MT, 2018.
4. S. Karn, S. McCarty, M. McGuire, "Recovery From Missed Thrust During Low Thrust Insertion of NASA's Gateway into a Near Rectilinear Halo Orbit", *AAS/AIAA Astrodynamics Specialist Conference*, 2024.


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