National Aeronautics and Space Administration

Trajectory Design and Early Mission Operations for the Lunar IceCube Mission

Robert Pritchett, Dave Folta
Sun Hur-Diaz, and Kyle Hughes

code 595

NAVIGATION & MISSION DESIGN BRANCH
NASA GSFC

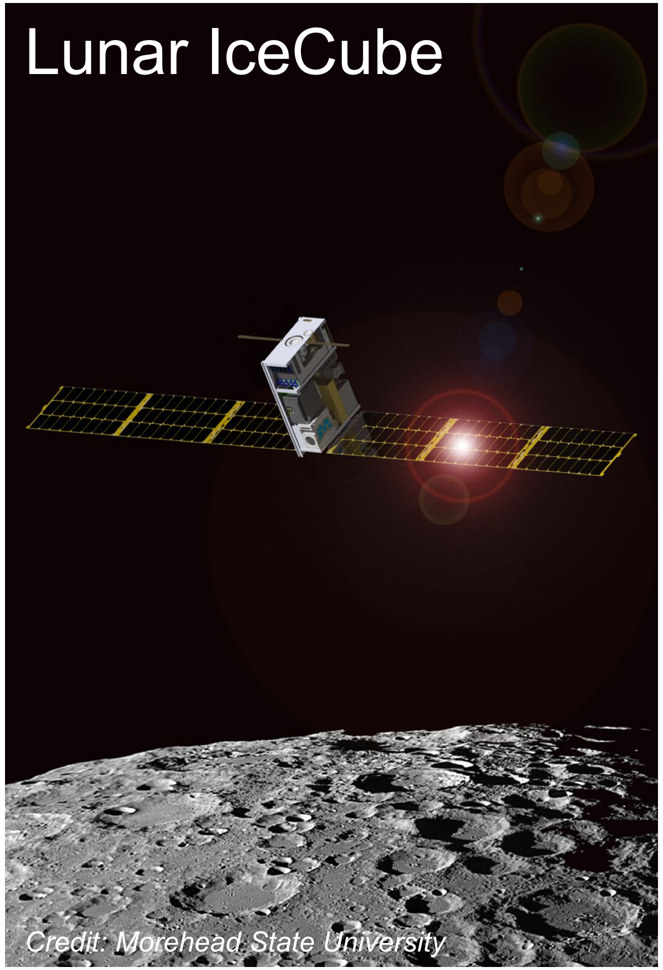
www.nasa.gov

Outline

- **Background**
- LIC Mission Stages & Early Mission Operations
- Baseline Trajectory Development
- Deployment Analysis
- Lessons Learned

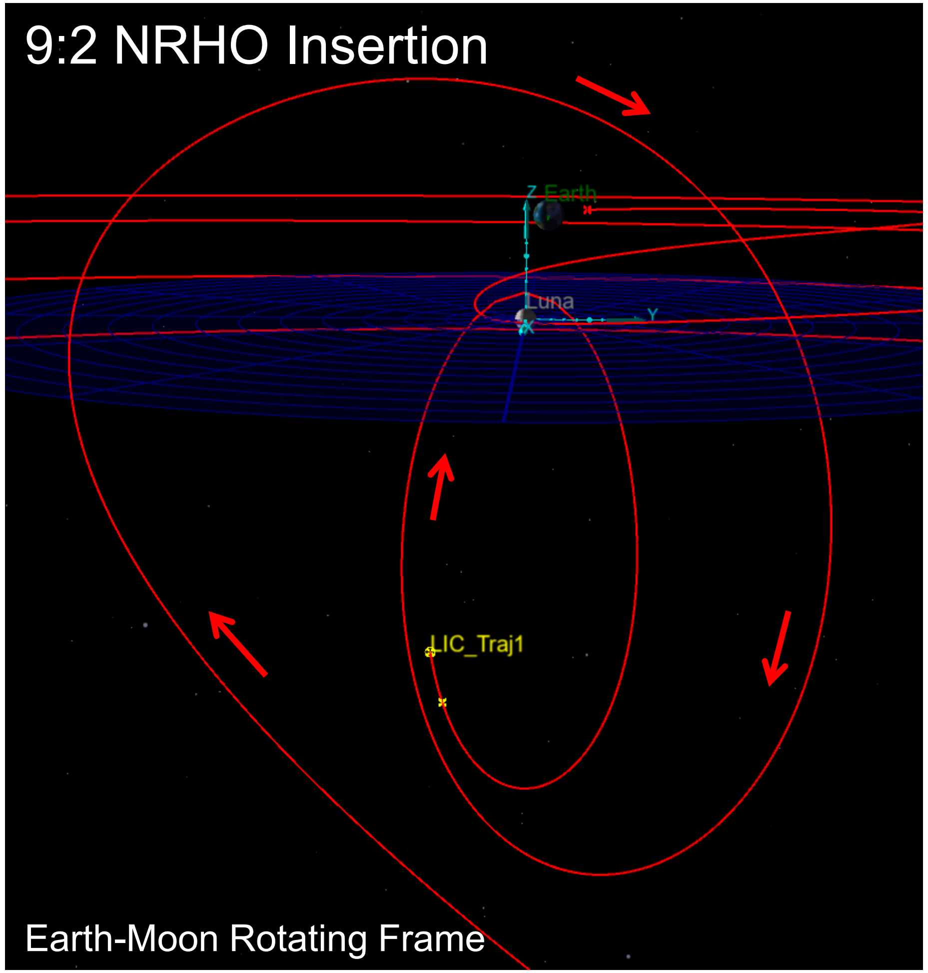
Background

- The Lunar IceCube (LIC) mission was launched as a rideshare onboard Artemis-I on November 16th, 2022.
- Led by the Space Science Center at Morehead State University and supported by scientists and engineers at NASA Goddard Space Flight Center.
- The science objectives of the LIC mission required the design of a trajectory to take the spacecraft from its high-energy escape trajectory at deployment to a polar elliptical lunar orbit.
- This challenging design problem was complicated by the limited control authority of the LIC spacecraft, and the need to adapt to changes in launch epoch necessitated by the primary mission.



Credit: Morehead State University

Background



9:2 NRHO Insertion

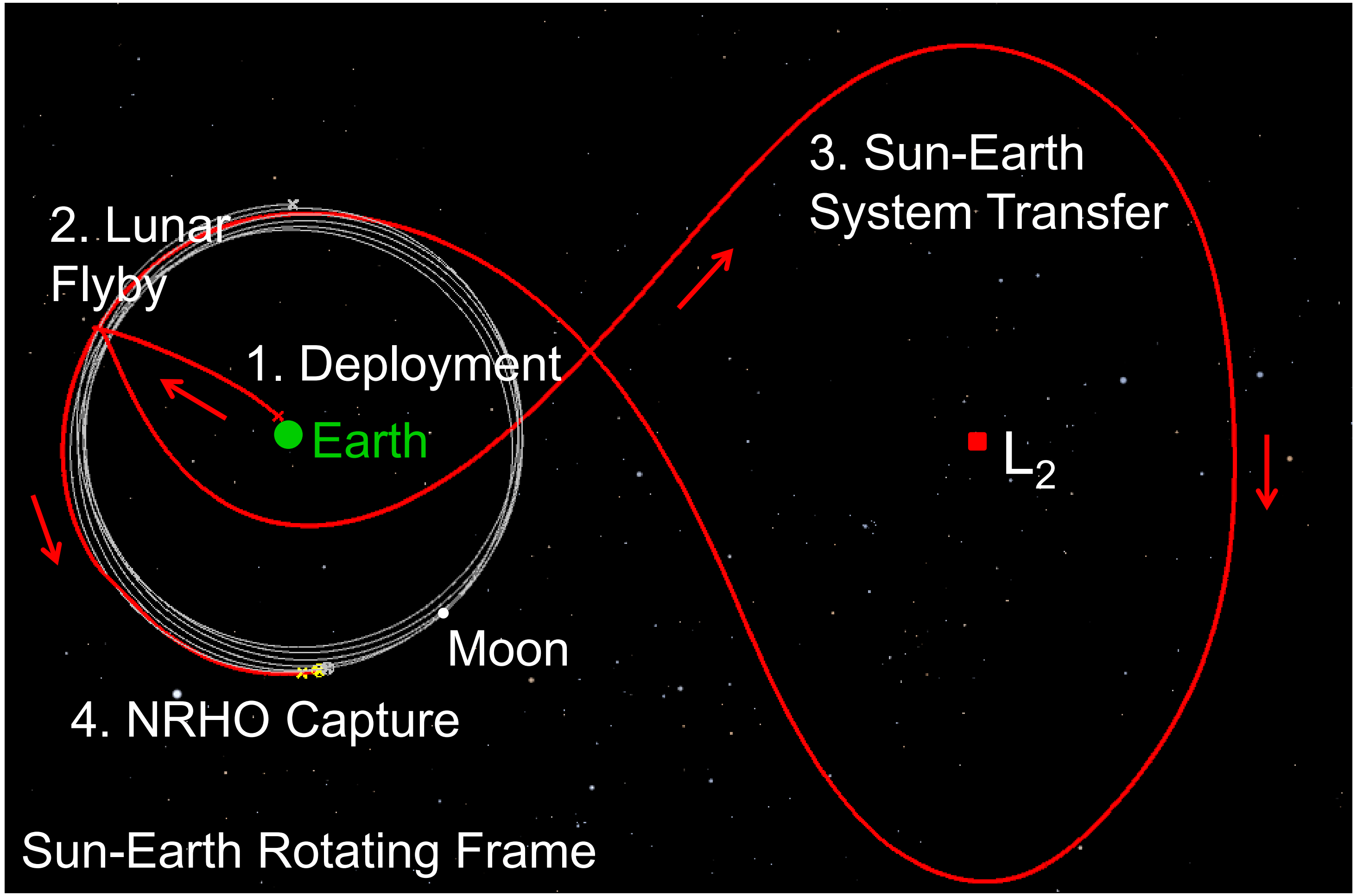
Earth-Moon Rotating Frame

- The complexity of the LIC mission design problem garnered interest from many researchers who proposed innovative approaches for designing the LIC trajectory.
- The work of these authors and GSFC engineers led to a design process that used a near rectilinear halo orbit (NRHO) as a staging orbit to divide the lunar transfer and low-thrust spiral phases of the mission.
- This presentation focuses on the design of the baseline trajectory to the NRHO along with analysis of the LIC deployment and early mission operations.

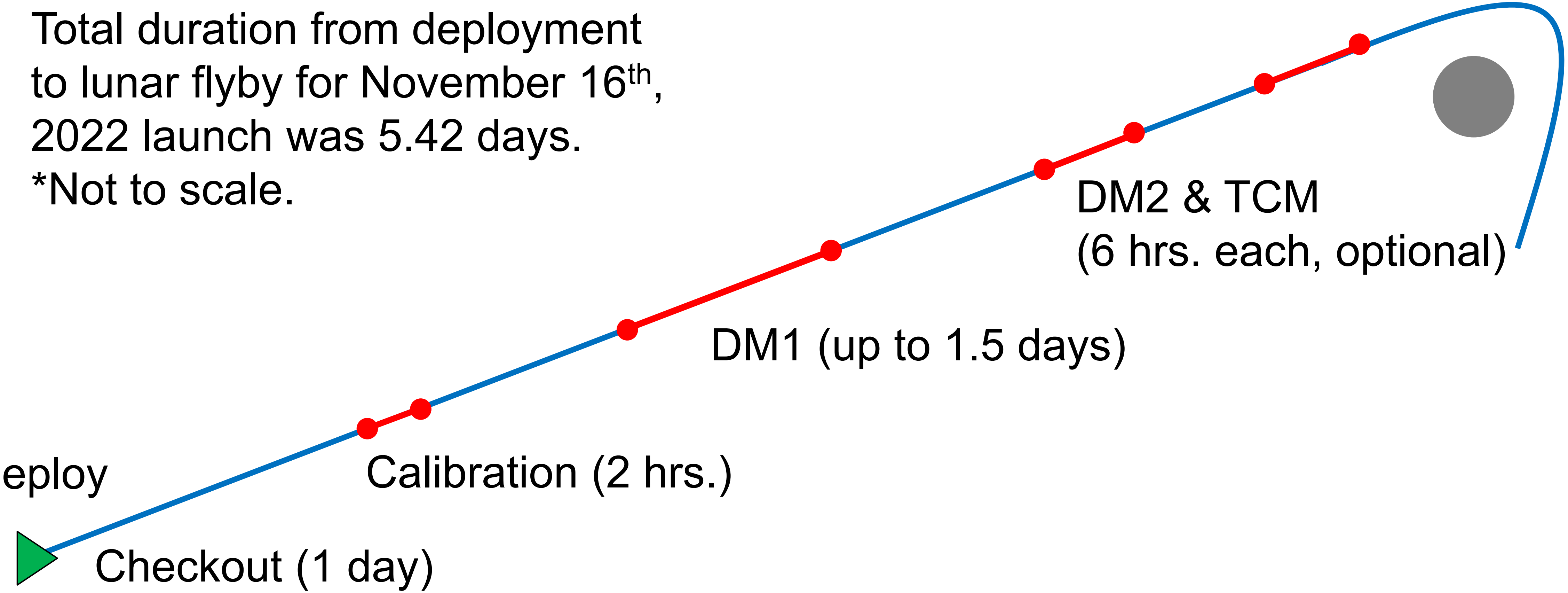
Outline

- Background
- **LIC Mission Stages & Early Mission Operations**
- Baseline Trajectory Development
- Deployment Analysis
- Lessons Learned

Lunar IceCube Mission Stages



Lunar IceCube Early Mission Stages



Lunar Flyby

Total duration from deployment to lunar flyby for November 16th, 2022 launch was 5.42 days.
*Not to scale.

DM2 & TCM
(6 hrs. each, optional)

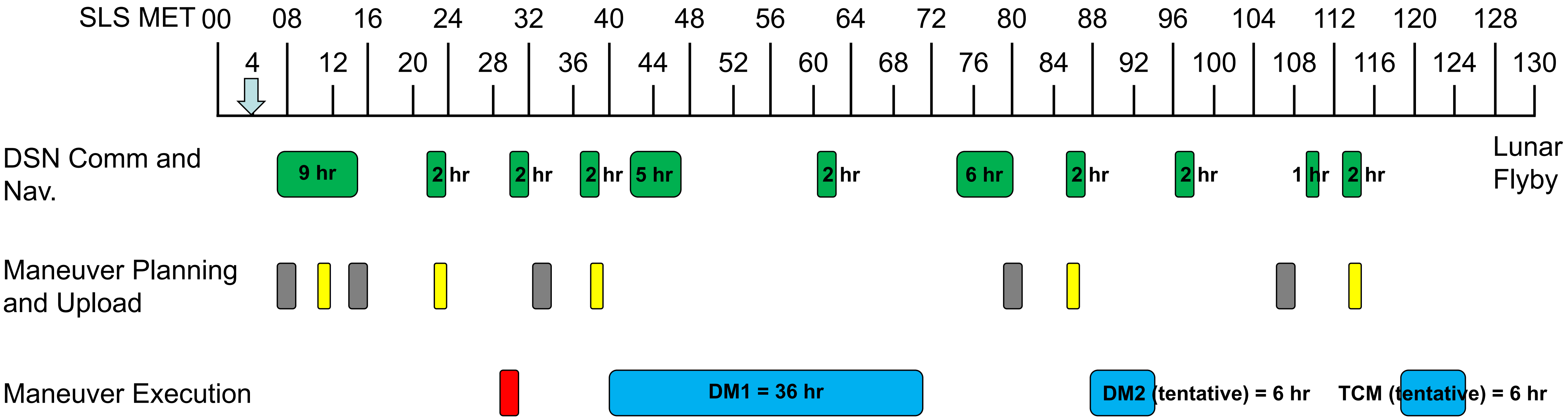
DM1 (up to 1.5 days)

Deploy

Calibration (2 hrs.)

Checkout (1 day)

Early Mission Operations Schedule – November 16th, 2022



Key:

⇨ Deployment

🟩 2-way Tracking (Doppler and/or Range Data)

🟨 Uploads of Commands (1 hr)

▬ Maneuver Planning (2 hr)

🟥 Low-Thrust Calibration (2 hr)

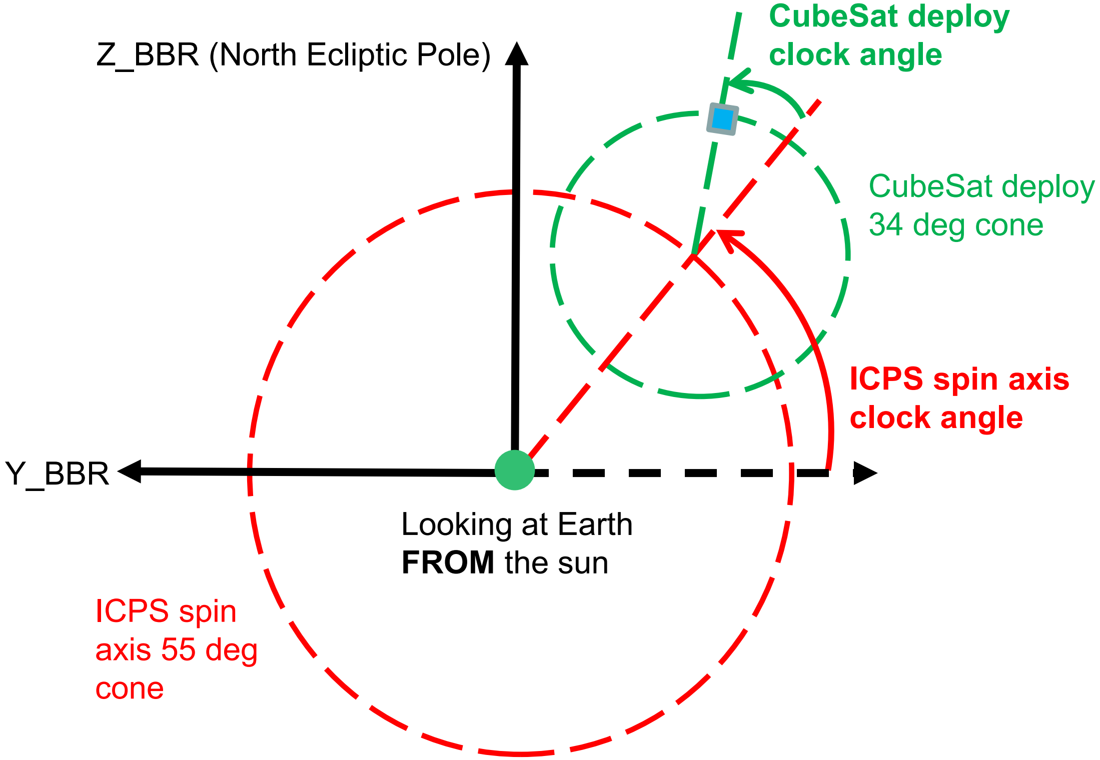
🟦 Low-Thrust Maneuver

Outline

- Background
- LIC Mission Stages & Early Mission Operations
- Baseline Trajectory Development
- **Deployment Analysis**
- Lessons Learned

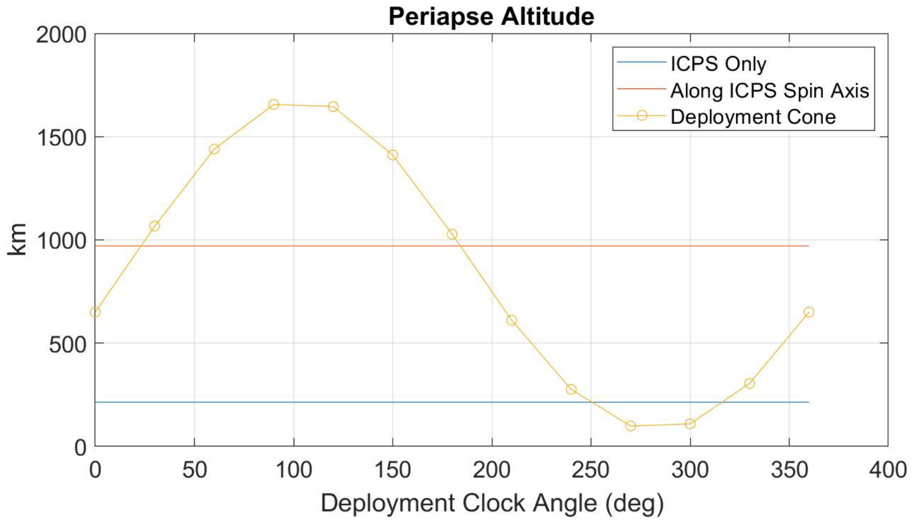
Deployment and Early Mission Operations

- Secondary payloads were deployed from the Interim Cryogenic Propulsion Stage (ICPS). A range of deployment “clock angles” and their impact on the resulting trajectory were considered.

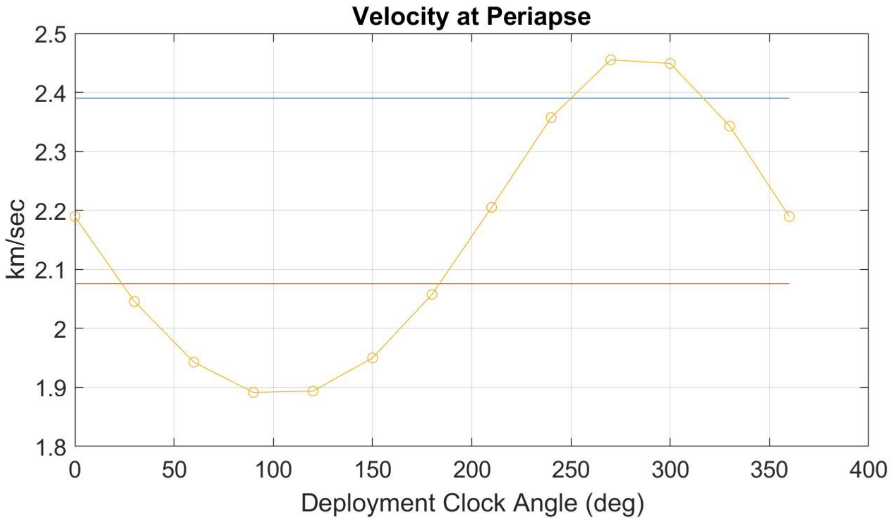


Deployment and Early Mission Operations

- The conditions of the initial lunar flyby varied with the deployment clock angle.
- For some launch date and clock angle combinations post-deployment trajectories could impact the Moon without execution of a maneuver.



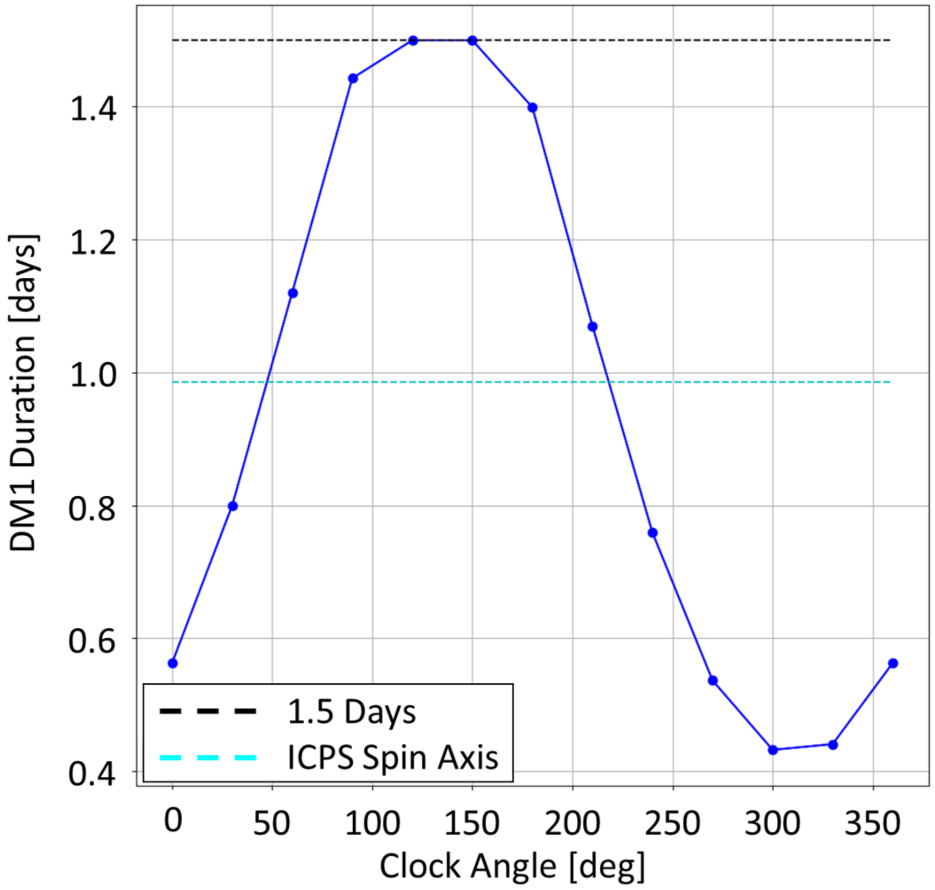
Periapse Altitude



Velocity at Periapse

Deployment and Early Mission Operations

- The impact of the deployment clock angle on the duration of the pre-flyby maneuver was analyzed.
- Though the necessary duration of DM1 varied with the deployment clock angle, a maneuver of 1.5 days, or less, could be used to target the required lunar flyby B-plane state in almost every case.
- “Canned” calibration and DM1 maneuvers, that is, maneuvers planned before knowing the deployment clock angle, could be used, if DM2 and TCM maneuvers were also executed prior to the flyby.



Outline

- Background
- Lunar IceCube Mission Stages
- **Baseline Trajectory Development**
- Early Mission Operations & Deployment Analysis
- Lessons Learned

Baseline Trajectory Design

- A three-stage process was used to design the LIC baseline trajectory

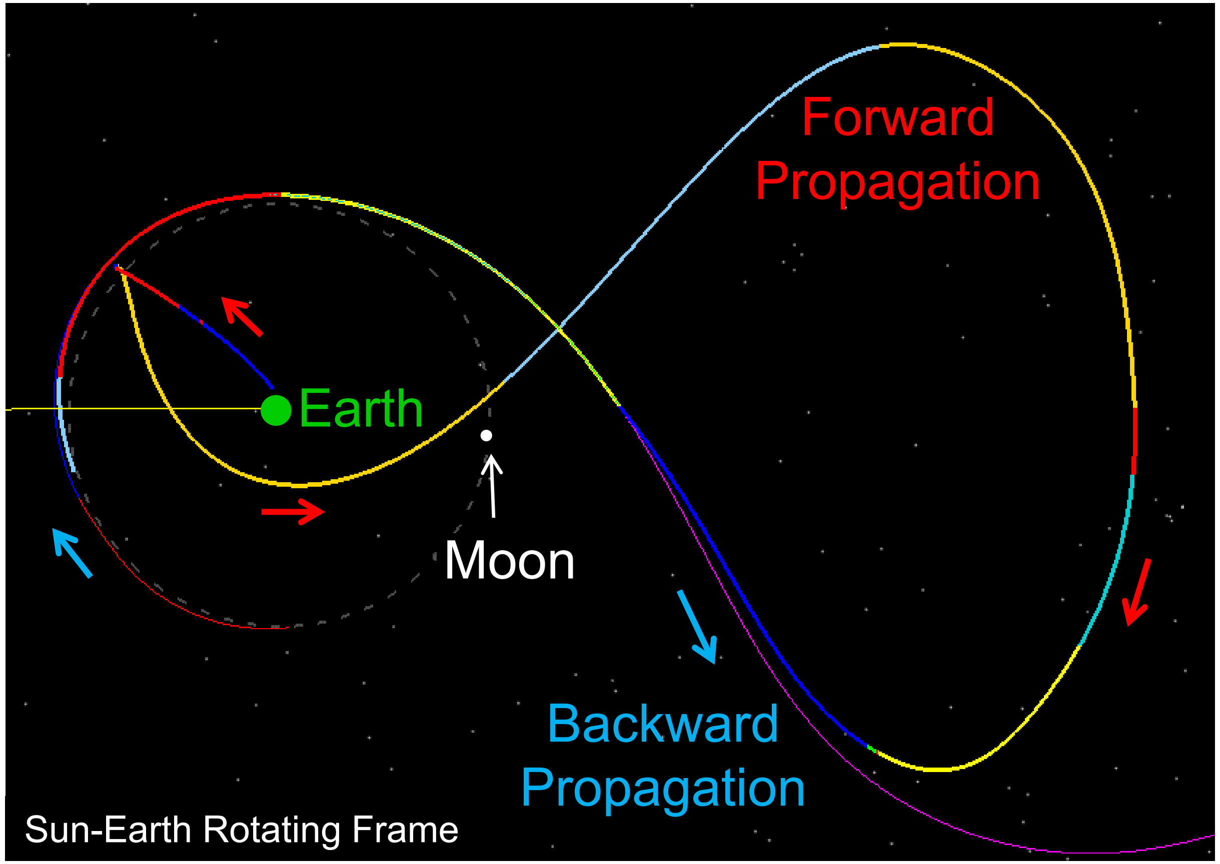
Discontinuous initial guesses are created based on designer expertise and knowledge of Dynamical Systems Theory.

Initial estimates are supplied to a trajectory optimization tool that enforces mission constraints and maximizes final mass.

Trajectory is reconverged in a high-fidelity dynamical model using the tool employed by the navigation and mission operations teams.

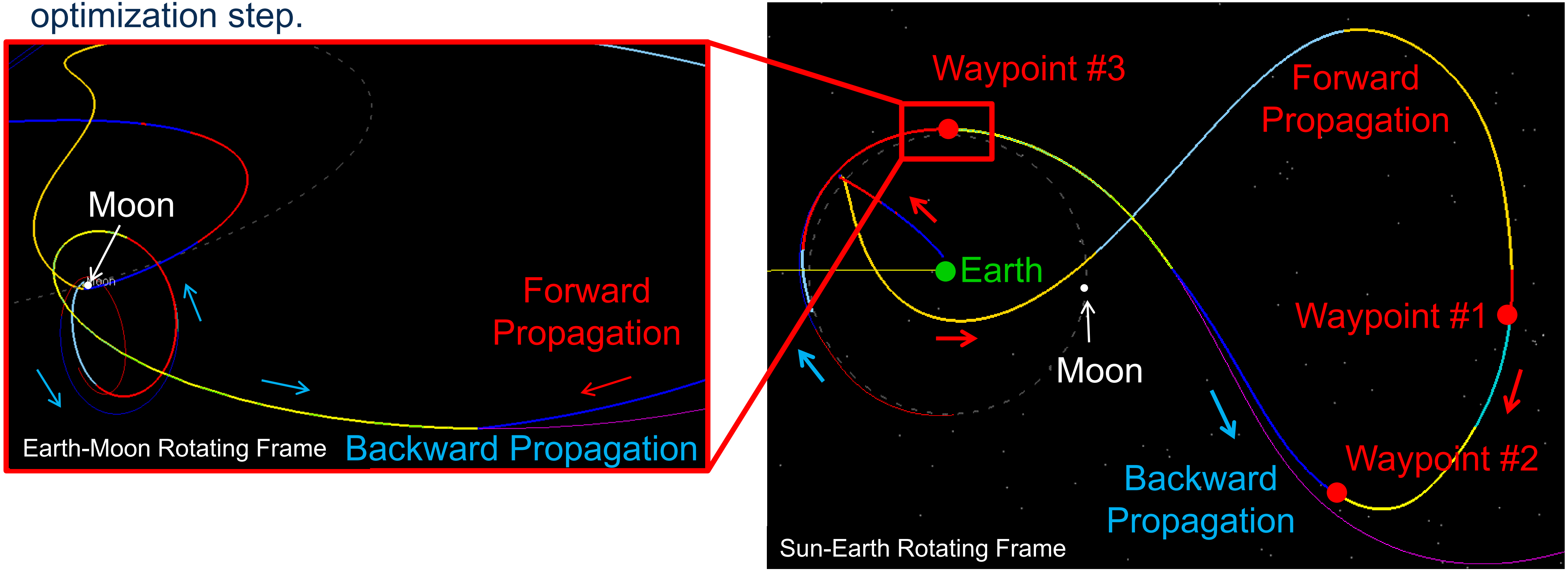
Baseline Trajectory Design – Initial Design Generation

- Initial trajectory designs were generated by propagating forward from the deployment state and backward from the final NRHO.
- Experience with mission design for other libration point missions, e.g., Artemis/Themis, informed the initial design process for LIC.
- Low-thrust maneuvers were added prior to the initial flyby, in deep space, and before NRHO capture.
- A differential corrector was used to update the thrust direction of these maneuvers, to reduce discontinuities in time, position, and velocity between the two forward and backward propagated segments.



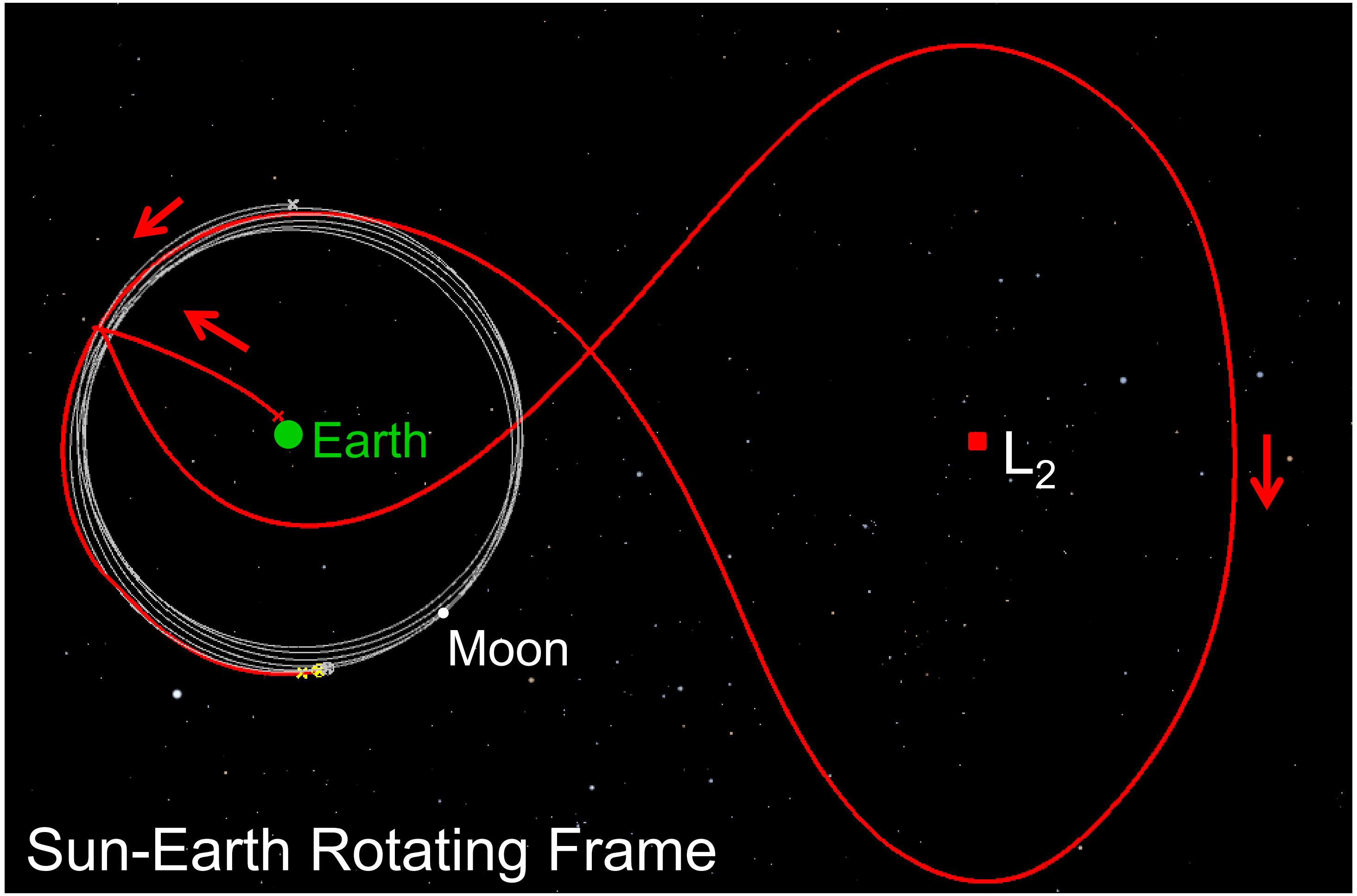
Baseline Trajectory Design – Initial Design Generation

- The initial design was discretized into waypoints that were inputs for the subsequent trajectory optimization step.



Baseline Trajectory Design – Trajectory Optimization

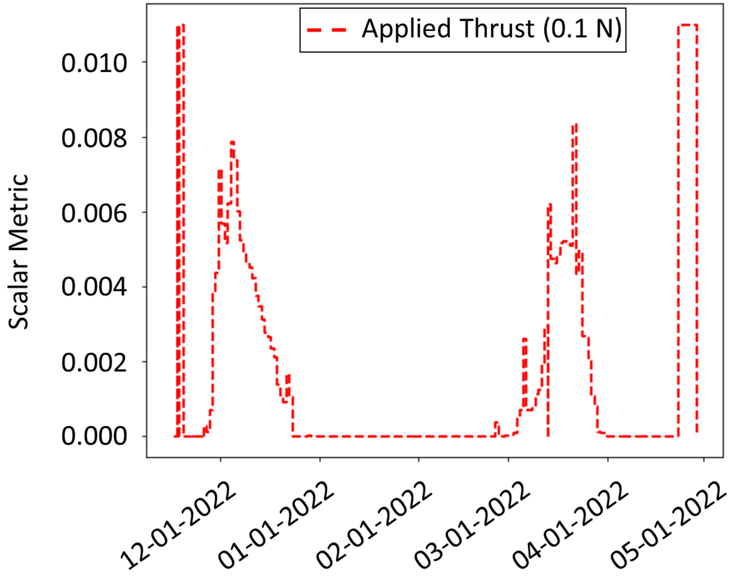
- NASA Goddard's Evolutionary Mission Trajectory Generator (EMTG) tool was used to eliminate discontinuities and maximize the final mass of LIC.
- Low and medium fidelity dynamical models were employed in EMTG to quickly identify, then successively refine, an optimal solution.
- The final state of the transfer was constrained in the Earth-Moon rotating frame while the final epoch was permitted to vary over a 2-month window.



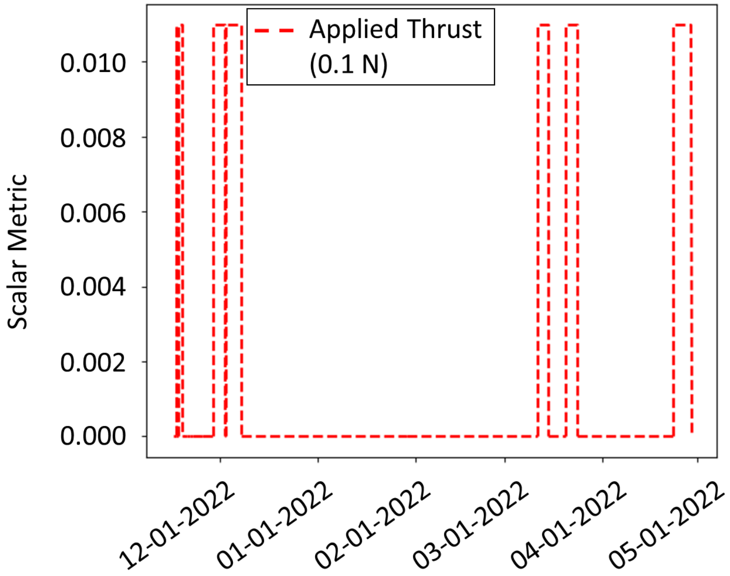
Baseline Trajectory Design – Trajectory Optimization

- Repeated solves of the optimization problem were performed to successively apply constraints on the thrust profile that limited the maximum duration of thrust arcs to 7 days and required at least a 7-day coast period between each thrust arc for performing navigation.

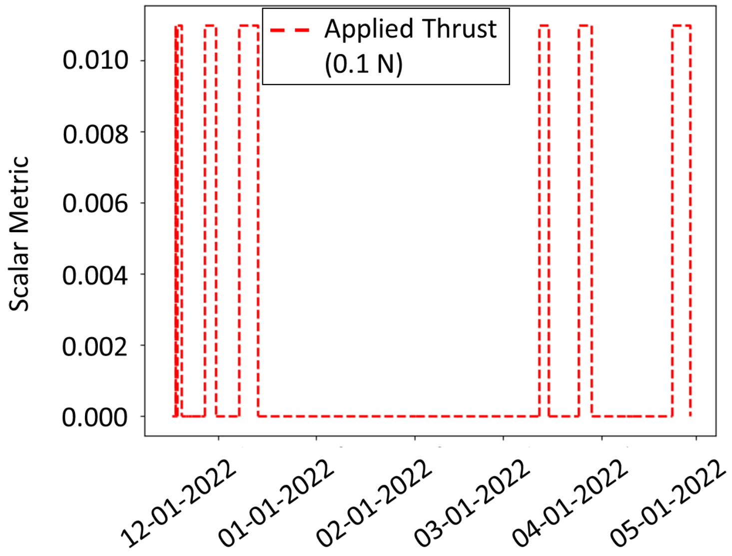
Initial Thrust Profile



Discrete Thrust and Coast Arcs

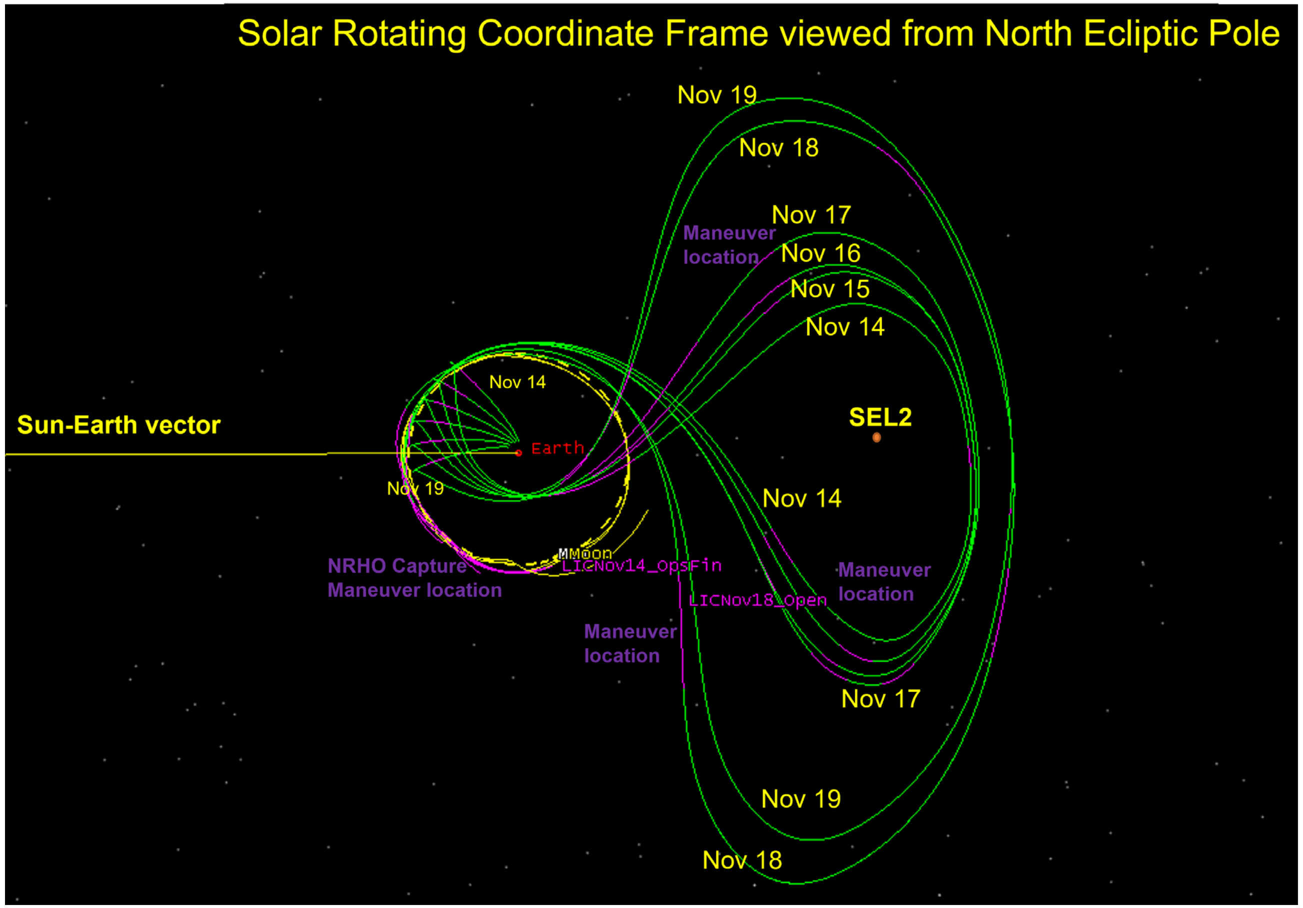


Navigation Coast Arcs Added



Baseline Trajectory Design – High-Fidelity Refinement

- A forward shooting algorithm that utilized a high-fidelity dynamical model defined in Systems Tool Kit (STK) was used to generate the final version of the baseline trajectory from the EMTG result.
- STK/Astrogator was used for mission operations and output several products delivered to the Deep Space Network, Mission Operations Center, and Flight Dynamics Facility.
- Trajectories for every launch date within each launch period were generated, and most trajectories exhibited a loop around the Sun-Earth L_1 or L_2 libration points.

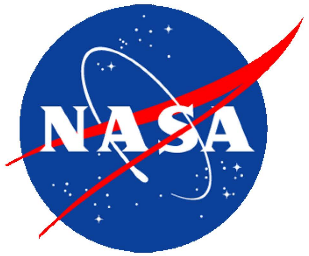


Outline

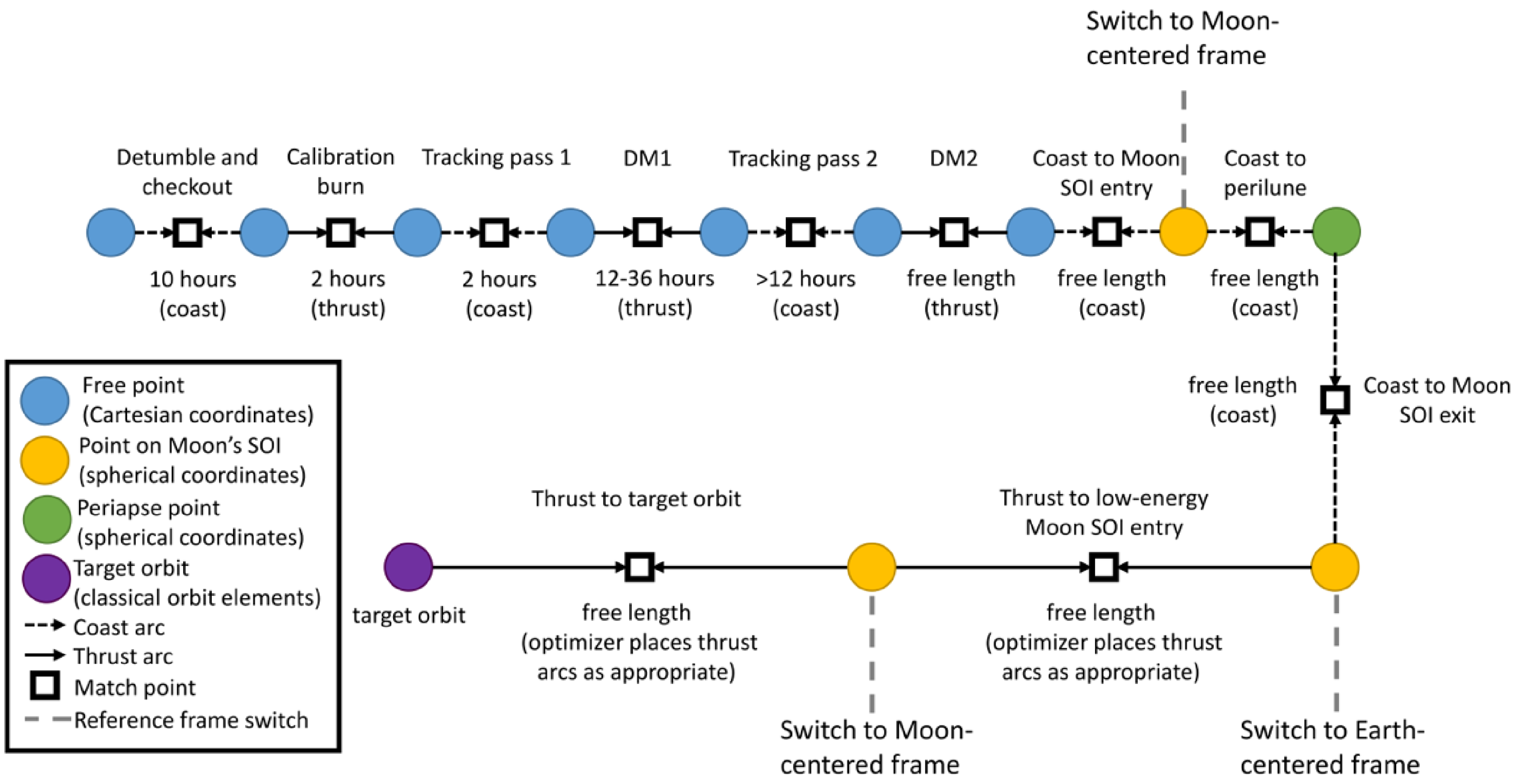
- Background
- LIC Mission Stages & Early Mission Operations
- Baseline Trajectory Development
- Deployment Analysis
- **Lessons Learned**

Lessons Learned

- Momentum wheel size and propulsion system choice resulted in the need for frequent desaturation maneuvers. The impact of these maneuvers should be accounted for in the baseline trajectory development process.
- Onboard power limitations prevented the LIC spacecraft from being tracked during maneuvers. The risks and challenges of accommodating this limitation emphasized that for spacecraft that utilize low-thrust propulsion, which requires long duration maneuvers, it is critical to provide some tracking capability during these maneuvers to enable a quick response to anomalies.
- Repeated processes should be automated as much as possible. This is particularly important for rideshare missions which often must adapt to changes in the mission profile necessitated by the primary mission.



Trajectory Optimization Problem Setup



Switch to Moon-centered frame

Detumble and checkout — 10 hours (coast)

Calibration burn — 2 hours (thrust)

Tracking pass 1 — 2 hours (coast)

DM1 — 12-36 hours (thrust)

Tracking pass 2 — >12 hours (coast)

DM2 — free length (thrust)

Coast to Moon SOI entry — free length (coast)

Coast to perilune — free length (coast)

Coast to Moon SOI exit — free length (coast)

Switch to Earth-centered frame

Thrust to low-energy Moon SOI entry — free length (optimizer places thrust arcs as appropriate)

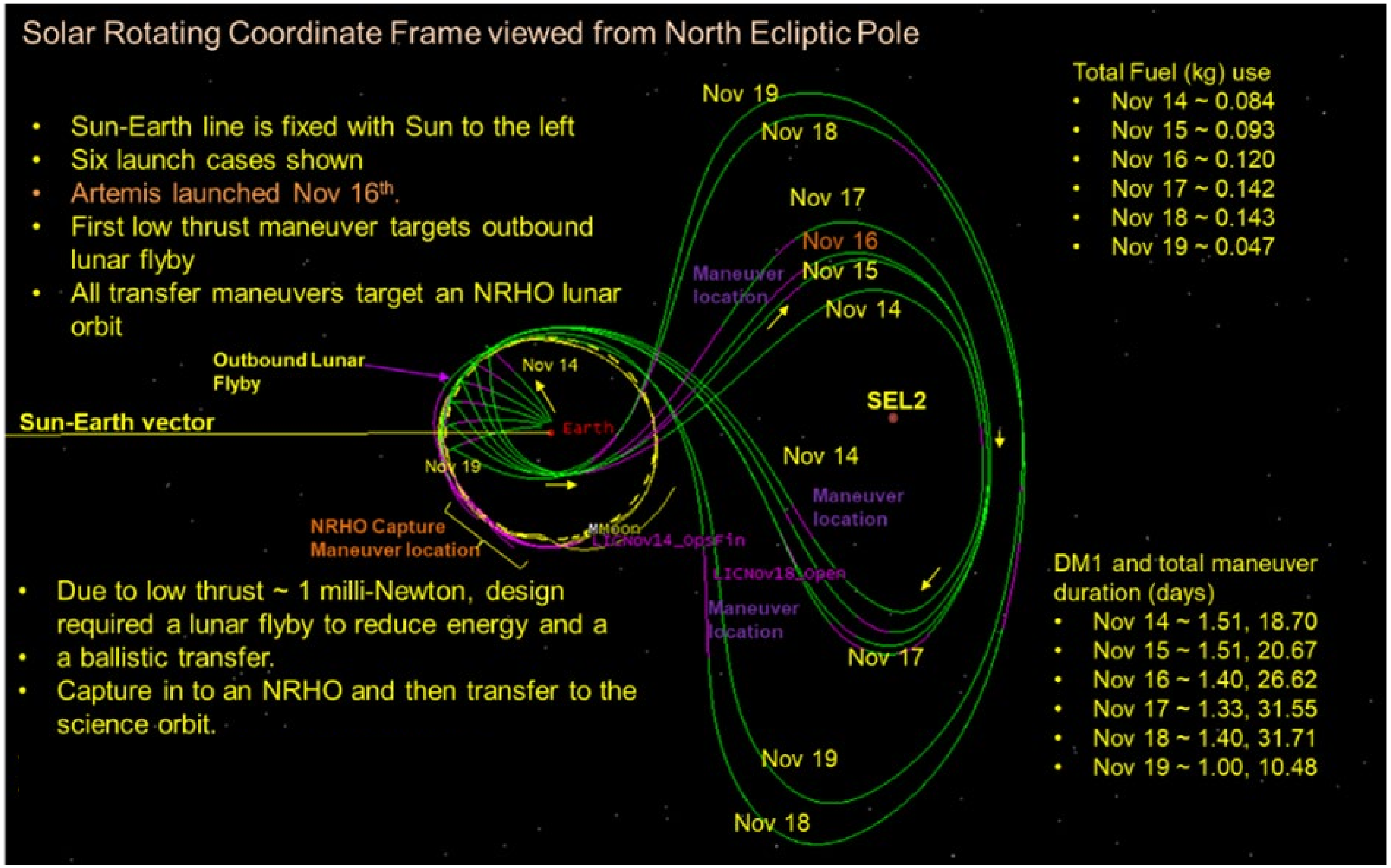
Switch to Moon-centered frame

Thrust to target orbit — free length (optimizer places thrust arcs as appropriate)

target orbit

- 🔵 Free point (Cartesian coordinates)
- 🟡 Point on Moon’s SOI (spherical coordinates)
- 🟢 Periapse point (spherical coordinates)
- 🟣 Target orbit (classical orbit elements)
- - - → Coast arc
- → Thrust arc
- ☐ Match point
- – – Reference frame switch

Baseline Trajectory Design – High-Fidelity Refinement



Solar Rotating Coordinate Frame viewed from North Ecliptic Pole

- Sun-Earth line is fixed with Sun to the left
- Six launch cases shown
- Artemis launched Nov 16th.
- First low thrust maneuver targets outbound lunar flyby
- All transfer maneuvers target an NRHO lunar orbit

- Due to low thrust ~ 1 milli-Newton, design required a lunar flyby to reduce energy and a
- a ballistic transfer.
- Capture in to an NRHO and then transfer to the science orbit.

Total Fuel (kg) use
- Nov 14 ~ 0.084
- Nov 15 ~ 0.093
- Nov 16 ~ 0.120
- Nov 17 ~ 0.142
- Nov 18 ~ 0.143
- Nov 19 ~ 0.047

DM1 and total maneuver duration (days)
- Nov 14 ~ 1.51, 18.70
- Nov 15 ~ 1.51, 20.67
- Nov 16 ~ 1.40, 26.62
- Nov 17 ~ 1.33, 31.55
- Nov 18 ~ 1.40, 31.71
- Nov 19 ~ 1.00, 10.48

Recovery Analysis

- Recovery trajectories were computed to deliver LIC to NRHO even without pre-flyby maneuvers.