Goddard Space Flight Center

PURDUE AERONAUTICS & ASTRONAUTICS

THE LUNAR ICECUBE MISSION CHALLENGE: ATTAINING SCIENCE ORBIT PARAMETERS FROM A CONSTRAINED APPROACH TRAJECTORY

AAS 17-319

David C. Folta, Natasha Bosanac, Andrew Cox, and Kathleen C. Howell
NASA Goddard Space Flight Center & Purdue University

27th AAS/AIAA Space Flight Mechanics Meeting, San Antonio, TX
February 6-9, 2017

Motivation

- Combination of Technology and Cost
  - Miniaturization of spacecraft technologies
  - Independent launch vehicle accessibility
- Selection of CubeSats as Secondary Deployment by the Exploration Mission-1 (EM-1) Space Launch System
  - Translunar trajectory with a lunar flyby
  - Deployed after Orion is place onto lunar trajectory
- Challenges
  - Fixed departure asymptote with translunar energy with a predefined launch window
  - Limited propulsion capabilities, a low thrust system
  - Constrained approach energy and direction; Sun-Earth to Earth Moon
  - Attain science orbit Keplerian elements, $i \sim 90$, $e \sim 0.57$, $\omega \sim 0$, RAAN optimal for lifetime
- Solution
  - Leverage dynamical system techniques to design trajectories that evolve to meet science orbit requirements

Lunar Ice Cube Mission Overview

- Lunar IceCube, is a 6U, 14kg CubeSat, selected for participation in the Next Space Technologies for Exploration Partnerships (NEXTSTEP)
- Primary objective is to prospect for water in solid, liquid and vapor forms, while also detecting other lunar volatiles
- Design includes radiation-hardened subsystems, a JPL IRIS-2 transceiver, a high power solar panel/actuator system and a robust payload processor
- Science requirement is ~90 deg inclination, 100 x 5000 km orbit with perilune at equatorial crossing
- Propulsion provided by a Busek Ion Thruster 3-cm (BIT-3) system using 1.5 kg iodine propellant with a baseline thrust < 1.15 mN and Isp ~ 2500 sec

Dynamical Models and Techniques

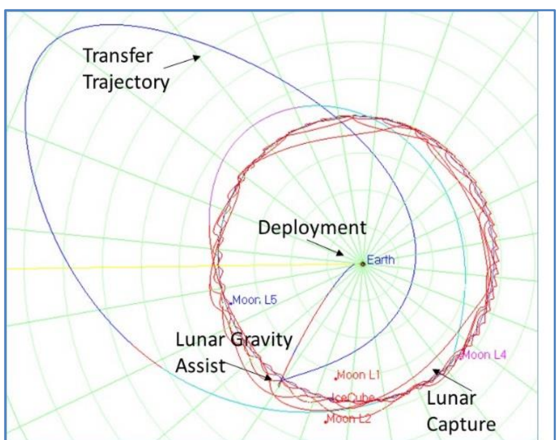
- Explore the lunar capture design space for low-thrust enabled transfers that link the arrival trajectory with the lunar science orbit
- Employ dynamical models of varying levels of fidelity: from CR3BP to an operational modeling environment
  - CR3BP provides autonomous approximation to Sun-Earth and Earth-Moon system dynamics
  - Place bounds on motion in the Earth-Moon system
  - Pass to ephemeris modeling to incorporate Sun, Earth, Moon and low thrust accelerations
  - Final design using operational models
- CR3BP analysis performed using the Adaptive Trajectory Design (ATD) and related Matlab algorithms
- Designs are then transitioned to a full ephemeris model such as those found in GSFC's General Mission Analysis Tool (GMAT) and AGI's STK Astrogator Module

A Sample Transfer

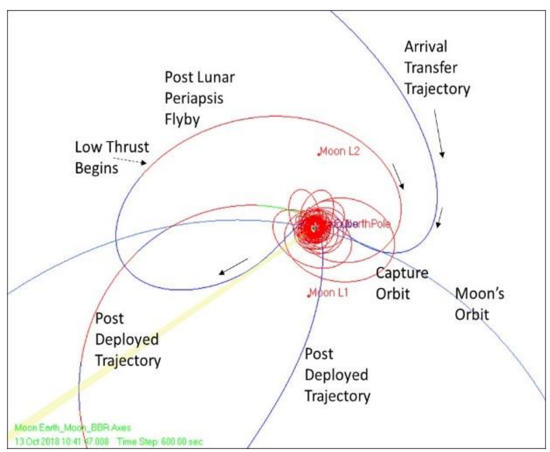
Goddard Space Flight Center

- Transfer trajectory from a constrained outbound asymptote with a trailing edge lunar gravity assist
- Transfer leverages a combination of natural (blue) and low-thrust-enabled (red) arcs to produce motion that is captured around the Moon
- But without dynamical information for design inputs, the achieved science orbit inclination is not readily achievable

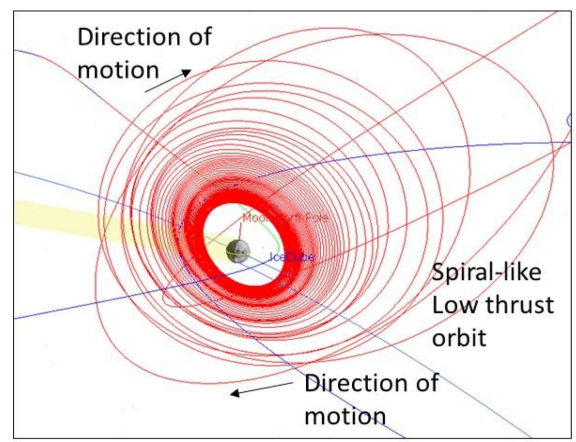
Lunar IceCube Trajectory Transfer



Arrival Trajectory in Earth-Moon Rotating Coordinates



Lunar Capture with Low Thrust

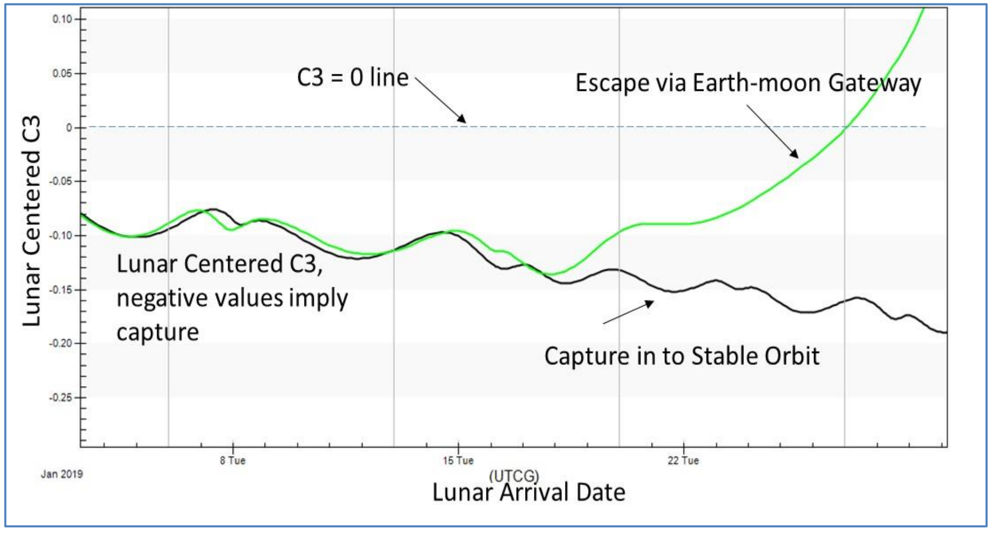


Goddard Space Flight Center

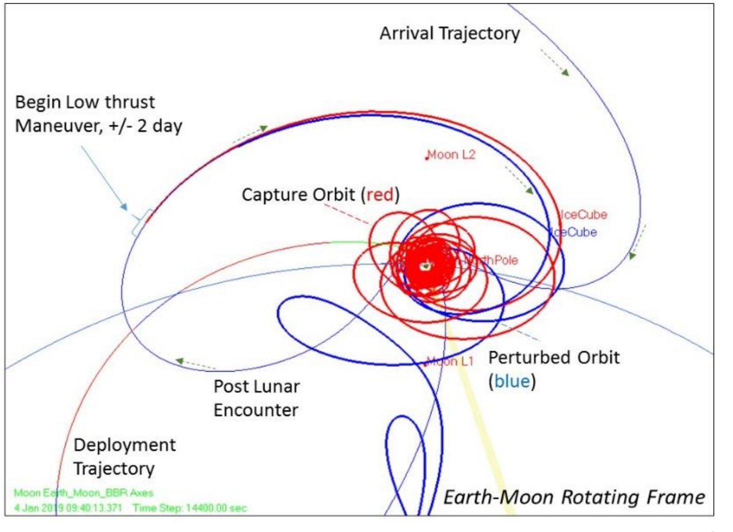
Sensitivity of Arrival and Lunar Capture

- Sensitivity of this design explored using a measure of the energy: lunar C3
- Thrusting arc timeline altered by 2 days from nominal
- Due to the chaotic nature of the multi-body Cislunar gravitational environment, small differences result in two distinctly different paths, reference trajectory (red) and perturbed trajectory (blue)
- Challenge includes obtaining motion that is quickly captured to the lunar vicinity and eventually evolves to an elliptical orbit with the desired orbital elements

Lunar C3



Earth-Moon rotating frame



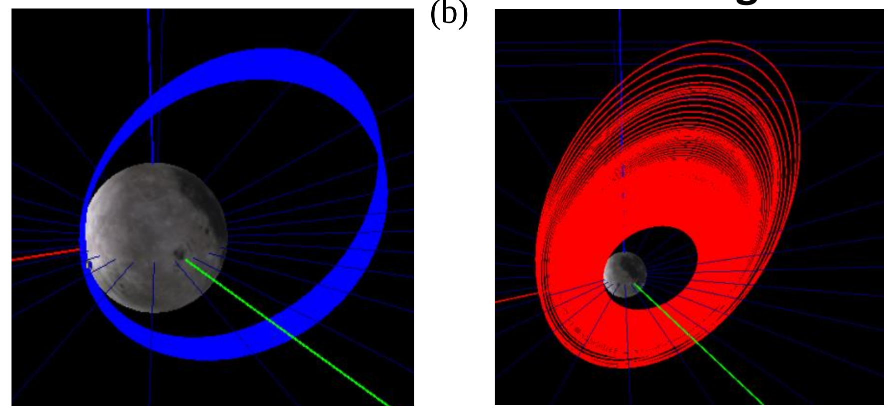
Goddard Space Flight Center

Science Orbit

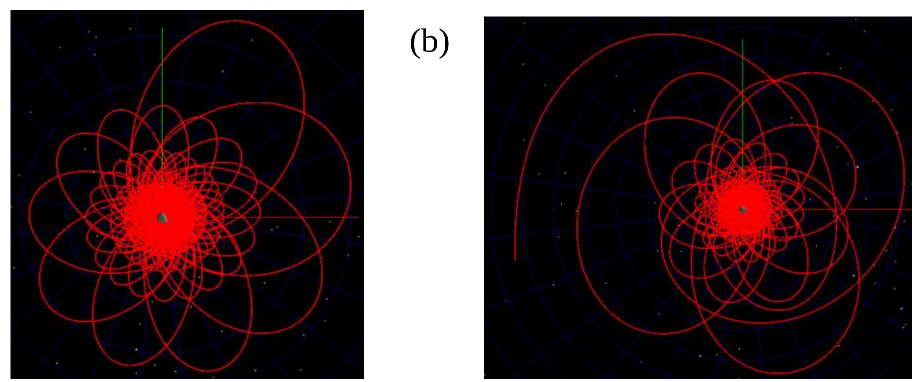
- Trajectories that approach / depart the science orbit computed via forward & backward integration
- Analyze with various RAAN (which determine the orbital lifetime)
- Thrust profiles for arcs can be limited heuristically by the total required thrust time
- Assumed thrust direction anti-velocity and magnitude 0.90 mN
- Affects Keplerian elements and rates and affects the 'entry' into the multi-body region
- Determine what design matches with predefined arrival conditions

Science Orbit **With backward thrusting**

(a) (b)



(a) (b)

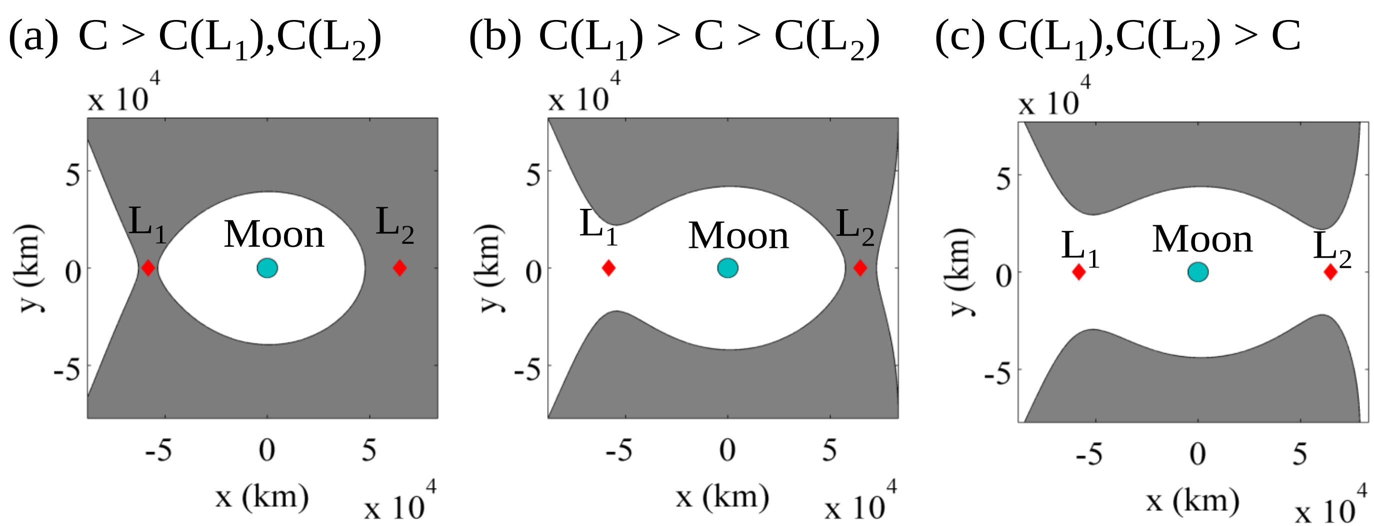


Various multi-body trajectories

Lunar Capture Dynamics and Gateways

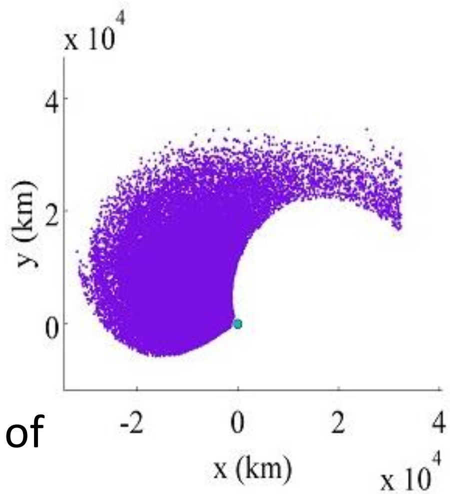
Goddard Space Flight Center

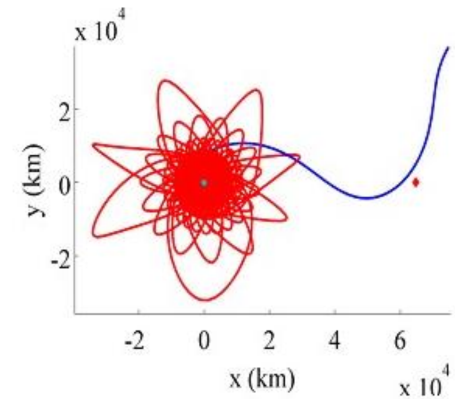
- Gateway analysis in the Earth-Moon CR3BP enables exploration of trajectory behavior as s/c approaches the lunar orbit
- Consider the process for generating a science orbit approach path: feasible science orbit is integrated backwards in time with the low-thrust
- For a given Jacobi constant, the L_1 and L_2 gateways are closed and motion cannot escape
- Velocity of the spacecraft increases over time, Jacobi constant decreases
- Examine orbit for Jacobi constant equivalent outside the L_2 gateway to guide construction of the trajectory generation process
- In particular, each initial condition located at a given true anomaly along a feasible science orbit is integrated backwards in time in a point mass ephemeris model with the thruster activated in the anti-velocity direction until a Jacobi constant equivalent to that of L_2 is achieved.

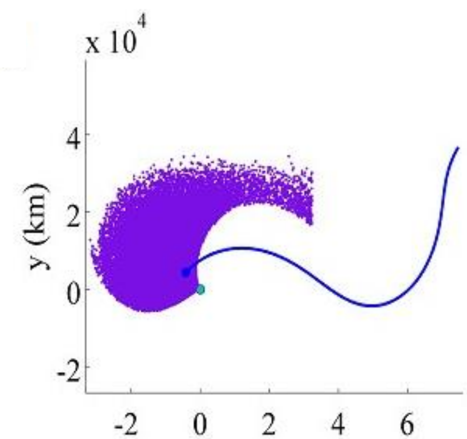


Manifolds of Feasible Approaches

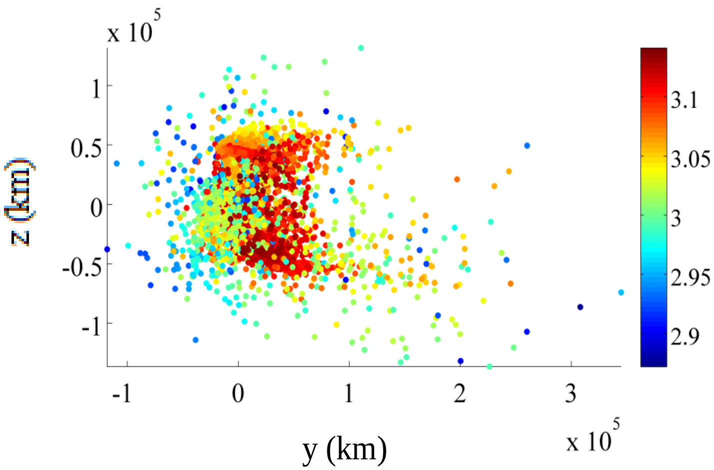
- For feasible science approach paths, each of the apses at which the low-thrust engine is activated must lie close to the unstable manifold of an L_2 libration point orbit
- States that lie within these manifolds pass through the L_2 gateway prior to evolving towards the lunar vicinity
- Implement a Surface od Section (SoS) mapping at E-M L2, with y and z seeded on hyperplane
- For each combination of position variables, (*x*,*y*,*z*), several velocities are defined to possess a negative x-component, with the relative values of the y- and z-components then varied
- Integrated forwards until their first periapsis
- Sample set of periapses in purple corresponding to trajectories that pass through the L_2 gateway, i.e., the unstable manifolds of L_2 periodic and quasi-periodic orbits, at a Jacobi constant of C = 3.138

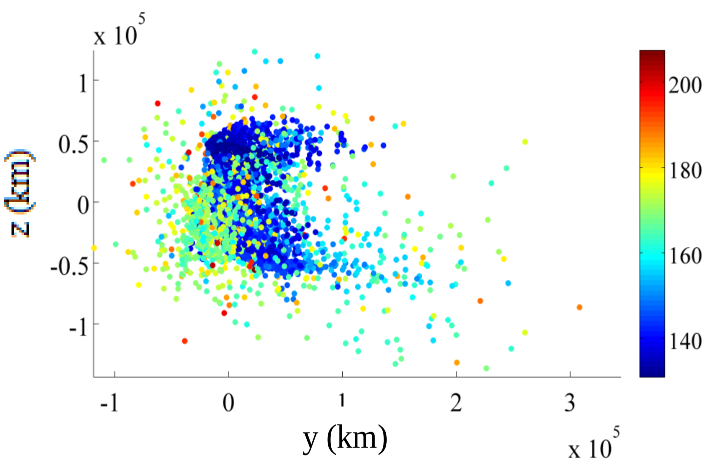






Visualization of Science Orbit Approach Paths

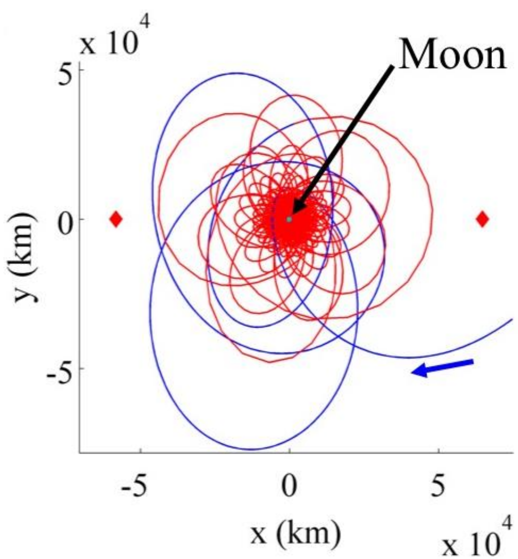


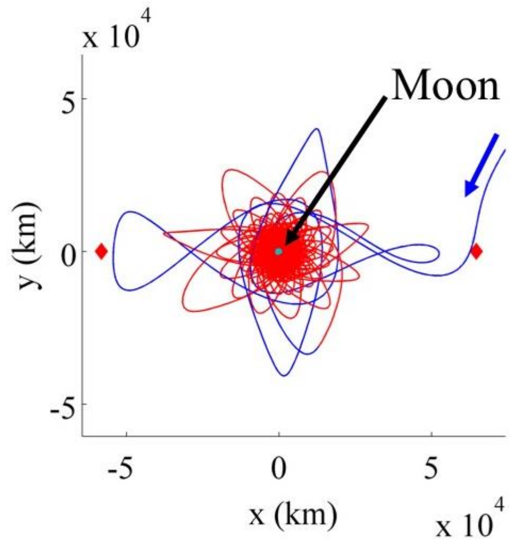


- L_2 gateway map depicts crossings of trajectories that arrive at the lunar science orbit in forward time with the assistance of a low-thrust engine
- Colored by Jacobi constant in the Earth-Moon CR3BP and the time of flight to the hyperplane
- At each periapsis or apoapsis with a Jacobi constant below that of L_2, the spacecraft state is propagated until it reaches the defined surface of section
- RAAN in the range [0, 360] in increments of 20 degrees
- Crossing of each feasible science orbit approach arc with the surface of section is represented by its y- and z-coordinates in an Earth-Moon rotating frame
- Velocity that is directed in the negative x direction and the negative y direction.

Example of an L_2 Gateway Map Capturing Motion

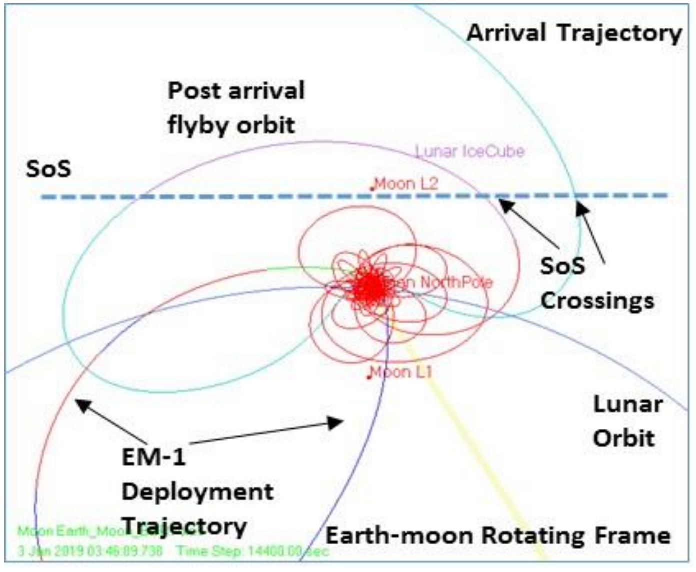
- L_2 gateway map captures motion that evolves towards the desired lunar orbit with a high inclination and periapsis over the equator
- Analysis reveals two types of trajectories that approach the desired polar science orbit:
  - A low Jacobi constant and longer time of flight to the L_2 gateway
  - A higher Jacobi constant and a shorter time of flight to the L_2 gateway
  - An example appears in an Earth-Moon rotating frame with blue arcs indicating natural motion and red curves locating low-thrust-enabled segments.

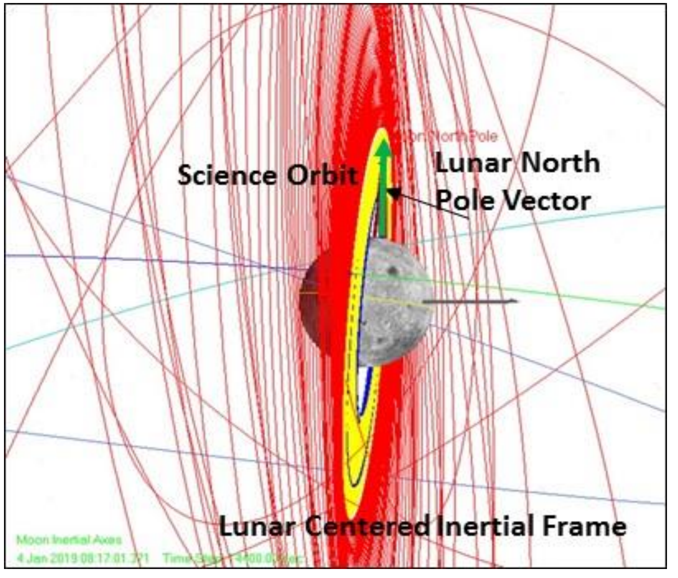




Comparison to Existing Point Solutions

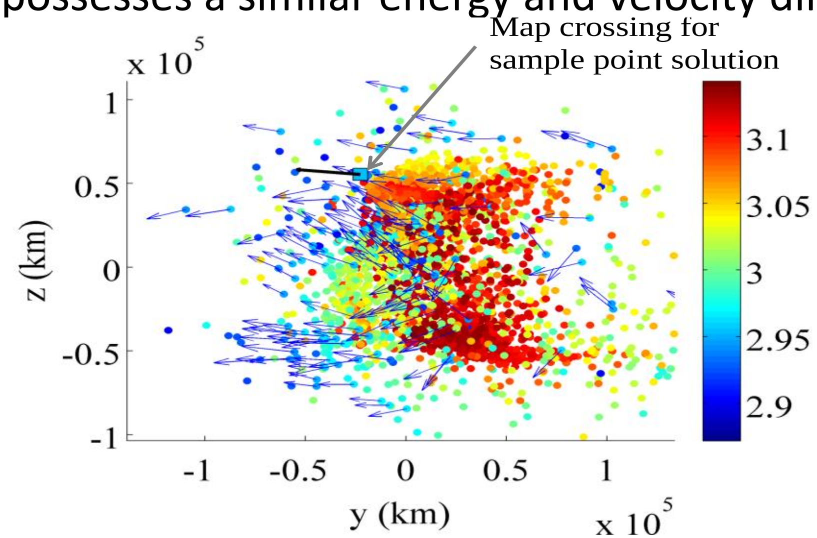
- Visualization of the natural flow through the Earth-Moon L_2 gateway and subsequent low-thrust-enabled capture via dynamical systems techniques useful in analysis of existing point solutions
- These point solutions, constructed in an operational high-fidelity model include transfers that reach a polar orbit and those that do not
- Arrival and capture trajectory in an Earth-Moon rotating frame and shows the inbound surface of section crossings
- Captured to a 93 deg inclined polar orbit with ω = 0 deg
- Directional low thrust maneuver alters the acceleration profile may be required to attain the precise orbital element requirements





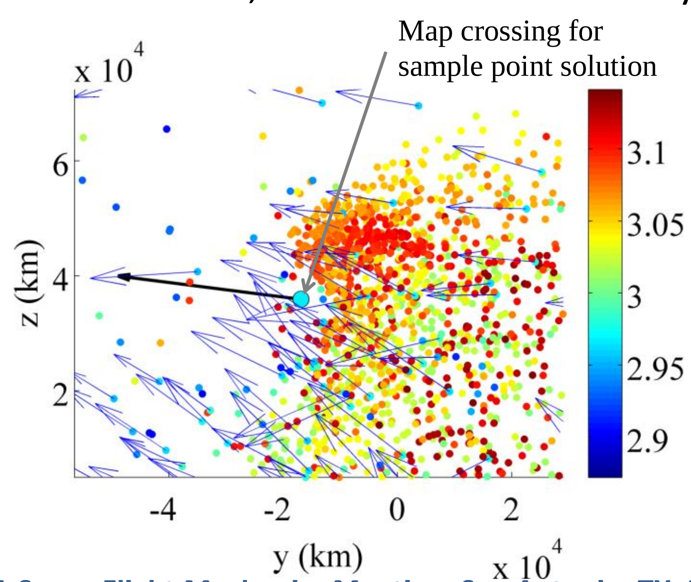
Comparison to Existing Point Solutions

- Generated science orbit approach paths are compared to existing point designs via their L_2 gateway map crossings
- L_2 gateway map captures motion that evolves towards the desired lunar orbit with a high inclination and periapsis over the equator
- Map crossings for a selected set of epoch values, colored by their Jacobi constant
- Map crossing marked by a light blue filled square represents the existing 93 deg inclined point solution – and is similar to Jacobi constant of nearby map crossings
- Blue vectors are added to map crossings that possess a value of the Jacobi constant
- Nearby the sample point solution, in position and Jacobi constant, the velocity vectors are pointed in a similar direction
- Map crossing associated with the sample solution falls in a region of the map where crossings occur and possesses a similar energy and velocity direction.



Comparison to Existing Point Solutions

- Maps support the analysis of problematic lunar approach arcs, i.e. those that do not reach a polar lunar orbit, the 45 deg inclined case
- Map crossings for a selected set of epoch values, colored by their Jacobi constant
- Map crossing marked by a cyan filled circle represents the existing 45 deg inclined case
- Blue vectors attached to each map crossing indicate the y- and z-component of velocity
- The scarcity of map crossings at a similar energy level in the vicinity of this point solution may indicate increased difficulty or sensitivity in attaining a polar orbit
  - Feasible transfers occur for a lower energy or higher Jacobi constant
  - Shift the crossing of the L_2 gateway hyperplane closer to the x-axis of the Earth-Moon rotating frame near the cyan map crossings
  - Adjustments to the energy and velocity produce a point solution with a similar crossing of the L_2 hyperplane in position coordinates, but with a lower velocity, Jacobi constant is above ~3.05



Concluding Remarks

- Address challenges involved in designing multi-body transfers into stable lunar orbits limited by a low thrust system
- Process that leverages dynamical system theory to identify transfers from a Moon-centered multibody trajectory to a stable, polar lunar orbit.
- Use CR3BP, high fidelity models, and surface of section (hyperplane) to identify useful position states and Jacobi Constant values
- Moon-centered manifolds employed to identify states and energies
- Low-thrust acceleration enables transfers from a stable lunar orbit to the hyperplane using backward integration
- Verified with operational software using forward integration and differential correction targeting
- Via dynamics systems several lunar arrival conditions that link to high energy deployment trajectories are identified and are successfully employed in a Lunar IceCube mission design process

THE LUNAR ICECUBE MISSION CHALLENGE: ATTAINING SCIENCE ORBIT PARAMETERS FROM A CONSTRAINED APPROACH TRAJECTORY

Thank You