Efficient NRHO to DRO Transfers in Cislunar Space

Gregory Lantoine

Jet Propulsion Laboratory, California Institute of Technology

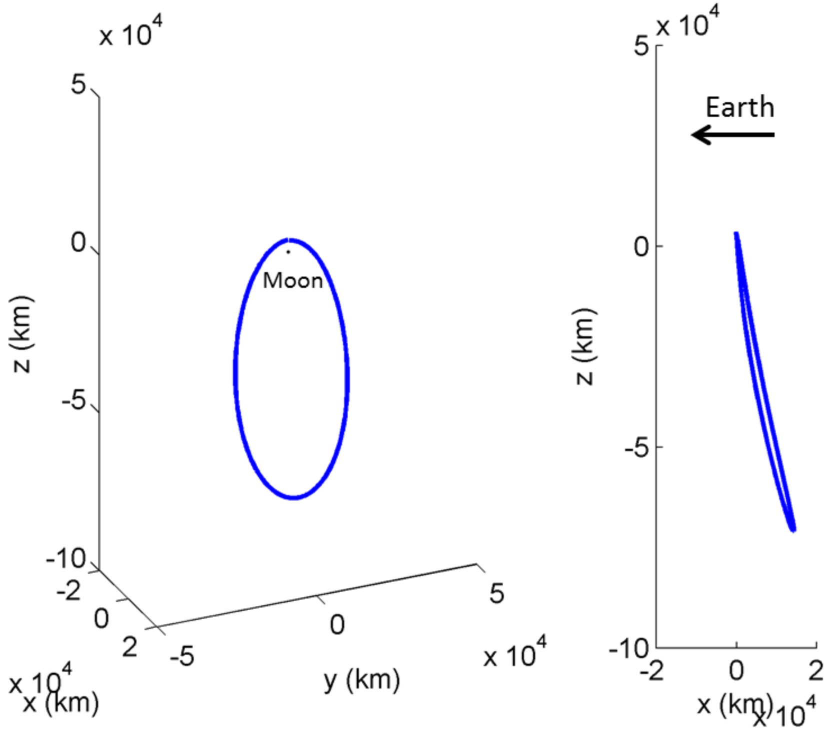
Introduction

- Growing interest in ciscular space missions
  - Stepping stone for human deep space exploration
- Two cislunar orbit types offer promising applications and are often considered in cislunar missions:
  - Near Rectilinear Halo Orbit (NRHO)
  - Distant Retrograde Orbit (DRO)
- NASA's Asteroid Redirect Robotic Mission (ARRM) concept takes advantage of these orbits:
  - Crewed mission for investigating the return boulder occurs in NRHO
  - Returned boulder stored in DRO
- How to systematically design efficient NRHO to DRO transfers ?
  - crucial to minimize as much as possible the transfer delta-v due to large masses involved (SEP modules, habitats…)
  - no analytical solution because of strongly perturbed cislunar environment
- The transfers shown here will rely on connecting effectively NRHO departure arcs to DRO insertion arcs, via Earth and solar gravity

ORBITS

NRHO

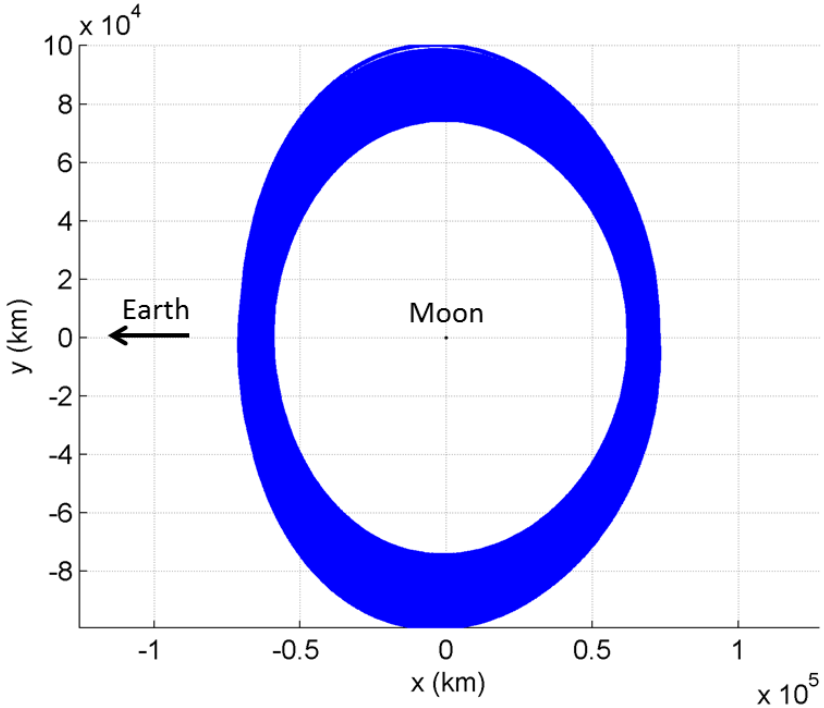
- NRHOs are members of the lunar Halo families with close approaches over one of the lunar poles
- 9:2 resonant NRHO (L2, South) considered:
  - 9 NRHO revs per 2 lunar months
  - 6.6 days period
  - 3250 km perilune radius
  - ~75,000 km apolune radius
- NRHOs are good staging orbits for space modules or habitats
  - favor both access from Earth and polar surface access
- Slightly unstable orbit (<10 m/s per year maintenance)



Lunar NRHO in Earth-Moon synodic frame propagated for 1 period

DRO

- Well-studied orbit which appears to orbit the Moon in a retrograde motion (when viewed in a frame rotating with the Moon)
- Planar 70k-DRO considered
  - Rotating x-axis crossing at ~70,000 km
  - 13-14 days orbital period
  - near 2:1 resonance with the Moon: launch opportunities from Earth every other revolution to access that orbit
- Highly stable with more than 150 years of lifetime without maintenance
- Ideal storage orbit for sample return missions

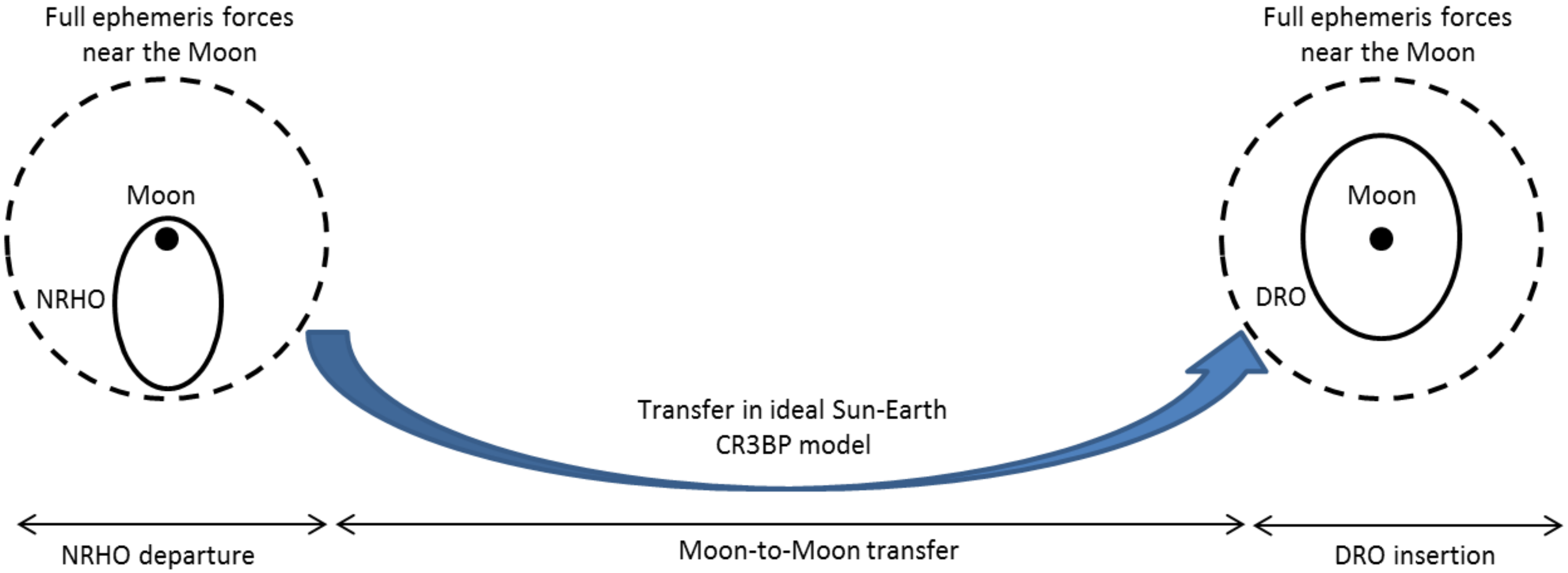


Lunar DRO in Earth-Moon synodic frame propagated for 10 years

INITIAL GUESS

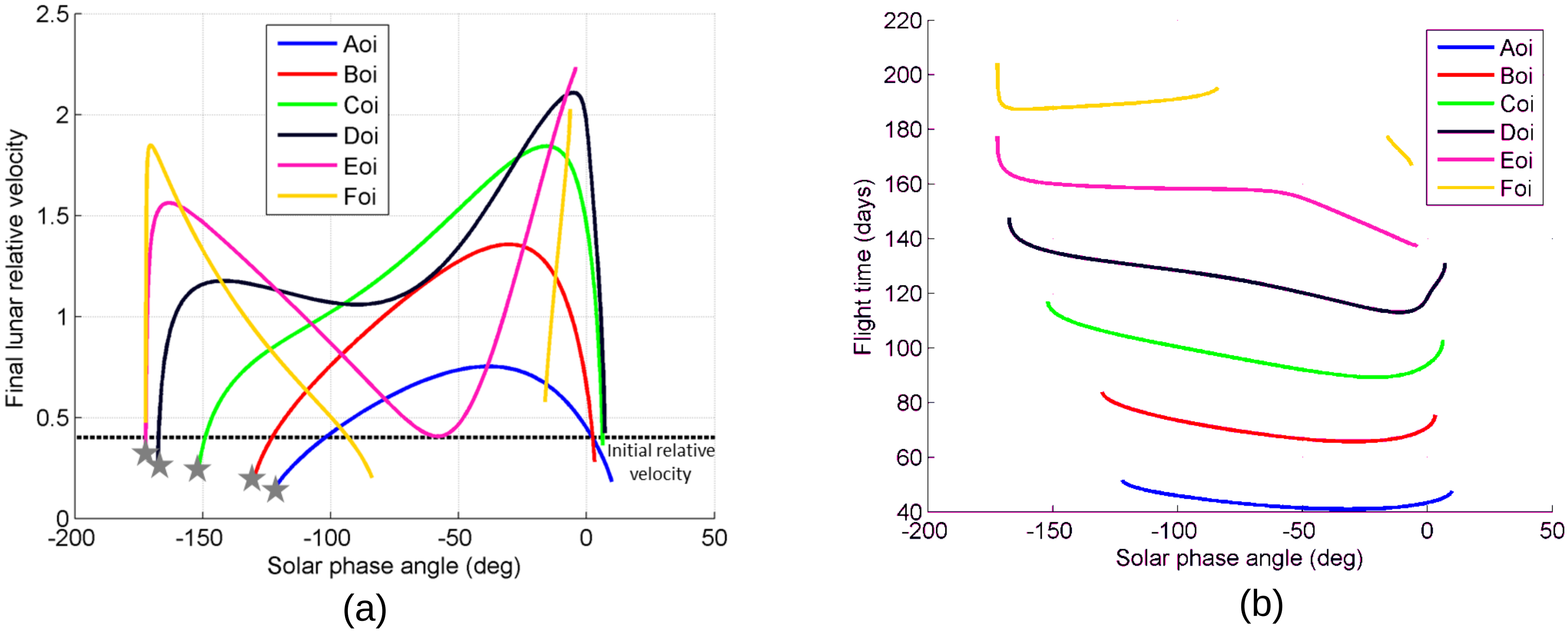
Initial Guess Structure

- NRHO to DRO transfers require significant inclination change
- Inclination changes are more efficient when performed far from the orbiting body
- → take an indirect route: escape the Moon, move far away, and come back
- Initial guess split in 3 phases:



Moon-to-Moon Transfer Families

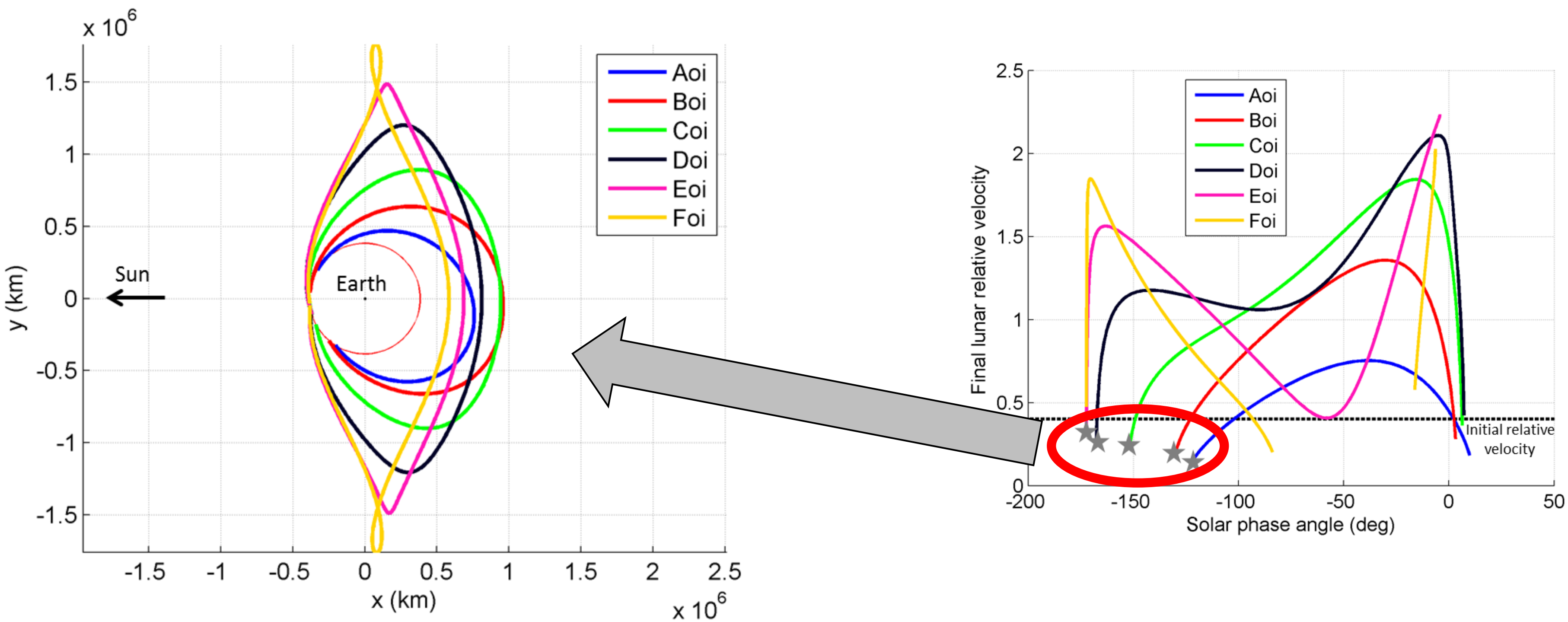
- When moving far away, solar perturbations become significant
- No analytical solutions are available
- → Look up pre-computed database of families of Moon-to-Moon transfers in the Sun-Earth CRTBP



Characteristics of the 'oi' Moon-to-Moon families ($v_{\infty,0}$ = 0.4 km/s): (a) final lunar relative velocity magnitude vs solar phase angle (b) flight time vs solar phase angle

Moon-to-Moon Transfer Candidates

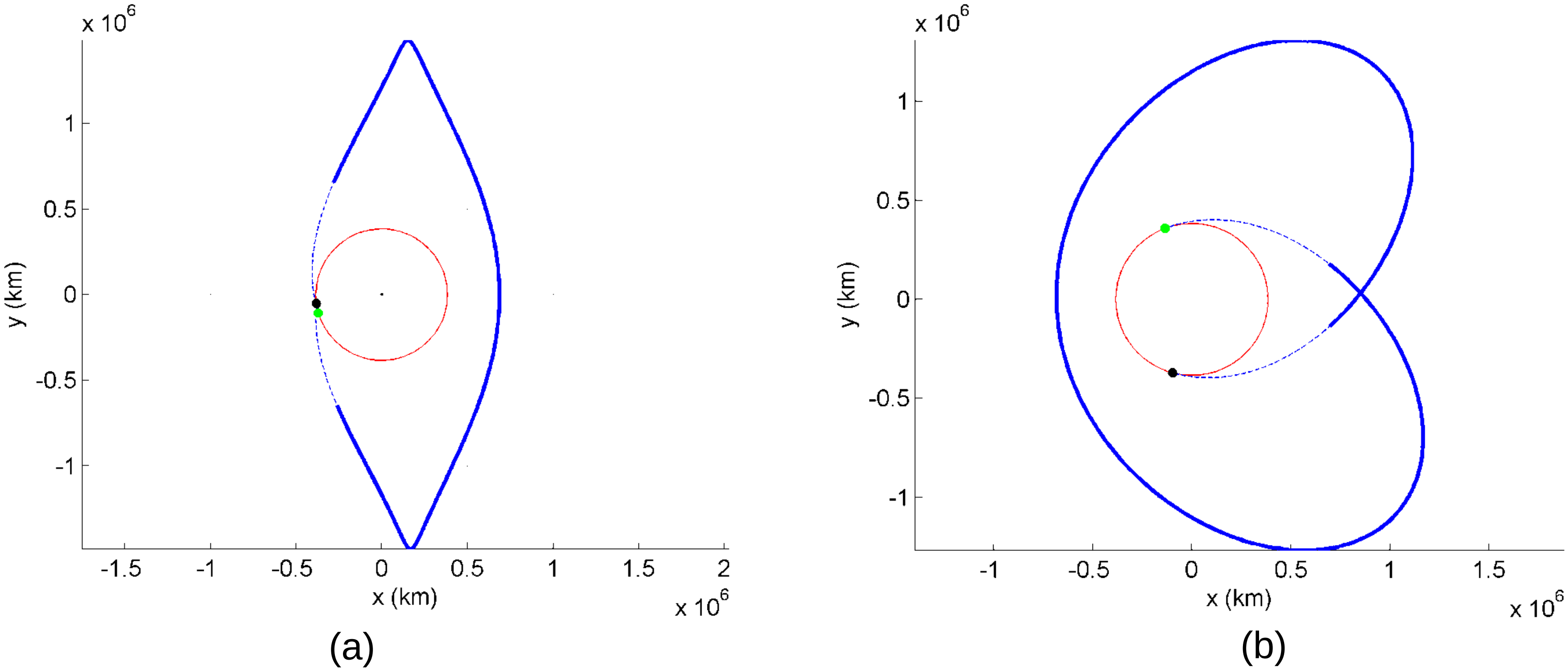
- Long transfer solutions shadow Sun-Earth Distant Prograde Orbits (DPOs) with apogees alternately leading and trailing the Earth in its orbit about the Sun.



Moon-to-Moon 'oi' solutions with small lunar relative velocity on both ends, plotted in the Sun-Earth rotating frame.

Chosen Moon-to-Moon Transfer Type

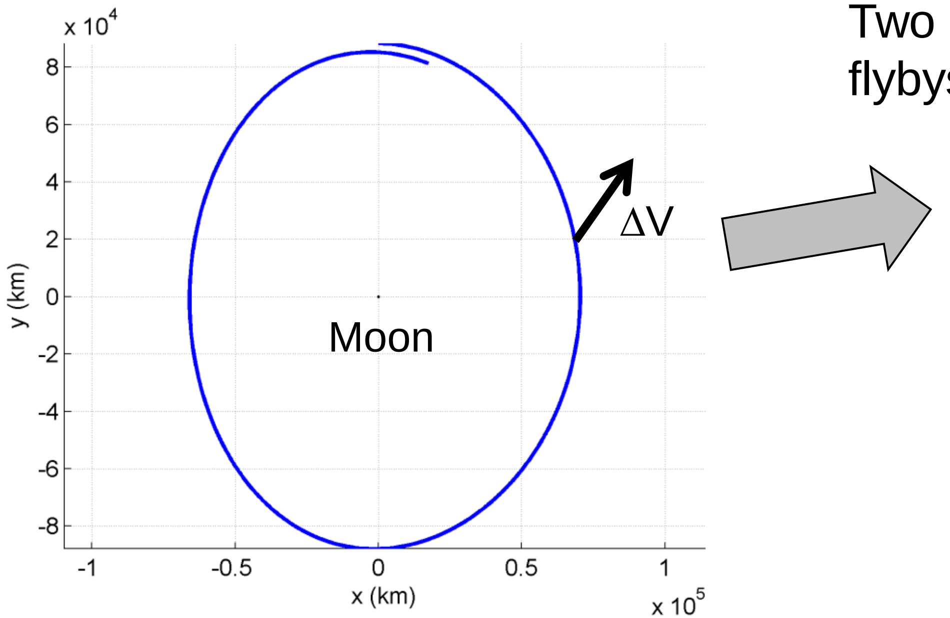
- Eoi Moon-to-Moon transfer is used to illustrate the methodology and construct a full initial guess

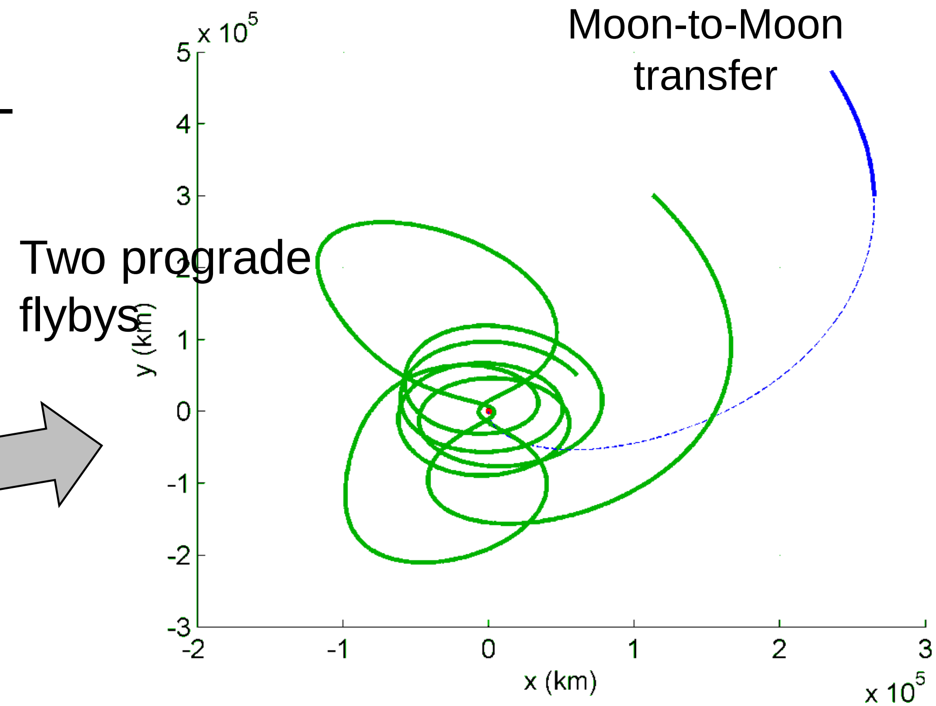


Selected Moon-to-Moon Eoi initial guess in: a) Earth-centered Sun-Earth rotating frame; b) Earth-centered inertial frame. The Moon's positions at the initial and final encounters are shown by black and green circles, respectively. Dashed lines are the chopped-off ends of the transfer that will be replaced by actual NRHO departure and DRO insertion trajectories.

DRO insertion

- Apply impulse and propagate backwards starting from the selected DRO orbit
  - Grid search on DV magnitude (~15-25 m/s typically), direction & location
  - Guess DRO insertion time (~3-6 months typically)
- Keep solutions with similar lunar approach conditions as Moon-to-Moon transfer

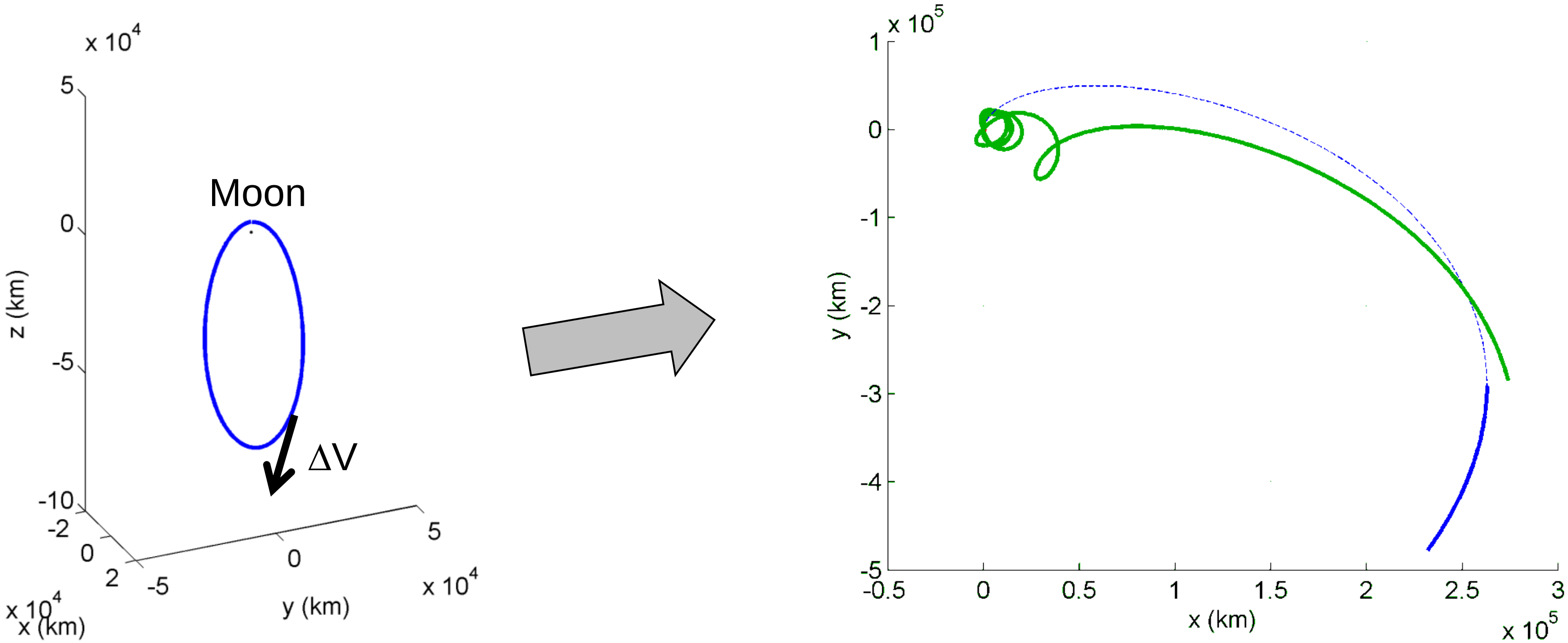




Example of DRO insertion trajectory (TOF = 98.7 days, DV = 17 m/s). Earth-Moon rotating frame

NRHO departure

- Similar idea as DRO insertion: Apply impulse and propagate forward starting from the selected NRHO orbit
  - Grid search on DV magnitude (~5-10 m/s typically), tangent direction only
  - Guess NRHO departure time (~1-2 months typically)

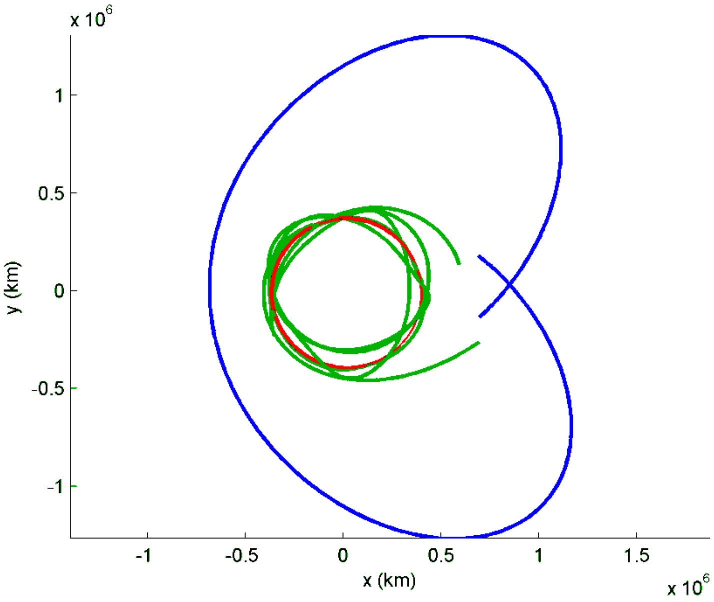


Example of NRHO departure trajectory (TOF = 45 days, DV = 9 m/s). Earth-Moon rotating frame

OPTIMIZATION & RESULTS

Full initial guess & optimization

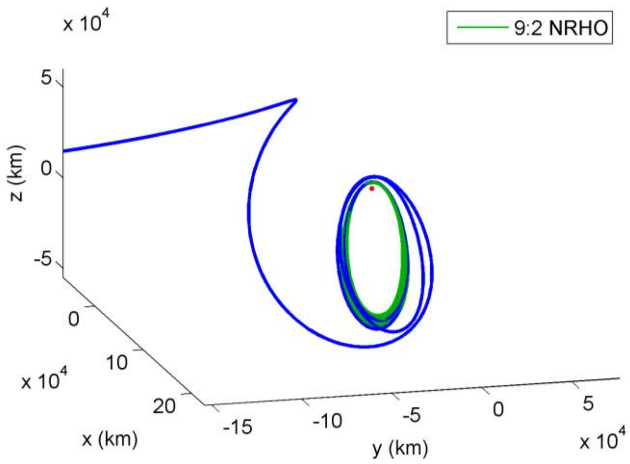
- Resulting initial guess has discontinuities
- To enforce continuity and minimize delta-v, a local optimizer is used to produce the final solution
- Endpoints (states and times) of the transfer are fixed to ensure the desired orbits are used
- Multiple shooting method: like the initial guess, complete trajectory is broken down into different legs
- Multiple impulsive maneuvers are distributed on each leg and can be varied by the optimizer
- SNOPT used to solve the resulting discrete problem



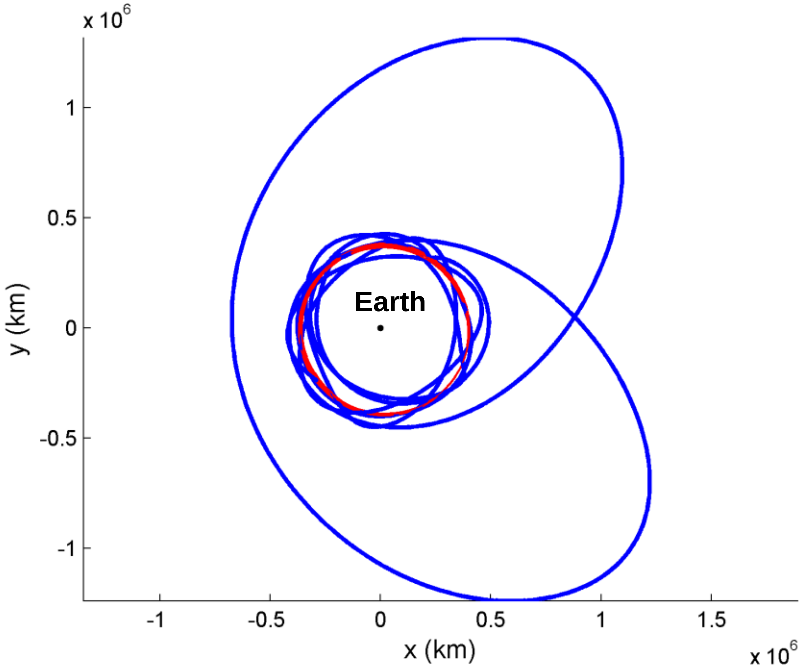
Complete initial guess of the NRHO to DRO transfer (Earth-centered inertial frame).

Optimized NRHO to DRO transfer

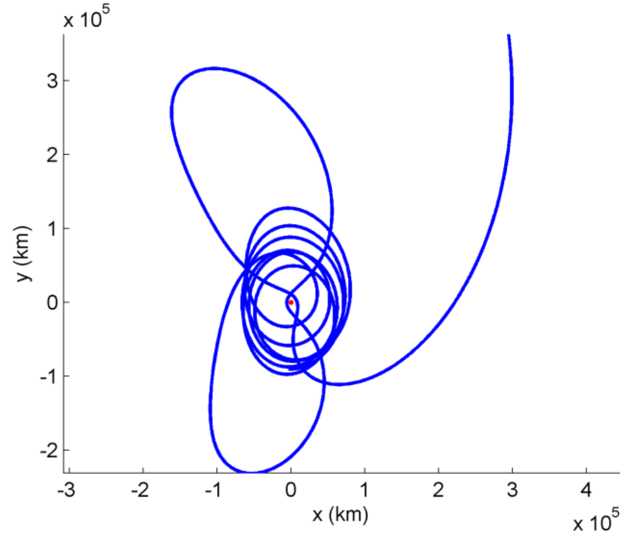
- After Orion rendezvous, the ARRM spacecraft transfers to a stable planar DRO
- Total ΔV = 56 m/s (NRO escape = 5 m/s, Solar Loop = 38 m/s, DRO insertion = 13 m/s)
- One 60-min lunar eclipse
- Flight Time ~11 months (336 days)
  - From Nov 18, 2027 to Oct 20, 2028



NRO escape (Earth-Moon synodic frame)



Earth-centered inertial frame



DRO insertion (Earth-Moon synodic frame)

Conclusion

- Systematic methodology to compute efficient NRHO to DRO transfers is described
- Accurate initial guesses are generated by using pre-computed solar-perturbed Moon-to-Moon transfers

- These transfers can be helpful for both robotic and human missions in cislunar space
- Methodology could be readily applied to other types of orbit transfers
  - DRO to L2 Halo
  - DRO to lunar polar orbit