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Using Gravity Assists in the Earth-Moon System as a Gateway to the Solar System

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Introduction

- How can we use the Moon and post-launch ΔV to explore the solar system?
  - Increased mass or smaller launch vehicles!
  - Flight time increase vs. benefit gained
  - Operational considerations
- Combined results of recent studies are presented here
  - Energy benefits of lunar flybys
  - Effectiveness of post-launch ΔVs
  - Approaches to develop an operational launch period

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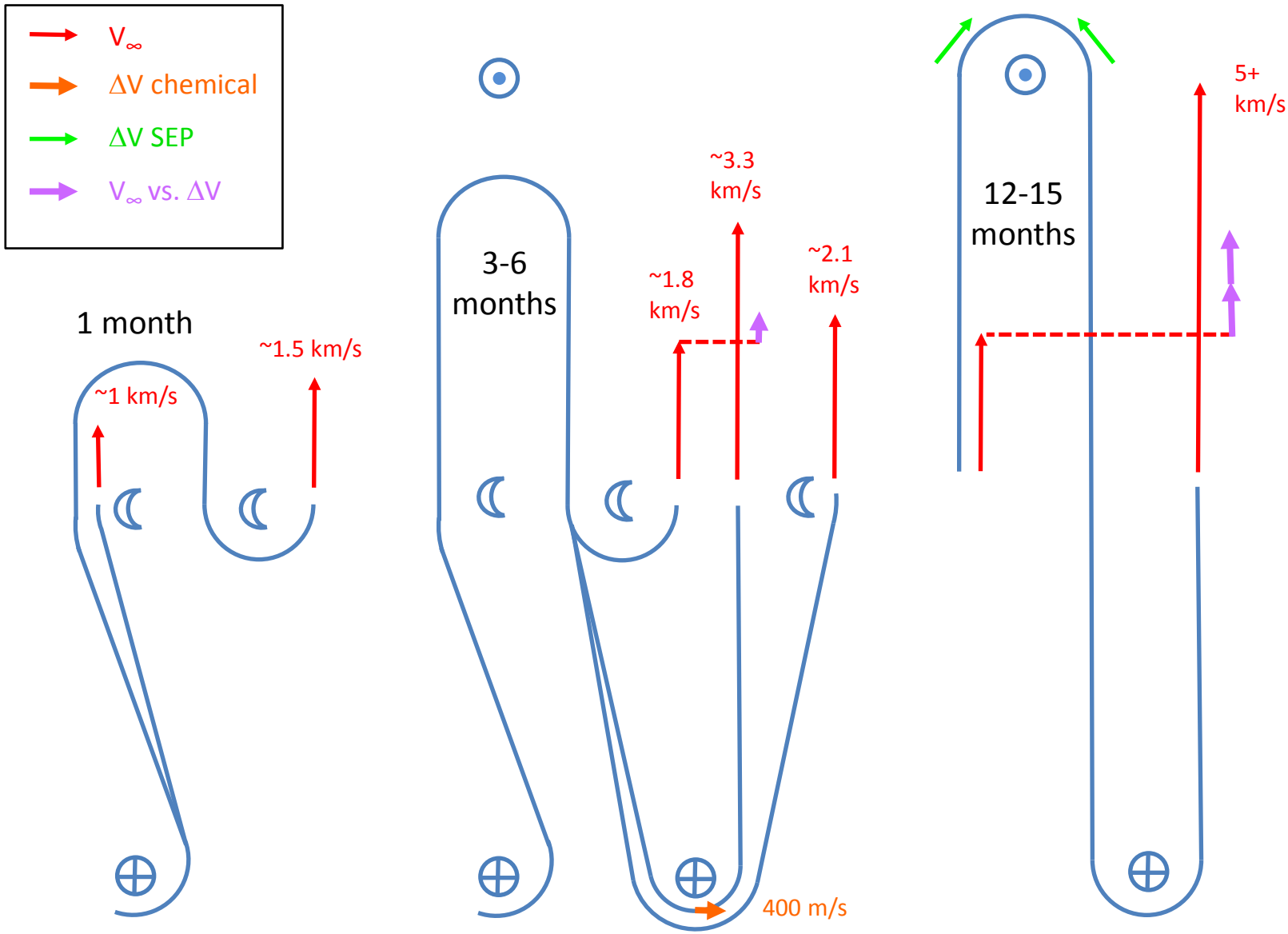
Lunar departure mode schematic



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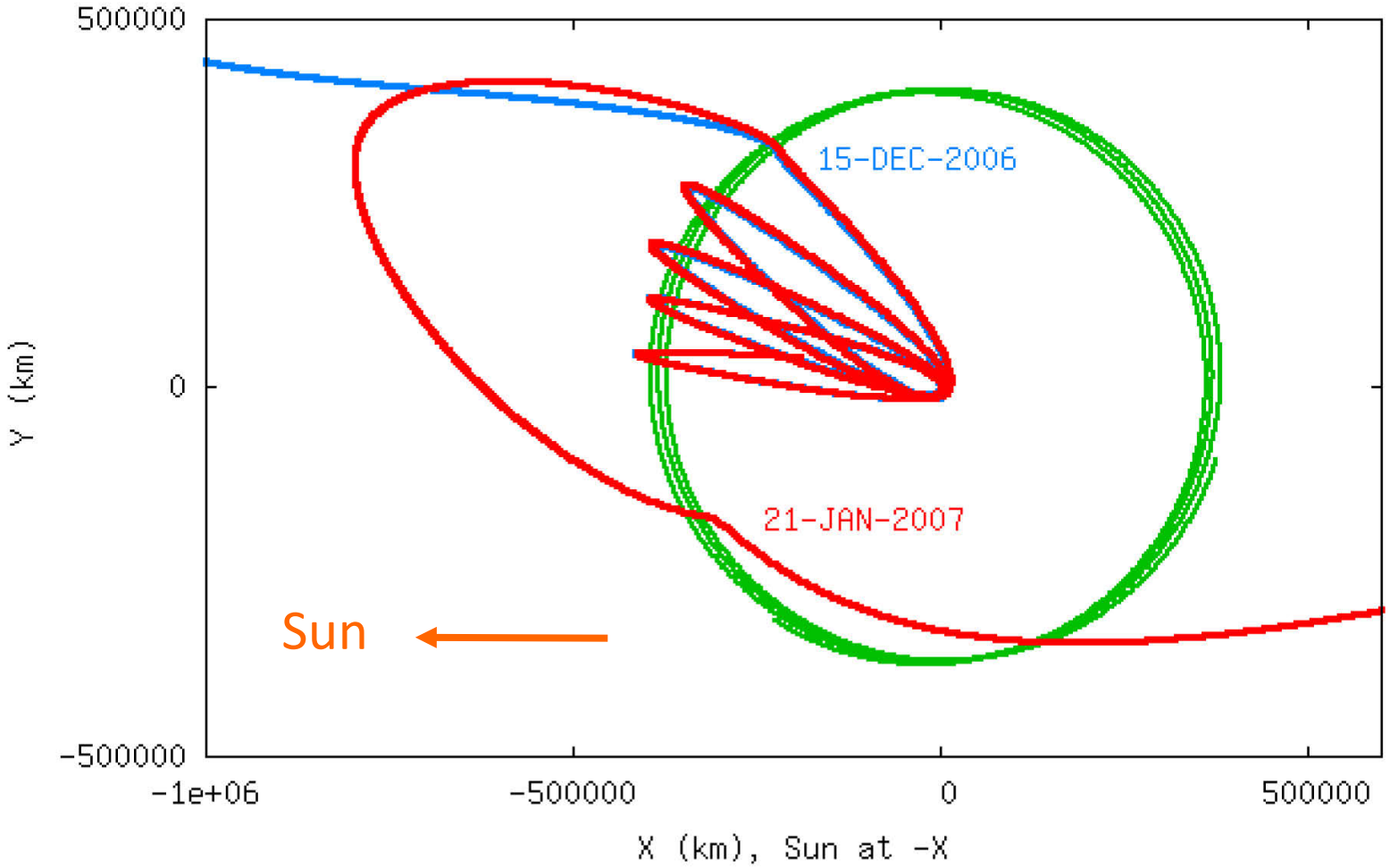
STEREO-A/B example

Lunar flybys used to set spacecraft in heliocentric drift-away orbits



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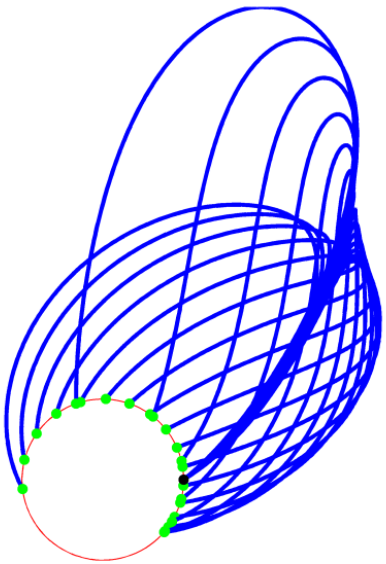
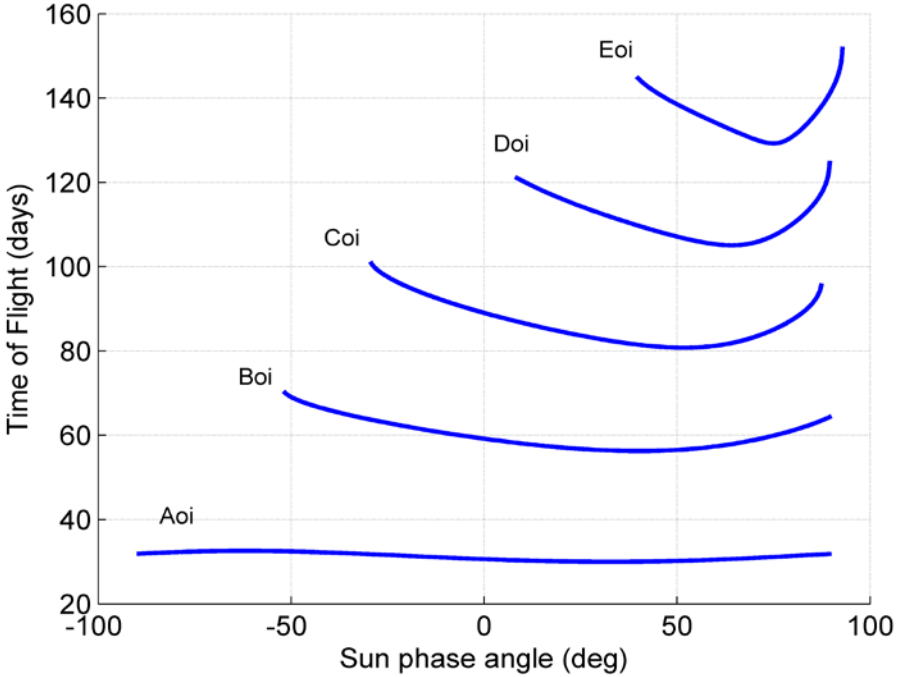
Solar-perturbed lunar flyby pairs



- Method: find trajectory segments that start and end at the Moon under solar gravitation perturbation
- Find full trajectory family by continuation in solar orientation of initial flyby and V_∞
  - Very sensitive to solar orientation, not very sensitive to V_∞

- Trajectory types can be categorized by:
  - Direction of each flyby (eg: inbound, outbound)
  - Number of months between flybys
- Ending flyby then oriented to maximize Earth-relative C3



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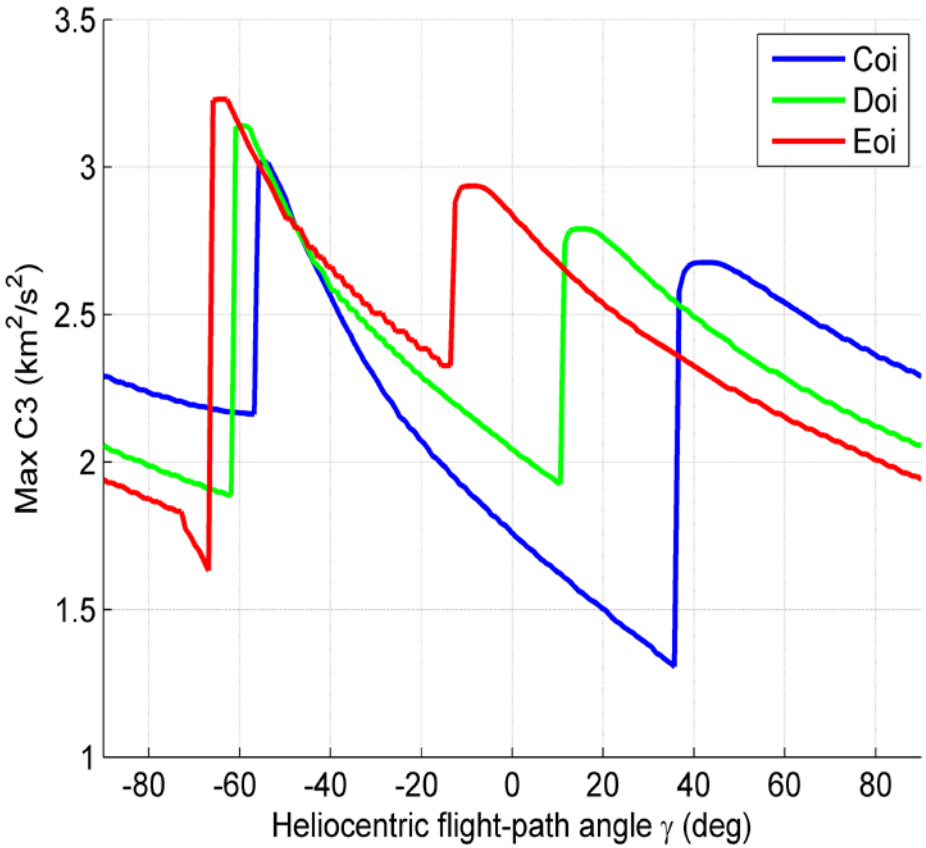
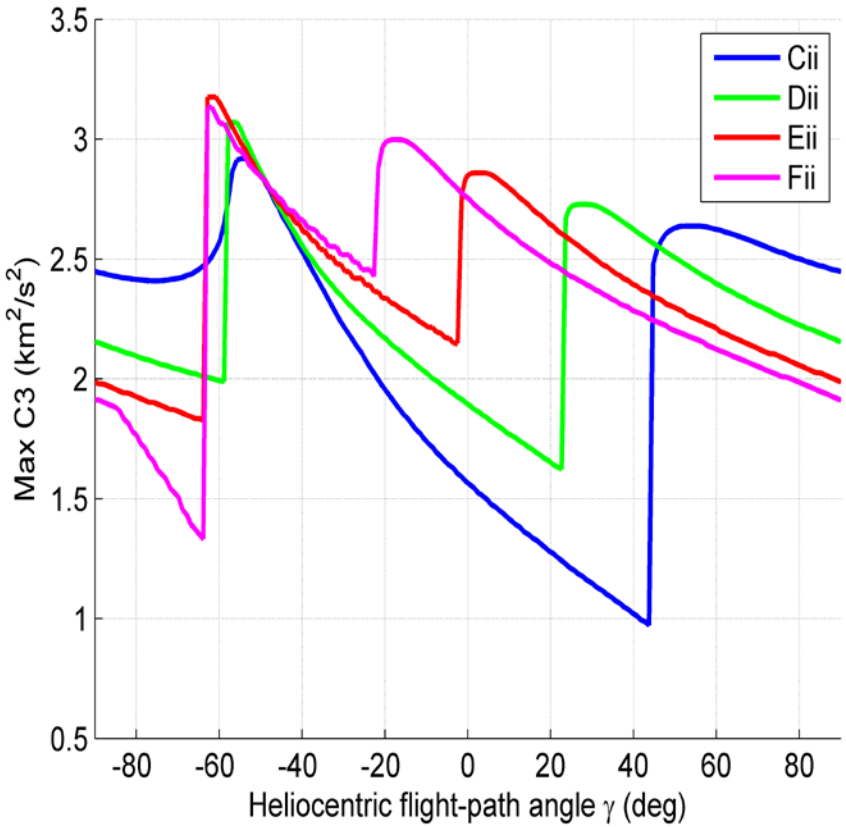
Double lunar flyby (DLF) performance



Outbound-to-inbound, for 3 to 5-month trajectories



Inbound-to-inbound, for 3 to 6-month trajectories

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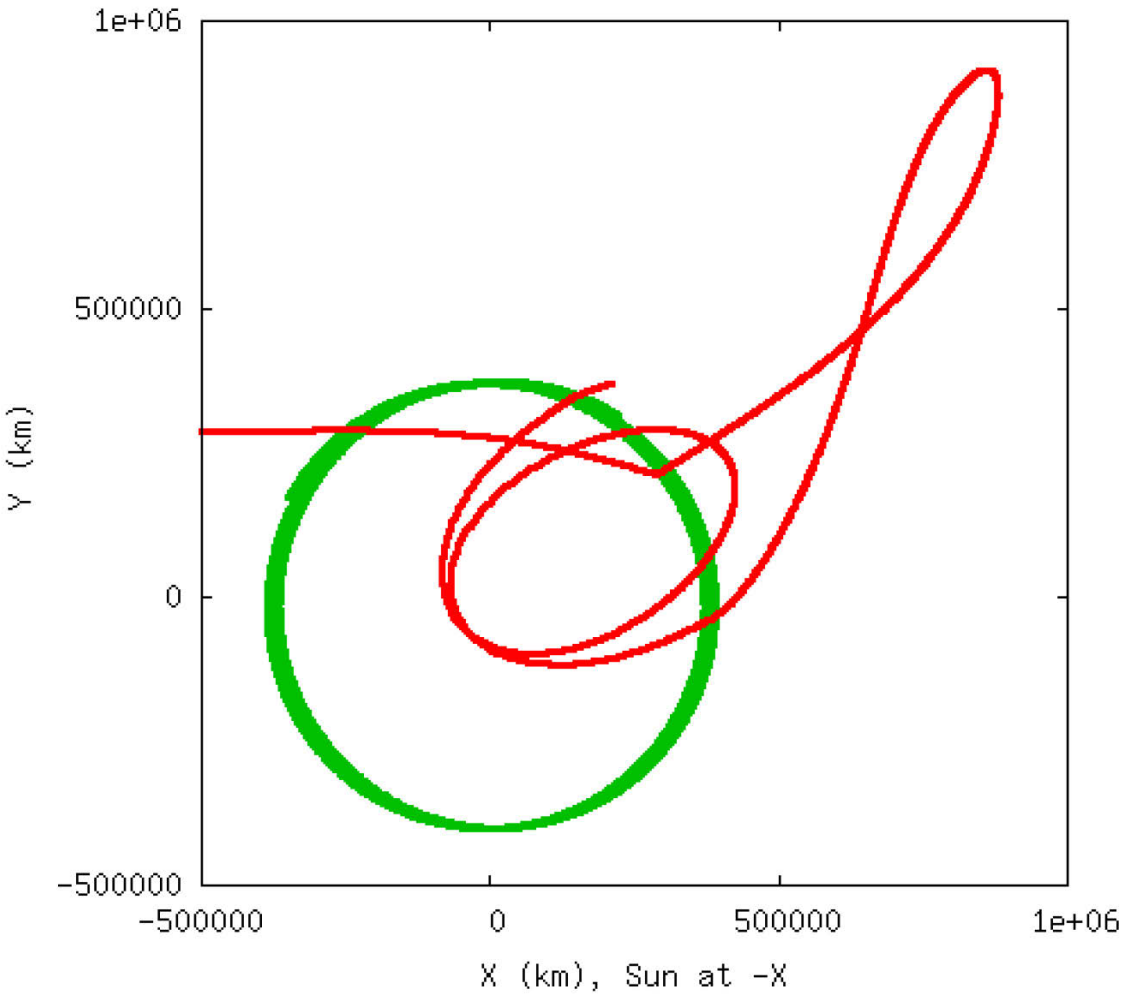
ISEE-3/ICE example (1983)

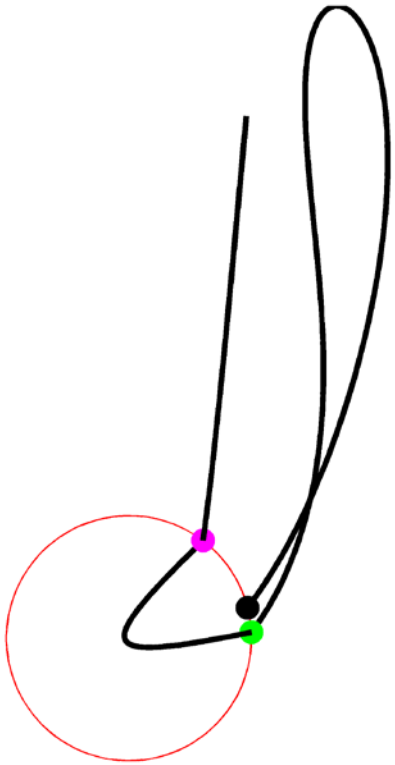


Final trajectory leg before departure is outbound to inbound, 2-month duration

- Earth departure C3 is 2.8 km^2/sec^2

Triple lunar flyby departure

- Last flyby on double lunar flyby trajectory can set up additional flyby
  - Must be retrograde to re-encounter the Moon
  - Constrained by perigee altitude
  - Improves performance by about 1+ C3 units



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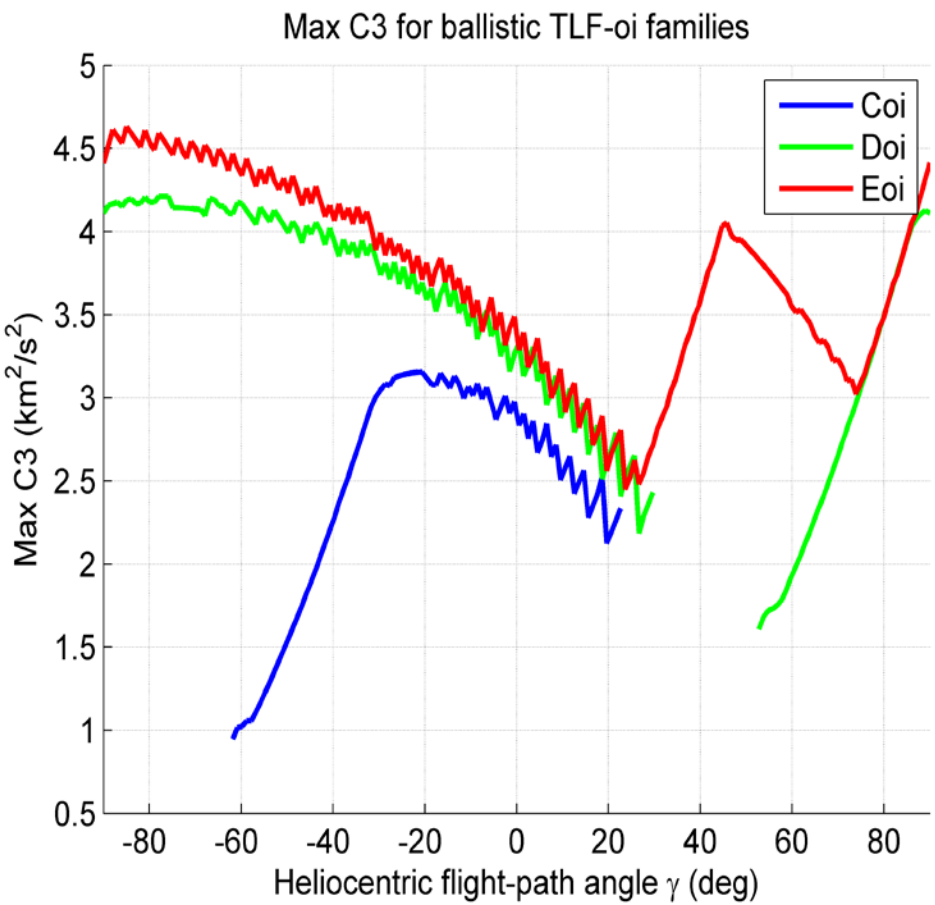
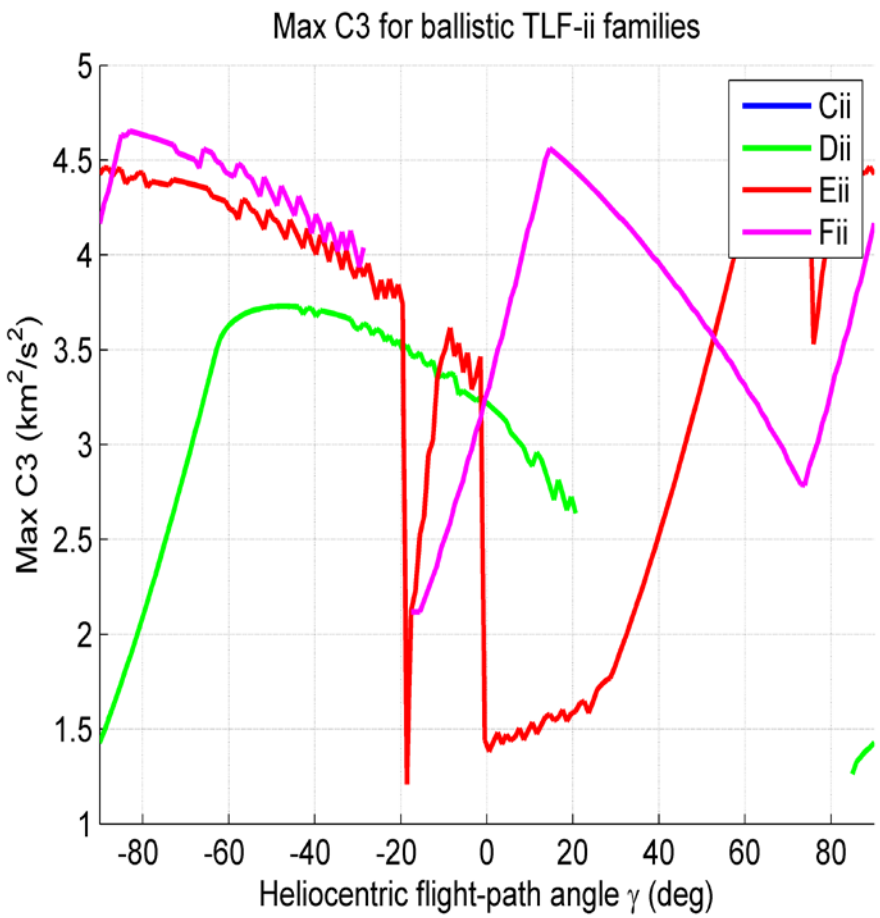
Triple lunar flyby (TLF) performance

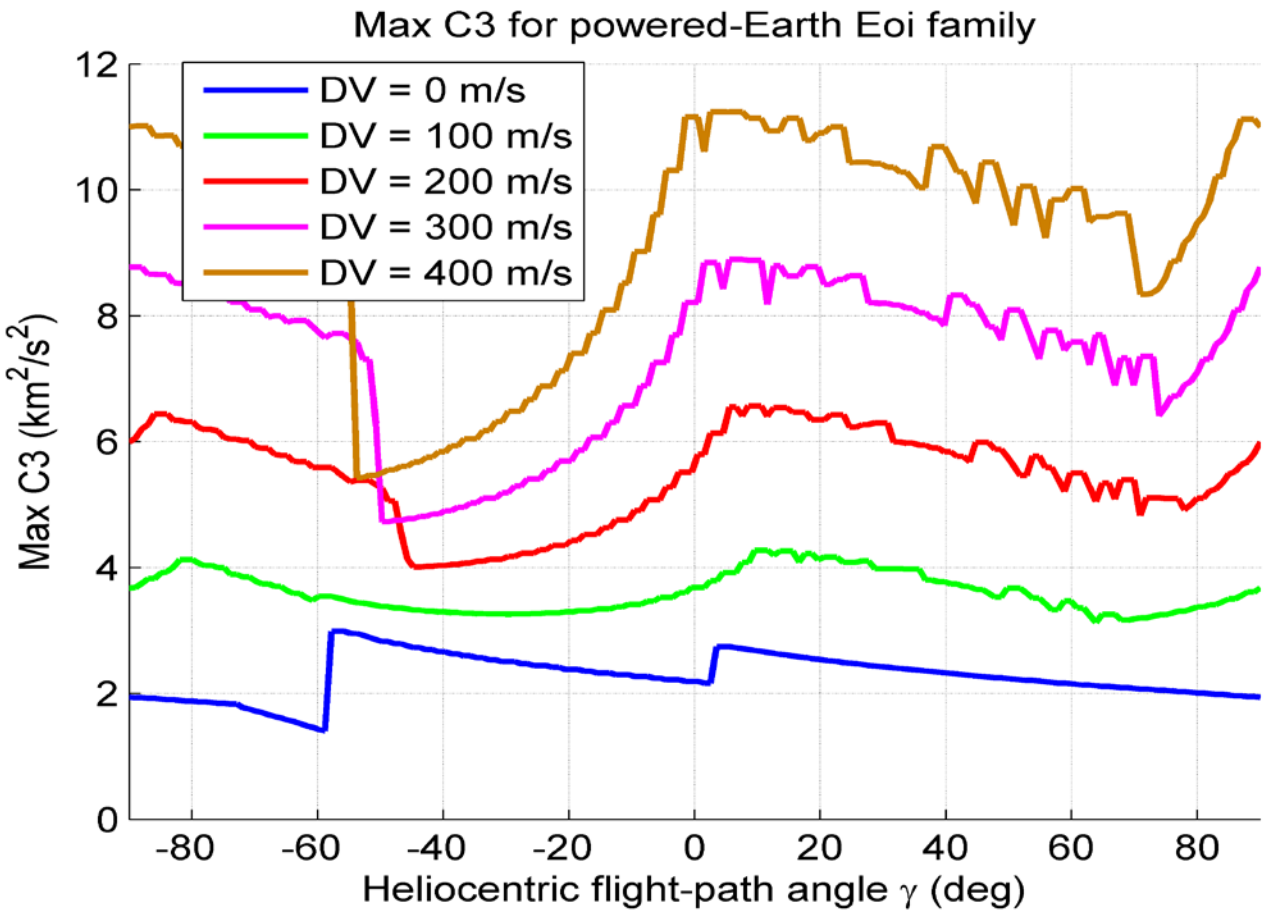


Outbound-to-inbound, for 3 to 5-month trajectories



Inbound-to-inbound, for 3 to 6-month trajectories

Powered flyby + DLF



Outbound-to-inbound, 5-month trajectory

Impulsive ΔV at perigee

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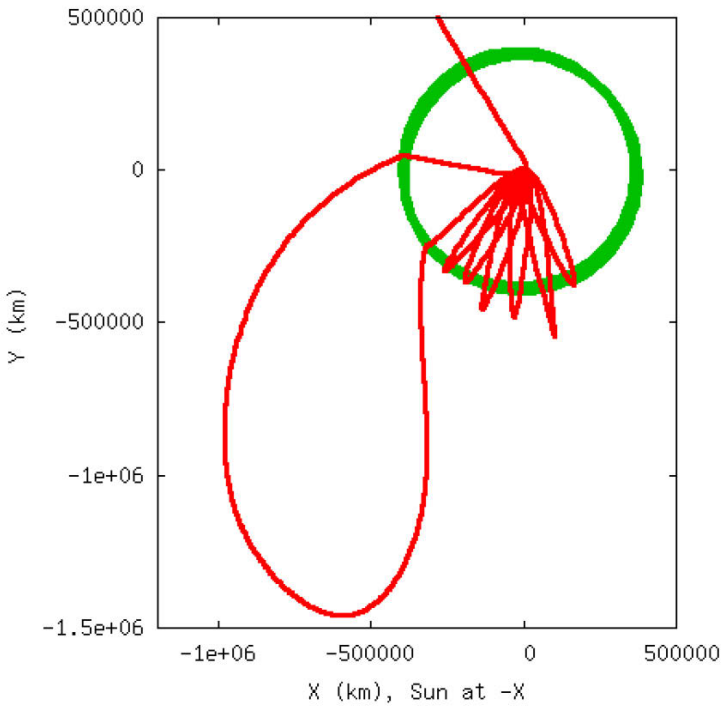
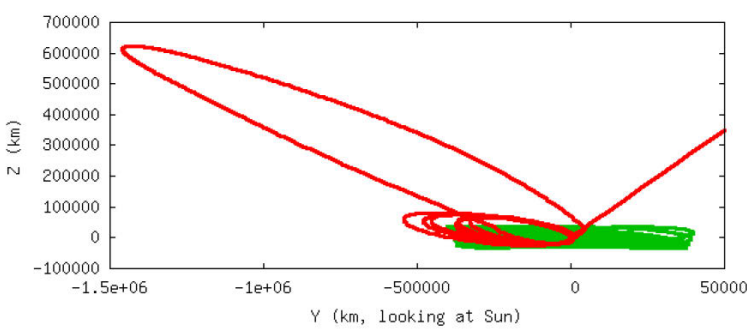
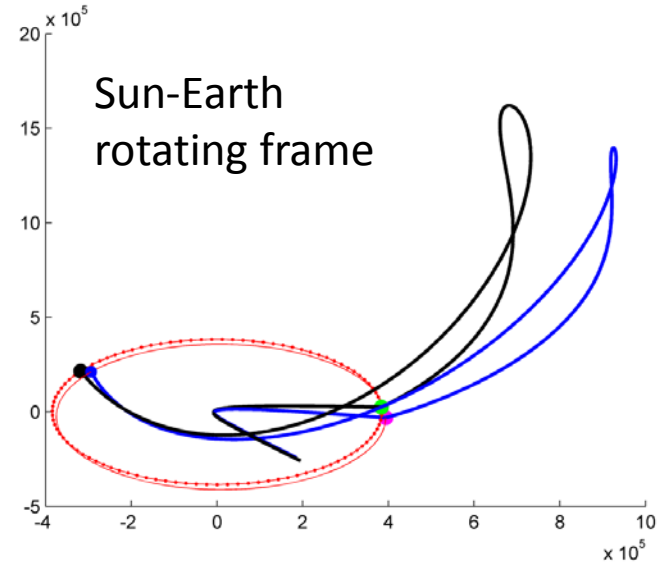
Example powered-DLF trajectories

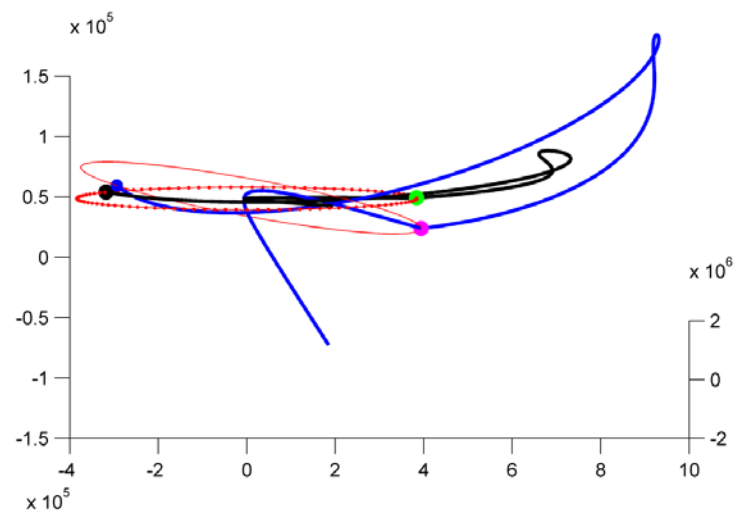


Planned Nozomi trajectory (1998)





Ideal (black) vs. ephemeris-based (blue) trajectory for Mars 2018 opportunity



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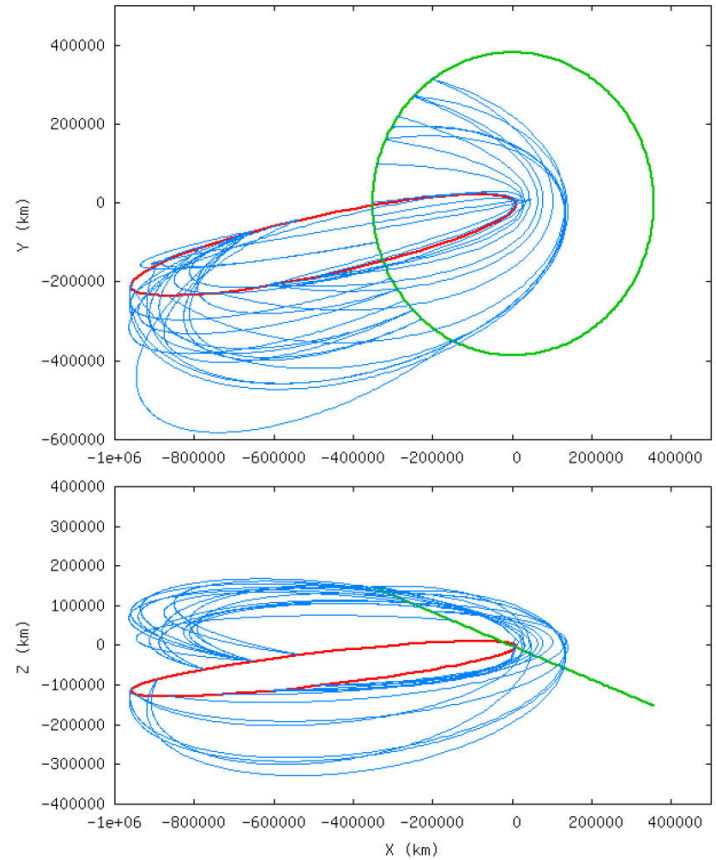
Methods for reaching first lunar flyby

- Need realistic launch period duration of ~3 weeks
- Dedicated launch methods:
  - Phasing loops
  - Variable initial period and/or flyby sequence
  - High apogee with solar perturbation
- Secondary launch methods:
  - Flyby sequence with lunar primary
  - Additional launch vehicle (LV) and spacecraft ΔV
    - Boosted GTO useful for SEP spacecraft
      - LV ΔV of 900 m/s after primary separation, 20 min post-perigee
    - Reaches lunar flyby for $\Delta V < 300$ m/s around apogee



- Boosted-GTO in worst-case orientation with near-apogee ΔVs to reach the Moon
- Variation in total duration to first flyby spans a lunar period

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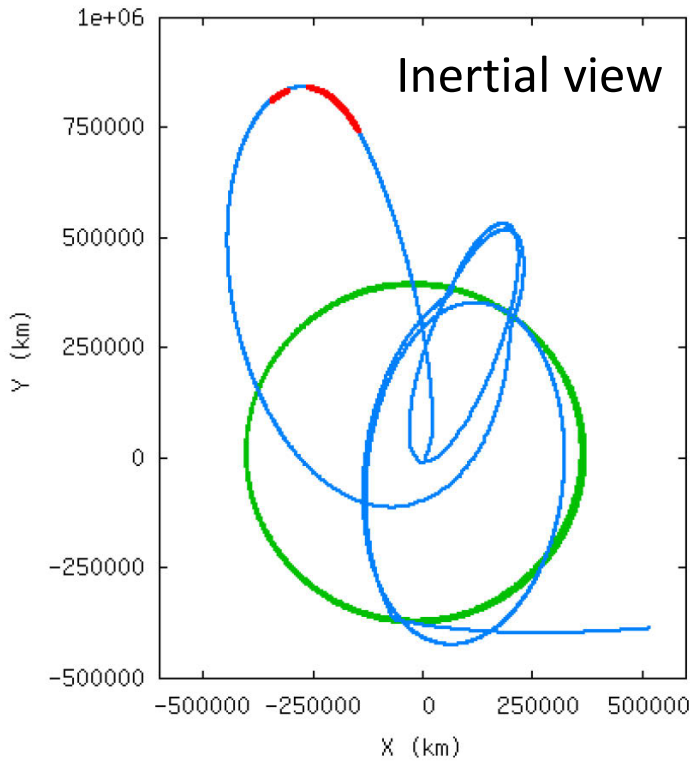
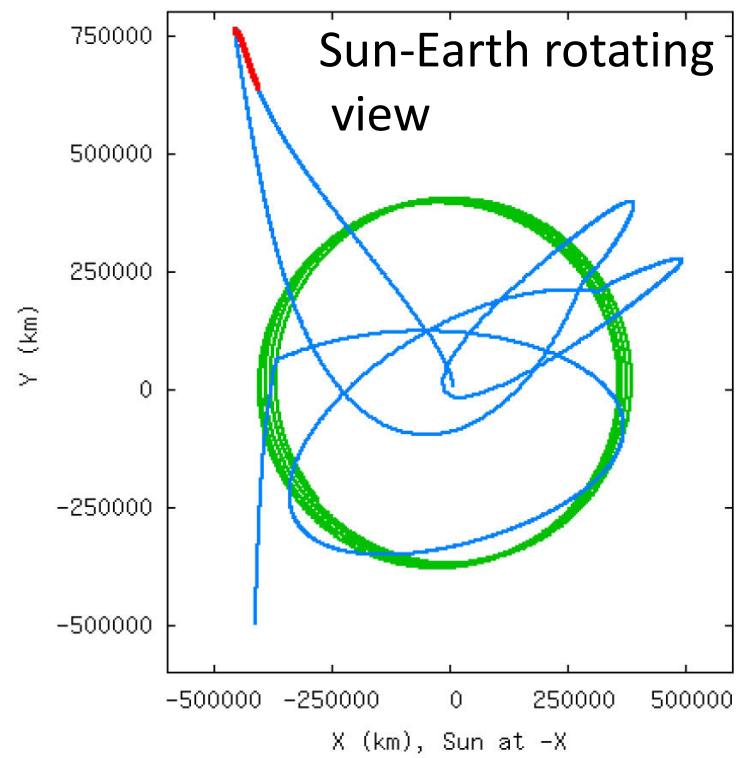
Optimized SEP trajectory, going from boosted GTO to Earth escape

- SEP thrust arcs near apogee (in red) transfer from boosted-GTO to lunar flyby
- Non-resonant apo-peri-apo transfer and 3π resonant inclined transfer set up final flyby
- In general, longer flyby sequence potentially needed to account for primary payload launch date uncertainty





Summary

- Flybys and modest post-launch ΔV significantly improve mission performance
  - Lunar flybys increase energy
  - Earth flybys change outbound direction
  - Post-launch ΔV:
    - Chemical burns at perigee
    - Heliocentric SEP thrust arcs
- Operational launch constraints are tractable, for:
  - Dedicated and secondary launches
  - Chemical and SEP spacecraft