Contingency Trajectory Design for a Lunar Orbit Insertion Maneuver Failure by the LADEE Spacecraft

Anthony L. Genova
NASA Ames Research Center

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Contingency Trajectory Design for a Lunar Orbit Insertion Maneuver Failure by the LADEE Spacecraft

- PURPOSE: Design a Rescue Trajectory for the LADEE spacecraft in case of a missed LOI

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- # Assumptions & Constraints
  - Primary Software Tool: STK/Astrogator
    - N-body: Earth (30X30), Moon (30X30), Sun (4X0), SRP, Runge-Kutta-Fehlberg numerical integrator with 8^{th} order error control
    - DE421 Ephemeris for both Earth and Moon orbits
  - LADEE Nominal Science Orbit
    - Retrograde (157 deg lunar orbit inclination)
    - Circular (altitude for LOI = 250 km)
  - Baseline assumption for spacecraft recovery time = 3 days
    - Safe-mode, Comm Loss, et al
  - Available Spacecraft ΔV for Recovery to Nominal Mission = 860 m/s (980 m/s reduced ops duration)

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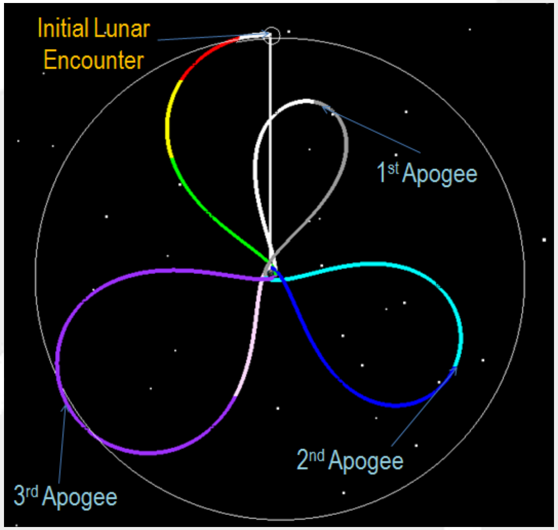
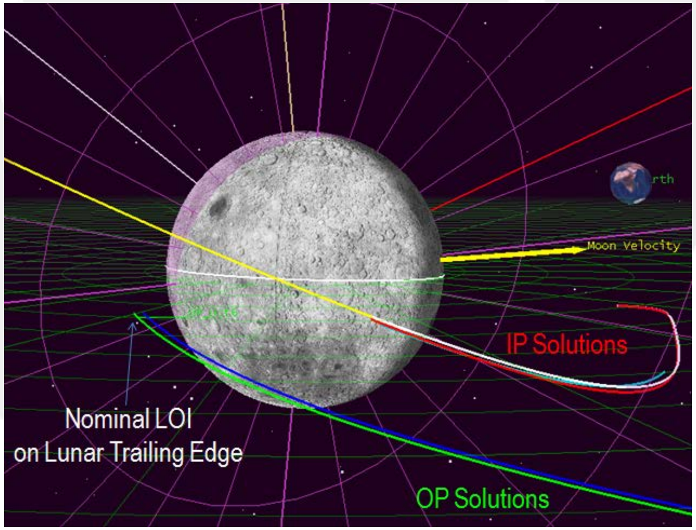
- LADEE Nominal Trajectory
  - Minotaur-V limitation
  - LV Injection Accuracy
  - Launch Window Flexibility



- Farside Trailing-Edge Approach to LOI
  - In-Plane (IP) Solutions
  - Out-of-plane (OP) Solutions



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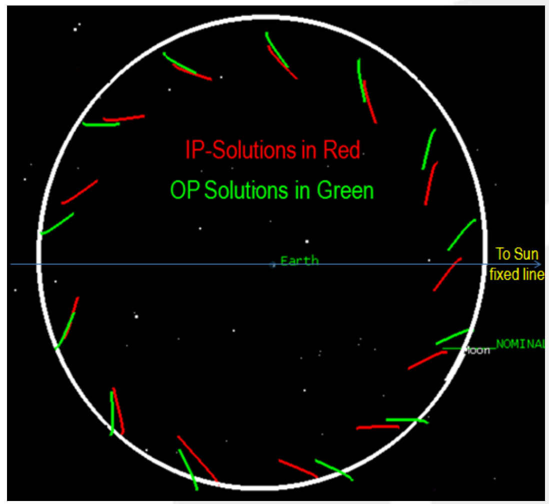
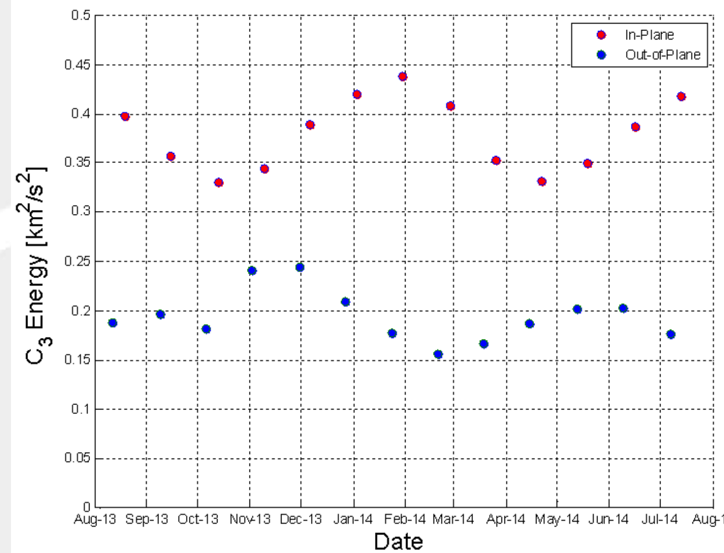
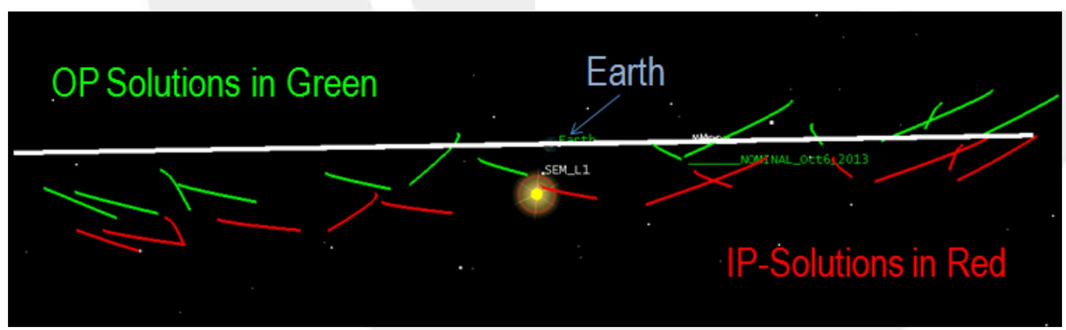
- LADEE Missed-LOI States
  - 1 yr span
  - Propagated to lunar SOI after LOI-miss
  - C3_Earth Plotted for both IP & OP Solutions







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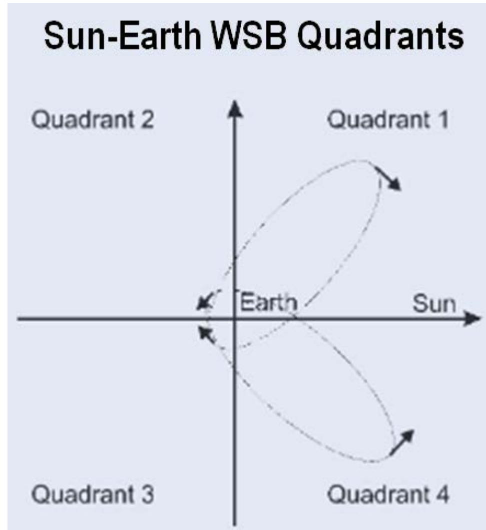
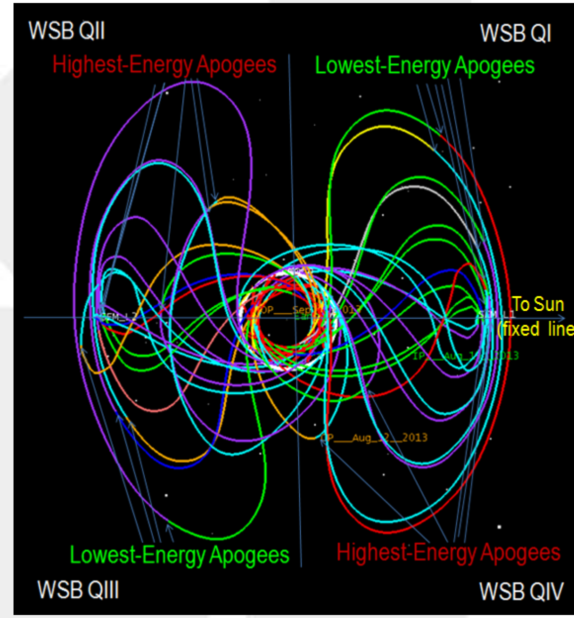
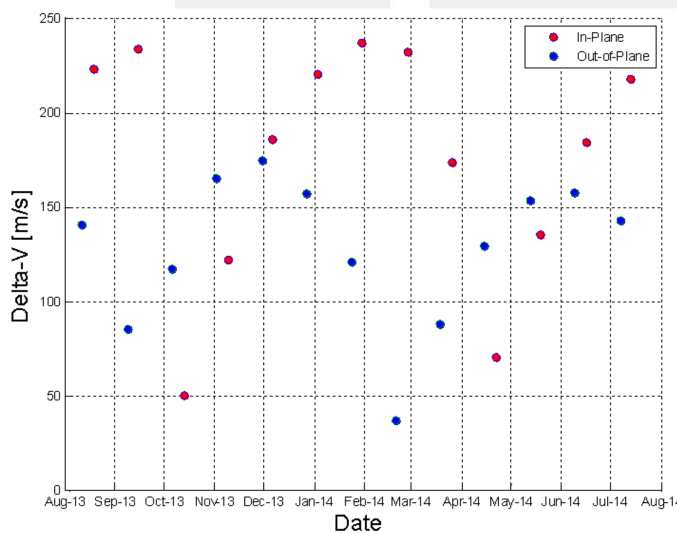
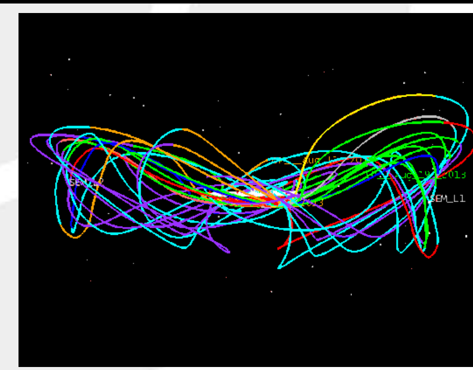
- Sun-Earth WSB Quadrant Effects
- Lunar-Return Trajectories
  - Lowest Recovery ΔV: apogee in QI & QIII
  - IP & OP Recovery ΔV Difference









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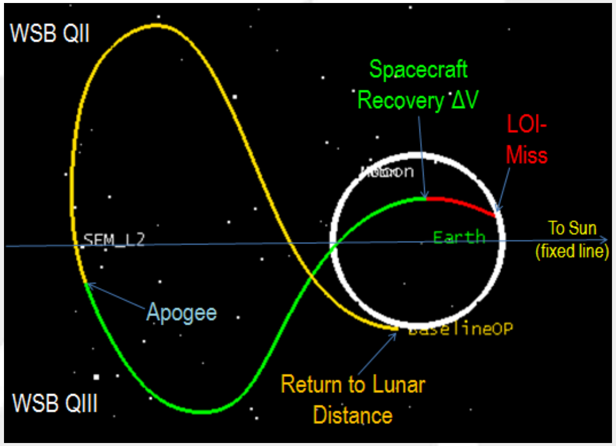
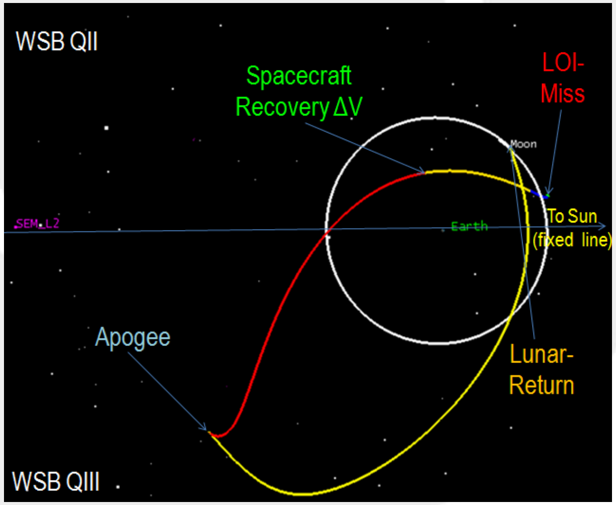
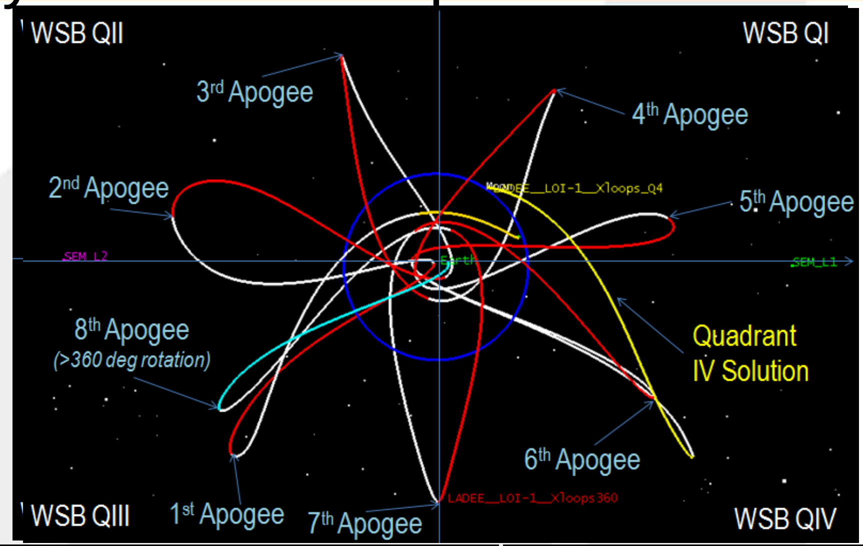
- Single-Loop Solution
- Lunar-Phasing Problem
  - Recovery ΔV performed 3 days after LOI-miss
  - With no other maneuvers, LADEE can reach lunar distance, but Moon not there
  - With an apogee maneuver performed, lunar phasing is solved but at added ΔV cost of 359 m/s

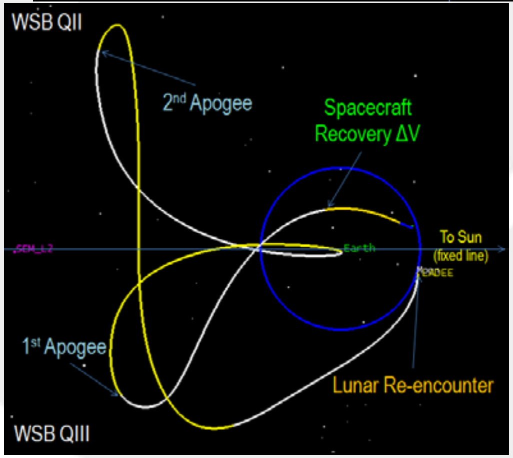


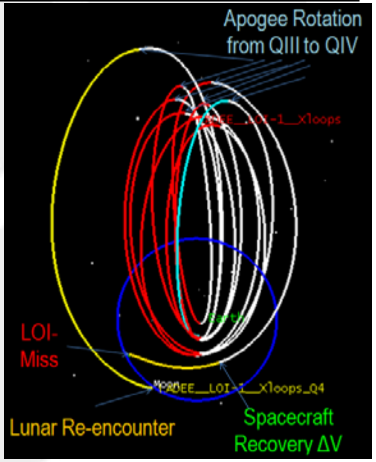


Contingency Trajectory Design for a Lunar Orbit Insertion Maneuver Failure by the LADEE Spacecraft

- Multiple-Loops for Lunar-Phasing, Apogee Rotation
- 1st-Attempt Solution w/ 2nd Apogee in QII
  - 80 m/s of apogee ΔV
  - High Arrival V_{inf} at Moon
- 2nd Apogee in QIV
  - Both Earth Inertial & Sun-Earth Rotating Frames
  - 1-yr Recovery Duration







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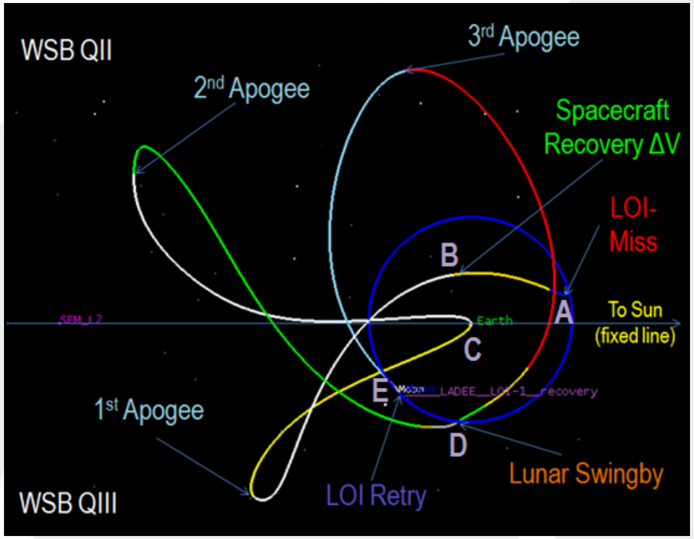
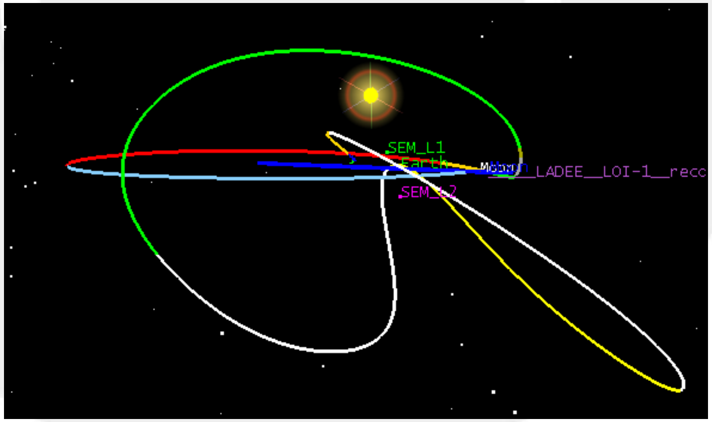
- 2nd Apogee in QII, *refined*
- Trajectory Sequence
  - LOI-Miss Oct. 6, 2013 (A)
  - 140 m/s Recovery ΔV (B)
  - Close-Earth Pass at 2600 km altitude (C)
  - Lunar-Swingby (D)
  - LOI-retry (643 m/s ΔV) May 15, 2014 (E)
  - Lunar Targeting ΔV = 63 m/s
  - Total ΔV = 846 m/s





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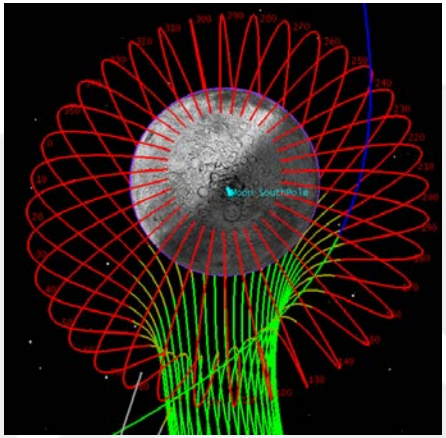
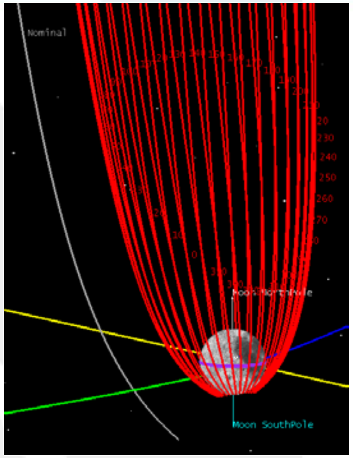
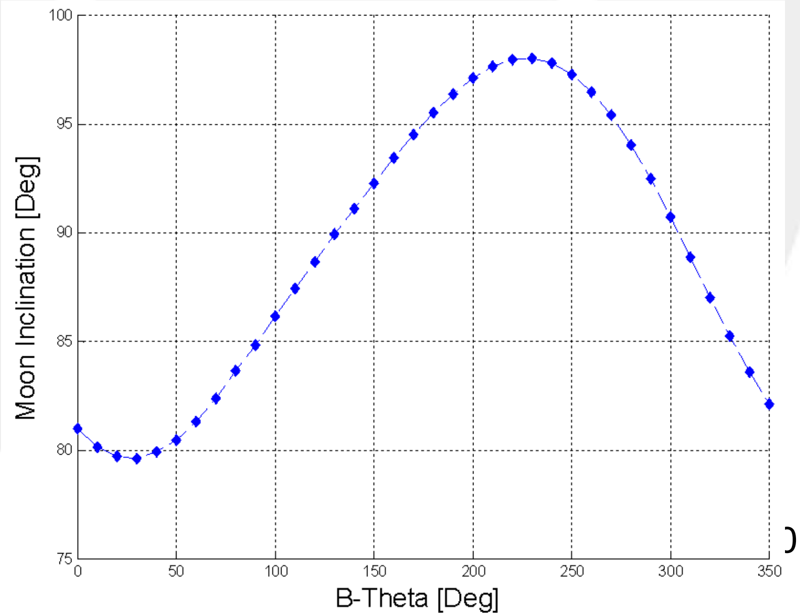
- Effects of Arrival Declination on Lunar Orbit Inclination
  - 85 deg arrival declination restricts lunar orbit inclination: 79.6 to 98 deg
  - Therefore lunar re-encounter used as swingby opportunity (3500 km altitude), not LOI-retry







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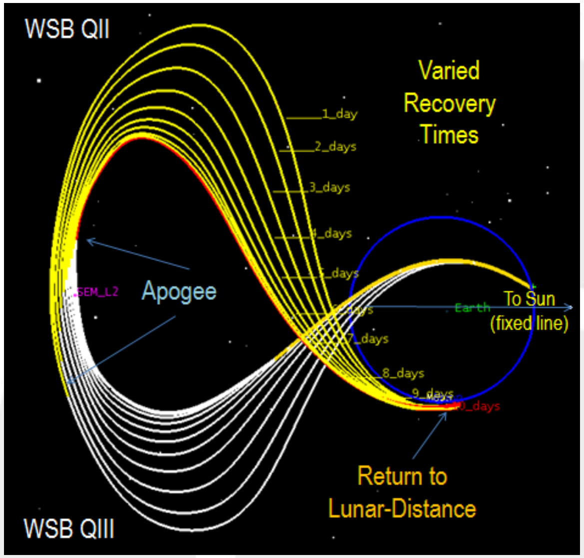
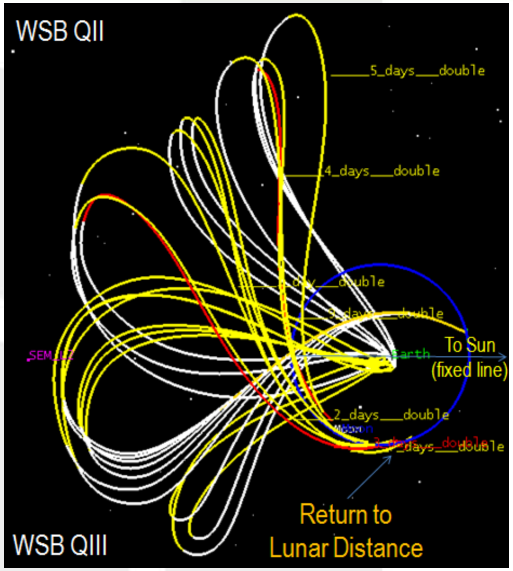
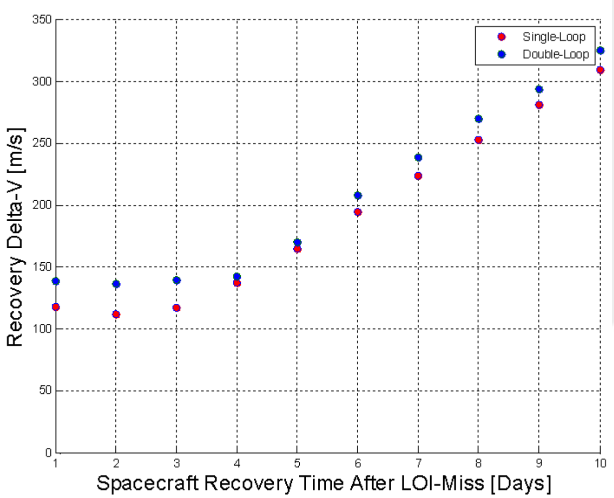
- Effects of Varying Recovery Time
- Single-Loop
  - 10 day recovery time is lunar-synchronous
- Double-Loop
  - Lunar-Synchronous Recovery Times are more frequent (3 and 10 days)







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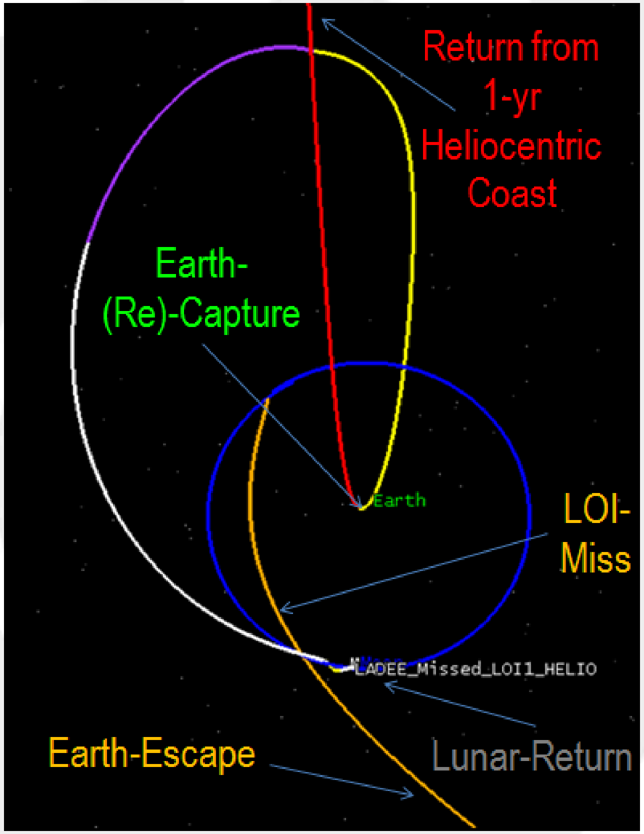
- Heliocentric Return to Moon via reverse WSB transfer
- Notional Case, >700 m/s, 30 days post-LOI miss to re-encounter Moon
  - Restricted to Elliptical Lunar Orbit → insufficient for science, but LADEE's laser tech-demo possible



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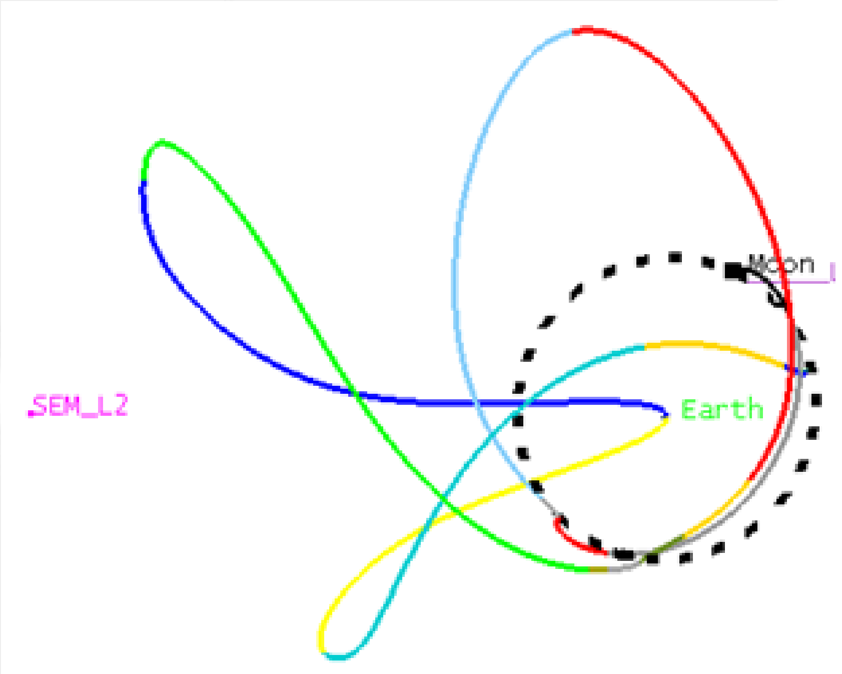
- 2 LOI Misses
- Recovery ΔV Budget
  - Recovery ΔV = 140 m/s
  - Targeting ΔV
    - At Apogee 1 et al, ΔV = 77 m/s
    - At Apogee 2 et al, ΔV = 65 m/s
  - LOI ΔV = 638 m/s
  - Total Recovery ΔV = 920 m/s
  - Recovery Time, LOI attempt #2 to #3 = 14 days
- Possible w/ reduced ops



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- Conclusions
  - Recovery ΔV requirements vary depending on apogee-location in Sun-Earth Rotating Frame (also on IP vs. OP solution type & recovery time)
  - Multiple Phasing Orbits allow more time to change period (than single-loop solutions) & solve lunar phasing problem
  - LADEE could have performed all recovery ΔV maneuvers performed 3 days after missing LOI with the 1-yr span of LOI states: Aug. 2013 to July 2014
  - For the 3-day baseline spacecraft recovery time and LADEE's Baseline LOI Case, the spacecraft can recover to its nominal science orbit (w/ reduced ops) after missing as many as 2 LOI maneuvers
- Applications
  - Other Missed-LOI Cases (or other Earth-orbits) that benefit from apogee-rotation in Sun-Earth rotating frame
  - Elements of trajectory design extended to other systems (e.g., Sun-Jupiter, Sun-Venus, Sun-Mars, et al)

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References

[1]Loucks, M. (2013, Sep. 12). Phasing Loops and the LADEE Trajectory. AstrogatorsGuild.com. Retrieved January 2, 2014, from http://astrogatorsguild.com/?p=814

[2]Biesbroek, R., and Janin, G., "Ways to the Moon?," *European Space Agency Bulletin 103* URL: http://www.esa.int/esapub/bulletin/bullet103/biesbroek103.pdf [cited 13 June 2014].

[3]Quantus, D., Spurmann, J., Dekens, E., and Pasler, H., "Weak Stability Boundary Transfer to the Moon from GTO as a piggyback payload on Ariane 5," *CEAS Space J* (2012) 3:49–59

[4]Belbruno, E.A., Miller, J.: Sun-perturbed Earth-to-Moon transfer with ballistic capture. J. Guid. Control Dyn. 16(4), 770–775 (1993)

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