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TITLE: Contingency Trajectory Design for a Lunar Orbit Insertion Maneuver Failure by the Lunar Atmosphere & Dust Environment Explorer (LADEE) Spacecraft

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Extended Abstract

The purpose of this extended abstract is to present results from a failed lunar-orbit insertion (LOI) maneuver contingency analysis for the Lunar Atmosphere & Dust Environment Explorer (LADEE) mission, managed and operated by NASA Ames Research Center in Moffett Field, CA. The LADEE spacecraft's nominal trajectory implemented multiple sub-lunar phasing orbits centered at Earth before eventually reaching the Moon (Fig. 1) where a critical LOI maneuver was to be performed [1,2,3]. If this LOI was missed, the LADEE spacecraft would be on an Earth-escape trajectory, bound for heliocentric space. Although a partial mission recovery is possible from a heliocentric orbit (to be discussed in the full paper), it was found that an escape-prevention maneuver could be performed several days after a hypothetical LOI-miss, allowing a return to the desired science orbit around the Moon without leaving the Earth's sphere-of-influence (SOI).

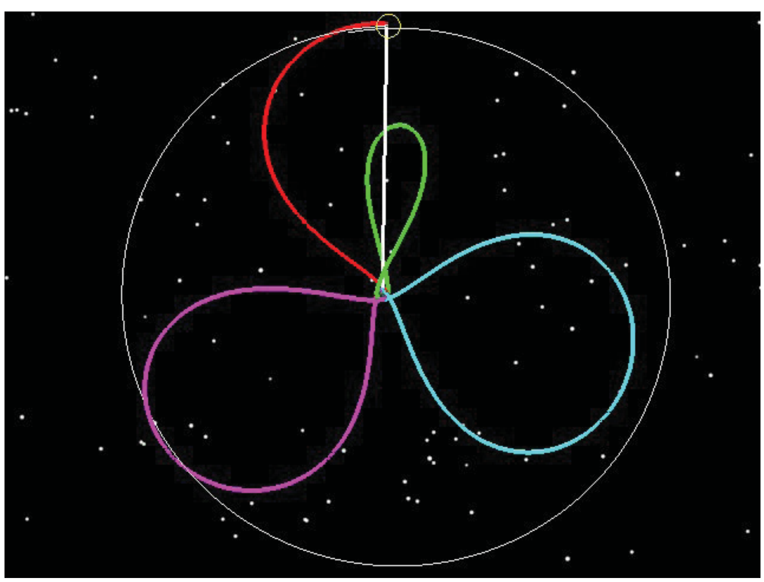

Figure 1: Nominal Trajectory Design for the LADEE Spacecraft. Earth-centered phasing loops are implemented to allow for launch window and launch insertion flexibility by the Minotaur V launch vehicle [1]

Details of the contingency trajectory design can be seen in Figures 2 & 3. This case was designed during the LADEE mission using a real state vector from about 1 week prior to the planned LOI, notably with the commercially-available Systems Tool Kit (STK) Astrogator software module. The LADEE spacecraft is first shown after the hypothetical LOI-miss (Fig.2, A). For the "nominal" contingency trajectory design, an anti-velocity escape-prevention maneuver (140 m/s delta-V) is performed 3 days after the LOI-miss (Fig. 2, B); note that the timing of this maneuver can be varied, generally resulting in increased delta-V requirements for increased wait-times before the prevention-maneuver. The 3-day value was chosen as a somewhat conservative and realistic recovery period and was thus ready for use in case the LOI maneuver failed, which it did not. After the escape-prevention maneuver, it was found that forces experienced near the Sun-Earth weak-stability boundary (WSB) made it costly (in terms of delta-V) to directly return to the Moon. Instead, an Earth-swingby (Fig. 2, C) is targeted that eventually sets up a low-energy return to the Moon 5-months after the LOI-miss (Fig. 2, D), although at a high arrival declination, resulting in an undesirable lunar orbit (nearly polar) if the LOI-retry was attempted at this point. Therefore, this lunar approach is utilized as an opportunity to change the spacecraft's orbital plane with respect to the Moon via a lunar swingby. The out-of-plane components of the trajectory are apparent in Figure 3. The LADEE spacecraft then approaches the Moon again, but this time it can achieve the desired science orbit of 158 deg inclination (Fig. 2, E), with a reduced delta-V cost for the LOI-retry (661 m/s as opposed to >850 m/s). The total delta-V for this recovery case is only 10-15 m/s more than that of the non-contingency case (i.e., successful LOI).

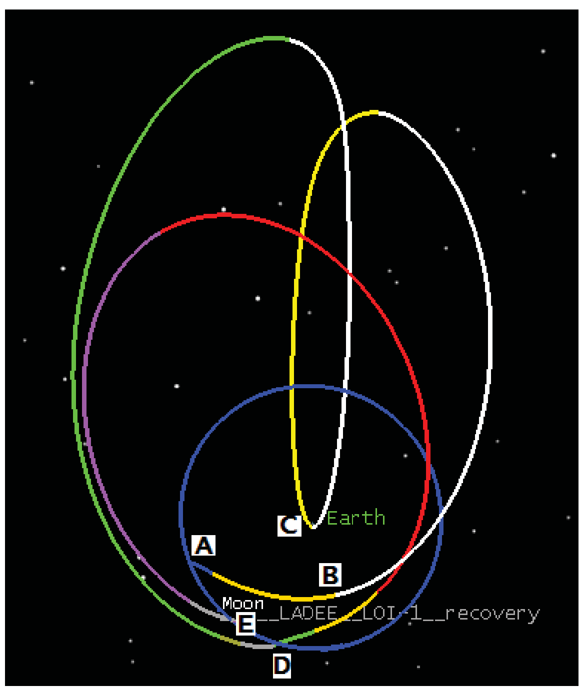

Figure 2: Contingency Trajectory Design for a missed LOI by the LADEE Spacecraft. A) Hypothetical LOI-miss; B) Escape-Prevention Maneuver 3 days after LOI-miss; C) Earth-swingby to set up low-energy return to Moon; D) Lunar encounter at near-polar inclination used as lunar swingby to change orbital plane; E) Lunar encounter in desired orbital plane, sets up LOI-retry to enter desired lunar science orbit, 7-months after hypothetical LOI-miss

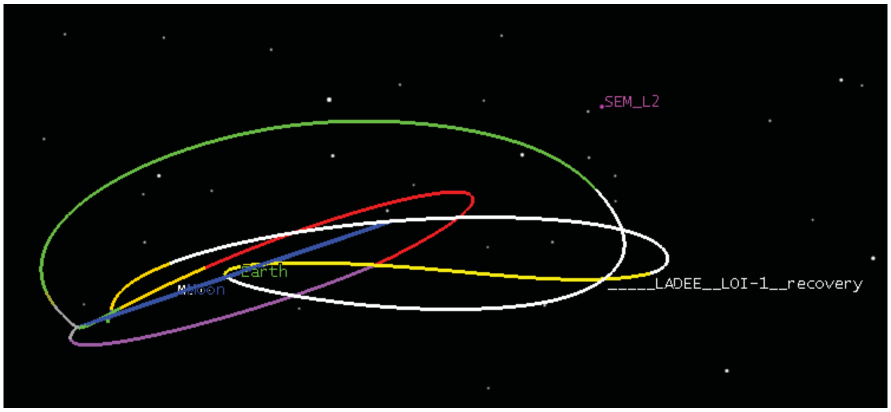

Figure 3: Contingency Trajectory Design for a missed LOI by the LADEE Spacecraft. Same trajectory as seen in Figure 1, except with a view edge-on the lunar orbit plane to show the out-of-plane components of the design. It is of note that a launch at a different time would have resulted in different forces (and thus different out-of-plane components) experienced by the spacecraft near the WSB region (to be discussed in the full paper).

References

[1] Astrogator Guild http://astrogatorsguild.com/?p=814

[2] Spaceflight 101 Space News and Beyond http://www.spaceflight101.com/ladee-mission-and-trajectory-design.html

[3] Christian Science Monitor: http://www.csmonitor.com/Science/2013/1008/Moon-mission-LADEE-arrives-after-an-amazingly-precise-looping-flight-video