EFFICIENT STATIONKEEPING OF VERY LOW LUNAR ORBITS. J. S. Parker,[1] A. Willebrand,[2] C. Cain,[3] V. Rankowicz.[4]
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Introduction: A Sustained Low-Altitude Lunar Orbital Mission (SLALOM) maintains an orbital path very close to the surface of the Moon: passing within 1–5 kilometers of topographical peaks and maintaining an average altitude near 10 kilometers. This extremely low orbit enables high-resolution observations of the Moon and new investigations of the Moon. It also requires a new class of autonomous navigation and stationkeeping. The autonomous software system, ALPINE (Auto-maneuver Location Processor using Integrated Navigation Estimates), fuses in situ tracking data to maintain continuous and autonomous custody of the spacecraft.

Previous papers by the authors have studied approaches to maintain such low-altitude orbits [1, 2]. While they did achieve low-altitude flight, they required numerous maneuvers and more fuel than necessary. A new approach is presented here that dramatically improves the stationkeeping performance, reducing the cadence and fuel requirements. This stationkeeping approach could be performed via conventional ground-based navigation, but it is preferred to have the ground supervise and be prepared to take over, while the spacecraft performs the nominal stationkeeping autonomously. The presentation demonstrates that the stationkeeping can achieve successful low-altitude orbiting for under 1 m/s per day with maneuvers every few days.

Approach: The fundamental approach to the ALPINE stationkeeping is to permit the natural dynamics of the Moon's gravity to perturb the spacecraft's orbit as much as possible before making an adjustment to the orbit. This strategy was employed by the GRAIL mission in its primary science mission with a modification in the extended mission. GRAIL was able to do this entirely above topography – only its very lowest periapse passages went beneath the highest peaks. SLALOM's challenge to lower the altitude further places a large fraction of the orbit within the topography and a dynamic corridor must continuously avoid that topography efficiently.

GRAIL and LADEE demonstrated the benefit of the eccentricity vector and its time profile in order to predict how the gravity field would change the spacecraft's orbit over time. GRAIL designed its mission using the eccentricity vector. This approach was not viable for SLALOM until the algorithms were derived to identify how to do this when the orbit dips into the topography. That has been performed here.

Navigating the Topography: The topography enters into the scenario by modifying portions of the eccentricity state space that may be traversed. If, for instance, a peak exists over the North Pole of the Moon, then the periapse of the orbit cannot be so low over the North and still be safe. Hence, a region of the eccentricity vector state space is removed in the vicinity of the ar-gument of periapse of 90 degrees. Conversely, when the periapse is over the South Pole – Aitken Basin (SPAB), then it may be possible to traverse lower over those lati-tude/longitude combinations with a higher eccentricity value, though that's quite rare compared to eliminating state space from topographical peaks. The modified regions of the eccentricity vector space extend clockwise and counterclockwise as well, away from the peaks and valleys. The remarkable feature is that, in the polar projection of the eccen-tricity vector, the eliminated region about a topographic peak is marked by an orthogonal line to the location of the peak along the groundtrack! This is illustrated in Figure 1. The interior of the polygon defined by the orthogonal projection of peaks is the domain in which the SLALOM spacecraft's eccentricity vector may persist.

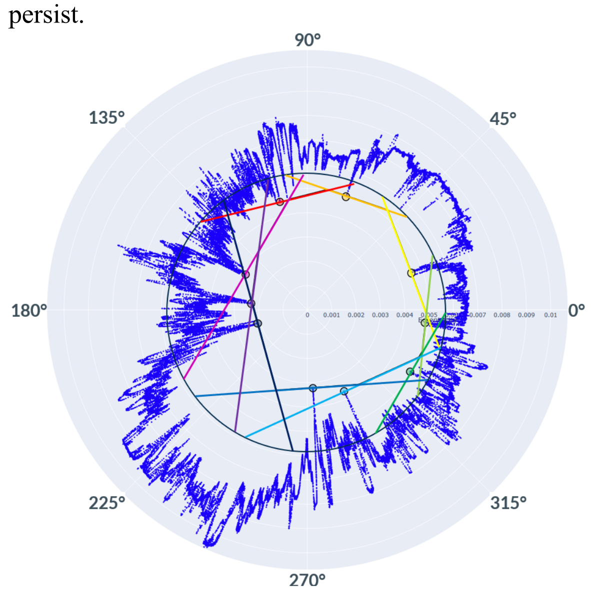

Figure 1. A polar projection of an example orbital groundtrack, with peaks identified in color, and keep-out zones defined based on those peaks.

A Dynamical Corridor: The SLALOM spacecraft must safely remain within a dynamic corridor. The spacecraft's eccentricity vector naturally evolves rapidly due to the gravitational field; the corridor evolves rapidly due to the varying topography beneath the spacecraft. These dynamics do not change in lockstep. The presentation describes how the stationkeeping maintains a safe passage through such dynamical variations. Figure 2 illustrates a snapshot for how the varying eccentricity vector (red) remains within the dynamic corridor (blue).

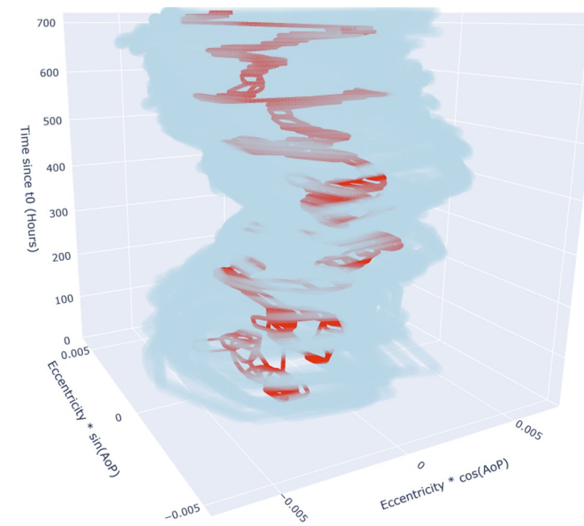

Figure 2. The time profile of the SLALOM corridor (blue) and the spacecraft's motion (red) in the eccentricity vector state space over a month.

Maneuver Placement: It depends on the circumstances, but it is often the case that the spacecraft must perform stationkeeping maneuvers strictly over the poles or strictly *not* over the poles. Both approaches have been implemented for numerous example month-long SLALOM simulations. Typical simulations show that one algorithm or othe other yields cost of 1-2 m/s per day; by taking the *better* of the two algorithms for each given stationkeeping maneuver, the total cost falls below 1 m/s per day.

Results: Figure 3 illustrates a first example of a time profile of the orbital radius of a spacecraft traversing an orbit that is maintaining a semimajor axis of 1749 km (average of approximately 12 km altitude). The radius of the topography is illustrated in red; the spacecraft's instantaneous orbital radius is shown in blue; green vertical lines illustrate maneuvers (some pairs, some single, each executed over a pole). Many features are visible (or will be when presented in person): first, one can see two regions where the red topography rises higher than other regions: these correspond to when the spacecraft is either ascending or descending over the lunar highlands. Similarly, there are two regions that happen to be near the highland peaks, where the topography is low: these correspond to the South Pole – Aitken Basin. One sees that the spacecraft orbit generally begins quite elliptical after a maneuver, transfers through near-circular at least once, and then grows to elliptical again before requiring another maneuver. This is behavior much like GRAIL's, but on a rapid timescale – and it illustrates the objectives of the stationkeeping algorithm, which aims to traverse the eccentricity vector space from one extreme eccentricity value to the next. The lower figure provides a zoom-in for the time period between 11 and 15 days of the month, illustrating how the orbital periapse passages interweave the lunar topography.

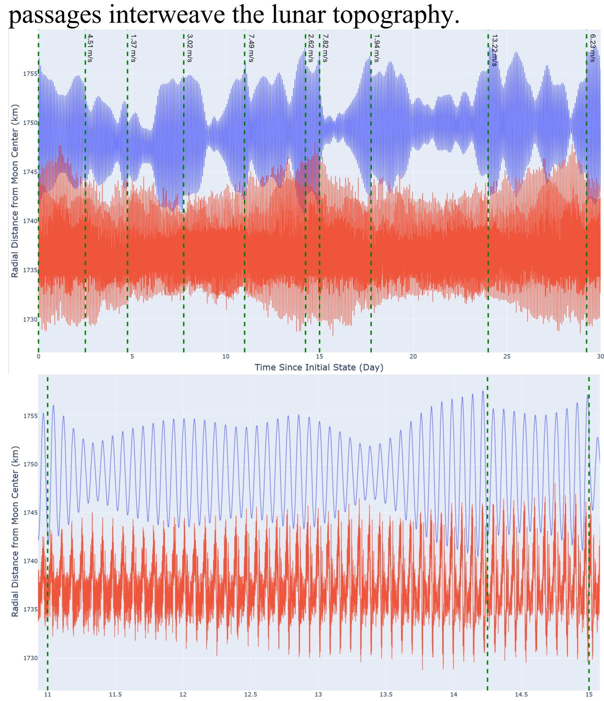

Figure 3. The time profile for the spacecraft's orbital radius (blue) against the topography (in red). Bottom: a zoom-in of Days 11-15.

References: [1] Parker, J.S., Chikine, S., Kayser, E., Cain, C., and Bolliger, M. (2021) "Sustained Low-Altitude Lunar Orbital Mission (SLALOM) Navigation Concept," Paper AAS 21-337, AAS/AIAA Space Flight Mechanics Conference. [2] Parker, J., Cheetham, B., Cain, C., & Kayser, E. (2025) "SLALOM: Enabling Spacecraft Operations in Very Low Lunar Orbit," Proceedings of the Small Satellite Conference, Advanced Technology 3, SSC25-II-04, Salt Lake City, Utah.