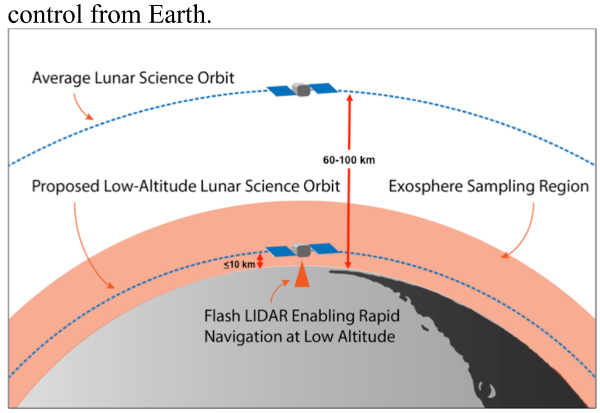
**SUSTAINED LOW-ALTITUDE LUNAR ORBITAL MISSION (SLALOM) NAVIGATION SYSTEM.** J. S. Parker,[1] S. Chikine,[2] C. Cain,[3] M. Caudill,[4] and Taylor Johnson[5]; [1]Chief Technology Officer, Advanced Space, 1400 W 122nd Ave, Suite 200, Westminster, CO 80234, parker@advancedspace.com; [2]Astrodynamicist, Advanced Space, sai.chikine@advancedspace.com; [3]Astrodynamicist, Advanced Space, charles.cain@advancedspace.com; [4]Astrodynamicist, Advanced Space, Michael.caudill@advancedspace.com; [5]Astrodynamicist, Advanced Space, taylor.johnson@advancedspace.com.

**Abstract:** This paper describes the navigation system that is being developed to demonstrate the autonomous navigation of a spacecraft traversing an incredibly low-altitude lunar orbit. The Sustained Low-Altitude Lunar Orbital Mission (SLALOM) is a mission concept that would place a spacecraft into an orbit with a mean altitude of < 10 km, sustained for multiple months. The autonomous navigation system includes a collection of onboard orbit determination filters and an autonomous maneuver design system, each of which must operate without any ground inputs for sustained periods of time, through multiple maneuvers. This enables new investigations at very low altitudes over the surface of the Moon.

**Introduction:** Investigations of the lunar environment have historically been limited to high altitude remote sensing or direct sampling of a single landing location, with extensions via rovers. This paper presents a new advancement in Guidance, Navigation, and Control (GNC) that enables an orbiting asset to get substantially closer to the surface of the Moon, blurring the lines between direct sampling of the surface and remote sensing. If an orbiter can fly within 10 km of the surface then it can directly sample some aspects of the environment, such as lofted particles in the lunar exosphere, and use instruments that require close proximity, such as neutron spectrometers. This paper demonstrates how it is now possible to break through this boundary, and sustain an orbit whose average altitude is below 10 km for multiple months. Of course, an orbiter will fly over craters, where the altitude is far higher than 10 km, but it also flies within a handful of kilometers from the terrain at other points in the orbit. This strategy enables many new scientific investigations, such as:

(1) Directly sampling particles that have been lofted from the surface at low altitudes, globally;
(2) Examining the distribution of near-surface water content around the Moon via a neutron spectrometer;
(3) Investigating the lunar magnetic "swirls";
(4) Deploying low energy sensors (such as the instrument on Lunar Prospector) to map and quantify water ice deposits; and many others.

To access this challenging orbital regime and fly Sustained Low-Altitude Lunar Orbital Missions (SLALOMs), Advanced Space is developing the integrated Auto-maneuver Location Processor using Integrated Navigation Estimates (ALPINE) system, that leverages previous investments by NASA and industry to operate autonomously in this highly demanding and rewarding environment. SLALOM combines optical imagery with spacecraft sensors, particularly flash or scanning LIDAR, that generate high accuracy, real-time in-situ navigation measurements, with the automated ALPINE flight software system needed to process that data with minimal latency. The result is a spacecraft equipped with the navigation knowledge and autonomous maneuver design capability needed to maintain extremely low-altitude lunar orbits with limited command and control from Earth.




**ALPINE:** ALPINE is being developed to process in-situ navigation measurements, autonomously plan and execute maneuvers, and monitor overall navigation system performance for extended periods of time. The prime application of interest is enabling missions operating in extremely low-altitude lunar orbits, which have the potential to enable global-scale sensing and assessment of the lunar surface and surrounding environment in a way that has been inaccessible by previous, current, and planned robotic missions to the Moon.

ALPINE's objective is to navigate a spacecraft within an orbital regime that continuously remains at or below a mean of 10 km above the lunar surface, which at times would be lower than some features on the lunar surface relative to the reference ellipsoid. This type of orbital geometry is an incredibly challenging proposition that requires an entirely new mission systems approach to spacecraft navigation, maneuver design, and spacecraft autonomy. This approach requires a spacecraft to operate autonomously within extremely short time horizons, where the spacecraft can impact the surface of the Moon within a timeframe of hours to several days if one or more maneuvers are not executed. Therefore, the enabling architecture must have a near-continuous stream of accurate and real-time relevant data that define the spacecraft's orbit, robust algorithms to process that data in a fail-safe fashion, the strategies to autonomously design and implement real-time efficient and effective maneuvers, and the ability to recover from potential errors rapidly. All of this must be performed onboard the spacecraft to an extent well beyond any previous orbiter about the Moon or other airless body.

## Relevance and Significance

The Moon is an ideal location to implement this technology due to the exciting new scientific investigations that may be enabled, and because previous missions (LRO, GRAIL, etc.) have already provided the environmental data (relative topography, detailed gravity field, etc.) necessary to implement the strategy. GRAIL's high-fidelity gravity field makes it possible to accurately predict the spacecraft's trajectory as it orbits at low-altitude over the surface [1]. LRO's topographic mapping of the surface provides the geodetic reference and terrain map to conduct Flash LIDAR Terrain Relative Navigation and accurately predict potential surface impact events [2]. The Autonomous Landing and Hazard Avoidance Technology (ALHAT) project, funded by NASA to improve methods of Terrain Relative Navigation and Hazard Avoidance for planetary landers, has successfully built and demonstrated Flash LIDAR systems with the performance caliber needed for SLALOMs. The intersection of these existing data sets and capabilities with NASA's renewed focus on cislunar operations, materializing through the Lunar Orbital Platform-Gateway and commercial lunar lander initiatives (CLPS), makes this the ideal time to invest in developing the proposed technology. There are many compelling science investigations that SLALOM enables that not only stand to expand our fundamental understanding of the cis-lunar environment, but that they themselves will enable future missions and investigations, in the same manner that LRO, GRAIL, and ALHAT have enabled SLALOM.

Extremely low-altitude lunar orbiters may be used to conduct science investigations that are difficult, if not impossible, at higher altitudes. For instance, an extremely low-altitude lunar orbiter may directly observe and collect lunar particles electrostatically lofted by their interaction with solar UV radiation [3] as a more thorough extension of the survey conducted by the recent LADEE mission. Figure 3 shows density measurements LADEE collected of the lunar exosphere during its six months in orbit around the Moon [4]. A SLALOM class orbiter would allow this data set to be completed for previously unsampled longitudes (top of Figure 3), and especially for the lower altitudes of the density measurements (bottom of Figure 3), establishing context for surface exploration.

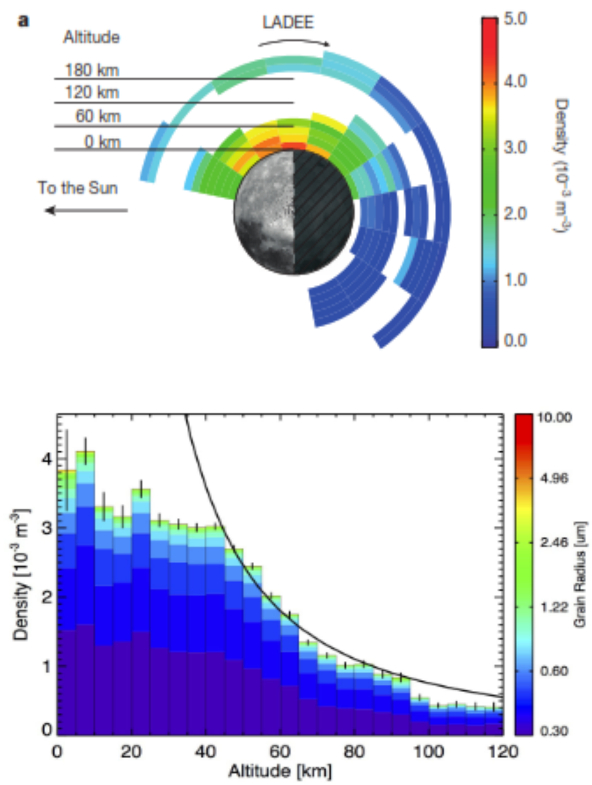



Figure 3. LADEE Exosphere Sampling, longitudinal (top) and altitude (bottom)

A SLALOM spacecraft equipped with a LIDAR navigation instrument may be used to further develop a higher resolution digital elevation map than was possible from the LRO data. By adding a science camera to the payload of such a spacecraft, the resolution of optical surface maps could be greatly improved, especially for specific areas of interest. Figure 4 shows the apsis history for the LRO mission, and identifies two low-altitude Apollo viewing excursions made for the purpose of photographing historic Moon landing sites. A SLALOM orbiter would have the ability to collect even higher resolution imagery at all times during its mission.

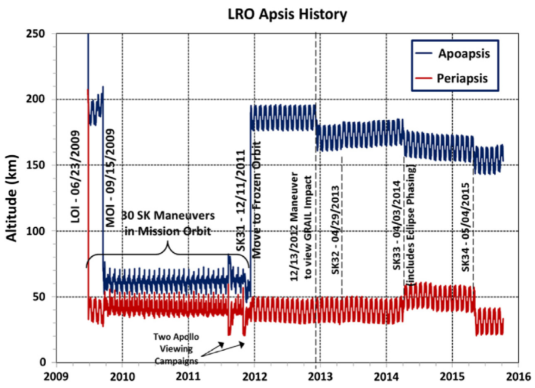



Figure 4. LRO Mission Apsis History

Another example of a high-priority science investigation to the lunar science community enabled by this class of SLALOM orbiter is the investigation of magnetic 'lunar swirls' in the regolith. This future orbiter may map the swirls, both in imagery and in magnetism, with very high precision and correlate findings with previous NASA missions, such as Lunar Prospector and Apollo 15's magnetic field mappings as well as GRAIL's maps of the Moon's interior structure. This investigation further probes the interior of the Moon, its formation, and its evolution from a laboratory in orbit - this is not limited to a single landing site, but to the entire lunar surface.

## Concept of Operation

ALPINE's concept of operations involves the processing of a steady stream of incoming navigation data collected and processed by the spacecraft (LIDAR or similar), the design of upcoming maneuvers, and a continual process of verifying that all aspects of ALPINE's processing are behaving as designed. ALPINE involves many parallel filters that evaluate the primary orbit determination methods to identify any issues. If an error, fault, or other issue is detected then ALPINE shifts to a backup filter while recovering the primary filter. These details are summarized in a high-level view in the timeline illustrated in Figure 5. Some details are still being identified and confirmed. Variations exist for orbits that contain a maneuver, a ground contact, or other activity.

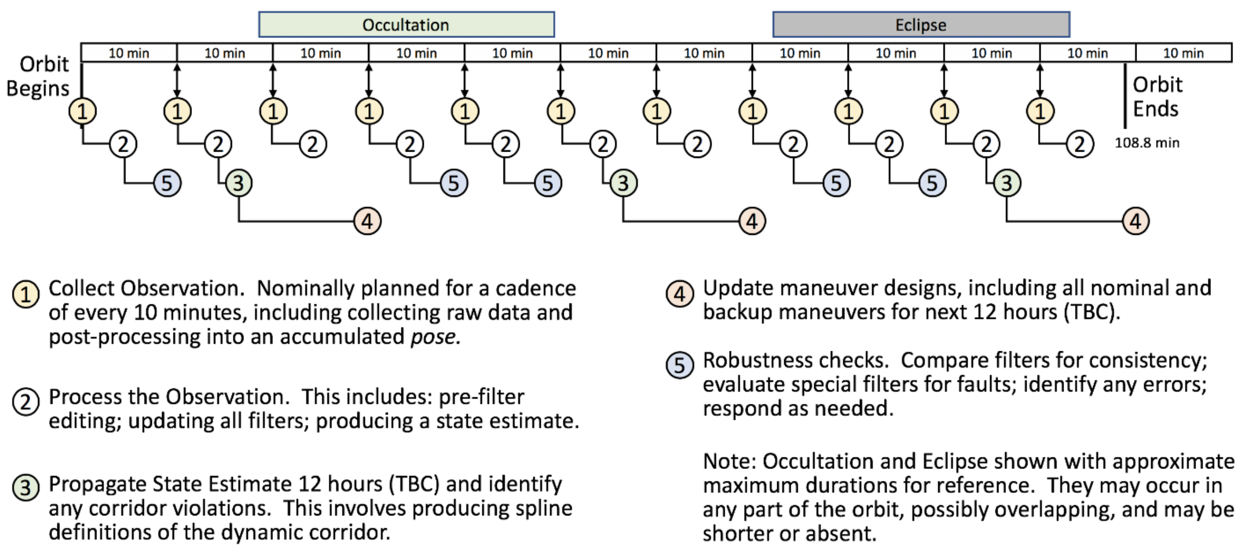



**Figure 5. The high-level concept of operations of ALPINE.**

ALPINE's stationkeeping methods result in orbits that appear similar to that illustrated in Figure 6. In the figure, the lunar topography below the spacecraft is illustrated with a dark black line. The lower altitude of the corridor is shown in a dotted line and is 500 meters above the topography to provide a minimum margin to accommodate navigation uncertainties and other allocated margins. The upper corridor is smoothed via a cubic spline so that it tracks the peaks and valleys of the topography without dipping so low that a spacecraft can't traverse the corridor. The upper corridor is shown in the smooth dotted line and the additional dotted line is the actual topography repeated 10 km higher for reference. One can see that the spacecraft comes quite close to the lower corridor, and around 5.2 hours into the prediction it dips below the corridor. Hence a maneuver is introduced around 0.6 hours into the predict to avoid that downstream maneuver.

The paper will further describe the navigation filters and stationkeeping algorithms employed by ALPINE in order to successfully traverse a very low-altitude lunar orbit within 10 km from the surface.

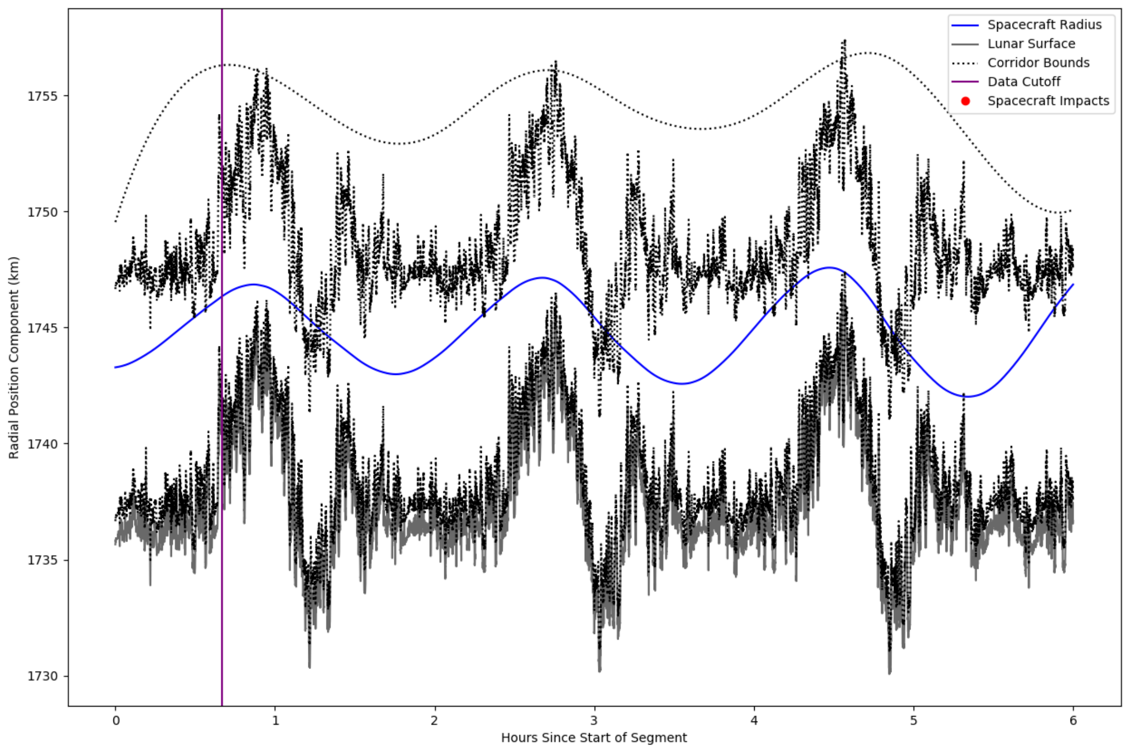



**Figure 6. The SLALOM Corridor, with a lower altitude corridor of 500 meters above the actual topography and an upper corridor of 10 km above a smoothed cubic spline of the topography. The spacecraft traverses the blue curve with a maneuver identified approximately 0.6 hours into the prediction.**

**References:** Use the brief numbered style common in many abstracts, e.g., [1], [2], etc. References should then appear in numerical order in the reference list, and should use the following abbreviated style:

[1] Zuber, M.T., et al., "Gravity Field of the Moon from the Gravity Recovery and Interior Laboratory (GRAIL) Mission," Science, Vol. 339, Issue 6120, pp. 668-671, 08 Feb 2013. DOI: 10.1126/science.1231507

[2] USGS, "LRO LOLA Elevation Model 118m (LDEM GDR)," Astrogeology Science Center, Planetary Data System Geosciences Node, 2014.

[3] NASA's Lunar Science Institute Dust and Atmosphere Focus Group, "The Lunar Dusty Exosphere: The Ex-treme Case of an Inner Planetary Atmosphere", http://www.lpi.usra.edu/decadal/leag/

[4] Horanyi, Mihaly & Szalay, Jamey & Kempf, Sascha & Schmidt, Jürgen & Grün, E & Srama, Ralf & Ster-novsky, Zoltan. (2015). A permanent, asymmetric dust cloud around the Moon. Nature. 522. 324-6. 10.1038/nature14479.