AN ORBITAL DYNAMICS MODEL FOR AN ULTRA-LOW ALTITUDE LUNAR ORBITER.

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Introduction: An ultra-low altitude lunar orbiter presents enhanced science returns with the possibility of targeted high-resolution datasets at the meter/cm scale. Many lunar orbiters collect their most useful data at the end of their mission, whilst slowly spiraling into the Moon. What if this low altitude flight could be extended for the duration of the mission? Ultra-low altitude Earth observation has been demonstrated by ESA's Gravity field and steady-state Ocean Circulation Explorer (GOCE), which used a low drag body, accelerometers, and solar electric propulsion to maintain a low altitude Earth orbit [1]. JAXA has also demonstrated an Earth based low altitude spacecraft, the Super Low Altitude Test Satellite (SLATS/ "Tsubame"), which employed agile maneuvers using an ion thruster and gas jet to respond to atmospheric drag [2]. Tethered satellites for low altitude measurements at the Moon have been proposed by [3] but these require two satellites, effectively doubling costs and operational efforts. The Moon is an airless body therefore a satellite could achieve extremely low altitudes with hazard avoidance. An agile high-thrust orbiter could approach any point of interest potentially within 10km of the surface [4].

Scientific Motivation: Many areas of lunar research would benefit from higher resolution data, we identify three areas: polar ice abundance; resource prospecting for in-situ resource utilization (ISRU) and crewed missions; and the lunar magnetic environment, including swirls.

Polar ice abundance. Multiple orbital missions including LRO and LCROSS have shown evidence for the existence of water ice in the polar regions of the Moon [5][6]. Much has been learned from this data concerning the nature of the lunar water cycle and reservoirs. However, to facilitate sustainable, long-term lunar exploration, higher resolution data for volatile abundance is required, particularly for global surface ice distribution. A neutron or gamma ray spectrometer payload could enable high resolution mapping of ice distribution. These instruments usually have a large field of view, so they would be less affected by smearing that would impact imagers at this low an altitude.

Resource prospecting. The need for higher resolution orbital data for resource prospecting for near-future crewed and robotic missions was emphasized in the 2019 Lunar Exploration Analysis Group Annual Meeting Findings. LROC's NAC has a spatial resolution of 0.5m/pixel [7]. A low altitude lunar orbiter could potentially observe down to ~cm scale spatial resolution with a high-resolution imager payload. An imager may be affected by smearing at this low an altitude, but imaging data could be supplemented by the neutron or gamma ray spectrometer payloads mentioned in the previous section for mineralogical characterization. Resource prospecting at depth could be enabled with a radar and/or gravity gradiometer payload. These instruments could also enable detection of lava tubes which have proved difficult to distinguish in current orbital data due to low spatial resolution [8]. The gravity gradiometer could take the form of an absolute accelerometer mounted on a boom projecting from the main body of the spacecraft, as described by [9].

Lunar magnetic environment. Lunar swirls are high-reflectance regions on the lunar surface that are associated with magnetic anomalies. Several formation theories have been proposed including solar wind shielding [10], surface scouring by cometary impacts [11], and electrostatic dust sorting [12]. The lowest altitude magnetometer observations of swirls come from JAXA's Kaguya spacecraft before it crashed into the lunar surface. These data extend below 10km altitude, as low as 5km over Mare Ingenii [13]. Repeated observations at ultra-low altitude over multiple swirl regions would be instrumental in exploring the structure of the magnetic and plasma environment at these anomalies, and to determine possible formation processes for swirls.

Methods: The dominant forces acting on a spacecraft at low altitude on the Moon are from variations in the lunar gravitational field (lunar mascons). These must be mitigated by an ultra-low altitude orbiter, unlike at the Earth where a low altitude orbiter contends primarily with atmospheric drag. The spacecraft would operate autonomously by using gravity field knowledge, with precision accelerometers and thrusters to maintain a near circular polar low altitude orbit.

Orbital algorithm. An algorithm was written to investigate the feasibility of this method using the Verlet Velocity Scheme described in [14] to simulate the spacecraft motion. This scheme is widely used due to its high precision and minimal computing requirements. To incorporate gravity into the integration scheme, the software package SHTOOLS, developed by [15], along with NASA's Gravity Recovery and Interior Laboratory (GRAIL) data [16], were used to determine the acceleration acting on the spacecraft at each position. SHTOOLS produces global maps of gravity accelerations for any altitude from the spherical harmonic coefficients of the gravitational field. SHTOOLS calculates gravitational potential, V and then converts to gravitational acceleration, B, using $B = \nabla V$ [15]. For this algorithm, the global map of gravity accelerations produced by SHTOOLS is initialized each time the satellite's altitude strays outside of a ±10m station-keeping altitude deadband to reduce computing requirements. Bilinear interpolation of topography data from NASA's Lunar Orbiter Laser Altimeter (LOLA) instrument [17] was used to determine the spacecraft's height above the lunar surface and whether its trajectory would intersect the surface.

Results: The algorithm was run with a spherical harmonic expansion for gravity to an order of 660 degrees in order to capture the smaller-scale variations in the gravitational field. The spacecraft was given a starting position of altitude=10km, latitude=88°, longitude=0° and launch angle=15°. Figure 1 shows the altitude of the spacecraft (red) over ~1.5 orbits with the topography from LOLA [17] (black) at each spacecraft position plotted below it. Interestingly, the spacecraft did not intersect the surface but likely would if the integration had been run for a full mission duration. This indicates that active propulsion is required to maintain a stable orbit at low altitude. Figure 2 shows the track of this orbit over a global map of the total gravity disturbance at 10km altitude.

Conclusion: The ultra-low altitude orbiter will use gravity and topography data knowledge to predict the gravitational variations that will be acting on the spacecraft based on its exact position, using an algorithm similar to the one we have developed. The spacecraft will then employ agile thrusters to mitigate these forces and avoid topographic changes. Due to the significant gradients in topography and need for constant altitude adjustment, mass efficiency and high specific impulse of a potential propulsion system will need to be prioritized. Further investigation is required to determine a sufficient propulsion system, such as a comparison between chemical and solar electric propulsions using delta-v outputs from the algorithm. Future work will also include improving algorithm performance by converting modules to Fortran in order to run the integration for a full mission duration.

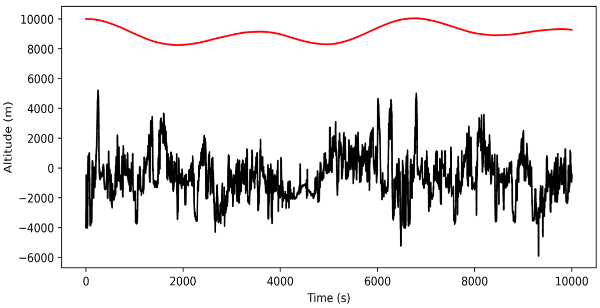

Figure 1: Plot showing interpolated height values from LOLA data (black) with the spacecraft altitude relative to the reference radius of 1738km along ~1.5 orbits (red). The spacecraft orbit was started at latitude=88°, longitude=0°, altitude=10km, launch angle=15°.

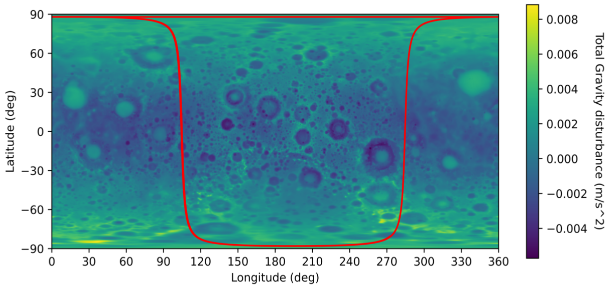

Figure 2: Global map of total gravity disturbance at 10km altitude above the reference radius of 1738km. Red line shows the spacecraft positions along ~1.5 orbits starting at latitude=88°, longitude=0°, altitude=10km, launch angle=15°, (the same orbit as in Figure 1).

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