A PRELIMINARY INVESTIGATION INTO THE EFFECT OF LUNAR GRAVITATIONAL FIELD VARIATIONS ON AN ULTRA LOW ALTITUDE LUNAR ORBITER.

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Introduction: A low altitude lunar orbiter presents enhanced science returns due to higher spatial resolution, bridging the resolution gap between current orbital data and surface data for use in future human surface missions, as well as opportunities for investigation of near-surface features such as magnetic anomalies. Ultra-low altitude Earth observation has already 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 Earth orbit [1], as well as JAXA's Super Low Altitude Test Satellite (SLATS/ "Tsubame") which employed agile maneuvers using an ion thruster and gas jet to respond to atmospheric drag [2]. This abstract outlines a preliminary investigation of whether similar approaches can be used to counteract orbital perturbations at the Moon due to lunar mascons. Previous work done by Song et al. [3] explored orbital maneuvers to stay within a low altitude lunar orbit deadband. In this study the spacecraft would operate autonomously by using gravity field knowledge, precision accelerometers and thrusters to maintain a near circular polar low altitude orbit.

Motivation: Song et al. [3] demonstrated that a low altitude orbiter would be able to achieve global coverage of the Moon's surface within a few months in the best-case scenario [3], this presents significant scientific returns depending on the instrument payload. Two possible payloads are discussed below.

Imager and/or spectrometer. LROC's NAC has a spatial resolution of 0.5m/pixel [4]. A low altitude lunar orbiter could potentially observe down to ~cm scale spatial resolution with a high-resolution imager payload, enabling scientific advancements for lunar surface processes and informing future human missions for possible ISRU sites. The recent LEAG 2019 findings highlighted that higher resolution orbital data is required for resource prospecting for near-future crewed and robotic missions, specifically global surface water ice distribution and abundance [5]. A spectrometer payload could also help fill this gap and inform on the lunar water cycle.

Magnetometer. Lunar swirls may be explored further at low altitude with a magnetometer. Our lowest altitude magnetometer observations of swirls come from the last moments of JAXA's Kaguya spacecraft before it crashed into the lunar surface. These data extend below 10km, as low as 5km over Mare Ingenii, revealing observations of the magnetic anomalies that are theorized to cause swirls [6]. Repeated observations at low altitude over multiple swirl regions are required to further probe the structure of these magnetic anomalies.

Method: The dominant forces at low altitude on the Moon are from variations in the lunar gravitational field (lunar mascons), which must be mitigated by any low altitude spacecraft, unlike at the Earth where a low altitude spacecraft must primarily counteract atmospheric drag. The gravitational field of a planetary body can be described using an expansion of spherical harmonics to degree (l) and order (m). NASA's GRAIL (Gravity Recovery and Interior Laboratory) measured the Moon's gravitational field to a very high spatial resolution (degree of expansion ≥ 1200 [7][8]). This ensured the smallest scale structures within the gravitational field were

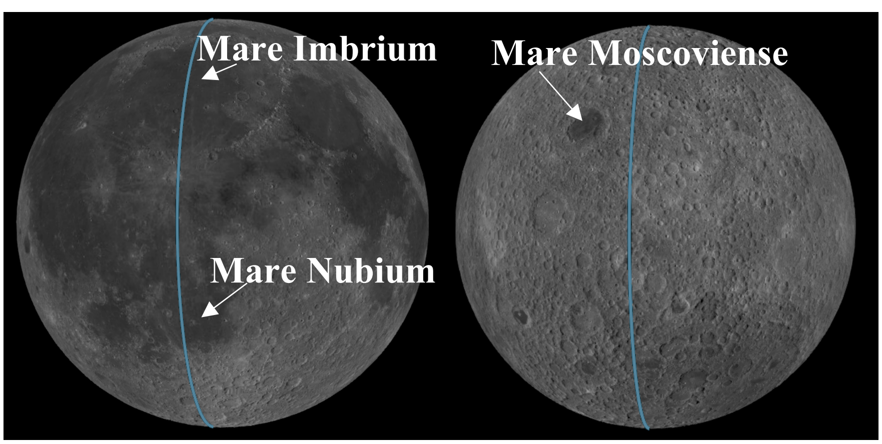

Figure 1: The blue line indicates the polar circular orbit that was selected for the gravitational acceleration variations in Figure 2, since this orbit passes over extreme mascon variations such as Mare Imbrium. Longitude values are -19° West for nearside orbit and 161° East for farside orbit. Images taken from ACT-REACT LROC QuickMap [9].

accurately captured. For the initial stage of this investigation, the software SHTOOLS developed by [10] was used to calculate the accelerations acting on the spacecraft due to the lunar gravitational field. SHTOOLS produces global maps of gravity accelerations for any altitude from the spherical harmonic coefficients of the gravitational field. SHTOOLS calculates gravitational potential, V, as

$$V = \frac{GM}{r} \sum_{l=0}^{l_{max}} \left(\frac{r_0}{r}\right)^l \sum_{m=-l}^{l} C_{lm} Y_{lm}$$

Where M is the Moon's mass, r_0 is the Moon's radius, r is the spacecraft's distance from the Moon's center (r_0 + spacecraft altitude), l is the degree and m is the order of the field, C_{lm} are the spherical harmonic coefficients provided by the GRAIL data and Y_{lm} are the associated normalized Legendre polynomials [10]. SHTOOLS then converts gravitational potential to gravitational acceleration, B, using $B = \nabla V$. The total acceleration variations from normal gravity, $g = GM/r^2$, were calculated along a fixed polar circular orbit for different altitudes to determine the effect altitude has on the magnitude of the acceleration variations. Figure 1 shows the polar circular orbit selected for this study as it passes over extreme mascon variations such as Mare Imbrium. Figure 2 shows total gravitational acceleration variations from normal gravity along this orbit for different altitudes from 10km to 50km.

Results and Conclusions: The results from SHTOOLS global maps indicated that the dominant acceleration direction at 10km altitude was radial to the lunar surface (positive values defined as away from the surface). The objective of a low altitude lunar orbiter would be to use thrusters to damp the acceleration variations at 10km altitude to that which would be seen at higher altitudes, lengthening mission duration. The thrust vector may be in the radial direction to directly offset the acceleration variations, or a more conventional method would be to thrust tangentially along the orbit track to alter the spacecraft altitude. Figure 2 shows that the spread of the acceleration variations increases significantly with decreasing altitude. The root-mean-square of the total gravity acceleration variations at 10km altitude was 0.0012 ms^{-2} (120mGal).

Future Work: Full orbit integrations will be carried out with Analytical Graphics Inc.'s Systems Tool Kit (STK). Topographic data from the Lunar Orbiter Laser Altimeter (LOLA) will also be integrated into the analysis to determine if and where the spacecraft trajectory would intersect the Moon's surface. Spacecraft maneuvers will be modelled using STK's Astrogator module to investigate agility for maximizing solar power and station-keeping of the spacecraft. Delta-v calculations will be carried out to select an appropriate thruster system. Possible scientific payloads will be investigated and prioritized within mass and volume constraints.

References: [1] Drinkwater M. R. et al. (2003) *Space Sciences Series of ISSI* Vol. 17. [2] "Tsubame Transition to Orbit Keeping Operations", JAXA Press Release, 18th March 2019. [3] Song Y-J. et al. (2019) *Journal of Astronomy and Space Sciences* Vol. 36 No. 3. [4] Robinson M. S. et al. (2010) *Space Sci Review* Vol 150 p.81-124. [5] Findings from the Annual Meeting of the Lunar Exploration Analysis Group 19th Dec 2019. [6] Saito Y. et al. (2019) *AGU Proceedings* #P33C-02. [7] Lemoine F. G. et al. (2014) *GRL* Vol. 41, Issue 10. [8] Goossens S. et al. (2016) *LPSC Abstract #1484*. [9] https://quickmap.lroc.asu.edu. [10] Wieczorek M. A. et al. (2018) *Geochemistry, Geophysics, Geosystems* Vol. 19, Issue 8.

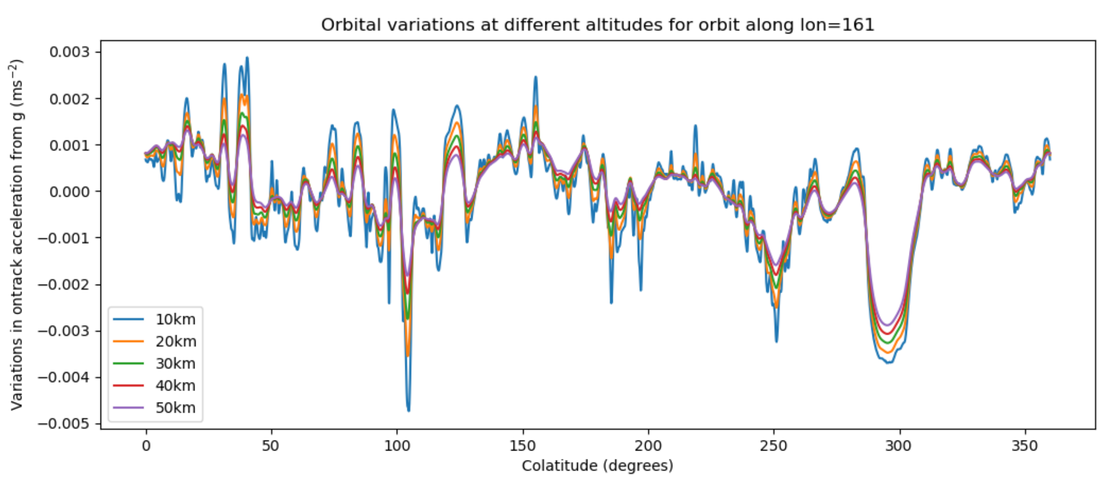

Figure 2: Variations in acceleration from normal gravity, g, at the specified altitude against colatitude, derived from SHTOOLS global maps at different altitudes. Variations are shown along a polar circular orbit which passes over extreme mascon variations such as Mare Imbrium (Figure 1), longitude values for this orbit are -19° West for nearside orbit and 161° East for farside orbit. Vertical range corresponds to -500/+300mGal.