DETECTION OF BURIED EMPTY LUNAR LAVA TUBES USING GRAIL GRAVITY DATA. R. Sood[1], L. Chappaz[1], H. J. Melosh[1,2], K. C. Howell[1], and C. Milbury[2]. [1]School of Aeronautics and Astronautics, Purdue University, West Lafayette, Indiana 47907, rsood@purdue.edu, [2]Earth, Atmospheric and Planetary Science, Purdue University, West Lafayette, Indiana 47907.

Introduction: As a part of NASA's Discovery Program, the Gravity Recovery and Interior Laboratory (GRAIL) spacecraft were launched in September 2011. The sister spacecraft, Ebb and Flow, mapped lunar gravity to an unprecedented precision [1]. High resolution data is currently being utilized to gain a greater understanding of the Moon's interior. Through gravitational analysis of the Moon, subsurface features, such as potential buried empty lava tubes, have also been detected [2]. Lava tubes are of interest as possible human habitation sites safe from cosmic radiation, micrometeorite impacts and temperature extremes. The existence of such natural caverns is now supported by Kaguya's discoveries [3] of deep pits that may potentially be openings to empty lava tubes. In the current investigation, GRAIL gravity data collected at different altitudes is utilized to detect the presence and extent of candidate empty lava tubes beneath the surface of the lunar maria.

Detection Strategy: Previous work done by Chappaz *et al.*, (2014) makes use of two detection strategies based on gradiometry and cross-correlation to detect subsurface features. Gradiometry technique encompass the calculation of the gravitational potential from a spherical harmonics data set. Specific truncation and tapering are applied to amplify the signal corresponding to the wavelength of the structures. By calculating the second partial derivatives of the potential function, the Hessian of the gravitational field is formulated. The largest eigenvalue and corresponding eigenvector associated with the Hessian determine the direction of maximum gradient. A secondary detection strategy, cross-correlation, utilizes the individual track data based on the relative acceleration between the two spacecraft as they move along their respective orbits. The gradiometry and cross-correlation detection techniques are applied to localized regions. Gravity models up to degree and order 1080 with predetermined truncation and tapers are utilized.

Detecting Underground Structures: The objective of our analysis is to determine the existence of underground empty structures, specifically lava tubes. Within this context, several regions in the maria with known sinuous rilles are considered, in particular a region around the known skylight of Marius Hills (301–307°E, 11–16°N). Cross-correlation analysis of this region is shown in Figure 1, with the red dot marking the location of a known skylight along the rille. The bottom-left map in Figure 1 corresponds to the co-

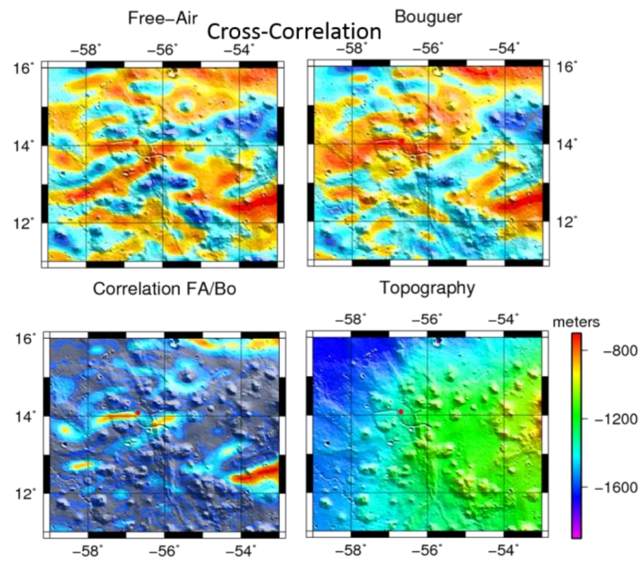

Figure 1: Free-air and Bouguer cross-correlation maps and free-air/Bouguer correlation along with regional topography in the vicinity of Marius Hills skylight.

rrelation between free-air and Bouguer maps where a strong correlation (red) is indicative of potential underground features. However, the structures that are the object of this analysis are a similar or smaller scale than the resolution of the gravity data. It is therefore challenging to determine whether a signal observed on an eigenvalue or cross-correlation map is, in fact, the signature of a physical structure or is a numerical artifact. To assess the robustness of an observed signal, rather than considering a single simulation, several different spherical harmonic solutions truncated between various lower and upper degrees are considered to produce a collection of maps. The cross-correlation maps in the top row and the bottom-left of Figure 1 yield an averaged map over a few hundred simulations. The bottom-right map provides a visual reference for the regional topography along with elevation in the vicinity of Marius Hills skylight.

The capability of both strategies to identify subsurface anomalies has led to the detection of additional candidate structures within the lunar maria. Figure 2 corresponds to a region around a newly found lunar pit in Sinus Iridum. The top row of Figure 2 illustrates the corresponding local averaged maximum eigenvalues for the free-air, Bouguer potentials, and the correlation between the two. The red dot marks the location of a newly found pit/skylight (331.2°E, 45.6°N) within Sinus Iridum. The pit itself is approximately 20 m deep with central hole of 70 m x 33Dde m and an outer funnel of 110 x 125 m. The maps overlay local topography, and the color represents the signed magnitude corresponding to the largest eigenvalue of the Hessian derived from the gravitational potential. Both free-air and

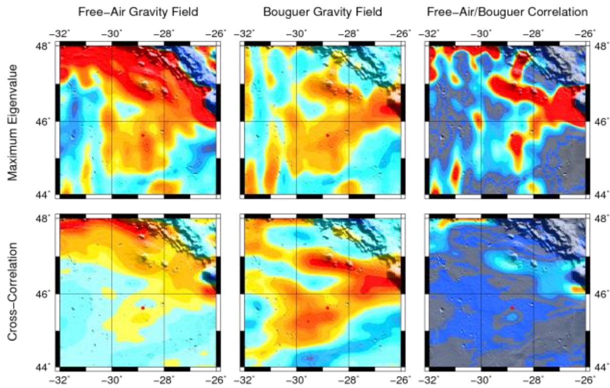

Figure 2: Local gradiometry (top), cross-correlation (bottom) maps for free-air (left), Bouguer (center), and free-air/Bouguer correlation (right) for Sinus Iridum pit.

Bouguer eigenvalue maps show gravity low in the vicinity of the lunar pit. The correlation map distinctively marks the region near the pit as a region of mass deficit with a potential access to an underground buried empty lava tube. The cross-correlation technique applied is shown in the second row of Figure 2. The schematic shows that for both free-air and Bouguer cross-correlation maps, the anomaly is detected in the same region as via the gradiometry technique. Both techniques provide evidence for a subsurface anomaly in the vicinity of the newly found lunar pit.

Free-air and Bouguer Gravity Anomaly: Continuing the validation of the subsurface anomaly, regional free-air and Bouguer gravity maps are generated. Figure 3 illustrates local maps for the free-air gravity on the left and Bouguer gravity on the right. On closer in-

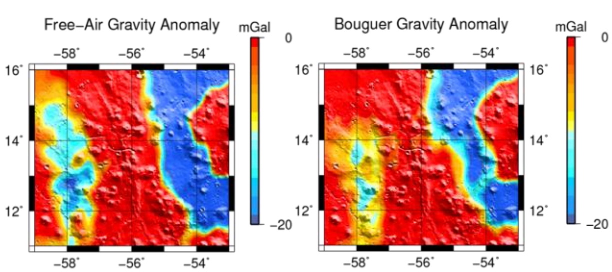

Figure 3: Local free-air (left) and Bouguer (right) gravity map for Marius Hills skylight with overlay of topography.

spection, the two gravity maps demonstrate a gravity low surrounding the rille along which the Marius Hills skylight lies. The Bouguer low adds to the evidence suggesting a potential buried empty lava tube along the rille with an access through the Marius Hills skylight.

Similar free-air and Bouguer gravity analysis is carried out for the newly found pit in Sinus Iridum as shown in Figure 4. The color bar is adjusted to visually

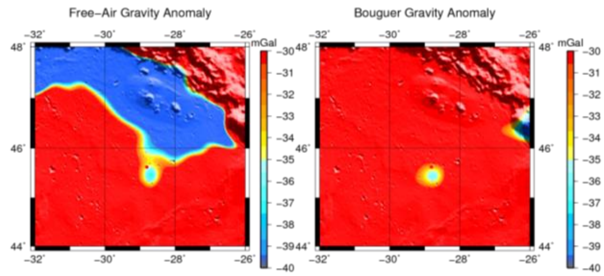

Figure 4: Local free-air (left) and Bouguer (right) gravity map for the newly found lunar pit in Sinus Iridum with overlay of topography.

distinguish the region in proximity to the lunar pit in Sinus Iridum. The gravity low shown in both the free-air and Bouguer gravity suggest an underground mass deficit in the vicinity of the pit. Although the pit itself is relatively small, it can potentially be an access to a larger underground structure as evident from the gravity maps and the two detection strategies. Additional maps have also been studied to identify a possible connection of this anomaly to a buried empty lava tube structure.

Conclusions: Two strategies are employed to detect small scale lunar features: one based on gradiometry and a second one that relies on cross-correlation of individual tracks. The two methods have previously been validated with a known surface rille, Schröter's Valley. Then, a signal suggesting an unknown buried structure is observed in the vicinity of Marius Hills skylight that is robust enough to persist on a map created from an average of several hundred simulations. A similar signal is also observed in the vicinity of the Sinus Iridum pit suggesting a possible subsurface mass deficit.

The technique has been extended to cover the vast mare regions. Multiple new candidates for buried empty lava tube structures have been discovered as a part of this study. Some of the candidates bear no surface expression but similar signals are observed from both the detection strategies as observed for candidates with surface expressions, i.e., skylights/pits.

References:

[1] Zuber *et al*. (2013) SSR 178, 1.
[2] Chappaz et al. (2014) AIAA 2014-4371.
[3] Haruyama et al. (2009), GRL 36, L21206.