SURFACE AND BURIED LAVA TUBE DETECTION WITH GRAIL DATA L. Chappaz[1], H. J. Melosh[1,2], K. C. Howell[1],and the GRAIL mission team. [1]School of Aeronautics and Astronautics, Purdue University, West Lafayette, Indiana 47907-2045, [2]Earth, Atmospheric and Planetary Science, Purdue University, West Lafayette, Indiana 47907-2051.

Introduction: The success of the NASA's GRAIL mission–a twin spacecraft formation revolving around the moon in a quasi-circular polar orbit–now provides the highest resolution and most accurate gravity data for the Moon. The low altitude at which some of this data was collected in the GRAIL extended mission potentially allows the detection of small-scale surface or subsurface features. We have focused on the specific task of detecting the presence and extent of empty lava tubes beneath the mare surface. In addition to their importance for understanding the emplacement of the mare flood basalts, open lava tubes are of interest as possible habitation sites safe from cosmic radiation and micrometeorite impacts [1]. The existence of such natural caverns is now supported by Kaguya's discoveries of deep pits in the lunar mare [2]. In this investigation, tools are developed to best exploit the rich gravity data toward the numerical detection of these small features. Two independent strategies are considered: one based on gradiometry techniques and a second one that relies on cross-correlation of individual tracks.

Gradiometry: The first strategy relies on the numerical inspection of the lunar gravitational potential, computed from a set of spherical harmonics that is truncated and tapered to some predeterminded degree and order to magnify the short wave length structures of interest. From any scalar field, a widely employed method to detect or highlight ridges or valleys within the field of interest involves the computation of the Hessian and consequently the eigenvalues and eigenvectors that are associated with the Hessian of the scalar field. In essence, the eigenvalue of largest magnitude and the corresponding eigenvector are associated with the direction of maximum gradient in the field. In this investigation, similar to [3], eigenvalue maps that depict the magnitude of the largest magnitude eigenvalue for each point on a grid on the lunar surface are produced. Either the Free-Air potential or the Bouguer potential (corrected for topography and terrain) can be employed in the analysis, depending on the objective. For the purpose of this study, very localized maps that focus on specific regions are most relevant; consider a region in the Aristharcus plateau that contains Aristachus crater and one of the largest known lunar rilles, Shroeder's Valley. Figure 1 illustrates the corresponding local eigenvalue maps for Free-Air and Bouguer potential, overlaid with the local topography from LOLA.

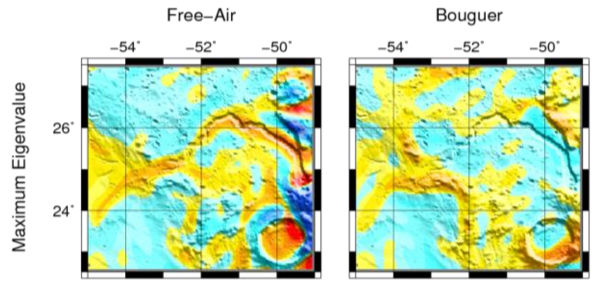

Fig. 1: Local eigenvalues map in the Schroeder's Valley region with an overlay of topography.

The color scale represents the signed magnitude of the largest magnitude eigenvalue of the Hessian of the gravitational potential. From these local maps, it is now evident that the structures that emerge from the Free-Air map do, in fact, correspond to the presence of the rille. Note that, as expected since the rille is a surface feature incorporated in the topography, there is no corresponding signal on the Bouguer map.

Cross-Correlation: Another strategy relies on directly exploiting the KBRR track data, that is, the relative acceleration of the two spacecraft as they move on their respective orbits. Only the horizontal component of the relative acceleration is directly available from the measurements, in contrast to the radial (i.e., vertical) or lateral components. From either the vertical or horizontal acceleration component, simple analytical expressions describe the acceleration anomaly experienced by the spacecraft along a flight path that is perpendicular to an infinitely long lava tube just beneath the surface; the tube is idealized as an empty horizontal cylinder. Figure 2 illustrates the horizontal and vertical acceleration sensed by the GRAIL spacecraft assuming an empty cylinder of diameter 1 km, given a flight altitude of 50 km, the average altitude for the nomial mission, as well as a distance of 20 km, the corresponding average altitude for the extended mission.

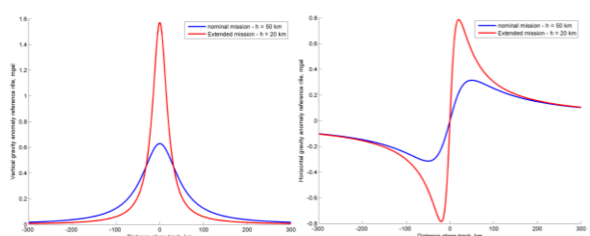

Fig.2: Analytical vertical (left) and horizontal (right) gravity anomaly.

These relations can be employed to construct a reference signal for the structures to be detected, that is, the lava tubes. Then, a mathematical construct in the form of the cross-correlation is employed between a reference signal and the KBRR signal. Track data is subdivided into individual tracks that correspond to a longitude value and a range of latitudes. Also, to exploit the assumed linearity of the lava tube, several tracks for a set of neighboring discrete longitudes are included in the same computation. At the time of this writing, the actual track data is not yet available. To refine this technique, we created proxy track data from available spherical harmonic models. We thus compute the horizontal gravitational acceleration along fictitious North-South tracks from the spherical harmonics. Recall the region in the Aristharcus plateau that was employed to demonstrate the gradiometry method. Figure 3 illustrates the cross-correlation strategy. This figure is constructed from the cross-correlation between 80 tracks and a reference signal constructed assuming a 2 km diameter lava tube and an altitude consistent with the spherical harmonic model (the spherical harmonic data is presented at the reference altitude whereas the track data must be evaluated at the actual spacecraft altitude). The color scale represents the cross-correlation coefficients, from dark blue to red (a range from -1 to 1). The more positive the value of the coefficients, the more closely this portion of the track data resembles the reference signal, as the cross-correlation operates as a matching filter.

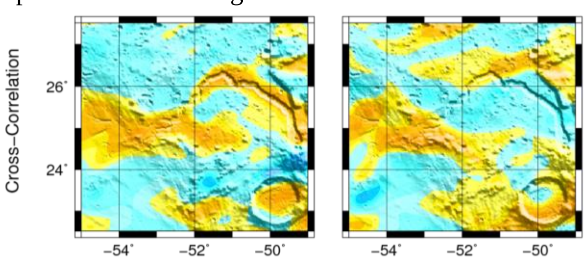

Fig.3: Local Free-Air (left) and Bouguer (right) cross-correlation map in the Schroeder's Valley region with overlay of topography.

The rille signal corresponding to the topographic Schroeder's Valley clearly appears on the Free-Air cross-correlation map and is absent of the Bouguer map.

Detecting Underground Structures: The capability of both methods to identify a large surface sinuous rille, that is, Schroeder's Valley, is demonstrated in the two previous sections. The objective of our analysis is to determine the existence of underground empty structures, or empty lava tubes. Within this context, several regions in the mare with known sinuous rilles are considered, in particular a region around a south channel of Rima Sharp, that is, for longitudes from 311º to 316º and latitudes from 35 to 40º. For this region, both the gradiometry and cross-correlation simulations are performed and the corresponding maps appear in Figure 4.

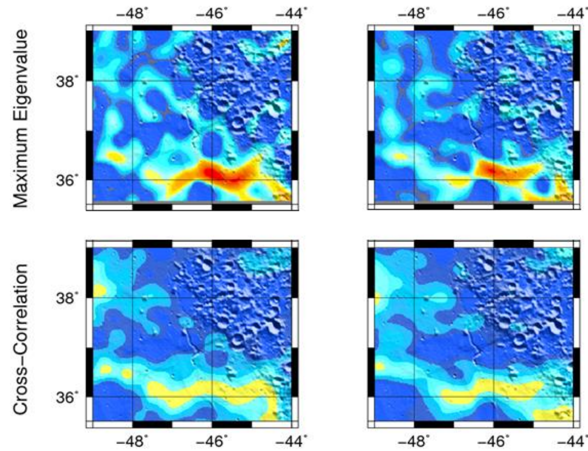

Fig.4: Local cross-correlation and eigenvalue map in the Rima Sharp region with overlay of the topography.

Although the Rima Sharp channel in the center of the figure is not resolved, another signal is observed in the bottom of the maps. This signal is present on the maps generated with both methods and on the Free-Air and Bouguer maps suggesting an underground feature. However, the size of the structures that are the object of this analysis is of same order of magnitude or smaller than the resolution of the gravity data. It is then 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 maps in Figure 4 yield an averaged map over a few hundred simulations.

Conclusions: In an effort to detect small scale lunar features, two methods are proposed: one based on gradiometry and a second one that relies on cross-correlation of individual tracks. The two methods are validated with a known surface rille, Schroeder's Valley. Then, using the two methods, a signal suggesting an unknown buried structure is observed south of Rima Sharp that is robust enough to persist on an averaged map corresponding to several hundred of simulations. Continuing work includes exploiting KBRR track data directly and forward modelling of observed features.

References: [1] De Angelis et al. (2001) BAAS 33, 1037. [2] Haruyama et al. (2009), GRL 36, L21206. [3] Andrews-Hanna et al. (2012) Science DOI:10.1126/science.1231753 .