Lunar Crustal Thickness and Velocity Model Inversion Using Constraints from GRAIL and Apollo data (and preparation for the InSight Mission Data Analysis Phase). Jean-François Blanchette-Guertin[1], Mélanie Drilleau[1], Taichi Kawamura[1], Philippe Lognonné[1] and Mark Wieczorek[1]. [1]Institut de Physique du Globe de Paris (5 rue Hélène Brion, Case 7071 Lamarck A, 75205 Paris Cedex 13, France, e-mail:blanchetteg@ipgp.fr)

Overview: We are building a new generation of 1-D lunar upper mantle and crustal seismic velocity models and 3-D crustal thickness models by combining recent high-resolution gravity data (from the GRAIL mission), and topography and photographic data (from the LRO mission), with legacy Apollo seismic data. This study will lead to improved scientific understanding of the present-day lunar interior structure, a critical tie point for viable models of lunar evolution. This study also lays the groundwork for future analyses of new lander (NASA InSight mission in 2016) and recent satellite datasets from Mars.

Motivation: Three powerful conclusions of the recent lunar crustal thickness study in **[01]** are that the lunar crust is substantially more porous than previously thought (between 4% and 21%, averaging at 12%), less dense (2500 kg/m^3 versus the previously-proposed 2800-2900 kg/m^3) and that the crust is overall thinner than previous gravimetric studies showed **[02, 03]**. The mean lunar crustal thickness values of 34 to 43 km are now in accordance with the average thickness values from recent re-analyses of Apollo seismic data **[04, 05, 06]**. However, quite a few issues that we aim to address with this study still remain. The uncertainty on mean crustal thickness values is still ±15%, and our joint gravity-seismic inversions could better this by constraining the values with seismic data. Furthermore, the large lateral variations in surface topography hinder the determination (using only gravity methods) of a deeper crustal layer of varying density, porosity and composition (e.g. a dual-layered crust), and of upper mantle density lateral variations. The confirmation of the presence (or lack of) of a deeper crustal layer would have important ramifications for the accretion and the cooling and thermal history of the Moon. Improved models for the overall crustal structure and in particular the near-surface region is important not just for understanding the shallow structure of the Moon but also influences the determination of mantle structure. For example, the new, higher porosity of the uppermost crustal layer(s) may have a significant influence on the travel time of seismic energy in the near-surface that trades off with estimates for seismic velocity in the mantle. The improved gravity data and impact locations used in our inversion project has the potential to address such issues and better determine crustal and mantle lunar structure.

Approach: We are building upon and improving the joint gravity-seismic inversion study done in **[07]** to obtain a new and more accurate upper mantle velocity model and a model for lateral variations in lunar crustal thickness. We use Markov chain Monte Carlo (McMC) inversions to identify the range of lunar crustal thicknesses as a function of latitude and longitude (within the limits of the models presented in **[01]**) that fits both the Apollo impact travel times **[04]** and an average (i.e. depth-dependent only) velocity model of the crust and mantle. We are improving on the study in **[07]** by:

1. Using the crustal lateral variations derived from the GRAIL gravity data as *a priori* constraints. This data was not available when the study in **[07]** was done;
2. Inverting for both the crustal thicknesses and the seismic velocities;
3. Relocating the artificial impact events used in the study using the high-definition (and more precisely geo-located) imagery from the LRO mission (Wide-Angle and Narrow-Angle Cameras aboard LRO);
4. Using the new impact event identified in **[08]** doubling this way the number of impact events used in the **[07]** inversions.
5. Using the new crustal porosity and density information from **[01]**, along with laboratory-derived ratios of seismic velocities / density based on regolith or soil properties (e.g. **[09]**) to estimate better mean crustal and upper mantle velocities;
6. Using the effect of the crust and subsurface regolith layers on the upper mantle temperature and associated density and seismic velocities perturbations (see **[05]** and **[10]** for 1-D case).

Point 5 is an important factor to consider as the relationships between P-wave velocity (v_p), S-wave velocity (v_s) and density (ρ) are controlled by the porosity, the shape and connectivity of cracks, and subsurface fluid content **[11].** For this project, we can not use the empirical ratio values developed on Earth given the intrinsically different nature of the lunar subsurface: the Moon environment is comparatively very dry.

Forward and Inverse Problems: The forward problem consists of travel time computations using a 3-D ray tracing method for each set of model parameters. Following **[12]**, the crustal and mantle physical properties (v_p, v_s, ρ) as a function of depth are defined at each site (Apollo stations and impact sites) using C^1 Bézier polynomials. Major advantages of such parameterization are that it does not impose specific layer thicknesses, and that both gradients and discontinuities can be retrieved in the inversion. Each site is defined by a different surface elevation and crustal thickness.

The inverse problem consists of a McMC algorithm that performs a non-linear guided search by sampling the parameter space according to the posterior probabilities. The principle is to perturb one of the parameters according to the *a priori* information in each model iteration. A randomized decision rule is used to accept or reject the proposed models according to their fit to the data and the *a priori* information. All accepted models are used to determine the probability density function of each model parameter. This approach goes beyond the classical computation of the unique best-misfit model by giving a quantitative measure of the model resolution, uncertainties and non-unicity, which are important items when inferring scientific conclusions from inverse calculations, especially when studying planetary bodies.

Mars Inversion (InSight/SEIS): We will build on, and extend this lunar study by developing, testing and integrating the data analysis and numerical modeling algorithms for analogous investigations of Mars during the upcoming InSight Mission data analysis phase. The InSight mission will acquire the first seismic data from Mars in Fall 2016. All the other necessary data is already available from the Mars Global Surveyor and previous orbital missions.

References: **[01]** Wieczorek, M. A., et al. (2013), *Science*, doi:10.1126/science.1231530. **[02]** Wieczorek, M. A., et al. (2006), *Rev. Mineral. Geochem.*, 60 (1), 221–364. **[03]** Ishihara, Y., et al. (2009), *GRL*, doi:10.1029/2009GL039708. **[04]** Lognonné, P., et al. (2003), *EPSL*, 211(1-2), 27–44. **[05]** Gagnepain-Beyneix, J., et al. (2006), *PEPI*, 159, 140–166. **[06]** Khan, A., and K. Mosegaard (2002), *JGR.*, 107(E6), 19–44. **[07]** Chenet, H., et al. (2006), *EPSL*, doi:10.1016/j.epsl.2005.12.017. **[08]** Gudkova et al. (2015), submitted to *EPSL*. **[09]** Barton, N. (2007), Rock quality, seismic velocity, attenuation and anisotropy, CRC Press. **[V01]** Vinnik, L. P., et al. (2001), *GRL*, 28(15), 3031–3034. [H80] Horvath, P., et al. (1980), *JGR*, 85(B11), 6572–6578. **[10]** Schumacher, S. and Breuer D. (2006), *JGR*, 111(E2). **[11]** Mavko, G., et al. (2009), The Rock Physics Handbook. **[12]** Drilleau, M. et al. (2014), *GJI*, doi: 10.1093/gji/ggt284.

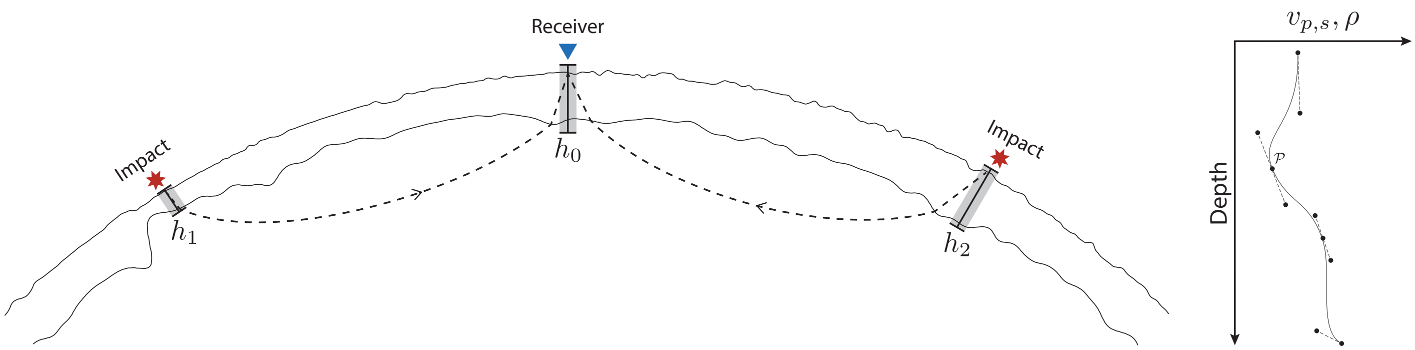

Figure 1: Schematic representation of the model showing two impact sites with seismic rays traveling towards the recording station. The right plot is an example set of the C^1 Bézier curves used in the model parameterization. The Monte Carlo inversion finds the lunar crustal thicknesses under each impact site and station (h_0, h_1, h_2, h_n), as well as the depth and value of the Bézier points ($\mathcal{P}$) producing velocity and density models that best describe the data.