GRAIL REFINEMENTS TO LUNAR SEISMIC STRUCTURE. R. C. Weber[1] and N. C. Schmerr[2], [1]NASA Marshall Spaceflight Center (renee.c.weber@nasa.gov), [2]University of Maryland (nschmerr@umd.edu).

Introduction: To probe a planet's interior, seismology provides the most direct constraints on the variables that govern the dynamic properties of the body. However, the GRAIL (Gravity Recovery and Interior Laboratory) mission's high-resolution measurements of the lunar gravity field provide constraints on crustal thickness, mantle structure, core radius and stratification, and core state (solid vs. molten). These data complement seismic investigations, and joint interpretation permits improved constraints on the Moon's internal structure.

Joint seismic and gravity inversion: Joint interpretation of disparate geophysical datasets helps reduce drawbacks that can result from analyzing them individually. The Apollo seismic network was situated on the lunar nearside surface in a roughly equilateral triangle having sides approximately 1000 km long, with stations 12/14 nearly co-located at one corner. Due to this limited geographical extent, near-surface ray coverage from moonquakes is low, but increases with depth (Figure 1). In comparison, gravity surveys and their resulting gravity anomaly maps have traditionally offered optimal resolution at crustal depths. Gravimetric maps and seismic data sets are therefore well suited to joint inversion, since the complementary information reduces inherent model ambiguity.

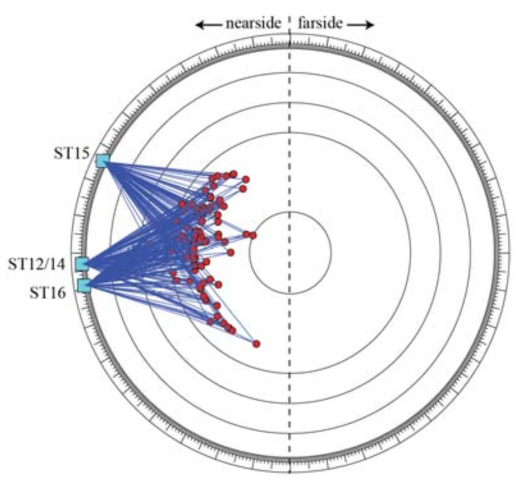

Figure 1: Cross-section showing P-wave coverage from deep moonquakes at the Apollo seismic station locations. Ray paths are projected onto the plane that slices the Moon along the prime meridian. Lateral sampling of rays is small near the surface (limited to the regions directly beneath the Apollo stations), and gradually increases with depth, with the mid-mantle most densely sampled.

Previous joint inversions of the Apollo seismic data (seismic phase arrival times) and Clementine- or Lunar Prospector-derived gravity data (mass and moment of inertia) attempted to recover the subsurface structure of the Moon by focusing on hypothetical lunar compositions that explored the density/velocity relationship. These efforts typically searched for the best fitting thermodynamically calculated velocity/density model, and allowed variables like core size, velocity, and/or composition to vary freely.

Seismic velocity profiles derived from the Apollo seismic data through travel time inversion vary both in the depth of the crust and mantle layers, and the seismic velocities and densities assigned to those layers. The lunar mass and moment of inertia likewise only constrain gross variations in the density profile beyond that of a uniform density sphere. As a result, composition and structure models previously obtained by jointly inverting these data retain the original uncertainties inherent in the input data sets.

We perform a joint inversion [1] of Apollo seismic delay times and gravity data collected by the GRAIL lunar gravity mission, in order to recover seismic velocity and density as a function of latitude, longitude, and depth within the Moon. We relate density (ρ) to seismic velocity (v) using a depth-dependent linear relationship [2]. The corresponding coefficient (B) can reflect a variety of material properties, including temperature and composition. The inversion seeks to recover the set of ρ, v, and B perturbations that minimize (in a least-squares sense) the difference between the observed and calculated data.

The model is parameterized using density blocks and velocity nodes (nodes are placed in the middle of each density block). The B-coefficient links density and velocity in each horizontal layer. The lateral and depth extent of the modeled region is dictated by the seismic data coverage. Lateral ray coverage is limited to the near side due to the dearth of farside sources. Vertical ray coverage from moonquakes does not extend deeper than ~1200 km due to the lack of farside receivers and attenuation effects of the core. We define the base of our model at 700 km to maximize the number of rays piercing the base layer.

The initial seismic velocity model is selected from a representative sample of previously published models [3-6]. GRAIL gravity coverage is global; to prevent edge effects, we model the entire extent of the nearside, leaving out those nodes that are not pierced by seismic rays.

Initial inversion results: The velocity, density, and B-coefficient perturbations obtained for every layer after each inversion are applied to the reference model, and the entire process can be repeated iteratively until the root-mean-square misfit stabilizes. This results in a final model that best fits the constraints jointly imposed by the seismic and gravity observations. Results for a sample run on a coarse grid are shown in Figure 2. Because the inversion is quite sensitive to the model parameterization and initial values, and tends to diverge rapidly if the grid size is too large, these results should not be interpreted as being representative of real structure within the Moon. A smaller grid produces a more stable inversion, but runs the risk of producing a signal that doesn't actually exist. Further work is needed to stabilize the inversion; a depth-dependent relationship for the density and velocity standard deviations may prevent the inversion from attempting to concentrate large contrasts in the upper portions of the model.

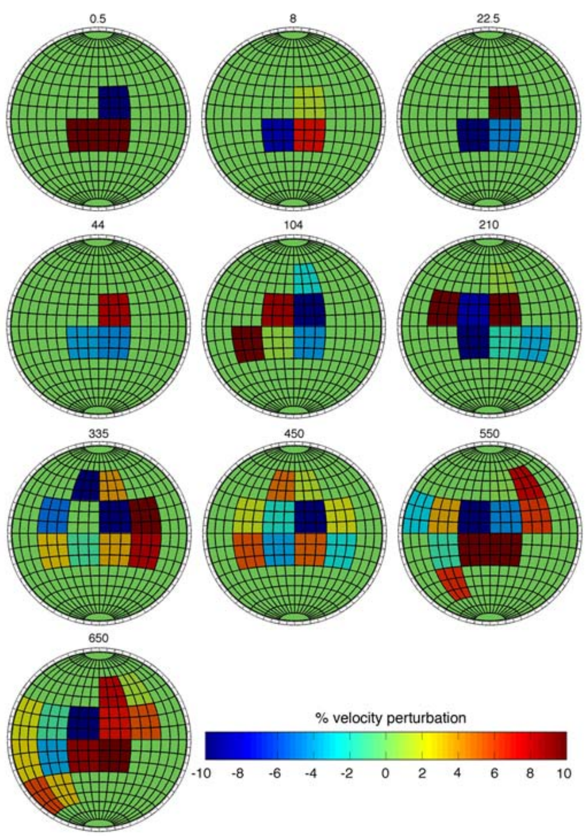

Figure 2: Near-side P-wave velocity anomaly (percent deviation from input model) resulting from the joint inversion, at the midpoints between the modeled layer boundaries. Blocks are 30° on a side, with a velocity node centered in each block. Note only those grid blocks pierced by seismic rays are perturbed at each depth increment.

Seismic array processing refinements: The array processing approach presented in [7] provided the first direct constraint on the size and state of the Moon's core through analyses of the Apollo seismic data. The method used travel time predictions made from pre-existing estimates of crust and mantle velocities and densities [4]. The approach assumed that each of the Moon's layers is a uniform shell, with no lateral variation or heterogeneity.

As demonstrated by the joint inversion, the structural properties of the Moon are likely inhomogeneous, and vary both laterally and with depth. Seismic travel time inversions of data recorded at the Apollo landing sites, and pre-GRAIL inversions of gravity and topography data, have all shown, for example, that the Moon's crust is neither uniform thickness, nor uniform in seismic properties.

To refine the core constraint presented in [7], we will adjust the predicted times of core-reflected seismic phases from the known distribution of lunar seismic events by including travel-time perturbations based on the following predictions: 1) Refined estimates of crustal thickness derived from GRAIL's gravity model, 2) variations in mantle velocities based on a suite of both pre-existing models and our joint inversion results, and 3) GRAIL's constraint on the core radius, layering, and state (solid vs. molten).

For a given ray path generated by a 1D ray-tracer, we will collect the predicted travel time variation from a single model perturbation along that ray path. This process can be repeated iteratively to account for all the perturbations we wish to include. The end result is a total travel time anomaly for the input ray path. For each of the moonquake ray paths shown in Figure 1, as well as the ray paths associated with all located impacts and shallow moonquakes, we will incorporate the accumulated travel time anomaly as time shifts made to the traces prior to stacking in our array processing technique. This approach will permit a refined seismic constrain on the lunar core.

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