GRAIL refinements to lunar seismic structure

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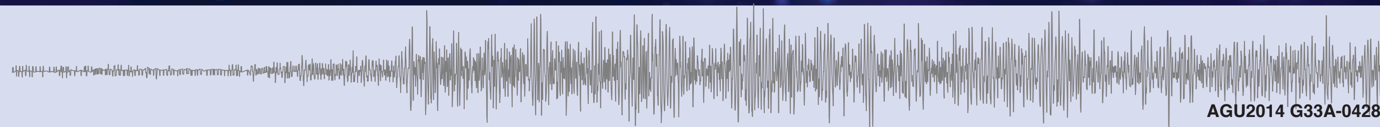

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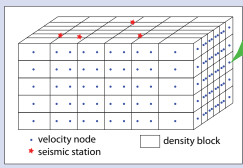
Joint seismic and gravity inversion

Goal:
Recover seismic velocity and density structure of the Moon as a function of latitude, longitude, and depth.

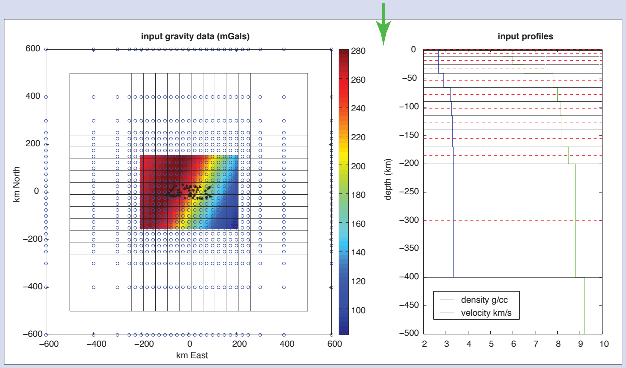
Method:
Jointly invert seismic delay times and gravity data by relating density to seismic velocity using a depth-dependent linear relationship. The scaling coefficient (B) encompasses material properties that vary with depth, including temperature and composition. The inversion minimizes (in a least-squares sense) the difference between the observed and calculated data.

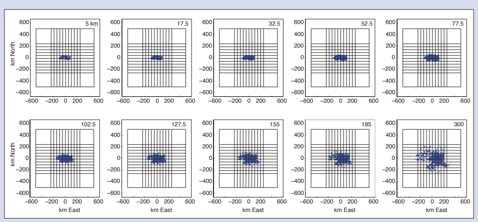
	observed data	calculated data
seismic data	P- and S-wave arrival times read from recorded seismograms	P- and S-wave arrivals predicted from existing velocity model
gravity data	map-projected radial gravity anomaly	space-dependent scalar estimated point-by-point from the input layer-cake density profile

Model parameterization:
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.



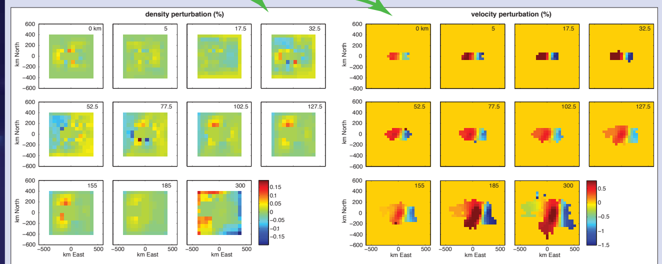
Test study: Earth seismic survey
A seismic survey of the Corinth Rift region in Greece consisted of 63 portable seismic stations that recorded 177 teleseismic events, resulting in a total of 2319 travel time residuals. The input Bouguer gravity anomaly, initial density and velocity profiles, grid parameterization, and ray pierce points through the model are shown below.





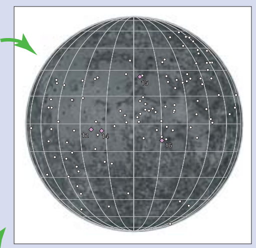
Joint seismic and gravity inversion - Earth study analysis

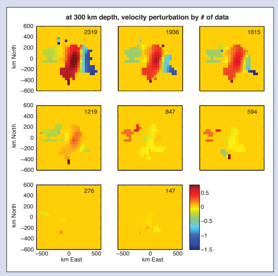
The inversion results in a map of density and velocity perturbations across the study region, at each depth slice in the model:

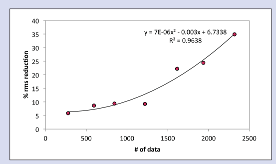


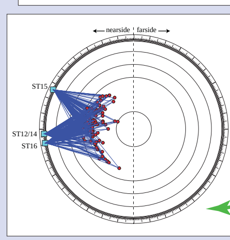
Adaptation to lunar-like study conditions:
The lunar seismic data are limited by the number of seismic stations in the Apollo array. When considering well-located deep moonquakes, there are 71 events recorded on 4 stations, resulting in 148 data.

The inversion results break down as the number of data in the Earth test study are reduced to lunar-like conditions. The overall % rms reduction in the delay-time data also decreases with decreasing number of data. This breakdown indicates that the model space is not properly parameterized for the available data.









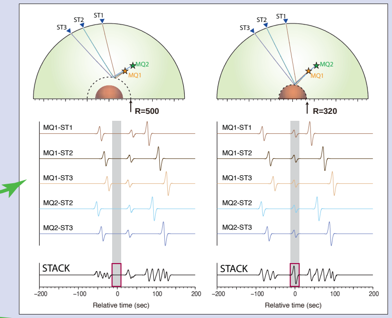
Moving forward:
The parameter space should reflect information density. The inversion is sensitive to grid spacing, and tends to diverge rapidly if the grid size is too large (under-fitting). A large grid can also force physically unreasonable density and velocity contrasts, concentrating large contrasts in the upper portions of the model. A smaller grid produces a more stable inversion, but may produce a signal that doesn't actually exist (over-fitting).

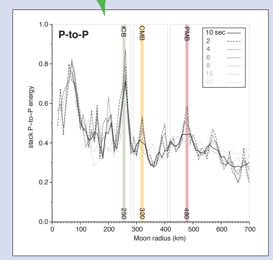
For the Moon, seismic rays that pierce the near-surface layers are densely clustered under the stations. The grid spacing should be highest in these regions, dictated by the average pierce-point spacing.

Seismic array processing refinements

Lunar core analysis:
A method to enhance and detect subtle seismic arrivals, typically used in terrestrial seismology, is to stack seismograms that have been time-shifted to the predicted arrival time of a hypothetical phase of interest. We previously applied this array processing approach to the Apollo lunar seismic data, providing the first direct constraint on the size and state of the Moon's core. This analysis used 1-D seismic velocity and density profiles.

We searched for lunar core reflections by time-shifting deep moonquake cluster traces according to predictions associated with different possible layer depths, then stacking the traces. The approach iteratively constrains the best-fit radii and overlying seismic velocities in each layer.





GRAIL-constrained crustal structure, combined with velocity and density perturbations constrained by the joint inversion, will introduce travel-time anomalies that can be summed to refine the seismic structure resulting from the array processing.