Lunar internal structure from reflected and converted core phases

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Goal: A seismic constraint on the size of the lunar core from analysis of the deep moonquake data recorded by the Apollo Passive Seismic Experiment.

Method: Compare predictions (core phase arrival times and amplitudes) to observations (manipulated seismograms).

330 km? 361? 250? 435?

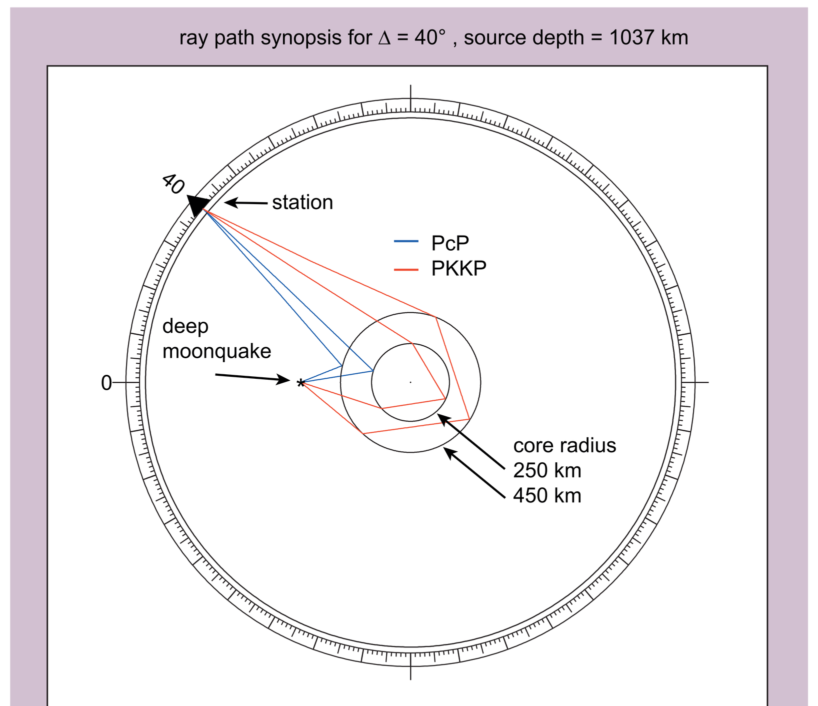
Constraints on the size of the core can be inferred from other measurements (including moment of inertia, electromagnetic sounding, LLR), but no direct seismic constraint has been found [1].

predictions: core arrival info

- travel times from ray theory (1)
- amplitudes from synthetic seismograms (4)

observations: techniques for enhancing core arrivals

- polarization filtered seismograms (2)
- deconvolved seismograms (3)



Small core: PcP travel time larger, PKKP travel time smaller

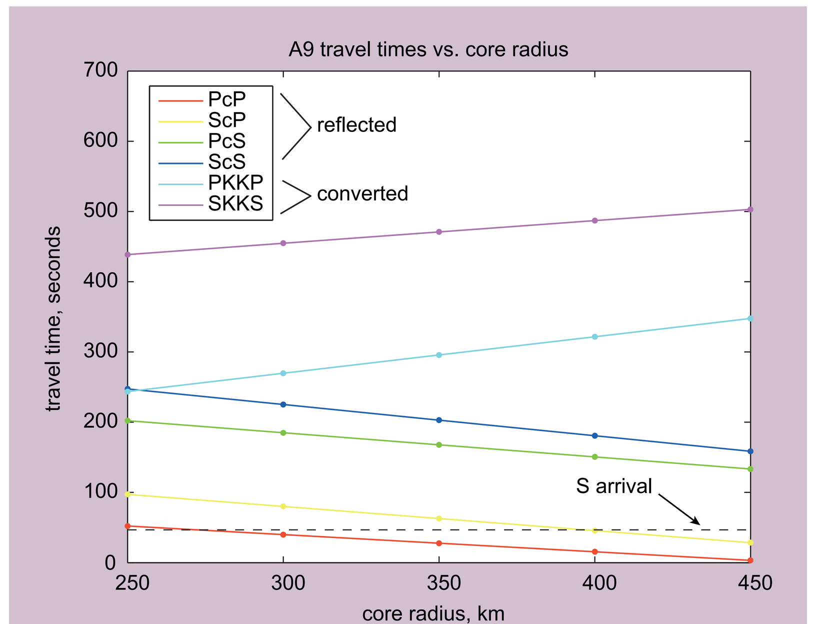
Large core: vice versa

1 Travel times

Travel times for core phases (PcP and PKKP shown at left) can be computed from ray theory [2]. These of course will depend on the radius of the core.

A small core increases travel times for reflected phases and decreases travel times for converted phases (example at right).

Comparison of arrival times with seismograms may be insightful.



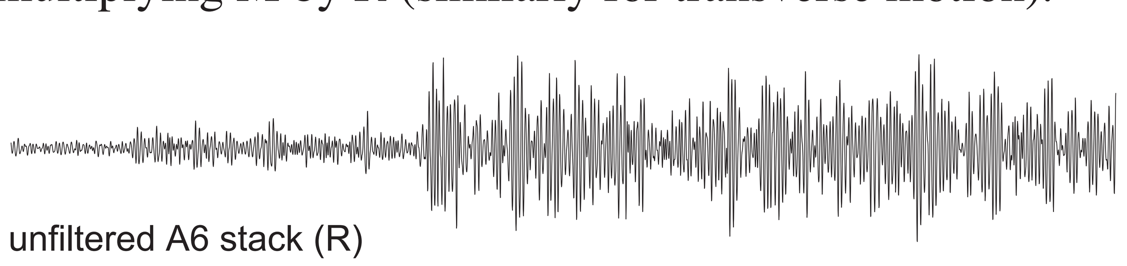
Travel times for core phases (computed for a plausible range of core radii) arriving from the A9 source at the Apollo 12 seismic station. The S arrival is marked with a dashed line.

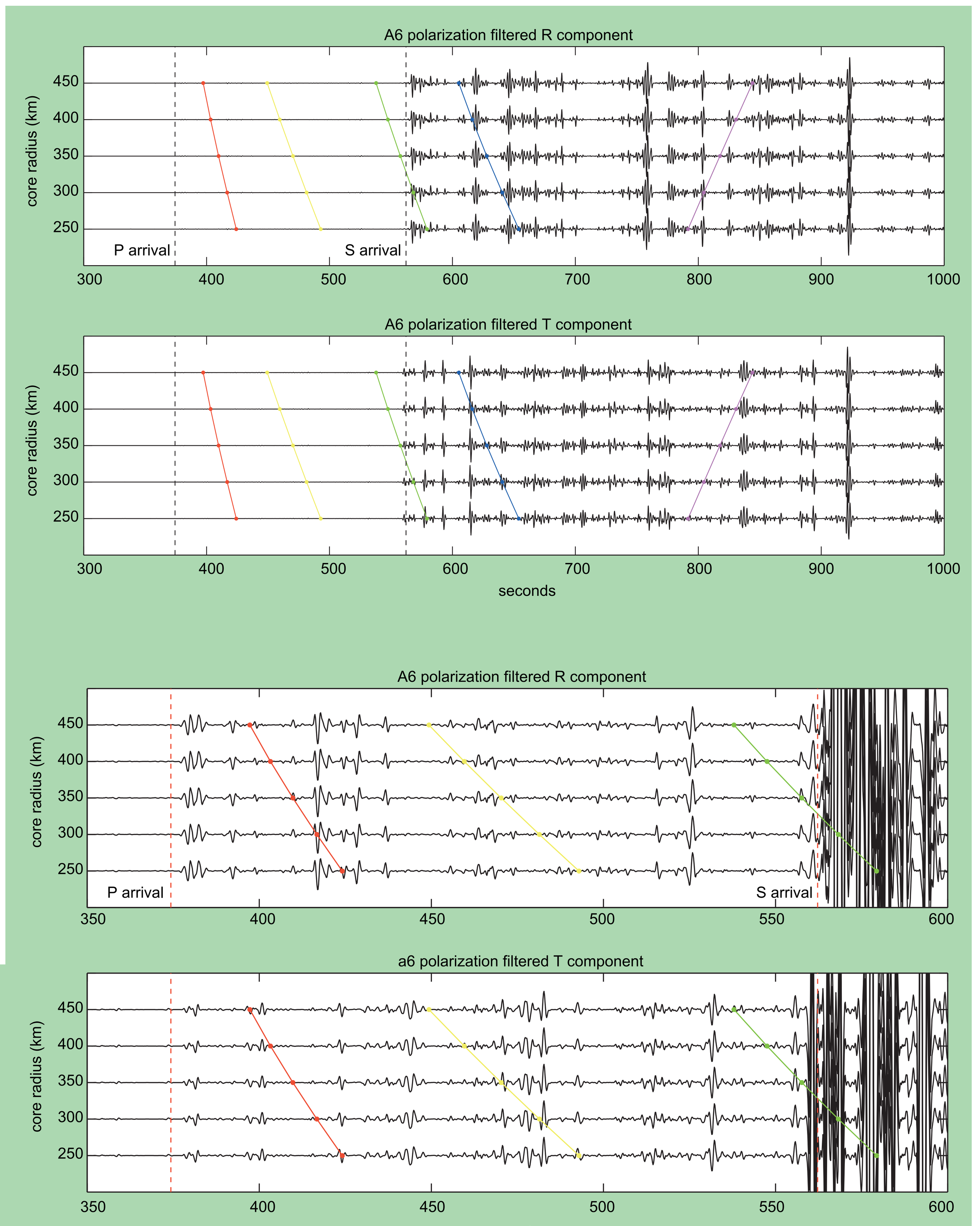
2 Polarization filtering

To account for the effect of scattering in the lunar crust (which hampers the identification of all but the main P and S arrivals) we apply a polarization filter [3]. The scattered energy is randomly polarized, while the arrivals are not. The filter M is computed as:

$$M_j = \sum_{i=-n}^{n} R_{j+i} Z_{j+i}$$

where R and Z are the radial and transverse seismogram components, respectively. Radial motion is enhanced by multiplying M by R (similarly for transverse motion).





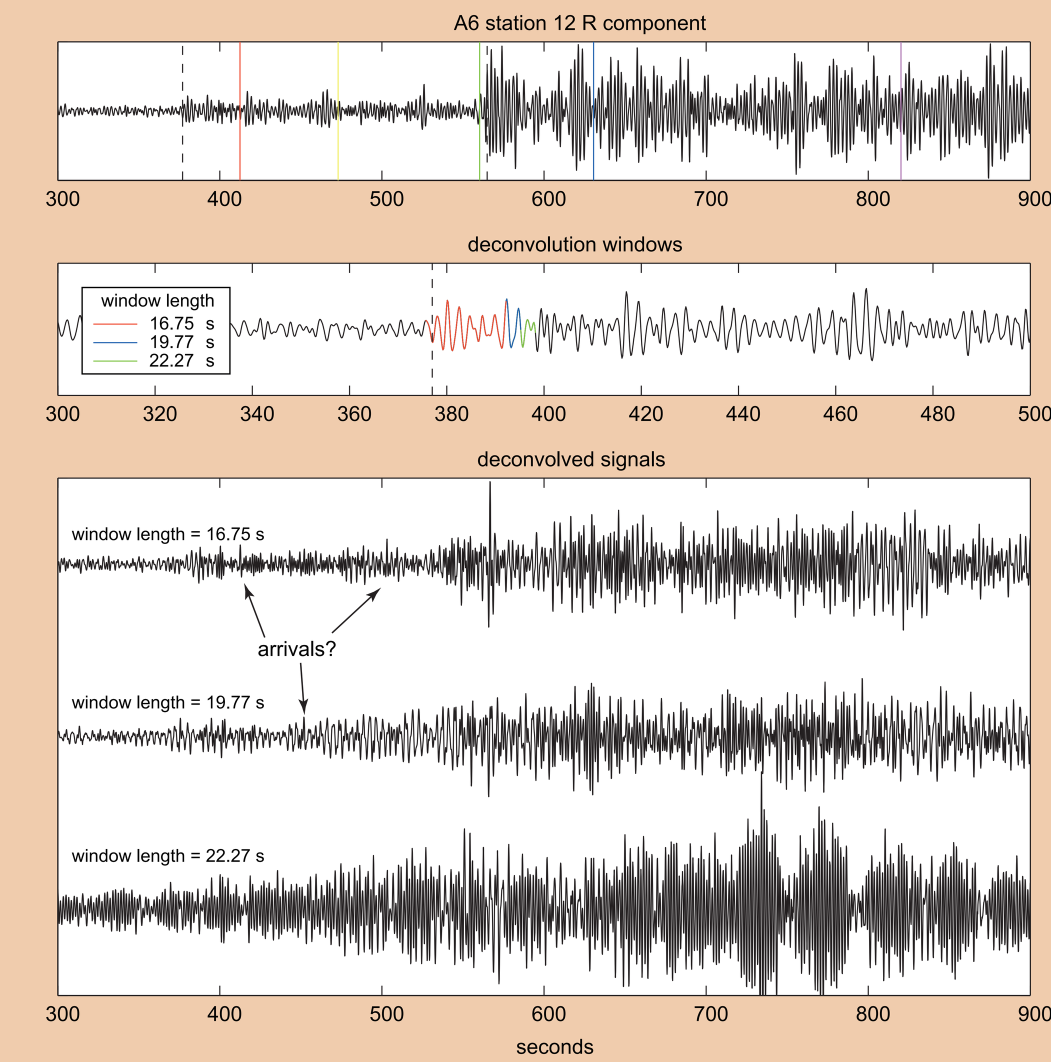
R and T polarization filtered traces from the A6 cluster showing the core arrivals for a range of core radii. The lower plots focus on the region before the S arrival. The timing of the predicted secondary phases alone is not enough to determine whether the observed arrivals are associated with the core.

3 Deconvolution

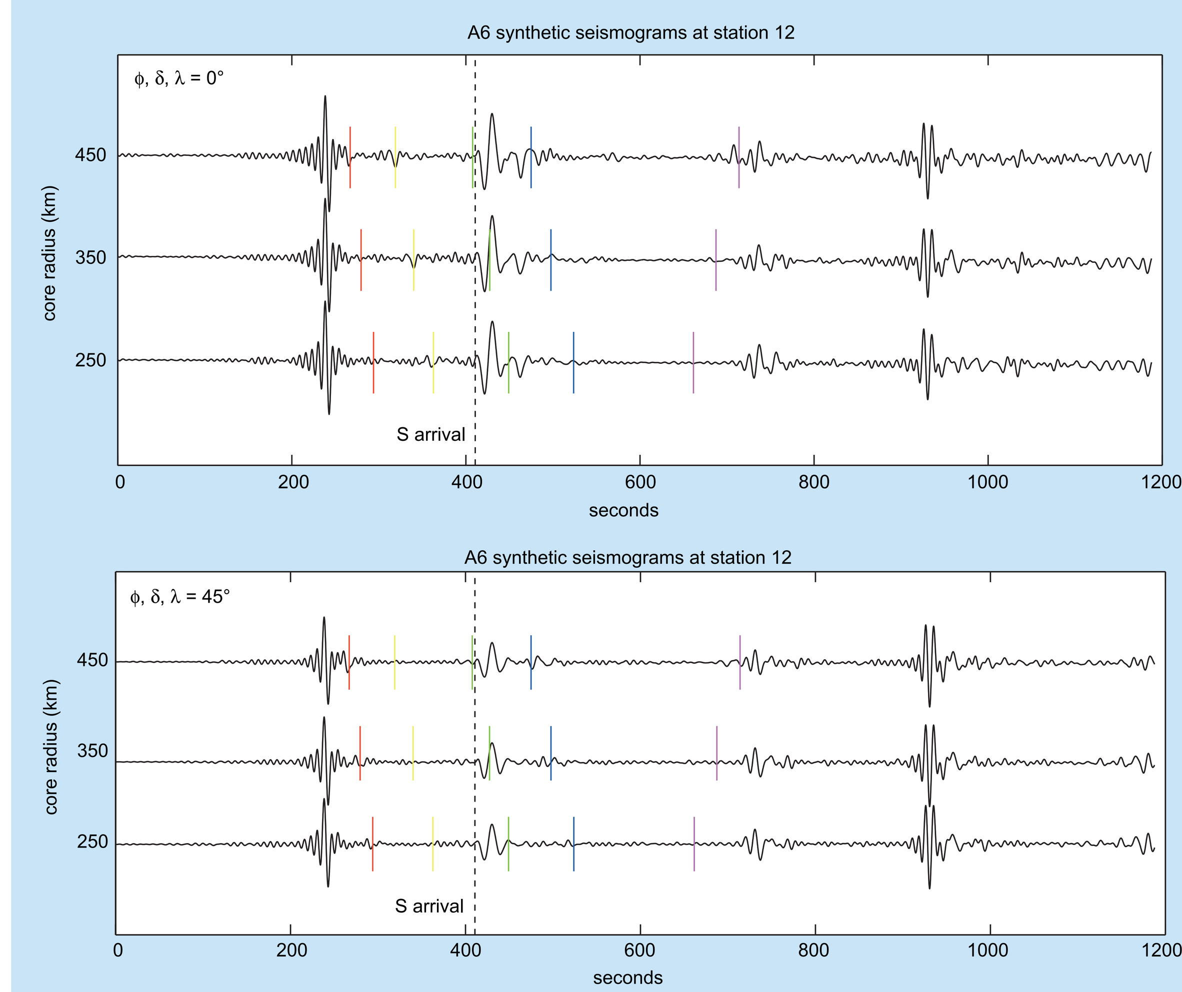
Deconvolution is commonly used to remove noise from a "corrupted" signal, in order to obtain the underlying "uncorrupted" signal. For the lunar data, the uncorrupted signals we wish to analyze are the core phase arrivals. The source of the corruption (the response function) is the coda associated with the scattering of seismic energy from the main P- and S-wave arrivals.

To attempt to account for this effect, we deconvolve the entire seismogram by the portion of the trace containing the initial segment of the P or S scattering coda, depending on the timing of the core arrivals. This is similar to the S receiver function technique used to detect the Sp phase from the lunar mantle-crust transition [4].

This technique does not seem to significantly enhance core arrivals. This is likely because deconvolution is sensitive to both noise in the input data and to the accuracy to which the response function is known. The additional process known as "optimal filtering" may be useful [5].



Top: A6 stack showing predicted arrival times. PcP, ScP, and PcS arrive before S, so the P-wave arrival is used for deconvolution. Middle: Three response functions of varying lengths which encompass the P arrival. Bottom: Deconvolved stack.



To help identify the predicted core arrivals, we compute synthetics using small, medium, and large core radii. The amplitudes will depend on the (unknown) focal mechanism. The examples shown here are for a fault at depth with strike, dip, and rake all equal to either 0° (upper) or 45° (lower). In the upper example, the ScP arrival is more evident; in the lower, PcP.

4 Synthetic seismograms

While the previous methods of manipulating the Apollo seismograms (Sections 2 and 3) revealed possible secondary arrivals, it is still difficult to discern which, if any, are associated with the lunar core. By computing synthetic seismograms for a range of lunar structure models, we can model both the amplitudes and arrival times of the secondary phases directly, and compare the synthetics to the results of our previous analyses.

We calculate the Moon's normal modes of oscillation [6] using the structure model of Lognonné et al. (2003) [7]. Seismograms for the desired source-receiver configuration are modeled using normal mode summation over the frequency range 0.2-200 mHz.

Finding a focal mechanism which correctly models the typically large S- to P-wave arrival amplitudes observed on the Apollo seismograms will help determine the expected amplitude of the core arrivals.

Conclusions

- Polarization filtering reveals possible core arrivals in the Apollo seismograms (with additional work, deconvolution may as well)
- Ray theory and synthetic seismograms predict the travel times and amplitudes of the core arrivals
- Comparison of these results on a large scale (many deep moonquake clusters) may allow correlations to be drawn, placing a seismic constraint on the size of the lunar core

References

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