Lunar Internal Structure from Reflected and Converted Core Phases

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Introduction

A direct seismic constraint on the size of the lunar core is difficult to obtain due to several factors. Core phases from naturally-occurring deep moonquakes are not observed on seismograms from the Apollo instruments, in part due to the strong scattering of seismic energy in the lunar crust. This leads to emergent P- and S-wave arrivals, with strong codas that hamper the identification of later arrivals. We investigate several methods of enhancing predicted reflected (e.g. PcP) and converted (e.g. PKP) core phases in order to constrain the structure of the lunar core. In addition, we asses the likelihood that a future lunar seismometer could detect such phases.

Predicted arrivals

The arrival times for a variety of seismic phases originating from the known distribution of deep moonquake clusters [1] can be computed from ray theory [2] for a range of lunar structure models. These could theoretically have been detected at the surface by the four Apollo seismic stations (Figure 1a). However, the scattering coda associated with the main P and S arrivals prohibit the immediate identification of secondary phases, even on stacked seismograms (Figure 1b).

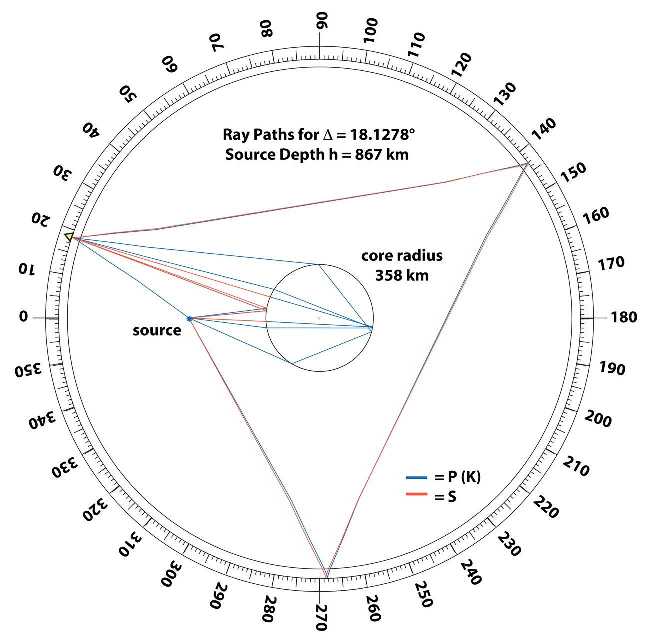

Figure 1a) Phases theoretically detectable at Apollo station 12 from the A1 source region (angular separation = 18.13°) - P, PcP, PPP, S, ScS, SSS, ScP, PcS, PKKP, and SKKS.

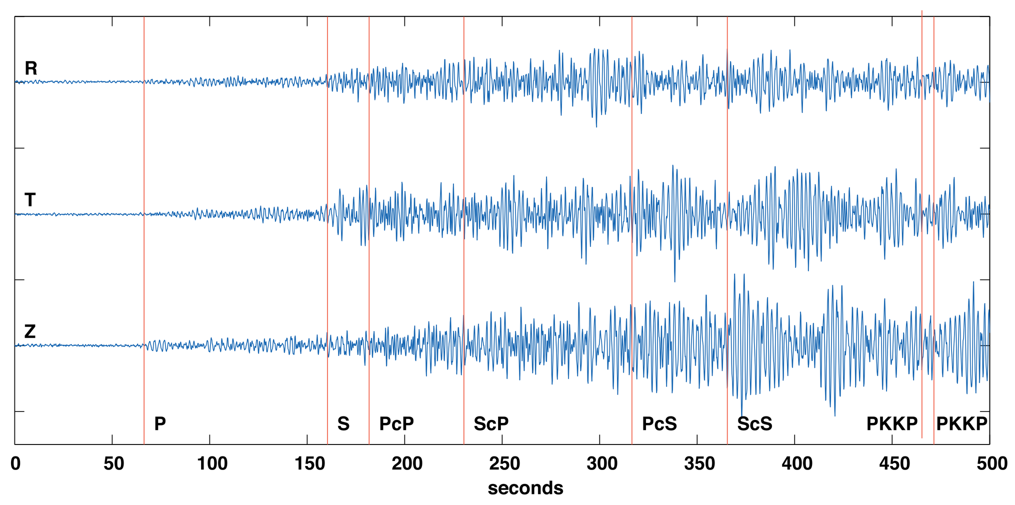

Figure 1b) Stacked A1 seismograms at Apollo station 12 (radial, transverse, and vertical components) with predicted seismic phase arrival times for a model with a core radius of 358 km (noted in red). Only P and S are readily discernible; their scattering coda mask later arrivals.

Techniques for enhancing core arrivals I - polarization filtering

Scattered seismic energy is randomly polarized; body wave arrivals are not. A polarization filter may therefore reduce the effects of scattering on the identification of core arrivals. This technique has been applied to signals from surface events (impacts and shallow moonquakes) to determine shallow structure and identify the presence of upper-mantle reflectors [3].

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

The polarization function (M) is the averaged cross product of the vertical (Z) and radial (R) components. Vertical, radial, or transverse (T) motion is enhanced by multiplying the filter (M) by the corresponding component Z, R, or T.

We begin with an averaging window of length 2.4 seconds (n=6). Figure 2 shows the unfiltered radial stack component (R), the filter (M), and the filtered R component (R*M). The predicted arrival times for a model with a core radius of 358 km are indicated in red as previously.

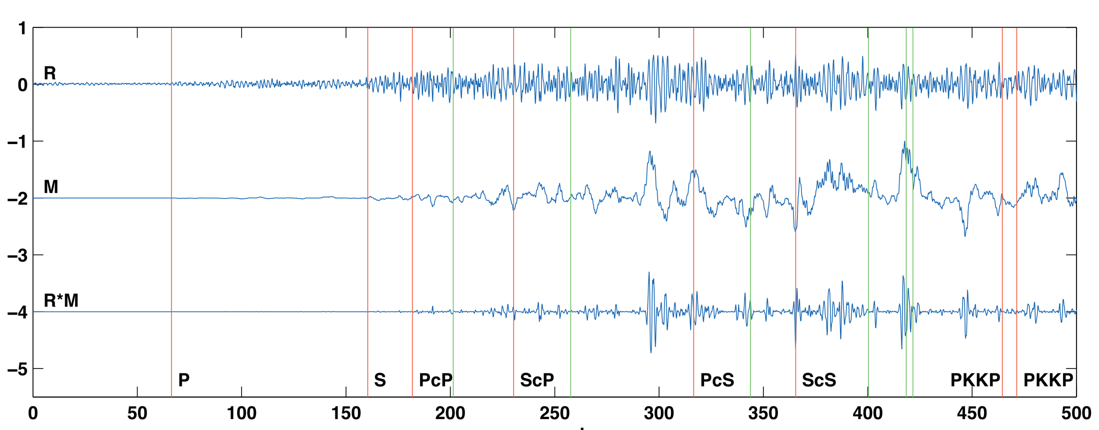

Figure 2) A1 radial stack component (top), polarization filter (middle) and filtered trace (bottom). Arrivals associated with a 358-km core are shown in red; those for a smaller core (275 km) are shown in green.

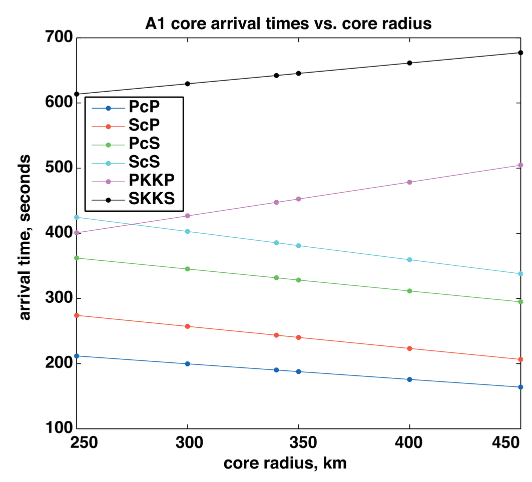

Figure 3) Core phase arrival times at station 12 from the A1 source for a range of core radii.

The core phase arrivals seem to align with some of the pulses in the filtered trace. However, adjusting the velocity model by changing the core radius results in different travel times for the core phases. For example, in Figure 2 the arrivals for a smaller core are shown in green. Which set of arrivals are "correct," and what about the pulses which don't align with a predicted arrival? Using this method, travel times alone are not sufficient to determine if certain pulses represent true arrivals or are simply anomalies. Figure 3 shows how core phase arrival times vary with core radius.

Techniques for enhancing core arrivals II - deconvolution

Deconvolution is commonly used to remove noise from a "corrupted" signal c(t), in order to obtain the underlying "uncorrupted" signal u(t) that we wish to analyze. The true signal u(t) may be smeared out by a known response function r(t) such that c(t) = r(t)*u(t). The term "response function" encompasses a wide range of blurring effects in seismology; in this case we are interested in the effects of scattering.

For the lunar data, the uncorrupted signals we wish to analyze are the core phase arrivals, and the response function, by which the entire seismogram will be deconvolved, is a portion of the trace containing the P or S coda. Since core phases for realistic structure models arrive after S, they are likely more effected by the S-wave coda, so we use the S arrival as the response function. This is similar to the S receiver function technique used to detect the Sp phase from the lunar mantle-crust transition [4].

The result of the deconvolution depends on the length of the window used as the response. In Figure 4 we show examples for three windows of differing lengths which contain the S arrival and a portion of the coda. While some secondary arrivals are arguably observed for a 40-second window, this technique does not seem to significantly enhance the seismograms. 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].

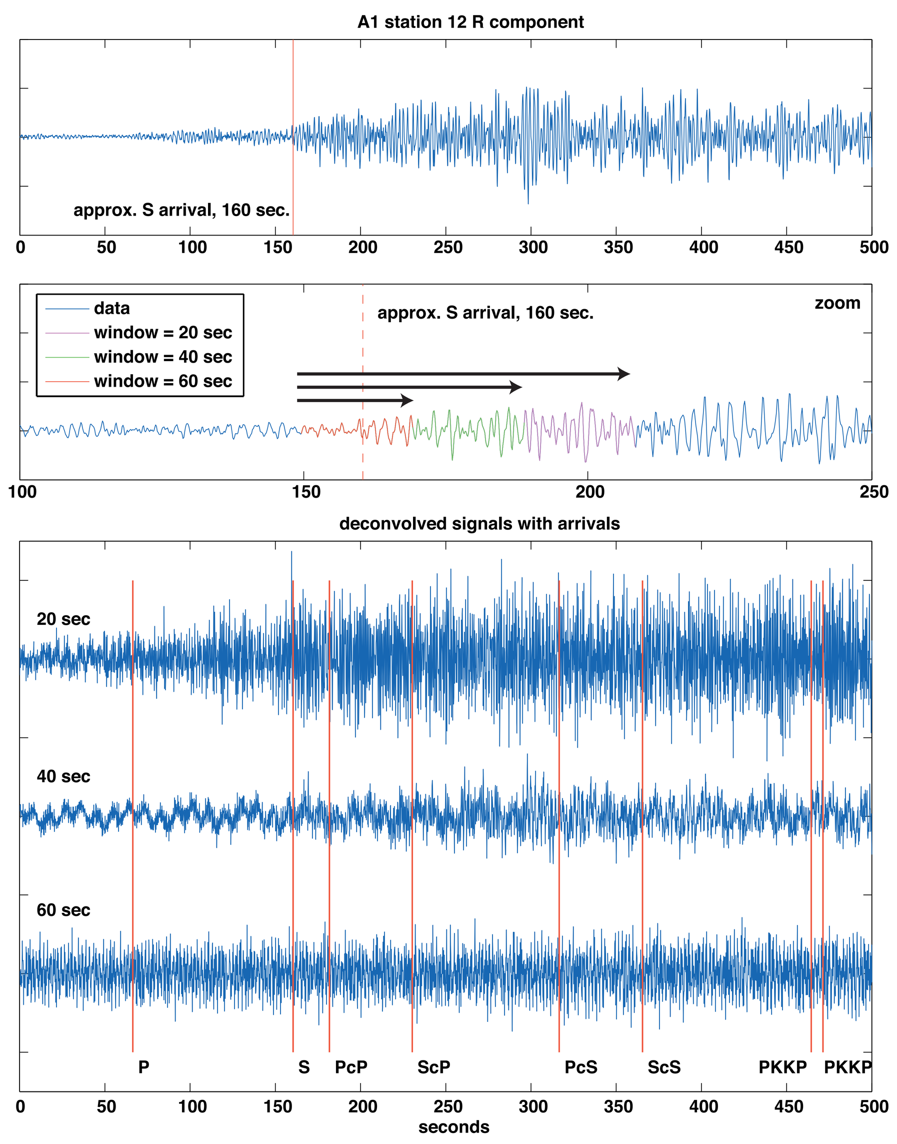

Figure 4) Top: A1 station 12 R component with S arrival noted in red. Middle: Three response functions of varying lengths which encompass the S arrival. Bottom: Results of deconvolving R by the three response windows. Arrivals are plotted as previously.

Modeling synthetic seismograms

While the previous methods of manipulating the Apollo seismograms 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.

Given a radial model of the Moon's structure, we calculate the normal modes of oscillation assuming a spherical body [6]. Seismograms for the desired source-receiver configuration are then modeled using normal mode summation over the desired frequency range. Although the focal mechanisms of deep moonquakes are not known, they are thought to represent shear failure due to the prominence of the shear wave arrival on the seismograms. We thus begin by assuming a moment tensor for a fault geometry with strike, dip, and rake all equal to 45°. An example synthetic for the A1 source at station 12 is shown in Figure 5.

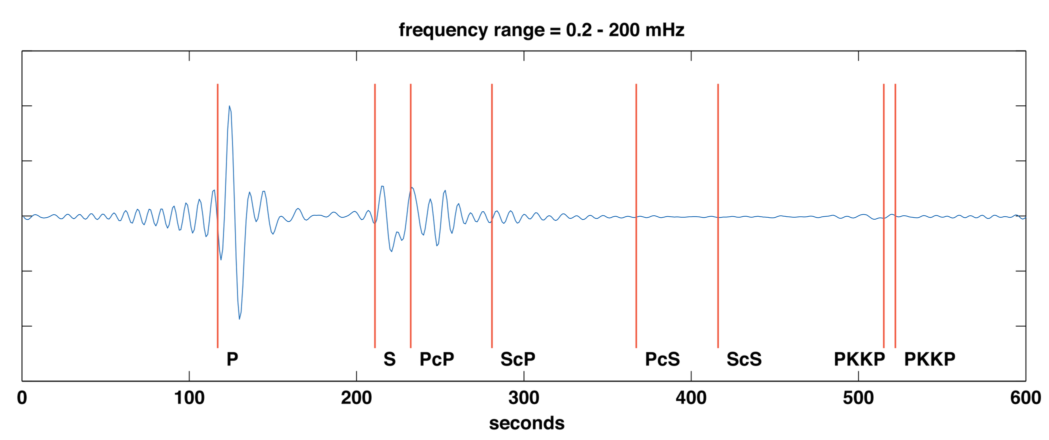

Figure 5) Synthetic seismogram for the deep moonquake cluster A1 computed at station 12, for a model with core radius = 358 km. A possible alignment exists for the PcP arrival.

Not all of the predicted arrivals are visible on the synthetics. This could be due to several factors. The frequency cutoff of 200 mHz may be too low to contribute significant energy to modes which sample the core. In addition, synthetics are very sensitive to attenuation. The Moon's low- attenuation crust may act as a waveguide and trap seismic energy, contributing to the length of the coda. Models which include a near-surface, highly attenuating layer, while non-physical, may reduce this effect.

Further work is needed to determine whether the three methods discussed here, considered either separately or in tandem, can provide a seismic constraint on the size of the lunar core.

The Future - a new seismic mission to the Moon

The repeatability of moonquake signals from known individual deep source regions, combined with the likelihood that these regions are still active, means that even a single new seismometer on the Moon could be beneficial. The SEIS instrument in development for ExoMars can easily be modified for use on the lunar surface. A seismic station near a south pole lunar base, for example, could detect both PcP and PKP from many deep source regions (Figure 6).

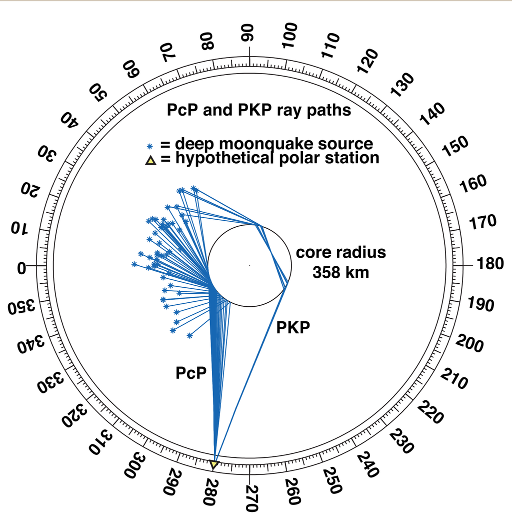

Figure 6: Cross-sectional view of PcP and PKP rays arriving from the known distribution of deep moonquake clusters at a lunar seismic station situated 10° from the South pole, at 0° longitude.

References: [1] Nakamura, Y. (2005) JGR vol. 110, doi:10.1029/2004LE002332. [2] Knapmeyer, M. (2004) SRL vol. 75, no. 6 (p. 726-733). [3] Voss, J. et al. (1976) Proc. Lunar Sci. Conf. 7th (p. 3133-3142) [4] Vinnik, L. et al. (2001) GRL vol. 28 no. 15 (p. 3031-3034). [5] Press, F. et al. (1992) in *Numerical Recipes*, Cambridge University Press. [6] Woodhouse, J. H. (1988) in *Seismological Algorithms*, Elsevier.