Extracting seismic core phases with array interferometry

Fan-Chi Lin,[1] Victor C. Tsai,[1] Brandon Schmandt,[1] Zacharie Duputel,[1] and Zhongwen Zhan[1]

[1] Seismic body waves that sample Earth's core are indispensable for studying the most remote regions of the planet. Traditional core phase studies rely on well-defined earthquake signals, which are spatially and temporally limited. We show that, by stacking ambient-noise cross-correlations between USArray seismometers, body wave phases reflected off the outer core (ScS), and twice refracted through the inner core ($PKIKP^2$) can be clearly extracted. Temporal correlation between the amplitude of these core phases and global seismicity suggests that the signals originate from distant earthquakes and emerge due to array interferometry. Similar results from a seismic array in New Zealand demonstrate that our approach is applicable in other regions and with fewer station pairs. Extraction of core phases by interferometry can significantly improve the spatial sampling of the deep Earth because the technique can be applied anywhere broadband seismic arrays exist. **Citation:** Lin F.-C., V. C. Tsai, B. Schmandt, Z. Duputel, and Z. Zhan (2013), Extracting seismic core phases with array interferometry, *Geophys. Res. Lett.*, *40*, doi:10.1002/grl.50237.

1. Introduction

[2] Ambient noise interferometry, which uses cross-correlations of low-amplitude but long-duration seismic noise to obtain the impulse response between two locations [*Lobkis and Weaver* 2001; *Tsai* 2010], is now routinely used to study shallow Earth structure with surface waves [*Shapiro et al.*, 2005; *Yao et al.*, 2006; *Lin et al.*, 2008; *Nishida et al.*, 2009; *Moschetti et al.*, 2010]. While storm activity can generate noise that propagates through the deep Earth as body waves [*Gerstoft et al.*, 2008], ambient noise is dominated by surface waves [*Yang* and *Ritzwoller* 2008]. This apparent disparity places broad limits on the retrieval of body wave phases by noise interferometry to specific areas and scales [*Roux et al.*, 2005; *Zhan et al.*, 2010; *Poli et al.*, 2012].

[3] Here we address the question of whether deep core phases traveling between stations can be extracted by seismic interferometry. Specifically, we look for evidence of core phases in ambient-noise cross-correlations processed with a standard method [*Bensen et al.*, 2007]. This method uses a running-average normalization to suppress earthquakes [*Bensen et al.*, 2007], but we take no further effort to remove earthquake energy from the continuous seismograms. The

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[1]Seismological Laboratory, Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, California, USA.

Corresponding author: Correspondence to: F.-C. Lin, Seismological Laboratory, Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA 91125, USA. (linf@caltech.edu)

"noise" therefore includes signals that cannot be identified by traditional earthquake analysis, including signals from distributed sources like ocean microseism and low-amplitude (e.g., coda) waves excited by earthquakes.

2. Data and Results

[4] We process continuous vertical seismic records between January 2007 and May 2011 observed by 1181 stations of EarthScope/USArray Transportable Array [*Lin et al.*, 2008]. More than 400,000 cross-correlations between station pairs with distances mostly less than 2000 km are calculated. We stack all cross-correlations in 50 km distance bins and normalize each resulting trace by the number of the cross-correlations stacked.

[5] To compare with our cross-correlations, we compute normal-mode synthetic Green's functions [*Masters et al.*, 2007]. For source-receiver distances less than 2000 km the two core phases ScS and $PKIKP^2$ are strong in synthetic Green's functions predicted by a reference Earth model (Figure 1) and can be easily identified based on their arrival times and small apparent slowness. The two phases and multiples of ScS are often observed in large earthquake records [*Revenaugh and Jordan*, 1987; *Shearer*, 1991; *Liu et al.*, 2011], but these phases do not provide uniform coverage of the core because earthquakes occur mostly near major plate boundaries.

[6] Clear body-wave core phases ScS and $PKIKP^2$ are observed in the stacked cross-correlation data (Figure 2) and several other weaker body-wave phases including P, S, PcP, and ScP/PcS can also be identified. Both the arrival times and the apparent slowness agree strikingly with the predicted Green's functions. An airwave propagating at the speed of sound is also observed in the stacked cross-correlations (see Figure S1 in the Supporting Information). Figure 2b also shows a number of weaker phases arriving between ScS and $PKIKP^2$, but are less consistent with the synthetics (Figure 1b). These phases may represent phases that reflect off mantle discontinuities, but may also be artifacts that are not entirely removed by the interferometry. A weak anomalously fast signal propagating at ~20 km/s that arrives earlier than the direct P wave is also observed, and is likely to be an artifact of the interferometry method. Several strong phases arriving later than the $PKIKP^2$ phase potentially represent other core propagating phases such as PKP^2, diffracted $PKP(BC)^2$, and $PKIIKP^2$ [*Rial and Cormier* 1980], but the exact nature of these phases remain to be studied.

3. Discussion

[7] To better understand the source of these signals, we investigate the temporal variation of the observed ScS and $PKIKP^2$ amplitudes. Figure 3a shows monthly stacks of
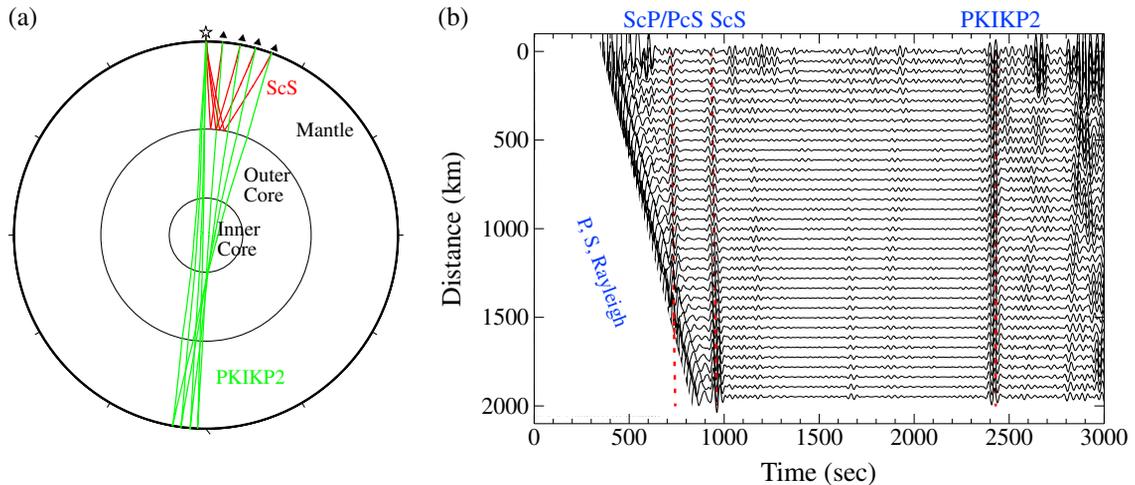
Figure 1. Synthetic Green's functions for short source/receiver distances. (a) Schematic plot of *ScS* and *PKIKP*[2] ray paths. The star and triangles denote source and receiver locations, respectively. (b) Normal-mode summation Green's functions based on the Preliminary Reference Earth Model (PREM) [*Dziewonski and Anderson*, 1981] for a vertical single-couple force at 3.5 km depth, bandpassed between 25 and 50 s period. The red dashed lines mark the ray-predicted arrival times for core phases based on the iasp91 Earth model [*Kennett and Engdahl* 1991]. The direct *P*, *S*, and Rayleigh waves have amplitudes larger than the plotted scale and are not shown.

cross-correlations between 1000 and 1050 km distance. Although both *ScS* and *PKIKP*[2] are clearly observable in most months, strong temporal variations are observed. For each monthly stack, we measure the *ScS* and *PKIKP*[2] amplitudes using a 100 s time window centered at the ray-predicted arrival time [*Kennett and Engdahl*, 1991]. The maximum amplitude of the envelope function within each time window is taken to be the amplitude of the phase. The monthly variations in *ScS* and *PKIKP*[2] amplitudes between January 2007 and May 2011 are shown in Figure 3b. There is no clear seasonal trend, implying that storm-generated ocean microseism is not the primary contributor of energy. However, the

amplitude variations are highly correlated ($r = 0.77$ for *ScS* and $r = 0.68$ for *PKIKP*[2]) with a global seismicity index (Figures 3b and S2), based on the sum of earthquake moment magnitudes (M_w) over a $M_w = 6.4$ threshold. This index characterizes the amount of earthquake-excited energy present in the continuous noise records that are cross-correlated. Figures 3b, S2, and S3 suggest that the core phases observed are related to multiple reflected or scattered phases excited by earthquakes. Because earthquake body-wave amplitudes die quickly after multiple scattering, and can be weaker than surface-wave coda and background noise levels, they effectively become part of the ambient seismic noise field. The
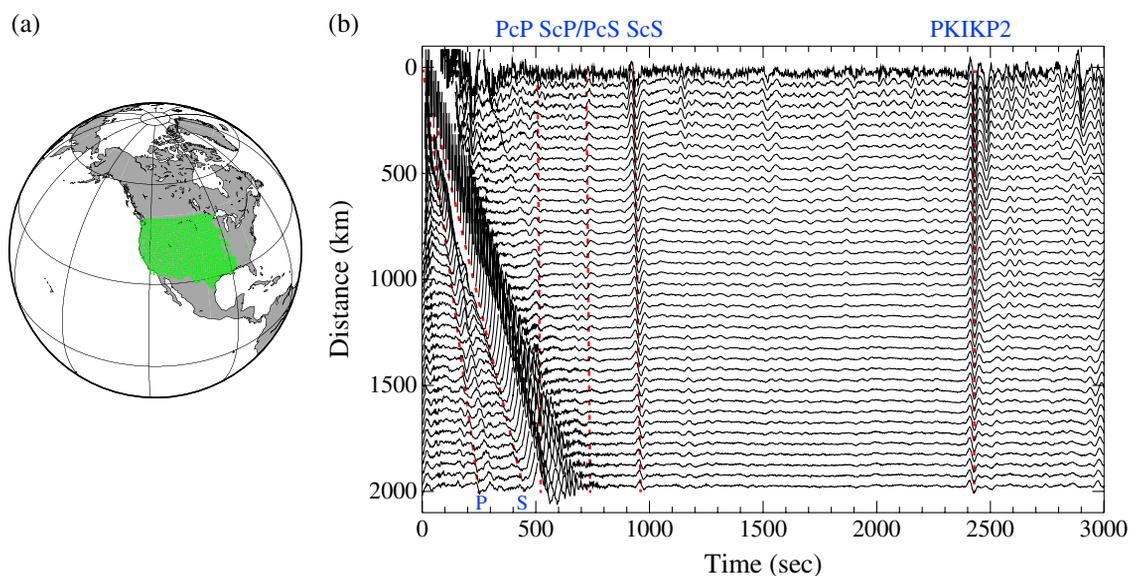
Figure 2. Stacked cross-correlations across USArray. (a) The USArray Transportable Array used in this study. Station locations are marked by green dots. (b) The observed broadband stacked cross-correlations sorted by distance. The red dashed lines mark the ray-predicted arrival times for core phases based on the iasp91 Earth model. Several observed body wave phases are indicated.
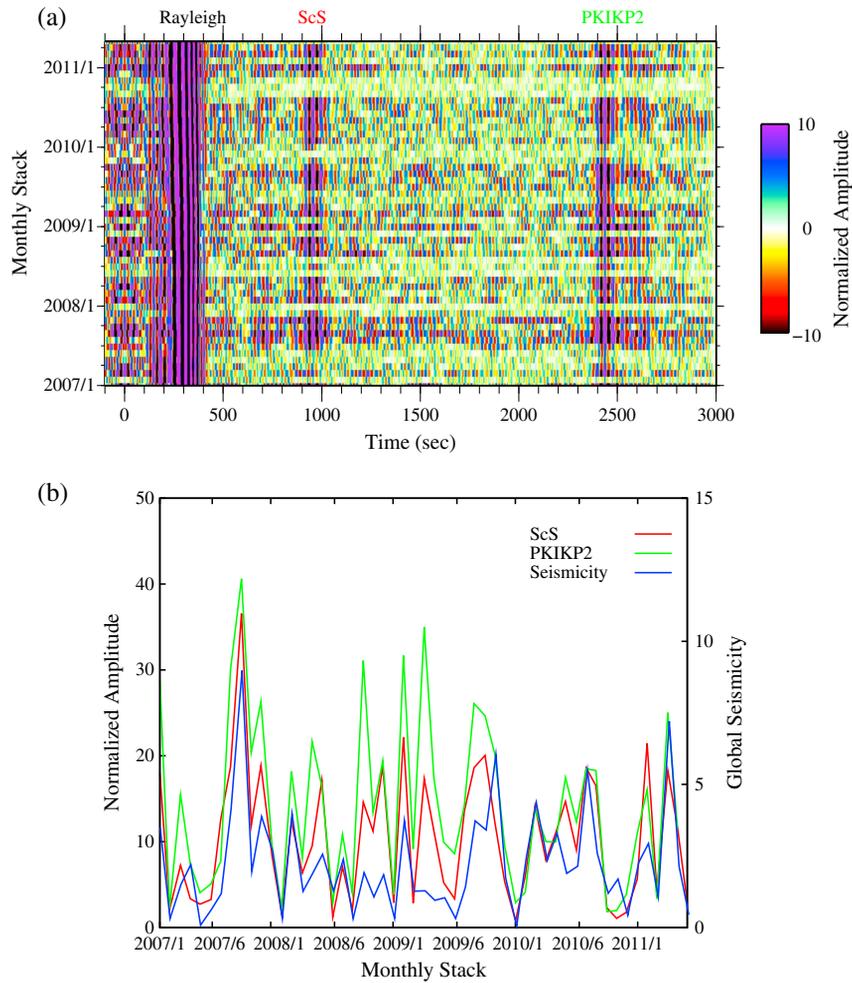
Figure 3. Temporal variation of the observed core phases. (a) Monthly stacked cross-correlations. For each month, all available cross-correlations with distances between 1000 and 1050 km are stacked and bandpassed between 20 and 50 s period. The results for other distance ranges are similar to that presented here. (b) The temporal variation of core phase amplitudes and global seismicity. *ScS* and *PKIKP²* amplitudes are measured based on Figure 3a. The global seismicity index is calculated based on the magnitude of earthquakes listed in the Global CMT Catalog [*Ekström et al.*, 2012] each month.
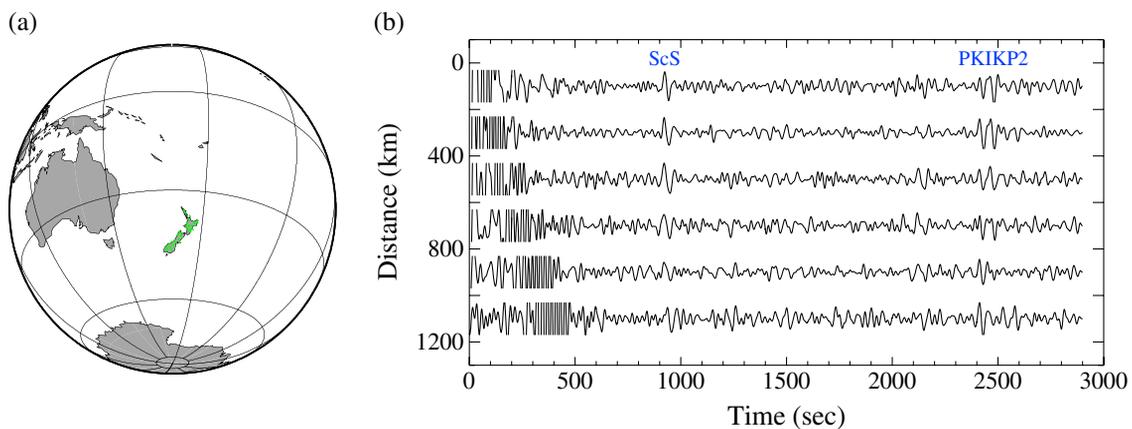
Figure 4. Stacked cross-correlations across the New Zealand national seismic network. (a) Station locations are marked by green dots. (b) The observed broadband stacked cross-correlations sorted by distance. The stacked waveforms are bandpassed between 20 and 100 s period.

exact duration of earthquake coda that contributes to the body wave phases observed in cross-correlations will be a topic of future work.

[8] To test whether the same core phases can be observed in other locations, we stack noise cross-correlations from the New Zealand national seismic network [*Lin et al.*, 2007]. We use one year of continuous data and 42 stations and stack the cross-correlations using 200 km distance bins (Figure 4). While the stacked cross-correlations are noisier due to the availability of fewer station pairs, the *ScS* and *PKIKP*^{2} phases can still be clearly observed, particularly for short distances where there are more station pairs.

[9] We interpret the successful retrieval of body-wave phases to be at least partly due to station-side array interferometry, unlike the source-side interferometry of most ambient noise applications [*Curtis et al.*, 2009]. Traditional source-side interferometry works when sources are well distributed because sources interfere constructively only near the stationary phase points [*Snieder et al.*, 2008; *Ruigrok and Wapenaar*, 2012]. In contrast, station-side array interferometry works if enough station pairs (that sample the same structure) are stacked that the stationary phase points are sampled. However, despite the earthquake origin of the observed core phases, the ability to extract robust *ScS* and *PKIKP*^{2} phases between stations seems to be mostly independent of earthquake location (Figure 3b). This suggests that both station- and source-side interferometry may be important, with earthquake body-wave energy becoming partly diffuse after multiple bounces and scattering within the Earth (Figures S2 and S3).

[10] The ability to extract core phases traveling between stations where and when stations are available gives global seismologists a new level of control in obtaining the necessary sampling geometries to test hypotheses regarding deep Earth structure. Exploration of the inner core is particularly well suited for advancement as a result of interferometric observations. Constraining the 3-D structure of inner core anisotropy requires seismic phases that sample the inner core at a variety of locations and directions [*Morelli et al.*, 1986; *Creager*, 1992; *Song and Helmberger*, 1993; *Niu and Wen*, 2001; *Su and Song*, 2008; *Deuss et al.*, 2010]. The approach taken here can fill important gaps such as polar sampling. In principle, an array could be placed precisely at the South Pole and it would measure *PKIKP*^{2} travel times at periods as short as 5–10 s (Figure S4), regardless of whether or not earthquakes occur at suitable distances for traditional measurements of *PKIKP*. Similarly, long-term seismic networks can be used to detect temporal variations in *PKIKP*^{2} travel times and constrain inner core differential rotation [*Song and Richards* 1996; *Vidale et al.*, 2000] without relying on the repeating occurrence of earthquakes in specific locations. While we focus only on vertical-vertical cross-correlations in this study, preliminary results suggest that similar body wave phases can also be extracted using horizontal-component cross-correlations.

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