Global Seismic Wave Propagation Simulation

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1. Introduction

The Earth's inner core is thought to have been formed by the precipitation of iron from the fluid outer core[1]. It is considered that a part of the inner core surface where iron in the fluid outer core is precipitated may be melted and forms a mushy region[2-4], but its position is not well understood seismologically. Butler and Tsuboi (2021)[5] show that the precursors of PKIIKP waves observed at the antipodal stations can be successfully modeled as reflected below a liquid/solid interface at a depth of 100 km below the inner core boundary. We discussed if the PKIIKP phase can be explained by a low P-wave velocity layer at the base of the outer core by using the synthetic seismograms calculated by SEM. We also discussed the existence of a S-wave discontinuity just below the inner core boundary by using the SEM synthetics in Butler and Tsuboi (2021)[5]. One of the advantages in using SEM to sample the inner core structure is that the Spectral Element Method is implemented with the adjoint simulations to generate finite-frequency sensitivity kernels, which can be used to perform tomographic inversions for 3-D Earth structure.

Here, we use our recent antipodal observations for PKIIKP and its precursors to compute the finite-frequency sensitivity kernels for a shear wave velocity structure on the inner core by using the Spectral Element Method.

2. Data

To investigate the three-dimensional structure of the proposed boundary at the top of the inner core, we use data from earthquake-receiver pairs studied in Butler and Tsuboi (2021)[5] —Tonga to a station in Algeria (TAM), Sulawesi to Amazon (PTGA), northern Chile to Hainan Island (QIZ), and central Chile to mainland China (ENH and XAN). In addition to these earthquake-receiver pairs, we also examined Spanish data (ECAL) from an earthquake in New Zealand. Waveform data from TAM and PTGA show that there are significant arrivals between PKIKP and PKIIKP, about 7 and 17 seconds before PKIIKP. In contrast to TAM and PTGA data, for Chinese stations (QIZ, ENH, XAN) no arrival of this waveform is seen. These results show two groups: TAM, PTGA, and ECAL with a clear PKIIKP precursor, and QIZ, ENH, XAN with no visible precursor, which may imply regional differences at the surface of the inner core. These lateral heterogeneities may generate observed differences in the PKIIKP phase. We try to locate these heterogeneities by using the sensitivity kernels computed by the adjoint method.

3. Sensitivity kernels

We calculate the sensitivity kernel of the inner core shear wave structure for the amplitude of precursor waves. In order to do so, we have included a spherically symmetric shear wave structure as: Vs = 0.5 km/s from the inner core surface to a depth of 100 km, Vs = 5.0 km/s from 100 km to 250 km, and a spherically symmetric structure with a PREM model below the depth 250 km. The spectral element method program, specfem3d_globe, is used, and the number of elements at the surface along the two sides of block, NEX_XI, is set to 640. We use 9600 cores of the Earth simulator to calculate the theoretical seismic waveform which is accurate to a shortest period of about 7 seconds.

The calculation of the finite frequency sensitivity kernel of the inner core shear wave velocity structure was performed by the adjoint method[6-12]. The finite frequency sensitivity kernel calculation is done in two steps. First, the hypocenter of the global CMT mechanism[13] is used to calculate the theoretical seismic waveform for the seismic station at the antipodal point corresponding to each earthquake. At this time, the global wave fields at the end of the time step—in which the theoretical seismic waveform is calculated—are saved in the disk. We apply the same band pass filter with a period of 8 seconds and 50 seconds to both theoretical and observed seismograms. From the calculated seismic and observed waveforms, we set the time window of arrival of PKIIKP waves and cut out these waveforms. We calculate the adjoint source for the amplitude of the seismic waveform from the difference between the observed waveform and the theoretical waveform. Since the accuracy of the theoretical seismic waveform used here is about 7 seconds, it is not possible to identify the PKIIKP wave and its precursor wave independently, so when cutting out the waveform, we set the window to include both of these phases. Then, using the adjoint source obtained in this way, the theoretical seismic waveform that propagates backward from the observation station to the seismic source is calculated by reversing the time. We calculate the finite-frequency kernel of the shear wave velocity in the inner core for the amplitude of the PKIIKP waves for the path, combining the propagation of the seismic waves from the source to the observation station used from the theoretical seismic waveform calculated beforehand.

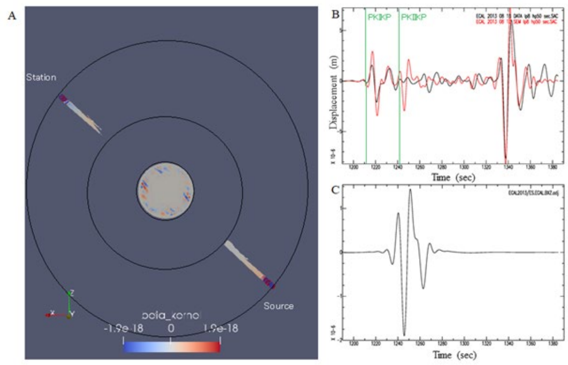

Figure 1. (A) A cross-sectional view of the event sensitivity kernel of the shear wave velocity structure with respect to the PKIIKP wave amplitude is shown. The vertical axis is parallel to the rotation axis with the top representing north. The location of the New Zealand earthquake is lower right and the station ECAL is upper left. The sensitivity kernel shows that the amplitude of the PKIIKP wave is sensitive to the shear wave velocity structure along the raypath of PKIIKP wave, which samples down to around depth 250 km below the top of the inner core. (B) The theoretical seismic waveform (red) and the observed waveform (black) for the August 16, 2013 earthquake in New Zealand are observed at the ECAL station in Spain. (C) The adjoint source is shown for the PKIIKP waves. These traces are ground displacement and bandpass filtered between periods 8 and 50 seconds.

Figure 1 shows both the theoretical seismic waveform and the observed waveform for the August 16, 2013 earthquake in New Zealand observed at the ECAL station in Spain, and the adjoint source of the amplitude for the PKIIKP waves. A cross-sectional view of the sensitivity kernel of the shear wave velocity structure with respect to the PKIIKP wave amplitude is shown. The figure confirms that the kernels are sensitive along the raypaths of the PKIIKP phases. Since we focus on the shear wave velocity structure along the surface of the inner core and we already have included 3D mantle structure in our computation. We assume that the amplitudes of the PKIIKP waves are sensitive to the shear wave velocity structure at the incident point and exit point of the inner core surface as these waves pass through the inner core. The adjoint kernel calculated for such an earthquake and its antipodal observation point is called an event kernel. For each of the twelve seismic source-receiver pairs used in this analysis, the event kernel for the shear wave velocity structure in the inner core was calculated. By adding the event kernels calculated in this way, the gradient of the misfit function to improve the initial model was calculated. We are now preparing for the inversion of the shear wave structure at the surface of the inner core by using these sensitivity kernels.

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