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CONSTRAINING OUTERMOST CORE VELOCITY WITH *SmKS* WAVES

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Abstract. SmKS waves (m=2,3,4), seismic waves that travel as S-waves in the mantle, P-waves in the core, and reflect (m-1) times on the underside of the core-mantle boundary, are well-suited for constraining outermost core V_P structure. This is due to closeness of the mantle paths and also the shallow depth range these waves travel in the outermost core. High quality digitized WWSSN and Canadian network recordings from a deep focus Java Sea event which sample the outer core beneath the northern Pacific, the Artic, and northwestern North America (roughly 1/8th of the globe), are utilized as an example to show the strength of SmKS waves to resolve outermost core structure. S3KS-S2KS and S4KS-S3KS differential travel times were measured and compared to those from reflectivity synthetics created from core models of past studies. Constraints and uncertainties in outer core structure using SmKS are discussed. For the event studied, the PREM core model, with possibly a small V_P decrease in the outermost 50 km of the core, provides a good fit to the data.

Introduction

Resolving the seismic properties of the Earth's outermost core is integral in gaining an understanding of the dynamics of the overall core-mantle boundary (CMB) region. The family of SmKS waves (m=2,3,4), waves that traverse the mantle as S-waves, converting to P-waves in the core and reflecting (m-1) times on the underside of the CMB [Choy, 1977], are well-suited to investigate such structure. In previous outer core studies, SKS times and SKKS-SKS differential times have played a dominant role and SKKKS-SKKS times a more minor role (if any) in deriving an outer core model. (Hereafter, SKKS, SKKKS, etc., are referred to as S2KS, S3KS, etc., respectively, and values of *m* for SmKS are printed as a subscript, e.g., $SmKS_{234}$ indicates m=2,3,4.) Due to 3D lateral variations in lower mantle V_S structure, great care must be taken when using just SKS and/or S2KS-SKS times to model core structure. Waveforms and difference times of $SmKS_{234}$ waves are ideal for studying the outermost core due to the proximity of their mantle paths, and their shallow outer core paths. The advantage of using $SmKS_{234}$ over $SmKS_{12}$ is minimizing possible contamination from unknown mantle heterogeneity.

Figure 1 displays typical scale lengths for $SmKS_{1234}$ for the PREM model [Dziewonski and Anderson, 1981] and a 500 km source depth. Figure 1a displays the geometric ray paths; Figure 1b gives distance between adjacent SmKS CMB crossing locations (e.g., S2KS vs. S3KS), measured at the CMB; Figure 1c shows bottoming depths into the core (from the CMB) of SmKS ray paths. CMB distances between S2KS and S3KS, and between S3KS and S4KS are relatively small (Figure 1b), and their differential times should thus be affected significantly less by 3D mantle structure than those of SKS and SKKS. For example, in a study of $SmKS_{123}$, Souriau and Poupinet [1991] report that residuals of S2KS-SKS times display strong coherent regional variations, while residual S3KS-S2KS time variations remain small. Figure 1c illustrates the usefulness of $SmKS_{234}$ in investigating the outermost core, since these waves, especially $SmKS_{34}$, travel in the outer 200 km of the core.

The purpose of this note is to explore the usefulness of $SmKS_{234}$ in resolving and placing constraints on outermost core V_P structure. A deep focus Java Sea event recorded throughout North America is used as an example to illustrate the power of $SmKS_{234}$ for these purposes. S3KS-S2KS and S4KS-S3KS differential times ($T_{S3KS-S2KS}$ and $T_{S4KS-S3KS}$, respectively) of the data are compared to predictions from synthetics generated using outer core models of past studies. For the event studied, the PREM model with a slight reduction in V_P in the outermost 50 km of the core matches the observations well.

Data and Reflectivity Synthetics

Long-period (LP) observations (10-20s) from the Java event (3/24/67, -6.01°S, 112.33°E, h606km) were optically scanned, digitized, and rotated into longitudinal components of motion. The event was well recorded by North American WWSSN and Canadian network stations. Figure 2 displays the great circle raypaths

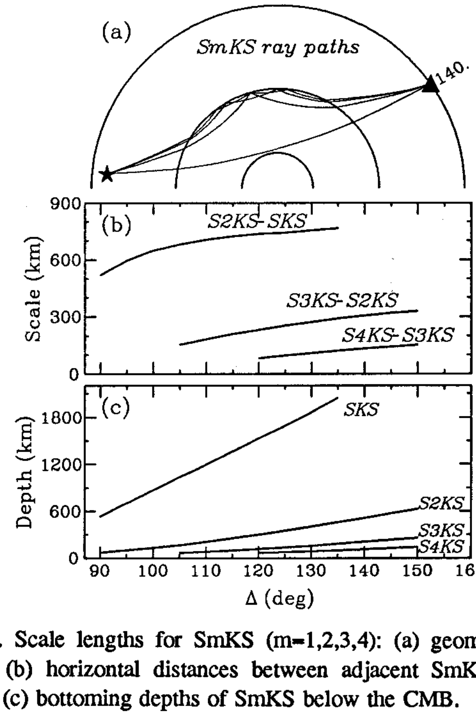

Fig. 1. Scale lengths for SmKS (m=1,2,3,4): (a) geometric ray paths; (b) horizontal distances between adjacent SmKS at the CMB; (c) bottoming depths of SmKS below the CMB.

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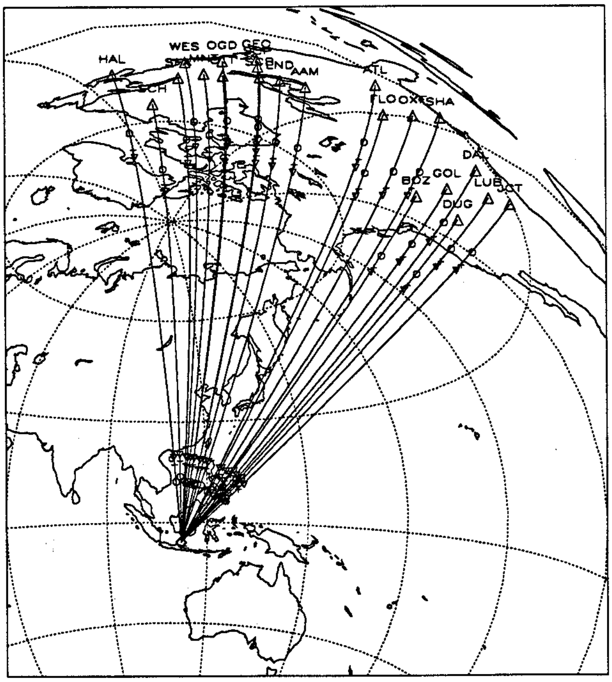

Fig. 2. Great circle raypaths for the 3/24/67 Java event. Surface projections of the CMB crossing locations of S2KS, S3KS, and S4KS are shown by circles, crosses, and triangles, respectively.

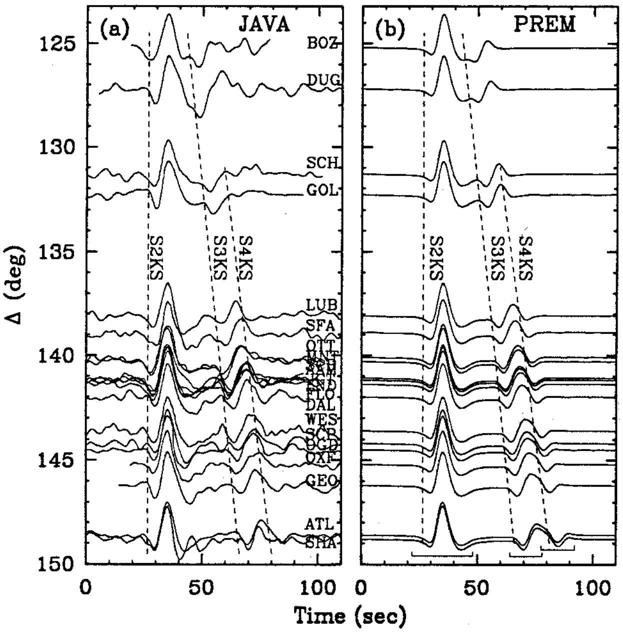

Fig. 3. (a) LP data from the Java event; (b) LP reflectivity synthetics for PREM. In both profiles, traces are lined up on S2KS peaks, and maximum amplitudes are normalized to unity.

along with surface projections of the CMB crossing locations of $SmKS_{234}$. For this source-receiver geometry, the azimuthal wavepath coverage spans roughly 1/8th of the Earth's outermost core. Figure 3a shows 21 recordings of the $SmKS_{234}$ wave group. All traces have maximum amplitudes normalized to unity, and are lined up on the S2KS peak. The dotted lines indicate the arrivals of S2KS, S3KS, and S4KS. Figure 3b displays synthetics generated using the reflectivity method [e.g., Fuchs and Müller, 1971] for the PREM model, filtered through a LP WWSSN instrument, for the appropriate source depth and distances of the data. The synthetics were computed using the focal mechanism for the Java event as determined by Fitch and Molnar [1970]. As seen in data, $SmKS_{23}$ are well-recorded for the whole distance range. S4KS, however, is expected to be small until distances greater than 140° or so. About half of our observations for the Java event at distances greater than 138° show contributions to the tail of S3KS in the form of S4KS, as in the synthetics. Large variabilities in S4KS amplitudes may be due to ray path perturbations caused by CMB topography, and will be investigated in a subsequent study.

An important consideration in analyzing $SmKS_{234}$ phases is the $\pi/2$ phase shift (Hilbert transform) that occurs each time a wave reflects at the underside of the CMB [e.g., see Choy, 1977]. S2KS, S3KS, and S4KS are phase shifted $\pi/2$, π, and $3\pi/2$, respectively, from SKS. The reflectivity method includes this affect.

Analysis of Travel Times

To measure the differential times $T_{S3KS-S2KS}$ and $T_{S4KS-S3KS}$, the standard cross-correlation method was used. For $T_{S3KS-S2KS}$ times, S2KS was Hilbert transformed (denoted H(S2KS)) prior to correlation to be in phase with S3KS. Similarly, for $T_{S4KS-S3KS}$ times, S3KS was Hilbert transformed (denoted H(S3KS)) prior to correlation. Thus $T_{S3KS-S2KS}$ and $T_{S4KS-S3KS}$ times discussed in this paper are in actuality S3KS-H(S2KS) and S4KS-H(S3KS) times, respectively. Times from the correlation procedure were cross-checked by overlaying synthetics with the data. Typical time window lengths of $SmKS_{234}$ phases used in the correlation procedure are shown at the bottom of Figure 3b by the brackets. The exact same measuring procedure was used for the data and synthetics. $SmKS_{234}$ times were also calculated from reflectivity synthetics computed using the following radially symmetric outer core models of past studies: KHR [Hales and Roberts, 1971], KLY [Lay and Young, 1990], KSP [Souriau and Poupinet, 1991], *isap91* [Kennett and Engdahl, 1991], SP6 [Morelli and Dziewonski, 1993], and KTH [Tanaka and Hamaguchi, 1993a]. Synthetics were also computed for the PREM model having the outermost 50 km of the core decreased to a CMB V_P of 7.94 km/sec (a 1.5% reduction, model KGHJ). Figure 4 displays the outermost 400 km of the above core models. Four observations having good signal-to-noise ratio (SNR) near 141° (from Figure 3a) are compared to waveform predictions for the above models (Figure 5). All traces are lined up and normalized in amplitude to the S2KS peak. The dotted lines correspond to peaks in $SmKS_{234}$ for PREM to illustrate the different relative arrival times. Data times scatter within 1 sec, and are very similar to predictions of PREM and KGHJ for this range.

Residual times of $T_{S3KS-S2KS}$ and $T_{S4KS-S3KS}$ ($\delta T_{S3KS-S2KS}$ and $\delta T_{S4KS-S3KS}$, respectively) are calculated with respect to PREM for the data and synthetics (Figure 6). The Java data (circles) have 1 sec error bars to emphasize that some error is expected from the digitization process, as well as from the correlation procedure when the SNR is low. The errors may easily be larger if phase mis-identification occurs, though $SmKS_{234}$ are easily identified in Figure 1. Figure 6a shows $\delta T_{S3KS-S2KS}$ of the data is scattered about the PREM time (zero line) within ±1 sec, with

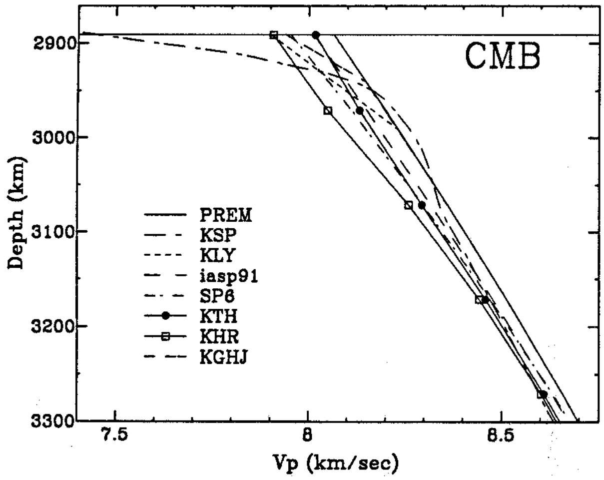

Fig. 4. V_P profiles of the outermost 400 km of the outer core. (Model names described in text).

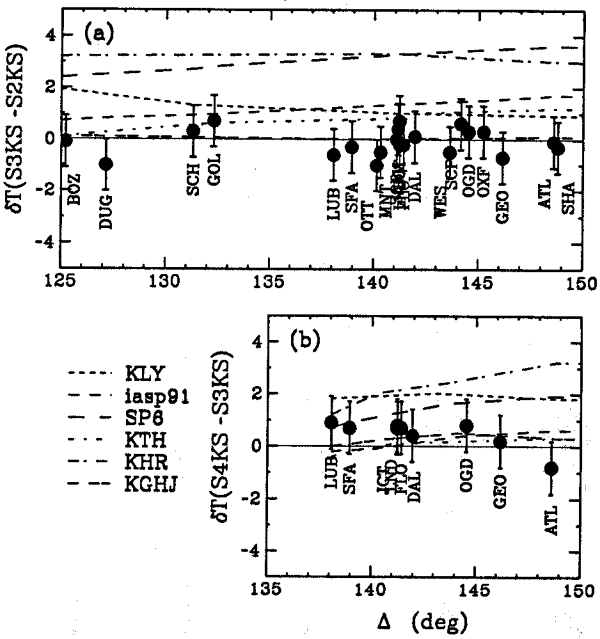

Fig. 6. (a) $\delta T_{S3KS-S2KS}$ and (b) $\delta T_{S4KS-S3KS}$ differential times (dots) and predictions (lines) with respect to PREM.

the PREM model providing the best fit for this path geometry. Predictions from model KGHJ are nearly identical to PREM, since S2KS and S3KS are not differentially affected by the thin LVZ. Other models tested predict S2KS and S3KS to be more separated than seen in the observations or PREM. This is due to having V_P values less than PREM in the outermost 100 to 700 km of the core, resulting in higher dV_P/dz values, thus preferentially slowing down S3KS relative to S2KS, and S4KS relative to S3KS. We were unable to confidently make $T_{S3KS-S2KS}$ and $T_{S4KS-S3KS}$ measurements from model KSP due to S3KS and S4KS waveform distortions (Figure 5) caused by the extreme low-velocity zone (LVZ) at the CMB. Such a strong LVZ changes the onset of these waves to appear even further phase shifted, and is incompatible with the Java Sea observations.

$\delta T_{S4KS-S3KS}$ times of the data are scattered at values greater than PREM, averaging near 0.5 sec (Figure 6b). We have interpreted this to imply the V_P reduction in the outermost core of PREM to make KGHJ, which in turn preferentially slows down S4KS relative to S3KS. Model KGHJ also yields $\delta T_{S4KS-S3KS}$ times greater than PREM. It is possible to trade-off such a LVZ with slightly increased V_P values at depths greater than those penetrated by S4KS. This would speed up S3KS relative to S4KS, thus increasing $\delta T_{S4KS-S3KS}$, and roughly equally speed up S2KS and S3KS, therefore not affecting $\delta T_{S3KS-S2KS}$. Such trade-offs must be pursued with absolute times (or differential times out to larger distances, hence deeper penetrating waves), though in this note we arbitrarily pursue a LVZ just beneath the CMB. The next best fitting models to $\delta T_{S3KS-S2KS}$ and $\delta T_{S4KS-S3KS}$ are KTH and *iasp91*, respectively. Slightly faster velocities in these two models for the depth range 3000-3300 km would serve to improve their fit to the Java data by speeding up S3KS more than S2KS and S4KS, hence reducing $\delta T_{S3KS-S2KS}$ and increasing $\delta T_{S4KS-S3KS}$ to better agree with the data. $\delta T_{S3KS-S2KS}$ and $\delta T_{S4KS-S3KS}$ residuals for model KLY are larger than the data by 1-1.5 sec, implying the LVZ in KLY is too large to fit the Java data. However, we perturb the PREM model in the same fashion as KLY, that is, to adjust outermost core velocities to fit the observations. Models SP6 and KHR both predict times nearly 3 sec larger than the data for $\delta T_{S3KS-S2KS}$ and 0-2 sec for $\delta T_{S4KS-S3KS}$, which is discussed in the next section.

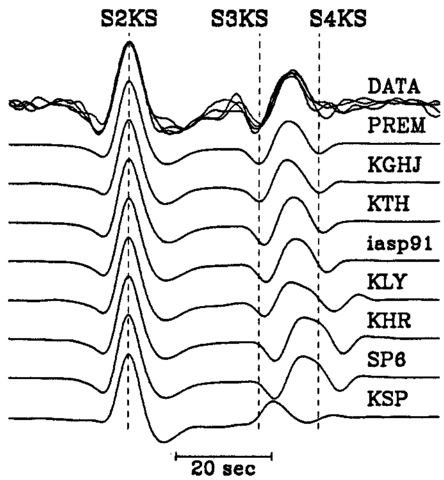

Fig. 5. Java Sea event data and synthetics near 141°.

The predictions of model KGHJ (Figure 4) are close to the PREM and data times for $\delta T_{S3KS-S2KS}$ and the data for $\delta T_{S4KS-S3KS}$. The thin LVZ in the outermost 50 km accomplishes this by slowing down S4KS more than S2KS and S3KS. This model is by no means unique, but provides an explanation of the data with relatively little perturbation to the PREM model. Our tests find that increasing the thickness of this LVZ layer will also slow down S3KS for the wavelengths we are studying, producing $T_{S3KS-S2KS}$ times larger than the Java data. Also, strongly decreasing the CMB V_P of this layer distorts the front of the S3KS and S4KS waveforms to be incompatible with observations. This emphasizes the importance of cross-checking predicted waveforms with data in the modeling process.

Discussion

An abundance of high-quality $SmKS_{234}$ data are available from the WWSSN archives for deep focus events. Until more broad-band data is available for these distance ranges, the WWSSN data will provide the opportunity to map out the details of outermost core structure.

The discrepancy between the observations and predictions for the Java event may be attributed to several different causes. Models KHR and SP6 overpredict the residual times in Figure 6. This may be related to the $\pi/2$ phase shift of S2KS not being taken into consideration in the Hales and Roberts [1971] study, which was subsequently used in constructing SP6 [Morelli and Dziewonski, 1993]. This will in turn result in larger values of $T_{S3KS-S2KS}$ when correlating peak to peak times. Predictions from the other models are closer to the data, but over predict the $\delta T_{S3KS-S2KS}$ times due to pronounced outer core low velocity zones. This may be due to not properly accounting for 3D mantle heterogeneity when constructing models using $SmKS_{12}$. The affects of such heterogeneity on $SmKS_{1234}$ needs to be further explored. The raypaths of $SmKS_{234}$ for the Java event (Figure 2) traverse V_S perturbations in D" of ±1 percent, according to the 3D mantle model SH12_WM13 [Su et al., 1992]. It is proposed that such small mantle anomalies are an explanation of the relatively small scatter seen in the data in Figure 6.

A different approach of reconciling the predictions of the radially symmetric core models and the Java data is outer core lateral heterogeneity [Tanaka and Hamaguchi, 1993b; Kohler and Tanimoto, 1992]. The Java data show no distance or azimuthal trend (from the hypocenter) of $SmKS_{234}$ times, though the data are restricted to 1/8th of the globe's outer core. If outer core heterogeneity exists, $SmKS_{234}$ phases are ideal to map it out, as well as assess the trade-off between D" and outer core heterogeneity.

Of geodynamical significance is the issue of outermost core chemical stratification [e.g., Lay and Young, 1990; and Tanaka and Hamaguchi, 1993a]. The inhomogeneity index η [Bullen, 1975] is often used to infer departures from chemical homogeneity in the Earth. Adopting this approach implies model KGHJ departs from homogeneity in the outermost 50 km of the core, however, we do not emphasize this due to the non-uniqueness of the model. With more $SmKS_{234}$ data over extended distance ranges (out to 170°), the details of this structure may be better mapped.

Conclusion

$SmKS_{234}$ waves are well-suited for constraining outermost core V_P structure due to the closeness of the mantle paths and the shallow depth range of paths in the outermost core. Records from a deep focus Java Sea event are well-modeled with the PREM model, with the possibility of an improved fit with slightly slower velocities in the outermost 50 km of the core relative to PREM. Future studies using this technique may help resolve issues of scale lengths of D" heterogeneity, outer core heterogeneity, and outer core chemical stratification.

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