# ON THE INVERSION OF Sd PARTICLE MOTION FOR SEISMIC ANISOTROPY IN D"

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*Abstract*

In order to make accurate estimates of anisotropy in D", as measured from observations of $Sdiff$ ($Sd$) it is necessary to correct the observed waveforms for anisotropy outside of the deepest mantle as well as side refraction along the path, and to pick arrivals of SVd and SHd as accurately as possible. We show that corrections based on estimates of upper mantle anisotropy inferred from $SKS/SKKS$ splitting measurements are sometimes insufficient and propose a master event method to directly obtain more accurate corrections on specific source-station paths. Our study illustrates the complexity of structure that needs to be taken into account when addressing issues of D" properties using seismic body wave methods. We also describe a method to accurately measure the arrival time of the corrected $SVd$ wave.

*Introduction*

In the past few years, evidence for the existence of anisotropy in the D" region of the mantle has been accumulating, based on observations of traveltime discrepancies between $SV$ and $SH$ components of waves sampling the deepest part of the mantle, such as $S$ diffracted ($Sd$) (Vinnik et al., 1989a;1995;1997; Lay and Young, 1991; Garnero and Lay, 1997) or $ScS$ ( Kendall and Silver, 1996; Matzel et al., 1996). As such studies become more quantitative, it is critical to accurately correct the records of $Sd$ (or $ScS$) for unwanted perturbing effects, and to pick the $SV$ and $SH$ arrivals as accurately as possible. Indeed, in the presence of strong $SHd$, $SVd$ can be easily distorted by coupling between $SV$ and $SH$, due to propagation of $Sd$ in the azimuthally anisotropic mantle outside D" or by side refraction of $SHd$. We here describe improved $Sd$ processing techniques, and demonstrate that the results thus obtained may depart significantly from those based on the standard approach. This is illustrated with examples for the paths between the Fiji-Tonga region and stations in north America (Fig. 1).

*Master event technique*

In the presence of azimuthal anisotropy outside D" (receiver anisotropy), the spectra of the observed S components of motion at the earth's surface, $SV(\omega)$ and $SH(\omega)$ respectively are related to the unperturbed spectra, $SV_0(\omega)$ and $SH_0(\omega)$ through (Farra et al., 1991):

$$(1) \qquad \left\{ \begin{matrix} SV_0(\omega) \\ SH_0(\omega) \end{matrix} \right\} = F^{-1}(\omega) \left\{ \begin{matrix} SV(\omega) \\ SH(\omega) \end{matrix} \right\}$$

where $\omega$ is angular frequency, and $F(\omega)$ is matrix of the frequency response of the anisotropic layer. The related waveforms: $SV_0(t)$, $SH_0(t)$, $SV(t)$ and $SH(t)$ can be found from their spectra by inverse Fourier transformation. For a small incidence angle and on the assumption of hexagonal receiver anisotropy with a horizontal axis of symmetry, the elements of $F(\omega)$: $SV_{sv}(\omega)$, $SV_{sh}(\omega)$, $SH_{sv}(\omega)$, and $SH_{sh}(\omega)$ can be expressed as functions of $\beta$ and $\delta t$, the angle in the horizontal plane between the fast direction of anisotropy and the radial ($R$) direction, and the delay of the slow split wave relative to the fast one, respectively (Vinnik et al., 1992).

Assuming $SH_0(\omega) = 0$, $SH_{th}(t)$, the theoretical $SH(t)$ for arbitrary $\beta$ and $\delta t$, can be obtained from the observed $SV(t)$ through

$$(2) \qquad SH_{th}(t) = (2\pi)^{-1} \int_{-\infty}^{\infty} (SH_{sv}(\omega)/SV_{sv}(\omega))SV(\omega)\exp(i\omega t)d\omega$$

Similarly, on the assumption of $SV_0(\omega) = 0$, the expression for $SV_{th}(t)$ to be derived from the observed $SH(t)$ is

$$(3) \qquad SV_{th}(t) = (2\pi)^{-1} \int_{-\infty}^{\infty} (SV_{sh}(\omega)/SH_{sh}(\omega))SH(\omega)\exp(i\omega t)d\omega)$$

The assumption of $SH_0(\omega) = 0$ in (2) corresponds to observations of $SKS$ or $SKKS$. The actual values of $\beta$ and $\delta t$ minimize the rms difference between $SH_{th}(t)$ and $SH(t)$ (Vinnik et al. 1989b). The values of the parameters of anisotropy thus found can be used to correct the recordings of $Sd$, using (1). Vinnik et al. (1989a, 1995) did not correct recordings of $Sd$ of Fiji-Tonga events at IRIS station HRV and a neighbouring Geoscope station WFM, because the analysis of $SKS$ and $SKKS$ for this path (Figure 1) has shown that $\beta = 0°$. In such a situation, $SV_{sh} = SH_{sv} = 0$. At some other stations, Kendall and Silver (1996) applied corrections, using the parameters of anisotropy derived from the analysis of splitting of $SKS$.

We here demonstrate that the corrections, if derived from observations of $SKS$ and $SKKS$, can be misleading. Instead, we propose a more efficient technique, where the corrections are derived directly from the observations of $Sd$. The idea is to derive the corrections from the 'master' recordings of $Sd$, with extremely weak $SV$ radiation in the source, as compared with $SH$. On the assumption of transverse anisotropy in D" (hexagonal anisotropy with the vertical axis of symmetry), there should be no coupling between $SHd$ and $SVd$. This means that the signal, which can be present in the $SV$ component of the master event is not $SVd$, but an effect of receiver anisotropy or side refraction of $Sd$. The critical assumption of transverse isotropy in D" is based mainly on the observation, that the amplitude of $SVd$ is correlated with that of $SKKS$ rather than $SHd$ (Vinnik et al., 1995). Additional arguments in favour of this assumption are provided by the results of data processing, which are obtained through this study and discussed in the last Section.

Receiver anisotropy is manifested by quarter-period phase shift between the $R$ or $SV$ and $SH$ components of $Sd$. The parameters of this anisotropy can be evaluated by minimizing the rms difference betwen $SV_t$ and $SV_{th}(t)$, as derived through (3). The correction eliminating this signal can then be applied to other records of $Sd$ with a similar wavepath. Contrary to azimuthal anisotropy, side refraction is manifested by either 0 or $\pi$ phase shift between the two components of $Sd$. The deviation from the theoretical back azimuth of the event can be evaluated by the analysis of the corresponding covariance matrix, and the effect can be eliminated by appropriate rotation of the $R, SH$ coordinate frame.

Further on, we demonstrate applications of the master event technique to the records of deep events at station HRV/WFM. The list of events is modified from Vinnik et al. (1995) by including two additional Fiji-Tonga events (88070 and 86146a). The numbers here indicate year and Julian day of the event. The records were integrated to obtain displacement and low-pass filtered with a corner at around 9 s. The records of radial (R) and vertical components were rotated by 25° to obtain $SV$ component of $Sd$. $SV$ amplitudes of $SKS$, $SKKS$ and $Sd$ are only slightly different from those in the $R$ component, but the rotation sometimes improves signal/noise ratio, if the noise is formed by multiply reflected P-waves. Figure 2 shows two recordings (88070 and 93190), with very weak or missing $SKS$ and $SKKS$, and for comparison, a record with strong $SKKS$ (93219). Take-off angles of $SKKS$ and $Sd$ are very close, and the weakness of $SKKS$ at these epicentral distances implies that the focal mechanism is unfavourable for generating $SVd$. This is further confirmed by calculations of synthetic seismograms with the reflectivity technique (Kind and Mueller 1975). The $SV$ component of $Sd$ in the records of events 88070 and 93190 is clearly coupled with $SH$: the $SV$ component of every record looks like the derivative of the $SH$ component, which is characteristic of azimuthal anisotropy.

For the records in Figure 2a,b, and one additional similar record, we deconvolved the two components of $Sd$ with the respective $SHd$. Deconvolution eliminates differences between the records depending on the differences between source functions and magnitudes of the individual events. To suppress noise, the deconvolved components are stacked (Figure 3A). There is a quarter-period phase shift between the components of $Sd$, which is characteristic of azimuthal anisotropy. The parameters of anisotropy are determined for the stacked components via (3). The resulting estimates of $\alpha$, azimuth of fast velocity counted clockwise from North, and $\delta t$ are $100°$ and $1.2s$, respectively and differ from $80°$ and $0.8s$, as found by Vinnik et al. (1989b) from the analysis of $SKS$. When the stacked $SVd$ is corrected by using (1) with $\alpha = 100°$ and $\delta t = 1.2s$, the signal is reduced to the level of noise (Figure 3B).

To verify that the particle motions of $SKS/SKKS$, in our records, are compatible with the direction of anisotropy determined by Vinnik et al. (1989b), we considered seven recordings of events with strong $SKS/SKKS$. We deconvolved both horizontal components with the $SV$ component of $SKKS$, and stacked the deconvolved components (Figure 3C). The stacked $SH$ component of $SKKS$ is correlated with the $SV$ component. The signal in the $SH$ component is reduced to the level of ambient noise by determining the principal motion direction in $SKKS$ and rotating the coordinate frame correspondingly (Figure 3D). The direction thus determined differs by $5°$ from the true back azimuth. A similar result is obtained in experiments with $SKS$. A signal with a quarter-period phase shift relative to $SV$ is clearly missing in $SH$ in Figure 3C, which suggests that the azimuth of fast axis of receiver anisotropy is close to back azimuths of the Fiji-Tonga events at HRV/WFM (around $263°$ or $83°$). The value of $\alpha$ found for $Sd$ is indeed distinctly different from that suitable for $SKS$ and $SKKS$. Another example of a similar discrepancy is provided by the data of station RSON (RSTN network), where the parameters of receiver anisotropy, as determined via (3), are $115°$ and $0.6s$, different from $80°$ and 1.7 s obtained from $SKS$ splitting (Vinnik et al. 1992). Effect of this anisotropy in the records of $Sd$ can be eliminated with the correction obtained from the master event analysis, but not using the parameters appropriate for $SKS$.

*Measurement of $SVd - SHd$ differential travel times*

The corrected records at HRV/WFM with detected $SVd$ are displayed in Figure 4a. The arrivals of $SHd$ in Figure 4a are identified by comparing them with the theoretical first motion directions for the respective focal plane solutions. In two cases (events 93080 and 86146a), when the first arrivals of $SHd$ are too weak to be seen, their arrival times are determined by interpolating $SHd - SKKS$ differential times for the neighbouring events (94068, 89320 and 86146b). The procedure for detecting first motion in $SVd$ and determining $SVd - SHd$ differential time, which is illustrated by Figure 4a, consists of several steps. First motion of $SKKS$ is identified by Hilbert transforming $SKKS$ and matching the first cycle of the transformed waveform of $SKKS$ to the raw $SKS$ (Choy and Richards 1975). We verify with the help of synthetic seismograms, that this technique works well even in the distance range where the $SKS$ waveform is distorted by $SPdKS$. To identify $SVd$ arrivals, synthetic seismograms are calculated with the isotropic reflectivity technique for the reference model PREM (Dziewonski and Anderson 1981) with an S velocity in D" reduced by 4%. The synthetics are calculated for the source functions providing good fit between the theoretical and observed waveforms of $SKKS$ and for the focal plane solutions of the corresponding events. Differential time between $SKKS$ and $SVd$ can be found accurately in synthetics calculated for an arbitrary source function with a sharp onset, and, using this time, the arrival of $SVd$ is identified in the synthetic corresponding to the actual source function. The $SVd$ arrival in the real record can be identified by comparing the real record with the theoretical waveform.

The synthetic $SVd$ waveforms in Figure 4a are generally not much different from the real ones. Some differences should not be surprising, considering extreme complexity of the lower mantle in the study region. A rule of thumb derived from our experiments is that the sign of $SVd$ first motion should always be the same as that of $SKKS$, and at large distances there should be correlation between the waveforms of $SKKS$ and $SVd$. Remarkable features of the $SVd$ signals are their distance- dependent delays relative to $SHd$, as indicated by the arrows in figure 4a. A similar trend is present in the records of RSON, where a generally similar processing procedure was applied to the raw data (Figure 4b). These measurements, as well as similar ones at other stations, have been used to infer the presence of strong anisotropy in D", locally reaching 10% or more (Vinnik et al., 1997), which is an order of magnitude stronger than previously reported.

*Discussion and conclusions*

The distance-dependent delays of $SVd$ relative to $SHd$ would hardly be detected without our technique. This is well illustrated by comparing the raw record of event 93219 (Figure 2c) and its processed version in Figure 4a. Whereas the first visible arrival in the $SV$ component of $Sd$ in Figure 2c is delayed relative to $SHd$ by about 15 s, the true $SVd$ arrival, as shown by Figure 4a, is delayed by only 6 s. In a number of other cases considered at HRV/WFM, the signals previously interpreted as the $SVd$ arrivals are either fully suppressed or significantly modified by the corrections. This eliminates some internal inconsistencies noted in previously published data (Maupin, 1995).

The delays of $SVd$ are similar in pairs of records at similar epicentral distances, one of which contains very strong $SHd$, and requires large correction for $SV$, whereas in the other, $SHd$ is weak, and the correction is insignificant: compare 94068 with 93080 and 86146a with 86146b in Figure 4a. This indicates that the assumption of transverse isotropy in D", which is used for deriving the corrections is most likely right. Strong discrepancies between the estimates of receiver anisotropy based on the $SKS/SKKS$ and $Sd$ data are found at some stations, but they are missing at other stations, along practically the same wavepaths in D". This observation, again, favours transverse isotropy rather than large-scale azimuthal anisotropy in D". The discrepancies can be an effect of unmodelled complexity of the crust and upper mantle beneath the receiver, but another explanation cannot be excluded. The wavepaths of $Sd$ and $SKKS$ are very similar in the upper mantle beneath the receiver, but they are strongly different in the lowermost mantle. Hence, it is conceivable that anisotropy in the lowermost mantle is azimuthal but laterally variable, and it contributes differently to $SKKS$ and $Sd$. Transverse isotropy in D" can be a result of averaging azimuthal anisotropies along the wavepath of $Sd$ or $ScS$.

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## Figure Captions

Figure 1. Surface projection of paths between Fiji-Tonga earthquakes and seismograph stations considered. The grey and black arrows indicate the fast direction of anisotropy, at each station, as obtained using standard $SKS$ splitting measurements and the master event method described in the text, respectively.

Figure 2. (a) and (b) Examples of records at HRV (88070 and 93190, respectively) for which no $SKS/SKKS$ energy is present. Polarity is inverted for the record of event 88070 (c) For comparison, a record (93219) with strong $SKS/SKKS$ presence.

Figure 3. (A): $SV$ (bold line) and $SH$ components of $Sd$ of the master events, deconvolved with $SH$ and stacked . $SV$ is amplified 3 times relative to $SH$. (B): The same $SV$ component, as in (A), but corrected for receiver anisotropy inferred from (A). (C): $SV$ and $SH$ components of $SKKS$, econvolved with $SV$ and stacked. $SH$ is amplified 3 times relative to $SV$. (D): The same $SH$ component as in (C), but corrected for the side refraction of $SKKS$.

Figure 4. (a) $SV$ and $SH$ components of the records at HRV/WFM. Left column - $SKS$. Central column - $SKKS$ (bold line), synthetic $SKKS$ (dashed line) and Hilbert-transformed $SKKS$ (thin line). Right column - $SV$ component of $Sd$ (bold line), synthetic $SV$ component of $Sd$ (dashed line) and $SH$ component of $Sd$ (thin line). $SV$ components of $Sd$ are amplified twice relative to $SH$. Arrivals of $SKS$, $SKKS$ and $Sd$ correspond to the vertical dashed lines. The records are corrected for receiver anisotropy.
(b) $R$ (bold line) and $SH$ components of the records at RSON, corrected for side refraction and receiver anisotropy . Arrivals of $SHd$ correspond to the vertical dashed line.