



AnisDep: A FORTRAN program for the estimation of the depth of anisotropy using spatial coherency of shear-wave splitting parameters

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ABSTRACT

We present a FORTRAN-77 program to estimate the optimal depth of the source of anisotropy using spatial coherency of teleseismic shear-wave splitting (SWS) parameters. For a given assumed depth of anisotropy, the program computes a variation factor which is a weighted sum of the arithmetic standard deviation (SD) of the splitting times and the circular SD of the fast directions over overlapping blocks. The optimal depth of anisotropy corresponds to the minimum variation factor. The program executes computations over different block sizes for testing the stability of the resulting optimal depth. A synthetic shear-wave splitting data set is provided for testing the program. In addition to anisotropy depth estimation, some of the subroutines in AnisDep can be used for other applications such as computing circular mean and SD of the observed fast directions, and for computing the coordinates of ray-piercing points. The program is designed for Linux and Sun Solaris platforms, but can be easily adapted for other platforms.

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1. Introduction

Over the past 30 years, the polarization direction of the fast shear-wave, ϕ , and the arrival time difference between the fast and slow waves, δt , of teleseismic *P*-to-*S* converted waves at the core-mantle boundary (XKS, including SKS, SKKS, and PKS) have been widely used to infer the existence, direction, and strength of mantle fabrics (e.g., Silver, 1996; Savage, 1999; Long and Silver, 2009). Unfortunately, mostly due to the steep incidence of the XKS waves, the depth of the anisotropic region responsible for the observed shear-wave splitting (SWS) is poorly constrained, leading to heated debates about the lithospheric or asthenospheric origin of the observed anisotropy.

In a recent study, Liu and Gao (2011) proposed and tested using synthetic and real data a procedure to estimate the optimal depth of the source of anisotropy by measuring the spatial coherency of XKS splitting measurements. This *technical note* introduces a FORTRAN-77 program which can be accessed from the on-line supplementary site of the journal.

2. The depth-estimation procedure

The procedure was described and tested in Liu and Gao (2011) and is briefly summarized below. A study area is first divided into dx by dx square degree blocks. A variation factor, F_v , is computed

at each assumed depth of anisotropy. F_v is the weighted sum of the standard deviations of the observed splitting parameters over all the blocks. A range of dx values are used in order to explore the stability of the resulting optimal depth of anisotropy which corresponds to the minimum F_v .

For a given dx value, the procedure includes the following steps:

- (1) Dividing the top $dep1$ to $dep2$ km of the Earth into thin layers of $ddep$ km thick.
- (2) For each layer, computing the geographic coordinates of the ray-piercing points at the top of the layer.
- (3) Dividing the area covered by the ray-piercing points into dx by dx degree² blocks, and for each block, computing the arithmetic SD of the splitting times and the circular SD of the fast directions with ray-piercing points inside the block, i.e., for the i th block

$$F_{\delta t}^{(i)} = \sqrt{\frac{1}{M_i - 1} \sum_{j=1}^{M_i} (\delta t_{ij} - \bar{\delta t}_i)^2} \quad (1)$$

$$F_{\phi}^{(i)} = \sqrt{-\frac{1}{2} \ln(R_i)} \quad (2)$$

where

$$R_i^2 = \left[\frac{1}{M_i} \sum_{j=1}^{M_i} \cos(2\phi_{ij}) \right]^2 + \left[\frac{1}{M_i} \sum_{j=1}^{M_i} \sin(2\phi_{ij}) \right]^2 \quad (3)$$

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M_i is the number of measurements for the i th block, ϕ_{ij} and δt_{ij} are the j th fast direction and splitting delay time measurement in the i th block, respectively, and $\bar{\delta t}_i$ is the arithmetic mean over all the splitting time measurements in block i . M_i should be ≥ 2 . Eq. (2) is based on Eqs. (2.3.5) and (2.3.14) of [Mardia \(1972\)](#) with $l=2$, and Eq. (3) is based on Eqs. (2.2.3) and (2.2.4). While it is technically feasible to weigh the individual measurements by the reciprocal of the standard deviations of the individual SWS measurements in the equations above, we choose not to do so because of the well-known strong dependence of the standard deviations of the individual measurements on the beginning and end of the XKS window, the filtering parameters, and the SWS measuring techniques ([Vecsey et al., 2008](#)). Such dependence leads to unreliably determined standard deviations of the individual events, which might introduce errors in the resulting variation factors.

- (4) Computing the variation factor, $F_v^{(i)}$, for the i th block as a dimensionless weighted sum of $F_\phi^{(i)}$ and $F_{\delta t}^{(i)}$, i.e.,

$$F_v^{(i)} = w_\phi F_\phi^{(i)} + w_{\delta t} F_{\delta t}^{(i)} \quad (4)$$

where w_ϕ and $w_{\delta t}$ are the weighting factor for the ϕ and δt measurements, respectively. Because the ϕ measurements have a maximum range of variation of 180° and the δt measurements have a range of about 2.0 s for most studies ([Long and Silver, 2009](#)), we use $w_\phi = 1/180 \text{ degree}^{-1}$ and $w_{\delta t} = 1/2 \text{ s}^{-1}$ so that the variation factors from the two sets of measurements can be combined.

- (5) Computing F_v and its SD at a given depth as the arithmetic mean and SD of $F_v^{(i)}$ over all the blocks, i.e.,

$$F_v = \frac{1}{N} \sum_{i=1}^N F_v^{(i)} \quad (5)$$

$$\sigma_{F_v} = \sqrt{\frac{1}{N-1} \sum_{i=1}^N (F_v^{(i)} - F_v)^2} \quad (6)$$

where N is the number of blocks.

The optimal depth corresponds to the minimum F_v value which can be observed on the diagram produced by a GMT (Generic Mapping Tools, [Wessel and Smith, 1991](#)) program provided in the package (plot.gmt, see below), or any other plotting programs.

3. Usage of AnisDep

The original version of AnisDep contained many subroutines residing in various folders in the authors' local computer. For easy handling and use, we have merged all the subroutines into a single file consisting of a main program and about 40 subroutines/external functions. The FORTRAN-77 program has about 2900 lines (including comments and empty lines).

The program (AnisDep.f), the Makefile, the test data set (test.dat), and all the other necessary files are bundled in a Linux tar file named AnisDep.tar. After the tar file is transferred to the user's local Linux or Unix computer from the journal's electronic supplement site, the files can be extracted using `tar -xf AnisDep.tar`. The program can then be compiled by typing `make`, and be executed by typing `AnisDep.exe` and entering the name of the input file containing the measured splitting parameters. A synthetic data set, test.dat, can be used to test the program and to serve as an example for the input file. The program displays the dx value, the latitudes/longitudes of the area covered by the ray-piercing points at a given depth, and the depth, F_v , σ_{F_v} ,

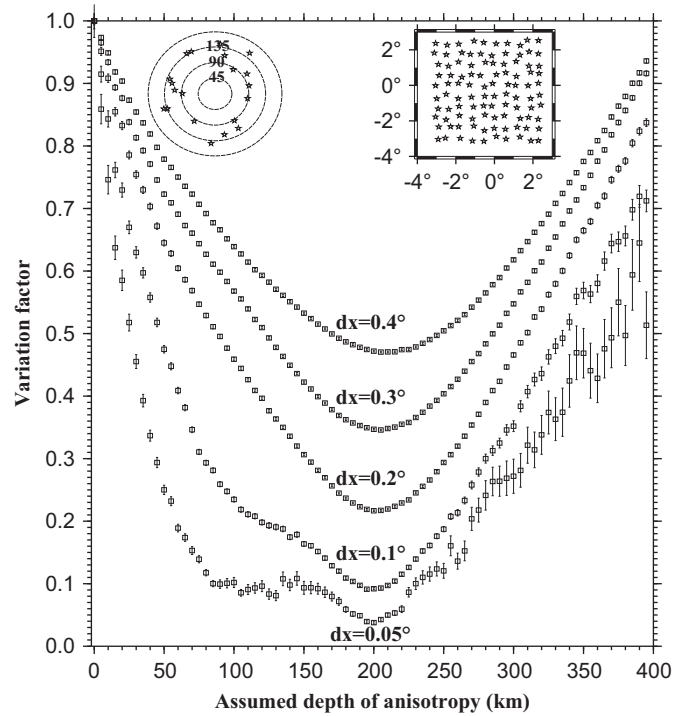


Fig. 1. Spatial variation factors computed using 2000 synthetic shear-wave splitting measurements at 100 stations (inset at the upper right corner) from 20 randomly distributed XKS events (upper left corner). Each curve represents F_v values calculated using a different block size, as labeled.

number of blocks, and the dx value for each assumed depth of anisotropy.

The compilation and execution of the program were successful on 64-bit Linux and Sun Solaris computers. Given the simplistic nature of the program and the input files, the program should be easily adapted onto other platforms. The CPU time needed for the computation is dependent on the number of XKS measurements, cell size, the area of the study region, and the CPU speed. As a reference, it took about 5 h on a Dell Precision T7400 workstation (which has a clock speed of 2.66 GHz) to produce the results shown in [Fig. 1](#) (See caption of the figure for the numbers of stations and events and other parameters.)

3.1. Files required by AnisDep

AnisDep requires a total of eight data or parameter files, which should all be placed under the same sub-directory where the main program resides.

The only file that needs to be created by the user is the one containing the SWS measurements. The columns of the file should be: (1) station longitude, (2) station latitude, (3) event longitude, (4) event latitude, (5) event depth in km, (6) fast polarization direction measured clockwise from the north, (7) splitting time in second, and (8) phase name (SKS, SKKS, or PKS, must be in upper case). Note that the unit for columns 1–4 is decimal degree, and fixed format of the columns is not necessary (see test.dat for an example input file).

The user is not expected to modify the rest of the files, including iasp91.6372, which is a re-sampled (into 1 km vertical interval) IASPEI91 Earth model ([Kennett and Engdahl, 1991](#)); iasp91.hed, iasp91.tbl, limits.inc, stdconst, stdparm, and ttlim.inc, which are parameter files in the original IASPEI91 package by Ray Buland and colleagues. Note that if the program is installed on a Sun Solaris computer, the original iasp91.hed and iasp91.tbl files (which are for Linux) should be removed and iasp91.hed.sun and

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