FFSWK User Manual (version 0.1)

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1 Introduction

This package includes programs for calculation of Finite-Frequency Surface Wave Kernels (FFSWK). In FFSWK, surface wave phase-delay sensitivity kernels $K^{\phi}_{\alpha_{\rm V}}$, $K^{\phi}_{\alpha_{\rm H}}$, $K^{\phi}_{\beta_{\rm V}}$, $K^{\phi}_{\beta_{\rm H}}$, K^{ϕ}_{η} and K^{ϕ}_{ρ} are calculated in a spherically symmetrical reference earth model, fully accounting for radial anisotropy. Surface wave phase delays can be written as (Zhou, 2009)

$$\delta\phi = \iiint_{\oplus} \left[K^{\phi}_{\alpha_{\rm V}}\delta\ln\alpha_{\rm V} + K^{\phi}_{\alpha_{\rm H}}\delta\ln\alpha_{\rm H} + K^{\phi}_{\beta_{\rm V}}\delta\ln\beta_{\rm V} + K^{\phi}_{\beta_{\rm H}}\delta\ln\beta_{\rm H} + K^{\phi}_{\eta}\delta\ln\eta + K^{\phi}_{\rho}\delta\ln\rho\right] d\mathbf{x}^3, \quad (1)$$

where $\alpha_{\rm H}$ and $\alpha_{\rm V}$ are wavespeeds of horizontally-polarized and vertically-polarized P waves; and $\beta_{\rm H}$ and $\beta_{\rm V}$ are wavespeeds of horizontally-polarized and vertically-polarized shear waves; the parameter η is the speed of waves propagating in an intermediate direction and ρ is density.

In isotropic case, phase delays are can written as

$$\delta\phi = \iiint_{\oplus} \left[K^{\phi}_{\alpha}\,\delta\ln\alpha + K^{\phi}_{\beta}\,\delta\ln\beta + K^{\phi}_{\rho}\,\delta\ln\rho\right] d\mathbf{x}^3, \quad (2)$$

where kernels for isotropic perturbations are simply the sum of kernels for anisotropic perturbations,

$$K^{\phi}_{\alpha} = K^{\phi}_{\alpha_{\rm V}} + K^{\phi}_{\alpha_{\rm H}}, \qquad K^{\phi}_{\beta} = K^{\phi}_{\beta_{\rm V}} + K^{\phi}_{\beta_{\rm H}}. \quad (3)$$

The observable $\delta\phi$ is phase difference between observed and reference seismograms. If we write the reference seismogram in the form $s(\omega) = Ae^{-i\phi}$, the observed displacement spectra can be written as $o(\omega) = Ae^{-i(\phi+\delta\phi)}$. In practice, we have to consider frequency averaging in spectra estimates which requires convolution of sensitivity kernels in frequency domain (Zhou *et al.* 2004, section 4.1; Zhou 2009, section 4). In FFSWK, we have used a fast computation scheme described in Zhou *et al.* (2004) to reduce frequency domain convolution to a simple time domain multiplication.

The following assumptions have been made: (1) synthetic and observed seismograms have been multiplied with a cosine taper centered at the group arrival of the reference fundamental-mode surface wave; and (2) the length of the cosine taper is at least several times longer than wave period. Fourier convention is the same as in Zhou *et al.* (2004), i.e.,

$$f(\omega) = \int_{-\infty}^{\infty} f(t)e^{-i\omega t}dt, \quad f(t) = \frac{1}{2\pi}\mathrm{Re}\int_{-\infty}^{\infty} f(\omega)e^{i\omega t}d\omega. \quad (4)$$

2 Quick Start Guide

1. The programs have been successfully compiled with Intel FORTRAN Compiler. If you use a different compiler, there are likely I/O problems.

2. This is a first testing version and has not been benchmarked with any other code. **Use it at your own risk**.

The example below will show you how to quickly get started with FFSWK. Bold texts are Linux command lines.

1. Compile minos
   - **ifort minos_bran.f -o minos_bran**

2. run minos to generate eigenfunctions
   - **minos_bran < minos_bran.in.love**
   - **minos_bran < minos_bran.in.rayleigh**

   The input file *minos_bran.in.love* looks like this:

   ```
   prem.aniso
   love.out
   eigf.love
   1E-8 2
   2
   10 600 5 50 0 0
   ```

   prem.aniso: file name of the reference earth model
   love.out: output mode catalogue file (don't change the file name!)
   eigf.love: unformatted binary output file of eigenfunctions (don't change the file name!).
   1E-8 2: the first parameter controls integration precision and the second one defines lowest frequency in millihertz (mHz) above which gravitational terms are neglected.
   2: toroidal modes only (for Love waves).
   10 600 5 50 0 0: define modes to be calculated. (10 600): range of angular degree and (5 50): range of frequency in mHz. (0 0): fundamental mode $n = 0$ only.

3. Compile and run program read_eigf to prepare eigenfunctions for kernel calculation.
   - **ifort -132 -w -o read_eigf read_eigf.f**
   - **read_eigf < read_eigf.in.love**
   - **read_eigf < read_eigf.in.rayl**

   The command line *read_eigf < read_eigf.in.love* reads toroidal mode eigenfunctions *eigf.love* and normalizes them. Normalized eigenfunctions are stored in directory *eigfs*.
   The command line *read_eigf < read_eigf.in.rayl* reads spheroidal mode eigenfunctions *eigf.rayleigh* and normalizes them. Normalized eigenfunctions are stored in directory *eigfs*.

4. Compile and run kernel calculation programs

   - **ifort -132 -o ffswk ffswk.f90 ffswk-sub.f90**
   - **ffswk < ffswk.input.love**

   The input file ffswk.input.love looks like this:

87	# mode l (1̃0 mhz) (see file love.out)
1	# love=1 rayleigh=2
eigfs	
182.58 -28.83 14.00	# source lon, lat, depth
7.130 -0.640 -6.500 0.860 3.790 -1.050	# moment Mrr Mtt Mpp Mrs Mrp Mtp
288.5090 42.611	# receiver lon, lat
600	# measurement window length in seconds
2 20	# Fresnel_number, sampling rate in Fresnel zone
200	# record sensitivity in the uppermost 200 km

   when *Fresnel_number=1*, only sensitivity in the first Fresnel zone will be calculated; when *Fresnel_number=2*, the calculation domain is twice the size of the first Fresnel zone. *sampling rate in Fresnel zone* determines kernel spacial sampling rate. In general, 20–30 samples per Fresnel zone will be sufficient for most applications.

   Output kernel files are:

   kern/example.kernel.ah (this is $K^{\phi}_{\alpha_{\rm H}}$)
   kern/example.kernel.av (this is $K^{\phi}_{\alpha_{\rm V}}$)
   kern/example.kernel.bh (this is $K^{\phi}_{\beta_{\rm H}}$)
   kern/example.kernel.bv (this is $K^{\phi}_{\beta_{\rm V}}$)
   kern/example.kernel.et (this is K^{ϕ}_{η})
   kern/example.kernel.rh (this is K^{ϕ}_{ρ})

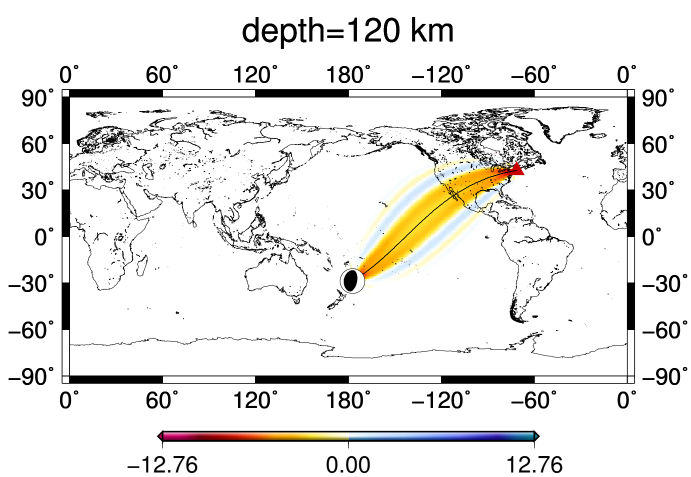
   The kernel files are data columns formatted as follow:

longitude	latitude	kernel_value	depth_in_km

5. Plot mapviews of sensitivity kernels

   - **plot-kernel.pl kern/example.kernel.bh 120**

   This command plots the kernel file *kern/example.kernel.bh* ($K^{\phi}_{\beta_{\rm H}}$) at a depth of *120* km. You should have a postscript file *kernel.xyz.ps* as shown in the Figure below. The unit of the sensitivity is $10^{-8} \times {\rm km}^{-3}$.



3 Calculate your own sensitivity kernels

- To change earthquake source, seismic station or frequency of surface wave, simply go back to step 4 and modify the input file *ffswk.input.love* (or *ffswk.input.rayl*).
- To calculate kernels for a different earth model, go back to step 2 and replace the model file *prem.aniso* in *minos_bran.in.love* (or *minos_bran.in.rayleigh*) with your own model file.

4 References

1. Ying Zhou (2009), "Multi-mode 3-D surface-wave sensitivity kernels in radially anisotropic media", *Geophysical Journal International*, **176**, 865-888.
2. Ying Zhou, F. A. Dahlen and Guust Nolet (2004), "3-D sensitivity kernels for surface-wave observables", *Geophysical Journal International*, **158**, 142-168.
3. To calculate synthetic seismograms using Mineos, please refer to the CIG Mineos Webpage: http://www.geodynamics.org/cig/software/mineos
4. FFSWK Webpage: http://seismo.geos.vt.edu/software.html

5 Report Bugs!

This package does not come with any warranty or technical support. However, if you find bugs, please report them to Ying Zhou (ying.yingzhou@gmail.com) and we will try to fix them and send updates to registered users.