The senskernel package. User Manual.

Introduction

The package **senskernel-1.0** provides the following opportunity for users working at Linux-based computers:

- Calculation of multi-modal surface wave dispersion and eigenfunctions in flat isotropic elastic Earth model consisting of homogeneous layers. Options for sphericity and attenuation corrections are included.
- Calculation of phase velocity sensitivity kernels for the same model.
- Calculation of group velocity sensitivity kernels for the same model.

Package includes three programs: **SURF_PERTURB, PHV_SENS_KERNEL ,GRV_SENS_KERNEL** and C-shell script **KERNELS.csh** .
The program **SURF_PERTURB** is based on original R. Herrmann's code [1] with many modifications, introduced by A. Levshin and B. Bukchin. It can be used as a part of package for obtaining dispersion curves, ellipticity, eigenfunctions for the given set of Rayleigh and Love modes and the given set of periods. It also may be used outside of package for the same goals.

The program **PHV_SENS_KERNEL** (written by A. Levshin) can be used as a part of package for obtaining the set of phase-velocity sensitivity kernels for the range of modes and periods using the outputs of **SURF_PERTURB**. The theory behind these calculations presented in many books (e.g., Aki and Richards [2], Levshin et al. [3]). It can be used outside this package following the execution of **SURF_PETURB**.

The program **GRV_SENS_KERNEL** (written by A. Levshin) is used only at this package for obtaining group velocity sensitivity kernels. The computational algorithm is described in Rodi et al.[4].

1. SURF_PERTURB program

Command line

SURF_PERTURB MODEL PREF rl kmin kmax tmin tmax tstep [-f] [-a] [-s *depth_step***] [-p** *perturb***]**

Description

SURF_PERTURB reads the named input MODEL with radial profile (1-D shear velocities model) of the elastic and nonelastic parameters and computes phase and group velocity dispersion curves and the set of eigenfunctions of the fundamental and higher modes of Rayleigh/Love surface waves. Program includes special algorithm to produce perturbed eigenvalues and eigenfunctions for further sensitivity kernel computation. Program **SURF_PERTURB** uses argument **PREF** as the prefix to tree output files. In the case of Rayleigh waves, **rl** = R, the names are `PREF.R`, `PREF.R.grv` and `PREF.R.phv` where
`PREF.R` file consists of complete set of eigenfunctions for all modes and all periods, file

`PREF.R.grv` consists of group velocity dispersion curves for all modes, and file `PREF.R.phv` consists of phase velocity dispersion curves for all modes. For Love case, **rl** = L, output files have the names `PREF.L, PREF.L.grv` and `PREF.L.phv`. The files keeps the same types of information computed for Love waves. See more details below in **Input/Output** data sections.

Parameters and options

rl - character "R" or "L". Define type of waves: "R" - Rayleigh, "L" - Love
kmin - minimal mode number. Modes numbered from 0 by 1. Mode 0 is fundamental
kmax - maximal mode number
tmin - minimal period, in sec
tmax - maximal period, in sec
tstep - step by periods, in sec
-f
apply correction for sphericity
-a
apply attenuation correction
-s *depth_step*
Define step by depth in eigenfunctions as *depth_step,* in km. By default *depth_step* = 1.0 km
-p perturb
Insert small perturbation ε= *perturb*-1.0 into periods as T_{pert}=T · *perturb*. ?
By default *perturb* = 1.0

Input data

MODEL file. The model file is a plain ASCII file given in tabular form. Each line in the file describes single layer of some thickness with constant parameters inside layer. The layers start from free surface downward to the center of the Earth. It is possible to set up the first layer only as the water layer.
The line fields are: *h, vp, vs, ρ, Q*
where,
h - layer thickness, (km)
vp - velocity of P waves, (km/s)
vs - velocity of S waves, (km/s)
ρ - density, (g/cm^3)
Q - intrinsic shear Q

An example of model file **`eus_model`** is stored under **`test1`** directory.
NOTE: The last field Q in the MODEL file might be omitted. In this case do not use **–a** option in command line. It leads to wrong results.
Format: informatted

Output data, Rayleigh case

PREF.R.phv file. This plain ASCII file contains in the sequential order **m** phase velocity dispersion curves (**m = kmax-kmin+1)** of Rayleigh waves in mode range **kmin÷kmax**. Each dispersion curve is the set of lines ended with two empty lines.
The line fields are: *T, Cr,Cv*
where,

T - period, (s)
Cr - phase velocity, (km/s), found as a root of the equation for the boundary conditions at the surface
Cv - phase velocity, (km/s), found from integral relations based on variational formulas.

The period range is defined as $\mathbf{T_i}$=**tmin**+**i×tstep**, where **i=0, … ,n** and **n=[(tmax-tmin)/tstep] .**

PREF.R.grv file. This plain ASCII file contains in the sequential order **m** group velocity dispersion curves of Rayleigh waves in mode range **kmax÷kmin**. Each dispersion curve is the set of lines ended with two empty lines.
The line fields are: *T, U*
where,
T - period, (s)
U - group velocity, (km/s)
The period range is defined as $\mathbf{T_i}$=**tmin**+**i×tstep**, where **i=0, … ,n** and **n=[(tmax-tmin)/tstep] .**

PREF.R file. This plain ASCII file consists of eigenfunctions grouped in m mode-sections. Mode-sections placed in PREF.R file in increasing mode number order. Each mode-section consists of header – the first line, separator "@", and body – rest of lines. The header is the text line form of
"   Rayleigh mode **k**"
where, **k** is mode number plus one. The line separator is the text line of 48 characters "@" followed by the space character, namely,
" @@"
The body includes **n**+1 eigenfunctions values computed for corresponding eigenvalues $\mathbf{T_i}$.
Eigenfuctions are divided by separator "@", and stored in increasing order by period $\mathbf{T_i}$.
Each eigenfunction consists of the header – two lines, horizontal component of eigenfuncton, separator "$", and vertical component. The separator "$" is the text line of 47 characters "$" followed by space, namely,
" $$$"

Header of eigenfunction.

Line 1. The line fields are: *T, C, U, k, ampf, ellip, QRapp*
Where,
T - period, (sec)
C - phase velocity, (km/s)
U - group velocity, (km/s)
k - wavenumber, (km^{-1})
Ampf - ampf=1/(2*C*U*sumi0)/sqrt(2*π)*10^{-15}
Ellip - ratio Vhoriz./Vvert components at the surface
QRapp - apparent Rayleigh wave Quality factor for given period
NOTE: If option "**-a**" is absent, *QRapp* = 20,000 by default. If option **"-f"** is present,
k = sqrt($(\boldsymbol{2\pi/CT})^{\mathbf{2}}$ $-1/R_0^2$), where R_0 is the Earth radius.

Line 2. The line fields are: sumi0, sumi1, sumi2, sumi3, flagr
sumi0- sumi3 - integrals related to the potential and kinetic energy for given period and mode number;
flagr - Lagrangian of this mode, which should be close to 0 if the roots of period equation are found accurately

Horizontal component of eigenfunctон. Each line consists of three field: *h, Vhor, dVhordh*
Where,

h	depth, (km)
Vhor	- horizontal eigenfunction component, normalized to be ellipticity value at the surface, nondimensional.
dVhordh	- derivative of *Vhor* by depth *h*, *dVhor/dh* (km^{-1})

Vertical component of eigenfuncton. Each line consists of three field: *h, Vver, dVver/dh*
Where,

h	- depth, (km)
Vver	- vertical component of eigenfunction normalized to be 1 for h=0
dVverdh	- derivative of *Vver* by *h, dVver/dh*, (km^{-1})

See examples of `PREF.R` file in **test1** directory of distribution set.

Output data, Love case

The output files `PREF.L.phv` and `PREF.L.grv` have the same structure as in Rayleigh case, but contains of phase and group velocity dispersion curves of different modes for Love waves. See examples in **test1** directory of distribution set.

PREF.L.phv file. This plain ASCII file consists of eigenfunctions grouped in m mode-sections. Mode-sections placed in PREF.L file in increasing mode number order. Each mode-section consists of header – the first line, separator "@", and body – rest of lines. The header is the text line form of
" Love mode **k**"
where, **k** is mode number plus one. The line separator is the text line of 41 characters "@" followed by the space character, namely,
" @@@"
The body includes **n**+1 eigenfunctions computed for corresponding eigenvalues $\mathbf{T_i}$. Eigenfuctions are devided by separator "@", and stored in increasing order by period $\mathbf{T_i}$.
Each eigenfunction consists of the header – two lines and eigenfuncton component.

Header of eigenfunction.

Line 1. The line fields are: *T, C, U, k, ampf, QLapp*
Where,

T	- period, (sec)
C	- phase velocity, (km/s)
U	- group velocity, (km/s)
k	- wavenumber, (km^{-1})
Ampf	- ampf=1/(2*C*U*sumi0)/sqrt(2*π)*10^{-15}
QLapp	- apparent Love wave Quality factor for given period

NOTE: If option "**-a**" is absent, *QLapp* = 20000 by default. If option **"-f"** is present ,
k = sqrt($(\boldsymbol{2\pi/CT})^{\mathbf{2}} - 1/R_0^2$), where R_0 is the Earth radius.

Line 2. The line fields are: sumi0, sumi1, sumi2, flagr
sumi0- sumi2 - integrals related to the potential and kinetic energy for given period and mode number;
flagr - Lagrangian of this mode, which should be close to 0 if the roots of period equation are found accurately

Eigenfunction. Each line consists of three field: *h, V, dVdh*
Where,
h - depth, (km)
V - eigenfunction value, normalized to be 1 at the surface,
dVdh - derivative of *V* by depth *h*, *dV/dh*, (km^{-1})

2. PHV_SENS_KERNEL program

Command line

PHV_SENS_KERNEL MODEL PREF rl SENS

Description

PHV_SENS_KERNEL reads the named input MODEL and files `PREF.R`, `PREF.R.grv`, `PREF.R.phv` (Rayleigh case) or `PREF.L`, `PREF.L.grv`, `PREF.L.phv` (Love case) created by **SURF_PERTURB** program and described in the previous section. **PHV_SENS_KERNEL** outputs files with normalized partial derivatives of phase velocity for all requested modes and all requested periods. Each file has name form of **SENS**`.phv.`**rl**_*mode_period.* Arguments **rl** is the character "R" or "L", it defines the type of wave Rayleigh or Love correspondingly. For example, `test.phv.R_0_60`, `test.phv.L_1_40`.

Output data

Rayleigh case. Each output file has 4 fields: h, *(δC/C)/(δb/b), (δC/C)/(δa/a), (δC/C)/(δρ/ρ)*
Where, *h* is depth, (km), *C* is phase velocity, *a* is P velocity, *b* is S velocity, and *ρ* is density. The first line contains additional fields with values of period, *T*, (s), phase velocity, *C* (km/s), group velocity, *U* (km/s), and mode number **k**.
Love case. Each output file has 3 fields: *h, (δC/C)/(δb/b), (δC/C)/(δρ/ρ),*
where *h* is depth, (km), *C* is phase velocity, *b* is S velocity, and *ρ* is density. The first line contains additional fields with values of period, *T* (s), phase velocity, *C* (km/s), group velocity, *U* (km/s), and mode number **k**.

3. GRV_SENS_KERNEL program

Command line

GRV_SENS_KERNEL PREF rl

Description

This program calculates group velocity sensitivity kernels for the MODEL used in SURF_PERTURB and PHV_SENS_KERNEL. The program uses output files of PHV_SENS_KERNEL corresponding to

the given wave type **rl**, mode **k** and period *T* for three values of *perturb* parameter (1-ε, 1,1+ε) where ε=0.01 and creates corresponding files of group velocity sensitivity kernels.
GRV_SENS_KERNEL outputs files with normalized partial derivatives of group velocity for all requested modes and all requested periods. Each file has name form of **SENS**.`grv`.**rl**_*mode_period.*
Arguments **rl** is the character "R" or "L", it defines the type of wave Rayleigh or Love correspondingly. For Love case you have to perform everything described above with **rl** = L. See for more details script **KERNERLS.**csh in bin directory of the distribution set.

Output data

Rayleigh case. Each output file has 4 fields: h, *(∂U/U)/(∂b/b), (∂U/U)/(∂a/a), (∂U/U)/(∂ρ/ρ)*
Where, *h* is depth, (km), *U* is group velocity, *a* is share P velocity, *b* is shared S velocity, and *ρ* is density. The first line contains has additional fields with values of period, *T*, (s), phase velocity, *C*, (km/s), group velocity, *U*, (km/s), and mode number **k**.
Love case. Each output file has 3 fields: *h, (∂U/U)/(∂b/b), (∂U/U)/(∂ρ/ρ)*
Where, *h* is depth, (km), *U* is group velocity, *b* is shared S velocity, and *ρ* is density. The first line contains has additional fields with values of period, *T*, (s), phase velocity, *C*, (km/s), group velocity, *U*, (km/s), and mode number **k**.

4. KERNELS.csh script

Command line

KERNELS.sh MODEL PREF rl kmin kmax tmin tmax tstep -s *depth_step* **-a**

Description

KERNELS.csh script provides the complete set of program calls to evaluate sensitivity kernels for phase and group velocity curves of Rayleigh/Love surface waves. The meaning of input arguments had been described before in Section 1. Note, that the script deletes some intermediate files. To get full file set of files comment two \rm commands at the end of script.

References

[1] R.B. Herrmann, Computer programs in seismology, http://www.eas.slu.edu/eqc/eqccps.html

[2] Aki, K., Richards P.G., 1980. Quantitative seismology, W. H.Freeman and Co.

[3] Levshin, A.L., Yanovskaya, T.B., Lander, A.V., Bukchin B.G., Barmin, M.P., Ratnikova L.I., Its E.N., 1989. Seismic Surface Waves in Laterally Inhomogeneous Earth. (Ed. V.I.Keilis-Borok), Kluwer Publ. House, Dordrecht/Boston/ London.

[4] Rodi, W., Glover, P., Li, T.M.C., Alexander, S.S., 1975. A fast, accurate method for computing group-velocity partial derivatives for Rayleigh and Love waves. Bull. Seismol. Soc. Am. 65 (5), 1105-1114.