User Guide for Direct Solution Method (DSM) Software

Last updated: May 20, 2023

This document provides information for users of the Direct Solution Method (DSM) software for computing toroidal (roughly speaking, SH) and spheroidal (roughly speaking, P-SV) synthetic seismograms in a spherically symmetric, transversely isotropic (TI) medium. The software is available for download from `https://github.com/UT-GlobalSeismology/DSMsynTI-mpi`. There are two programs, one for toroidal waves and one for spheroidal waves. The outputs of these programs are the Fourier transform of the velocity. The SPCSAC program must then be used to produce synthetics in the time domain.

IMPORTANT WARNING

It is necessary to run both programs and sum the outputs in order to obtain accurate horizontal component synthetic seismograms.

Installation

After downloading, you should change the FC, FC2, and FFLAGS in the makefiles to fit your environment. Then, compile:

```
% cd tish-mpi
% make
% cd ../tipsv-mpi
```

```
% make
```

By default, this only compiles the single-thread versions of the softwares.
To use the MPI versions, compile as:

```
% cd tish-mpi
% make all
% cd ../tipsv-mpi
% make all
```

You can install this anywhere. If you will be a frequent DSM user, you
should set the tish-mpi and tipsv-mpi directories in PATH.

Usage

The program for toroidal synthetics is called "tish," and the program
for spheroidal synthetics is called "tipsv." Each has a version for single-
thread and a version for MPI. Execute them as follows:

- tish, single-threaded:

  ```
  % tish < (sh_parameter_file)
  ```

- tipsv, single-threaded:

  ```
  % tipsv < (psv_parameter_file)
  ```

- tish, with MPI:

  ```
  % mpirun -n (N_core) mpi-tish < (sh_parameter_file)
  ```

- tipsv, with MPI:

```
% mpirun -n (N_core) mpi-tipsv < (psv_parameter_file)
```

The input parameters for these programs are described below. Following those descriptions, example input files for the toroidal and spheroidal programs are presented and explained.

Input parameters for tish and tipsv

- tlen $\cdots$ (floating point) Time length (in s) of calculated synthetic seismograms. The starting time $t = 0$ will be the CMT median time, so the time length will be equal to the maximum of t.
- np $\cdots$ (integer) The number of points in the frequency domain. The frequency interval is $\Delta f = 1/\text{tlen}$ and the Nyquist (maximum) frequency (in Hz) calculated by this program is $f_{Nyquist}(= \text{np} \cdot \Delta f)$. Note that the programs do not compute the $f = 0$ (static) component of the synthetics.
- four parameters controlling the error of the synthetics
  - re $\cdots$ (floating point) Upper limit on relative error due to the vertical gridding (see Geller & Takeuchi, GJI, **123**, 449–470, 1995, eq. 6.2). (The default value is 10^{-2}.)
  - ratc $\cdots$ (floating point) The ratio between the maximum amplitude of the vertically dependent part of the solution for a given frequency and the amplitude at the cut-off depth for a given angular order (see Kawai *et al.*, GJI, **164**, 411–424, 2006, pg 420–421 and Fig. 12). (The default value is 10^{-10}.)
  - ratl $\cdots$ (floating point) The ratio between the maximum amplitude and the amplitude at the angular order where the solution is truncated for a given frequency (see Kawai *et al.*, GJI,

164, 411–424, 2006, pg 419–420 and Fig. 9). (The default value is 10^{-5}.)

- adamp $\cdots$ (floating point) An artificial damping factor given by $\exp(-\omega_I(\mathsf{tlen}))$ which is used to prevent wrap-around (see Geller & Ohminato, GJI, **116**, 421–446, 1994, § 5.1, pg 431–432). (The default value is 10^{-2}.)

- imin, imax $\cdots$ (integer) The index of the minimum and maximum frequencies for the computation in the frequency domain. Thus $f_{min} = \mathsf{imin}\ \Delta f$ and $f_{max} = \mathsf{imax}\ \Delta f$. Users with multiple processors can compute synthetics pseudo-parallelly.

- parameters for Earth structure model
  - nzone $\cdots$ (integer) The number of layers of the Earth structure model. The density and elastic properties in each layer are given by cubic splines (Dziewonski & Anderson, PEPI, **25**, 297–356, 1981, pg 307). The form of the cubic splines that gives the elastic modulus or density in a given layer is $P = a_0 + a_1 x + a_2 x^2 + a_3 x^3$, where P is a physical property (density, velocity, or dimensionless parameter) and $x = r/r_{\mathrm{max}}$ is the normalized radius, where r_{max} is the outermost radius at the upper surface. This will usually be 6371 km, but the user can vary it arbitrarily to suit the application (e.g., to the Moon or Mars). The units of the density and elastic moduli are discussed below.
  - Physical properties for each layer [rmin, rmax, rho, vpv, vph, vsv, vsh, eta, qmu, qkappa] (floating point). The definitions of vpv, vph, vsv, vsh and eta are given by Dziewonski & Anderson (PEPI, **25**, 297–356, 1981, pg 304–305).
    * rmin $\cdots$ minimum radius of layer (km)

4

* rmax $\cdots$ maximum radius of layer (km)
* rho $\cdots$ density (g/cm^3)
* vpv $\cdots$ velocity of vertically propagating P (V_{PV}) waves (km/s)
* vph $\cdots$ velocity of horizontally propagating P (V_{PH}) waves (km/s)
* vsv $\cdots$ velocity of vertically propagating S (V_{SV}) waves (km/s)
* vsh $\cdots$ velocity of horizontally propagating S (V_{SH}) waves (km/s)
* eta $\cdots$ $\eta = F/(A - 2L)$ (dimensionless)
* qmu $\cdots$ Q_μ (dimensionless, > 0)
* qkappa $\cdots$ Q_κ (dimensionless, > 0)

For a TI model, the relation between $V_{PV}, V_{PH}, V_{SV}, V_{SH}, \eta$ and the anisotropic elastic moduli A, C, F, L, N are as follows:

$$V_{PV} = \sqrt{A/\rho} \qquad\qquad V_{PH} = \sqrt{C/\rho}$$
$$V_{SV} = \sqrt{L/\rho} \qquad\qquad V_{SH} = \sqrt{N/\rho}$$
$$\eta = F/(A - 2L)$$

The velocities and η are defined with respect to a reference frequency of 1 Hz, and are set as 3rd order polynominals as described above. Q_μ and Q_κ are assumed to be constant in the frequency band being considered. There are nzone $\times$ 3 lines for the Earth model for tish, and nzone $\times$ 6 lines for tipsv.

* parameters for the source
  - r0 $\cdots$ (floating point, > 0) The radius (in km), latitude (note: <u>not</u> co-latitude; in degrees), and longitude (in degrees) of the source (r_0, θ_0, ϕ_0).

- mt $\cdots$ (floating point) The 6 elements of the moment tensor $(M_{rr}, M_{r\theta}, M_{r\phi}, M_{\theta\theta}, M_{\theta\phi}, M_{\phi\phi})$ in units of 1×10^{25} dyne cm $(= 10^{18}$ N m). Note that the source is assumed to be a point moment tensor; single point forces are currently not supported. The time dependence of the moment tensor is assumed to be a δ-function, so the computed displacement seismograms can be also viewed as the Fourier transform of velocity synthetics for a step-function source. To compute synthetics for some source time function, convolve that function to the waveforms that are output from DSM.

- parameters for the stations
  - nr $\cdots$ (integer) The number of stations. nr lines (one for each station) as follows.
  - lat, lon $\cdots$ (floating point) The locations of stations where lat is the latitude, and lon is the longitude in degrees. Stations will be set at the surface of the planet.

- output $\cdots$ (character) The file name of outputs of which number is nr.

Example input file for tish

Input parameters are separated by spaces. Any information after the last parameter on a line is treated as a comment. Any line beginning with a "c" (case-insensitive) is treated as a comment. The above is also true for tipsv.

c parameter for the period range

5120.0 256 tlen(s), np

c relative error (See GT95 eq. 6.2)

1.d-2 re

c ampratio using in grid cut-off (1.d-10 is recommended)

1.d-10 ratc

c ampratio using in l-cutoff

1.d-5 ratl

c wrap-around attenuation for omegai

1.d-2

c parameter for the trial function

c imin imax

0 256

c parameter for the structure

10 nzone

c — Radius(km) — — Density (g/cmˆ 3) —

c — Vsv (km/s) —

c — Vsh (km/s) — - Qmu (dimensionless)-

3480.0 3630.0 7.9565 -6.4761 5.5283 -3.0807 r_0 r_1 and four cubic spline coefficients for ρ

6.9254 1.4672 -2.0834 0.9783 four cubic spline coefficients for V_{SV}

6.9254 1.4672 -2.0834 0.9783 312.0 four cubic spline coefficients for V_{SH} followed by value of Q_μ (constant) in layer

3630.0 5600.0 7.9565 -6.4761 5.5283 -3.0807

11.1671 -13.7818 17.4575 -9.2777

11.1671 -13.7818 17.4575 -9.2777 312.0

5600.0 5701.0 7.9565 -6.4761 5.5283 -3.0807

22.3459 -17.2473 -2.0834 0.9783

7

22.3459 -17.2473 -2.0834 0.9783 312.0
5701.0 5771.0 5.3197 -1.4836 0.0000 0.0000
                        9.9839 -4.9324 0.0000 0.0000
                        9.9839 -4.9324 0.0000 0.0000 143.0
5771.0 5971.0 11.2494 -8.0298 0.0000 0.0000
                        22.3512 -18.5856 0.0000 0.0000
                        22.3512 -18.5856 0.0000 0.0000 143.0
5971.0 6151.0 7.1089 -3.8045 0.0000 0.0000
                        8.9496 -4.4597 0.0000 0.0000
                        8.9496 -4.4597 0.0000 0.0000 143.0
6151.0 6291.0 2.6910 0.6924 0.0000 0.0000
                        5.8582 -1.4678 0.0000 0.0000
                        -1.0839 5.7176 0.0000 0.0000 80.0
6291.0 6346.6 2.6910 0.6924 0.0000 0.0000
                        5.8582 -1.4678 0.0000 0.0000
                        -1.0839 5.7176 0.0000 0.0000 600.0
6346.6 6356.0 2.9000 0.0000 0.0000 0.0000
                        3.9000 0.0000 0.0000 0.0000
                        3.9000 0.0000 0.0000 0.0000 600.0
6356.0 6371.0 2.6000 0.0000 0.0000 0.0000 $r_{\max}$ is 6371 km
                        3.2000 0.0000 0.0000 0.0000
                        3.2000 0.0000 0.0000 0.0000 600.0
c
c parameter for the source
5771.0 -22.49 -68.09 r0(km), lat, lon (deg)
0.0 1.0 0.0 0.0 0.0 0.0 mt (Mrr, Mrt, Mrp, Mtt, Mtp, Mpp) (1.e25 dyne
cm)
c parameter for the station

2 nr

-51.6753 -58.0637 lat,lon (deg)

-51.6753 -58.0637 lat,lon (deg)

c names of the output files (one for each station)

examples/test1.1sh.spc

examples/test1.2sh.spc

c

end

Example input file for tipsv

c parameter for the period range

5120.0 256 tlen(s),np

c relative error (See GT95 eq. 6.2)

1.d-2 re

c ampratio using in grid cut-off (1.d-10 is recommended)

1.d-10 ratc

c ampratio using in l-cutoff

1.d-5 ratl

c wrap-around attenuation for omegai

1.d-2

c parameter for the trial function

c imin imax

0 256

c parameter for the structure

12 nzone

c - Radius(km) - — Density (g/cm^ 3)—

c — Vpv (km/s) —

c — Vph (km/s) —

c — Vsv (km/s) —

c — Vsh (km/s) —

c — eta (ND) — - Qmu (ND) - - Qkappa (ND) -

0.0 1221.5 13.0885 0.0000 -8.8381 0.0000 r_0 r_1 and four cubic spline coefficients for ρ

11.2622 0.0000 -6.3640 0.0000 four cubic spline coefficients for V_{PV}

11.2622 0.0000 -6.3640 0.0000 four cubic spline coefficients for V_{PH}

3.6678 0.0000 -4.4475 0.0000 four cubic spline coefficients for V_{SV}

3.6678 0.0000 -4.4475 0.0000 four cubic spline coefficients for V_{SH}

1.0000 0.0000 0.0000 0.0000 84.6 1327.7 four cubic spline coefficients for η followed by value of Q_κ (constant) and Q_μ (constant) in layer

1221.5 3480.0 12.5815 -1.2638 -3.6426 -5.5281

11.0487 -4.0362 4.8023 -13.5732

11.0487 -4.0362 4.8023 -13.5732

0.0000 0.0000 0.0000 0.0000

0.0000 0.0000 0.0000 0.0000

1.0000 0.0000 0.0000 0.0000 -1.0 57823.0

3480.0 3630.0 7.9565 -6.4761 5.5283 -3.0807

15.3891 -5.3181 5.5242 -2.5514

15.3891 -5.3181 5.5242 -2.5514

6.9254 1.4672 -2.0834 0.9783

```
                    6.9254 1.4672 -2.0834 0.9783
                    1.0000 0.0000 0.0000 0.0000 312.0 57823.0
3630.0 5600.0 7.9565 -6.4761 5.5283 -3.0807
                    24.9520 -40.4673 51.4832 -26.6419
                    24.9520 -40.4673 51.4832 -26.6419
                    11.1671 -13.7818 17.4575 -9.2777
                    11.1671 -13.7818 17.4575 -9.2777
                    1.0000 0.0000 0.0000 0.0000 312.0 57823.0
5600.0 5701.0 7.9565 -6.4761 5.5283 -3.0807
                    29.2766 -23.6027 5.5242 -2.5514
                    29.2766 -23.6027 5.5242 -2.5514
                    22.3459 -17.2473 -2.0834 0.9783
                    22.3459 -17.2473 -2.0834 0.9783
                    1.0000 0.0000 0.0000 0.0000 312.0 57823.0
5701.0 5771.0 5.3197 -1.4836 0.0000 0.0000
                    19.0957 -9.8672 0.0000 0.0000
                    19.0957 -9.8672 0.0000 0.0000
                    9.9839 -4.9324 0.0000 0.0000
                    9.9839 -4.9324 0.0000 0.0000
                    1.0000 0.0000 0.0000 0.0000 143.0
57823.0 5771.0 5971.0 11.2494 -8.0298 0.0000 0.0000
                    39.7027 -32.6166 0.0000 0.0000
                    39.7027 -32.6166 0.0000 0.0000
                    22.3512 -18.5856 0.0000 0.0000
                    22.3512 -18.5856 0.0000 0.0000
                    1.0000 0.0000 0.0000 0.0000 143.0 57823.0
5971.0 6151.0 7.1089 -3.8045 0.0000 0.0000
                    20.3926 -12.2569 0.0000 0.0000
```

20.3926 -12.2569 0.0000 0.0000

8.9496 -4.4597 0.0000 0.0000

8.9496 -4.4597 0.0000 0.0000

1.0000 0.0000 0.0000 0.0000 143.0 57823.0

6151.0 6291.0 2.6910 0.6924 0.0000 0.0000

0.8317 7.2180 0.0000 0.0000

3.5908 4.6172 0.0000 0.0000

5.8582 -1.4678 0.0000 0.0000

-1.0839 5.7176 0.0000 0.0000

3.3687 -2.4778 0.0000 0.0000 80.0 57823.0

6291.0 6346.6 2.6910 0.6924 0.0000 0.0000

0.8317 7.2180 0.0000 0.0000

3.5908 4.6172 0.0000 0.0000

5.8582 -1.4678 0.0000 0.0000

-1.0839 5.7176 0.0000 0.0000

3.3687 -2.4778 0.0000 0.0000 600.0 57823.0

6346.6 6356.0 2.9000 0.0000 0.0000 0.0000

6.8000 0.0000 0.0000 0.0000

6.8000 0.0000 0.0000 0.0000

3.9000 0.0000 0.0000 0.0000

3.9000 0.0000 0.0000 0.0000

1.0000 0.0000 0.0000 0.0000 600.0 57823.0

6356.0 6371.0 2.6000 0.0000 0.0000 0.0000 $r_{\max}$ is 6371 km

5.8000 0.0000 0.0000 0.0000

5.8000 0.0000 0.0000 0.0000

3.2000 0.0000 0.0000 0.0000

3.2000 0.0000 0.0000 0.0000

1.0000 0.0000 0.0000 0.0000 600.0 57823.0

c

c parameter for the source

5771.0 -22.49 -68.09 r0(km), lat, lon (deg)

0.0 1.0 0.0 0.0 0.0 0.0 mt (Mrr, Mrt, Mrp, Mtt, Mtp, Mpp) (1.e25 dyne cm)

c parameter for the station

2 nr

-51.6753 -58.0637 lat,lon (deg)

-51.6753 -58.0637 lat,lon (deg)

c names of the output files (one for each station)

examples/test1.1psv.spc

examples/test1.2psv.spc

c

end

Example output file

The output file with an spc extension (.spc) contains five lines of the header and $3*(\mathsf{nr} +1)$ lines of the frequency spectrum. The header includes tlen, np, $-\ln(\mathsf{adamp})/\mathsf{tlen}$, lat, lon, and r0. Three lines for each frequency include the frequency identifier and vertical components in the first line and radial and transverse components in the second and third line. In order to transform frequency spectrum in an spc ascii format computed by DSM software to time-domain data in a SAC format, you can use 'spcsac', which is also available for download from our GitHub page.

5120.00000000000

256

8.994473019507991E-004 -51.6753000000000 -58.0637000000000

-22.4900000000000 -68.0900000000000 5771.10000000000

0 0.000000000000000E+000 0.000000000000000E+000

0.000000000000000E+000 0.000000000000000E+000

0.000000000000000E+000 0.000000000000000E+000

1 0.000000000000000E+000 0.000000000000000E+000

1.332008193512236E-010 -1.191758660646394E-011

2.936555534747134E-011 -1.099413452624025E-012

2 0.000000000000000E+000 0.000000000000000E+000

1.354412481783691E-010 -3.348437720627575E-011

3.320351537754224E-011 -2.152170537504254E-012

$\vdots$

256 0.000000000000000E+000 0.000000000000000E+000

-1.871403960084000E-010 -1.863536856682632E-011

-1.035879514956147E-009 7.757174274650619E-011

Papers describing the methods used by this software

The following papers explain the theory used by the DSM software to compute synthetic seismograms:

Kawai, K., Takeuchi, N., Geller, R.J., 2006. Complete synthetic seismograms up to 2 Hz for transversely isotropic spherically symmetric media. *Geophysical Journal International*, **164**, 411–424, https://doi.org/10.1111/j.1365-246X.2005.02829.x.

Takeuchi, N., Geller, R.J., Cummins, P.R., 1996. Highly accurate P-SV complete synthetic seismograms using modified DSM operators. *Geophysical Research Letters*, **23**, 1175–1178, `https://doi.org/10.1029/96GL00973`.

Geller, R.J., Takeuchi, N., 1995. A new method for computing highly accurate DSM synthetic seismograms. *Geophysical Journal International*, **123**, 449–470, `https://doi.org/10.1111/j.1365-246X.1995.tb06865.x`.

Cummins, P.R., Geller, R.J., Hatori, T., Takeuchi, N., 1994. DSM complete synthetic seismograms: SH, spherically symmetric, case. *Geophysical Research Letters*, **21**, 533–536, `https://doi.org/10.1029/GL021i007p00533`.

Cummins, P.R., Geller, R.J., Takeuchi, N., 1994. DSM complete synthetic seismograms: P-SV, spherically symmetric, case. *Geophysical Research Letters*, **21**, 1663–1666, `https://doi.org/10.1029/94GL01281`.

Geller, R.J., Ohminato, T., 1994. Computation of synthetic seismograms and their partial derivatives for heterogeneous media with arbitrary natural boundary conditions using the Direct Solution Method. *Geophysical Journal International*, **116**, 421–446, `https://doi.org/10.1111/j.1365-246X.1994.tb01807.x`.

Authorship of software

This software was written and improved by the members of the Global Seismology Group of the University of Tokyo from 1994 to present.

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`https://www.gnu.org/licenses/gpl-3.0.en.html`

Contact us

If you have any questions, please use the Discussions tab on our GitHub page. If you find any bugs, please report them in the Issues tab.