User Guide for Direct Solution Method (DSM) Software

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

The following paper explains 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`.

The program for toroidal synthetics is called "tish," and the program for spheroidal synthetics is called "tipsv." The input parameters for these programs are described below. Following this description, example input files for the toroidal and spheroidal programs are presented and explained.

Input parameters for tish and tipsv

- tlen ··· (floating point) time length (in s) of calculated synthetic seismograms.
- np ··· (integer) the number of points in the frequency domain. The frequency interval is $\Delta f = 1/\mathsf{tlen}$ and the Nyquist (maximum) frequency (in Hz) calculated by this program is $f_{Nyquist}(= \mathsf{np}\cdot\Delta f)$.
- four parameters controlling the error of the synthetics
  - re ··· (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 ··· (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 ··· (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 ··· (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 ··· (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). The form of the cubic splines that gives the elastic modulus or density in a given layer is $P = a_0 + a_1x + a_2x^2 + a_3x^3$, where P is a physical property (density, velocity, or dimensionless parameter) and $x = r/r_{\max}$ 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).
  - physical properties for each layer [rmin, rmax, rho, vpv, vph, vsv, vsh, eta, qmu, qkappa] (floating point). The velocities and η are defined with respect to a reference frequency of 1 Hz, and Q_μ and Q_κ are assumed to be constant in the frequency band being considered.
    - rmin $\cdots$ minimum radius of layer (km)
    - 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; see below)
    - 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 ⋯ velocity of horizontally propagating S (V_{SH}) waves (km/s)
  * eta ⋯ $\eta = F/(A-2L)$ (dimensionless)
  * qmu ⋯ Q_μ (dimensionless)
  * qkappa ⋯ Q_κ (dimensionless)

  For a TI model, the relation between vpv, vph, vsv, vsh, eta and the anisotropic elastic moduli A, C, F, L, N are as follows:

$$\mathsf{vpv} = \sqrt{A/\rho} \qquad \mathsf{vph} = \sqrt{C/\rho}$$
$$\mathsf{vsv} = \sqrt{L/\rho} \qquad \mathsf{vsh} = \sqrt{N/\rho}$$
$$\mathsf{eta} = F/(A-2L)$$

  As discussed above, rho, vpv, vph, vsv, vsh, and eta are given by 3rd order polynominals as is done by Dziewonski & Anderson (PEPI, **25,** 297–356, 1981) for PREM. There are nzone $\times$ 3 lines for the Earth model for tish, and nzone $\times$ 6 lines for tipsv.

- parameters for a point source
  - r0 ⋯ (floating point) 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 ⋯ (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). The time dependence of the moment tensor is assumed to be a δ-function, so the computed displacement seismograms can be also viewed as velocity synthetics for a step-function source.
- parameters for the stations
  - nr ⋯ (integer) the number of stations. nr lines (one for each

station) as follows.

  - lat, lon ··· (floating point) the locations of stations where lat is the latitude, and lon is the longitude in degrees.

- output ··· (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

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
                    3.2000 0.0000 0.0000 0.0000
                    3.2000 0.0000 0.0000 0.0000 600.0
```

$r_{\max}$ is 6371 km

```
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*(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' prepared in our webpage.

```
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
⋮
```

256 0.000000000000000E+000 0.000000000000000E+000

-1.871403960084000E-010 -1.863536856682632E-011

-1.035879514956147E-009 7.757174274650619E-011