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The DMG Quick Reference Manuals

Surface Waves Tomography

Flat and Spherical Earth

QR

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Surface Waves Tomography

The SWT programs are designed for reconstruction of 2D velocity variations from the data on 'path velocities' – average velocities along different paths. The programs are mainly used for surface wave tomography, but may be also applied for estimation of the velocity variations in some other studies in seismology and seismic prospecting, where the waves propagate in 2D space (e.g. in vertical seismic sounding, when receivers are placed in a borehole, and sources are either on the surface or in another borehole).

Required input files

Required input files can be found in **/XDST/Examples/TomoSW/Base**. Copy them into a directory dedicated to the computations. Different computations should be performed in different directories.

Here is what you should have in the directory before you execute the programs:

```
-rwxr-xr-x  1 locvac  staff    710 May  5 23:24 a.gmt
-rwxr-xr-x  1 locvac  staff    921 May  5 23:24 ex.gmt
-rw-r--r--  1 locvac  staff     22 May  5 23:24 param
-rw-r--r--  1 locvac  staff     10 May  5 23:24 period.list
-rw-r--r--  1 locvac  staff   1060 May  5 23:24 period100DST
-rw-r--r--  1 locvac  staff  41975 May  5 23:24 period20DST
-rw-r--r--  1 locvac  staff  18192 May  5 23:24 period40DST
-rwxr-xr-x  1 locvac  staff    758 May  5 23:24 tomc.sh
-rwxr-xr-x  1 locvac  staff    936 May  5 23:24 vel.gmt
```

⚠️➡️It is highly suggested that you store in a dedicated directory (usually named `Base`) a copy of the input files used for each run , so that you can easily retrieve them later to repeat the computation or to use them as a starting point for a modified configuration of the modelling.⬅️⚠️

Description of input files

For the tomographic analysis at one single period two files are required: `param` and `veldata`. They must be named like this, so when dealing with multiple periods, a well defined naming convention should be used, and a shell script must be prepared in order to process all the files.

param

This is the control file written in free format describing the region of study and other 2 parameters governing the tomography process. In the next line is an example for such file:

```
30 2 14 2 6 11 0.15 3
```

30 is the minimum latitude, 2 is the step used for tomography. It means that your region will be gridded with 2° in latitude, 14 is the minimum longitude, 2 is the step for longitude (like in latitude), 6 is number of steps in latitude, 11 number of steps in longitude, 0.15 parameter of regularization and finally 3 is Sigma which is the parameter used for data selection. Where the product of Sigma and the Mean Unaccounted Residual is calculated and if it is greater than the final residuals the path is eliminated (it is recommended to be 3).

The parameter of regularization depends on accuracy of the data (path velocities); the recommended values are 0.1 – 0.3. The larger is the value of the regularization parameter, the larger is smoothness of the resulting velocity distribution.

veldata

This file contains epicenter and station coordinates of every path (1:4 columns ”lat long Lat Long) and corresponding velocities at the selected period (5th column) in addition to the number of paths used to obtain this velocity (6th column). The file is read in free format, so space- or tab-separated files can be used.

```
  29.670   34.951   38.12   23.60     4.253 1
  29.670   34.951   41.94   20.40     3.835 1
  29.927   31.829   37.00   35.84     3.813 1
  29.927   31.829   38.08   29.00     3.612 1
  29.927   31.829   42.80   17.94     3.780 1
  29.927   31.829   43.09   12.82     4.036 1
  32.817   -4.614   43.09   12.82     3.597 1
  35.867   14.523   34.29   38.71     3.972 1
  35.867   14.523   36.19   35.94     3.990 1
  35.867   14.523   38.10   30.14     4.137 1
  35.867   14.523   40.62   32.97     3.708 1
  45.279    4.542   37.20   20.84     3.978 1
  48.216    7.158   39.06   24.24     3.651 1
  48.216    7.158   40.15   21.69     3.792 1
  49.777   17.543   40.15   21.69     3.930 1
 28.83  34.80  11.53  42.85   3.50 1
 35.05  32.28  49.69  11.22   3.69 1
 35.06  26.66  48.33   8.33   3.77 1
 35.23  -3.96  34.98  24.89   3.69 1
 36.89   3.78  34.96  33.33   3.77 1
 36.89   3.78  38.31  38.43   3.65 1
 39.18  20.74  49.66   6.15   3.79 1
 42.45  43.67  29.93  31.83   3.60 1
30.129 57.589 43.955 42.686 3.684  1
33.918 59.430 43.955 42.686 3.813  1
```

So `veldata` has to be generated for every single period you need to run tomography at. Usually, several files are prepared, one for each considered period, with the period appearing in their name. Then, a script loops through the files, copying each of them in turn to `veldata`, and renaming the output files accordingly.

The above means, that the dispersion curves obtained along the different paths must be sampled at common periods, before running the tomography software. How this is done is left to the user, Some programs exist to interpolate and resample the dispersion curves (`interpola`), but have been prepared for specific dispersion curve formats, and have not been thoroughly tested yet.

Tomography program execution

Program *`tomo04.out`* is the core program used for the computations.

`tomo04.out` will read `param` and `veldata` files for one period and will generate the local velocity, mean velocity and resolving power files (locvel, meanvel, respow respectively).

During the execution of *`tomo04.out`* it appears the “number of paths” and whether some paths are eliminated (for the presence of the parameter SGM): if at least one path is eliminated, the number of the paths eliminated and how many remain are shown; the program restarts and calculates another time the mean velocity. The loop ends when no path is eliminated and in this case the calculated knot of the grid, from (kx=1,ky=1) to (kx=13, ky=15) appears on the screen, step by step.

Description of output files

Three files are generated by the execution of *`tomo04.out`*:

locvel

This file contains the geographical coordinates (lat and long) of the knots, the velocities and the percent deviation velocities (in the last column) calculated by the following equation:

$$\frac{dU(i)}{U} = \left(\frac{V_{mean} - V(i)}{V(i)}\right)$$

An example is given here:

```
30.0   14.0  3.701  -2.644
30.0   16.0  3.738  -1.624
30.0   18.0  3.772  -0.723
30.0   20.0  3.800   0.020
30.0   22.0  3.821   0.580
30.0   24.0  3.835   0.945
30.0   26.0  3.841   1.093
30.0   28.0  3.837   0.982
30.0   30.0  3.820   0.540
30.0   32.0  3.784  -0.406
30.0   34.0  3.791  -0.215
32.0   14.0  3.729  -1.888
32.0   16.0  3.774  -0.670
32.0   18.0  3.814   0.393
32.0   20.0  3.847   1.246
32.0   22.0  3.872   1.889
32.0   24.0  3.890   2.336
32.0   26.0  3.900   2.584
32.0   28.0  3.900   2.587
32.0   30.0  3.870   1.843
32.0   32.0  3.855   1.441
32.0   34.0  3.789  -0.258
34.0   14.0  3.754  -1.205
34.0   16.0  3.815   0.409
34.0   18.0  3.865   1.711
34.0   20.0  3.903   2.669
34.0   22.0  3.931   3.365
34.0   24.0  3.953   3.901
34.0   26.0  3.971   4.321
34.0   28.0  3.949   3.797
34.0   30.0  3.905   2.718
34.0   32.0  3.837   0.990
34.0   34.0  3.787  -0.313
36.0   14.0  3.766  -0.883
36.0   16.0  3.873   1.918
36.0   18.0  3.935   3.447
36.0   20.0  3.976   4.439
36.0   22.0  4.000   5.019
36.0   24.0  4.022   5.550
36.0   26.0  3.996   4.917
36.0   28.0  3.943   3.637
36.0   30.0  3.843   1.139
36.0   32.0  3.805   0.163
36.0   34.0  3.776  -0.608
38.0   14.0  3.749  -1.324
38.0   16.0  3.819   0.512
38.0   18.0  3.880   2.093
38.0   20.0  3.919   3.068
38.0   22.0  3.912   2.879
38.0   24.0  3.903   2.658
38.0   26.0  3.881   2.121
38.0   28.0  3.830   0.804
38.0   30.0  3.769  -0.801
38.0   32.0  3.731  -1.812
38.0   34.0  3.704  -2.566
40.0   14.0  3.804   0.117
40.0   16.0  3.859   1.547
40.0   18.0  3.871   1.867
40.0   20.0  3.831   0.837
40.0   22.0  3.774  -0.661
40.0   24.0  3.753  -1.217
40.0   26.0  3.733  -1.779
40.0   28.0  3.711  -2.367
40.0   30.0  3.692  -2.888
40.0   32.0  3.683  -3.148
40.0   34.0  3.678  -3.285
```

meanvel

This file contains the mean velocity and other values obtained processing the data relative to a single period.

With *tomo04.out*, when a path is rejected, the values of Mean velocity, Initial residual and Unaccounted residual are recalculated, and the rejected paths are indicated.

When no path is eliminated, the last values of Mean velocity, Initial residual, Unaccounted residual are the values to consider for the further processing.

The expressions for the mentioned quantities are describe in the following:

A control matrix of the values:

$$(xx2, xx1, yy2, yy1, ss, t, sf, tf)$$

is calculated for each epicenter-station path at the fixed period considered.

xx1,**yy1** and **xx2**, **yy2** are the transformed coordinates respectively of the station and of the epicenter, and are calculated by the following equations:

$$a = \frac{pi}{180} = \frac{3.14159265}{180}$$
$$yy1(i) = yy1(i) \times a$$
$$yy2(i) = yy2(i) \times a$$
$$xx1(i) = (90 - xx1(i)) \times a$$
$$xx2(i) = (90 - xx2(i)) \times a$$

ss is the distance between the two points;

t is the time employed to cover the path with the velocity at the fixed period;

sf and **tf** are two sums on the number **n** of paths defined as follows

$$ss(i) = \sqrt{(xx2(i) - xx1(i))^2 + (yy2(i) - yy1(i))^2}$$
$$t(i) = \frac{ss(i)}{V(i)}$$
$$sf = \sum_{i=1}^{n} (ss(i) \times t(i))$$
$$tf = \sum_{i=1}^{n} (t(i))^2$$

Mean Velocity V_{mean} is the average of the velocities of all the knots of the grid at that fixed period calculated by:

$$V_{mean} = \frac{\sum_{i=1}^{n} (ss(i) \times t(i))}{\sum_{i=1}^{n} (t(i))^2}$$

Initial Residual MSR is the root mean square of the time delay calculated by:

$$\sqrt{\frac{\sum_{i=1}^{n} (t(i) - t0(i))^2}{n}}$$

$$t0(i) = \frac{ss(i)}{V_{mean}}$$

Unaccounted Residual MSR is calculated by the following equation where α is the fixed parameter of regularization in the file `param`, ndat(i) is the number of data corresponding to the i-th path, n is the number of paths:

$$\sqrt{\frac{\sum_{i=1}^{n}(aa(i)\times\alpha\times\frac{spur}{ndat(i)})^2}{n}}$$

$$Smat(i,j)=\frac{DisplacementMatrix(i,j)}{V_{mean}^2}$$

$$spur=\frac{\sum_{i=1}^{n}Smat(i,i)}{n}$$

$$aa(i)=\sum_{j=1}^{n}Smat(i,j)\times dt(j)$$

An example of `meanvel` file is given below:

```
    Mean velocity=   3.79912
 Initial residual   21.32
Unaccounted residual   12.42

   1    28.847   -39.652
   2    -0.769    -4.917
   3     1.670    -1.577
   4   -15.504    12.670
   5   -11.432     2.494
   6    17.811   -34.786
   7    -1.644    15.128
   8    11.436   -27.042
   9    11.076   -25.553
  10    19.735   -31.020
  11   -11.159     9.739
  12    15.442   -20.568
  13   -11.758    18.058
  14     4.224     0.559
  15    12.282    -9.956
  16   -14.737    46.825
  17    -9.496    17.847
  18    -5.327     4.164
  19    -2.770     7.838
  20    -6.744     0.864
  21   -13.903    27.139
  22     2.716     0.825
  23   -13.920    19.553
  24     0.795   -11.997
  25    15.267   -31.884
  29.670    34.951    38.120    23.600      4.25   1
  29.670    34.951    41.940    20.400      3.83   1
  29.927    31.829    37.000    35.840      3.81   1
  29.927    31.829    38.080    29.000      3.61   1
  29.927    31.829    42.800    17.940      3.78   1
  29.927    31.829    43.090    12.820      4.04   1
  32.817    -4.614    43.090    12.820      3.60   1
  35.867    14.523    34.290    38.710      3.97   1
  35.867    14.523    36.190    35.940      3.99   1
  35.867    14.523    38.100    30.140      4.14   1
  35.867    14.523    40.620    32.970      3.71   1
  45.279     4.542    37.200    20.840      3.98   1
  48.216     7.158    39.060    24.240      3.65   1
  48.216     7.158    40.150    21.690      3.79   1
  49.777    17.543    40.150    21.690      3.93   1
  28.830    34.800    11.530    42.850      3.50   1
  35.050    32.280    49.690    11.220      3.69   1
  35.060    26.660    48.330     8.330      3.77   1
  35.230    -3.960    34.980    24.890      3.69   1
  36.890     3.780    34.960    33.330      3.77   1
  36.890     3.780    38.310    38.430      3.65   1
  39.180    20.740    49.660     6.150      3.79   1
  42.450    43.670    29.930    31.830      3.60   1
  30.129    57.589    43.955    42.686      3.68   1
  33.918    59.430    43.955    42.686      3.81   1
-44.5952     0     0
-40.1356     1     0
-35.6761     1     0
-31.2166     2     0
```

```
-26.7571     2     0
-22.2976     1     0
-17.8381     0     0
-13.3785     1     7
 -8.9190     1     2
 -4.4595     1     2
  0.0000     4     4
  4.4595     2     2
  8.9190     2     1
 13.3785     2     4
 17.8381     3     2
 22.2976     0     0
 26.7571     1     1
 31.2166     0     0
 35.6761     0     0
 40.1356     0     0
 44.5952     0     0
```

At first, Mean Velocity, Initial Residual and Unaccounted residuals are written to `meanvel`.

Then a first block of data is listed, one record for each path, containing the values for dtc(i) and dt(i) for each path i.

After that, the original `veldata` file content is reported, only for the retained paths.

Finally, the third block of data contains the values required for the production of a histogram for the time delay are added. In the first column the time delay steps are written, in the second one how many paths have the value of

$$dtc(i) = \left(aa(i) \times \alpha \times \frac{spur}{ndat(i)}\right)$$

in the range indicated by the steps, in the third one how many paths have the value of

$$dt(i) = (t(i) - t0(i))$$

in that same range.

respow

This file contains the geographical coordinates (**long** and **lat**) of the point, the values of the velocity **V** calculated at that knot, the mean averaging length **a**, the stretching **ex**=2b/a, the azimuth of the poorest resolution **alp** and the standard error of the solution **MSR** are presented knot by knot:

```
 14.0   30.0  3.701   2417.3   0.6367    20.79   0.0309
 16.0   30.0  3.738   2319.4   0.5909    18.88   0.0296
 18.0   30.0  3.772   2213.5   0.5446    16.92   0.0286
 20.0   30.0  3.800   2094.0   0.4920    15.35   0.0281
 22.0   30.0  3.821   1953.9   0.4382    14.18   0.0286
 24.0   30.0  3.835   1783.5   0.3976    13.20   0.0305
 26.0   30.0  3.841   1571.2   0.3851    10.16   0.0344
 28.0   30.0  3.837   1327.3   0.4236     4.37   0.0403
 30.0   30.0  3.820   1062.4   0.5773   175.08   0.0480
 32.0   30.0  3.784    866.7   0.8401   167.30   0.0556
 34.0   30.0  3.791    916.8   1.0308   156.41   0.0532
 14.0   32.0  3.729   1801.3   0.4348    23.09   0.0336
 16.0   32.0  3.774   1725.3   0.4236    20.97   0.0324
 18.0   32.0  3.814   1640.6   0.3947    17.81   0.0315
 20.0   32.0  3.847   1550.4   0.3382    14.38   0.0308
 22.0   32.0  3.872   1442.4   0.2691    11.28   0.0308
 24.0   32.0  3.890   1295.7   0.2046     5.95   0.0326
 26.0   32.0  3.900   1099.0   0.1834   174.11   0.0378
 28.0   32.0  3.900    850.0   0.3067   156.17   0.0468
 30.0   32.0  3.870    610.6   0.6125   147.78   0.0575
 32.0   32.0  3.855    517.2   0.6033   150.09   0.0608
 34.0   32.0  3.789    644.4   0.4490   164.62   0.0573
 14.0   34.0  3.754   1234.7   0.2237    56.71   0.0385
 16.0   34.0  3.815   1155.7   0.2398    50.35   0.0386
 18.0   34.0  3.865   1072.2   0.1871    47.74   0.0387
 20.0   34.0  3.903   1004.6   0.0995    64.17   0.0377
 22.0   34.0  3.931    934.3   0.1449   101.29   0.0367
 24.0   34.0  3.953    832.5   0.3024   115.96   0.0378
 26.0   34.0  3.971    683.4   0.5775   125.43   0.0433
```

```
  28.0   34.0  3.949    535.9   0.9176    130.79   0.0504
  30.0   34.0  3.905    462.1   0.9353    133.73   0.0547
  32.0   34.0  3.837    530.8   0.4353    121.81   0.0511
  34.0   34.0  3.787    534.4   0.3148     47.33   0.0598
  14.0   36.0  3.766    777.9   1.0050     90.41   0.0466
  16.0   36.0  3.873    673.8   0.9945     88.23   0.0517
  18.0   36.0  3.935    598.4   0.9248     87.77   0.0518
  20.0   36.0  3.976    572.5   0.9130     90.18   0.0488
  22.0   36.0  4.000    550.9   0.9484     95.98   0.0452
  24.0   36.0  4.022    501.3   1.0292    107.70   0.0463
  26.0   36.0  3.996    454.3   1.2075    117.57   0.0496
  28.0   36.0  3.943    472.7   1.0549    118.29   0.0483
  30.0   36.0  3.843    487.5   0.6802    117.99   0.0532
  32.0   36.0  3.805    596.3   0.5778     98.53   0.0506
  34.0   36.0  3.776    631.0   0.4511     78.17   0.0545
  14.0   38.0  3.749    723.8   0.7708     90.74   0.0438
  16.0   38.0  3.819    677.2   0.7197     98.20   0.0420
  18.0   38.0  3.880    598.6   0.7219    101.54   0.0437
  20.0   38.0  3.919    530.5   0.8250    100.40   0.0461
  22.0   38.0  3.912    480.5   0.8301    102.40   0.0467
  24.0   38.0  3.903    448.2   0.7919    111.54   0.0496
  26.0   38.0  3.881    480.2   0.6984    110.81   0.0484
  28.0   38.0  3.830    537.5   0.6461    111.09   0.0485
  30.0   38.0  3.769    629.3   0.5256    105.69   0.0485
  32.0   38.0  3.731    747.9   0.5381     93.87   0.0465
  34.0   38.0  3.704    808.5   0.5059     83.57   0.0496
  14.0   40.0  3.804    696.2   0.5035    104.87   0.0435
  16.0   40.0  3.859    628.3   0.7284    118.88   0.0475
  18.0   40.0  3.871    604.9   0.8093    124.35   0.0443
  20.0   40.0  3.831    593.3   0.8650    128.64   0.0415
  22.0   40.0  3.774    543.2   0.8839    129.29   0.0467
  24.0   40.0  3.753    556.3   0.6889    121.61   0.0470
  26.0   40.0  3.733    581.4   0.5450    114.91   0.0493
  28.0   40.0  3.711    650.9   0.5082     99.99   0.0517
  30.0   40.0  3.692    782.6   0.5571     89.14   0.0515
  32.0   40.0  3.683    945.7   0.5375     85.94   0.0473
  34.0   40.0  3.678   1075.8   0.4907     80.86   0.0450
```

Script execution for considering several periods

tomc.sh

This is the main script made available for the purpose of computing the tomography for several periods with a single command.

```
a=0

# prepare the .cpt files for plotting

makecpt -T-29/20/0.1 -Cseis > cpt_vel
makecpt -T0.0/1.5/0.1 -Ccool > cpt_res

# read periods from file period.list
# velocity data expected to be found in files named period*DST

while read line

do
      export i=`echo  "$line"`

      # prepare the path files for plotting
      awk '{print $2, $1, "\n", $4, $3, "\n", ">"}' period"$i"DST > path$i.dat
      echo $i

      # copy the input velocity data to the required "veldata" file
      cp period"$i"DST veldata

      # run the tomography program for the requested period
      tomo04.out

      # rename the output files to have the period in their name
      mv respow ResPow$i.dat
      mv locvel Vel$i.dat
      mv meanvel MeanVel$i.dat

      # do the plotting
```

```
      a.gmt $i
      ex.gmt $i
      vel.gmt $i

done < period.list
```

For each period, the script properly copies and renames the input/output files as expected by program *tomo04.out*, and plot the results by calling scripts *a.gmt*, *ex.gmt* and *vel.gmt*. The parameters describing the region coordinates and other plot characteristics must be adapted from case to case in **.gmt* scripts.

period.list

This file must contain the list of periods for which the tomography must be executed. For instance:

```
20
40
100
```

period*DST

For each considered period, the user must prepare one file, containing the velocity along the paths.

For 20 s:

```
  29.670   34.951   31.54   27.64     2.783 1
  29.670   34.951   33.76   25.58     2.888 1
  29.670   34.951   34.44   20.18     2.243 1
  29.670   34.951   34.82   24.28     1.837 1
  29.670   34.951   35.59   21.09     2.413 1
  29.670   34.951   36.81   35.25     2.287 1
  29.670   34.951   38.10   30.14     2.501 1
  29.670   34.951   38.12   23.60     2.389 1
  29.670   34.951   40.95   31.57     2.793 1
  29.670   34.951   41.94   20.40     2.603 1
  29.670   34.951   42.60   26.51     2.498 1
  29.927   31.829   34.00    8.24     2.738 1
...
...
```

For 40 s:

```
  29.670   34.951   33.76   25.58     4.223 1
  29.670   34.951   34.44   20.18     3.300 1
  29.670   34.951   35.59   21.09     3.344 1
  29.670   34.951   36.81   35.25     2.827 1
  29.670   34.951   38.10   30.14     3.403 1
  29.670   34.951   38.12   23.60     3.292 1
  29.670   34.951   40.95   31.57     3.533 1
  29.670   34.951   41.94   20.40     3.500 1
  29.670   34.951   42.60   26.51     3.512 1
  29.927   31.829   34.00    8.24     3.684 1
...
...
```

For 100 s:

```
  29.670   34.951   38.12   23.60     4.253 1
  29.670   34.951   41.94   20.40     3.835 1
  29.927   31.829   37.00   35.84     3.813 1
  29.927   31.829   38.08   29.00     3.612 1
  29.927   31.829   42.80   17.94     3.780 1
  29.927   31.829   43.09   12.82     4.036 1
  32.817   -4.614   43.09   12.82     3.597 1
  35.867   14.523   34.29   38.71     3.972 1
  35.867   14.523   36.19   35.94     3.990 1
  35.867   14.523   38.10   30.14     4.137 1
...
...
```

These files must be properly named. In the example, script *tomc.sh* expects the files to be named `period20DST`, `period40DST` and `period100DST`.