User's manual for ***tomoDD-SE (Regional-Scale DD tomography)*** for determining event locations and velocity structure from both absolute and differential data

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1. Description

TomoDD is a computer program that realizes the double-difference (DD) seismic tomography method. DD tomography makes use of both absolute and differential arrival times to jointly determine event locations and velocity structure. By taking into account path anomaly biases between event pairs explicitly, DD tomography has the ability to determine the absolute and relative event locations and velocity structure accurately with the direct use of the more accurate differential arrival times (from catalog and/or waveform cross correlation (WCC) data). TomoDD adopts a hierarchical weighting scheme to combine different data types into one system. Initially, higher weighting is applied to catalog absolute times to image the velocity structure at a large scale, followed by applying higher weighting to the catalog differential times and/or WCC data (if available) in order to refine the event locations and the velocity structure near the source region. **TomoDD** is modified from the double-difference location code **hypoDD** (Waldhauser 2001). For both methods, please refer to Waldhauser & Ellsworth(2000), and Zhang & Thurber (2003) for details. The users are strongly recommended to be familiar with hypoDD before using tomoDD.

TomoDD uses a regular three-dimensional grid to represent the velocity model, the same as simul2000 algorithm (Thurber and Eberhart-Phillips, 1999). The travel times between events and stations are calculated using the pseudo-bending ray tracing algorithm (Um and Thurber, 1987). This version of tomoDD is only applicable to the local scale tomography problem (<100 km). For the larger scale, please refer to another computer program tomoFDD that deals properly with the spherical shape of the Earth.

2. Install and syntax

This program has been tested successfully on both Sun/Unix and linux platforms. Before executing the *Makefile* (Makefile.gfortran for gfortran and gcc compilers or Makefile.intel for Intel icc or ifort compilers) to compile and install the program, change the array dimensions in *tomoDD.inc* and *ray_common.inc* according to the solved problem and computer memory space. You should also choose correct compiling options for the corresponding compilers. **There is a README file that is helpful before compiling the program.**

Syntax to run the program

tomoDD

In the new version (tomoDD-SE), it first outputs some information about the Software License Agreement before running the program. Here is a screen output from tomoDD-SE:

> Regional-Scale Double-Difference Seismic Tomography (tomoDD-SE)
> ©2007-2015 Wisconsin Alumni Research Foundation.
> All rights reserved.
> By running this program, you represent and warrant to WARF that you have read, understand and agree to the terms of the Agreement enclosed in copyright.txt and that you have full authority to enter into this Agreement without obtaining any other approvals.

The control file refers to tomoDD.inp that contains the control parameters for running the program.

3. Array dimensions in *tomoDD.inc* and *ray_common.inc (in the directory include)*

In *tomoDD.inc:*

It is only necessary to change MAXEVE, MAXSTA, MAXDATA, MAXNODE, and MAXND to satisfy the solved problem and computer memory space. For other **hypoDD** parameters MAXEVE0, MAXDATA0, MAXLAY, MAXCL, **tomoDD** does not use them any more and you can leave them unchanged.

MAXEVE: maximum number of events used in the inversion.
MAXSTA: maximum number of stations used in the inversion.
MAXDATA: maximum number of phase data including both absolute and differential data.
MAXNODE: maximum number of inversion nodes for each ray to sample (~4*MAXNZ).
MAXND: it is used to control the maximum number of nonzero slowness partial derivatives (MAXND*MAXDATA) (<4*MAXNZ).

In *ray_common.inc*:

The following parameters control the number of grid nodes used to represent the Earth in the three directions.

maxnx---maximum number of nodes in x direction
maxny--- maximum number of nodes in y direction
maxnz--- maximum number of nodes in z direction
mxpari--- maximum number of parameters to invert for.

maxpar--- maximum number of potential parameters that could be included in the inversion. For **tomoDD**, mxpari is equal to maxpar. Both of them should be at least equal to iuses*(maxnz-2)*(maxny-2)*(maxnz-2).

4. Control file (*tomoDD-SE.inp*)

This file is an interface for the users to control how tomoDD runs, which has a similar structure to hypoDD.inp, as follows. Sentences staring with a star indicate the commentaries.

```
* tomoDD-SE.inp:
*--- input file selection
* cross correlation diff times:
dt.cc
*
*catalog P diff times:
dt.ct
*
* event file:
event.dat
*
* station file:
station.dat
*
*--- output file selection
* original locations:
tomoDD.loc
* relocations:
tomoDD.reloc
* station information:
tomoDD.sta
* residual information:
tomoDD.res
* source paramater information:
*tomoDD.src

*DWS and velocity structure
tomoDD.vel
*final Vp model
Vp_model.dat
*final Vs model
Vs_model.dat
* catalog absolute data
absolute.dat
*
*--- data type selection:
* IDAT:  0 = synthetics; 1= cross corr; 2= catalog; 3= cross & cat
* IPHA: 1= P; 2= S; 3= P&S
* DIST:max dist [km] between cluster centroid and station
* IDAT   IPHA   DIST
    2     3      40
*
*--- event clustering:
* OBSCC:    min # of obs/pair for crosstime data (0= no clustering)
```

```
* OBSCT:    min # of obs/pair for network data (0= no clustering)
* Air_dep: the shallowest depth of the earthquake
* OBSCC  OBSCT  Air_dep
    0      0     -0.0
*
*--- solution control:
* ISTART:       1 = from single source; 2 = from network sources
* ISOLV:        1 = SVD, 2=lsqr
* NSET:   number of sets of iteration with specifications following
* wlat, wlon:   the location (latitude and longitude) of the
*               coordinate center
* CC_format:    the format of dt.cc
* weight1, weight2, weight3: the smoothing parameters of the
*           direction of longitude, latitude and depth
*
*  ISTART  ISOLV  NSET
     2       2     4
* iuses iuseq invdel  stepl
    2     0     0       5
* wlat   wlon   rota
  30.3   103.3   0
* weight1 weight2  weight3  CC_format
    40      40       15        1
*
*--- data weighting and re-weighting:
* NITER:             last iteration to used the following weights
* WTCCP, WTCCS:            weight cross P, S
* WTCTP, WTCTS:            weight catalog P, S
* WRCC, WRCT:  residual threshold in sec for cross, catalog data
* WDCC, WDCT:  max dist [km] between cross, catalog linked pairs
* WTCD:   relative weighting between absolute and differential data
* DAMP:              damping (for lsqr only)
* THRES: Scalar used to determine the DWS threshold values
*       ---  CROSS DATA ----- ----CATALOG DATA ----
* NITER WTCCP WTCCS WRCC WDCC WTCTP WTCTS WRCT WDCT WTCD DAMP JOINT THRES
  3      0.01  0.01 -9  -9   0.1   0.08    -9   -9   10  300   1    0.2
  3      0.01  0.01 -9  -9   0.1   0.08     8   -9   10  300   1    0.2
  3      0.01  0.01 -9  -9   1.0   0.80     6   -9  0.01 250   1    0.2
  3      0.01  0.01 -9  -9   1.0   0.80     6   20  0.01 250   1    0.2
  3         1  0.8  -9  -9  0.01  0.008     6   20  0.1  200   1    0.2
  3         1  0.8   6  -9  0.01  0.008     6   20  0.1  200   1    0.2
**
*--- event selection:
* CID:   cluster to be relocated (0 = all)
* ID:    cuspids of event to be relocated (8 per line)
* CID
    1
* ID
```

Parameters description for file *tomoDD.inp*

CC_FORMAT--- cross-correlation data format: 1= hypoDD format; 2= tomoDD format.

WGH1, WGH2, WGH3--- 1st order smoothing constraints applied to slowness changes in X, Y and Z directions, respectively.

AIR_DEPTH--- The depth above it is defined as air. This is for the purpose of defining air quakes, which will be removed from inversion.

IUSES---1= invert Vp only; 2=invert both Vp and Vs.

LAT_ORIG, LON_ORIG: user defined coordinate center.

ROTA: coordinate system rotation angles (anticlockwise: -; clockwise: +).

Weighting parameters:

WTCCP, WTCCS:	weight cross P, S
WTCTP, WTCTS:	weight catalog P, S
WRCC, WRCT:	residual threshold in sec for cross, catalog data
WDCC, WDCT:	max dist [km] between cross, catalog
WTCD :	relative weighting between absolute and differential catalog data.

Joint-----0 event relocation only
1 simultaneous inversion of event locations and velocity structure

THRES---Derivative Weight Sum (DWS) scalar for both Vp and Vs. The actual DWS threshold values are THRES times the average P-wave and S-wave DWS values. If a node has a DWS value less than THRES, this node is fixed during this inversion.

DAMP--- damping value for LSQR. The damping value is normally chosen to make the condition number to be around ~60.

5. Input files

5.1 Cross-correlation data file (*dt.cc*)

This file stores differential time data from waveform cross-correlation techniques.

For CC_format=1 (**hypoDD** format):

Each event pair is listed by a header line and followed by lines with observations, as follows,
ID1, ID2, OTC
STA, DT, WGHT, PHA
…
ID1, ID2, OTC
STA, DT, WGHT, PHA
…

This file can be obtained using BCSEIS (Bispectrum Cross-correlation package for SEISmic events) (Du and Thurber, 2004).

For CC_format=2 (**tomoDD** format):
Each line lists one event pair and their associated observations (it assumes that the origin times from waveform data are the same as catalog data), as follows,
ID1, ID2, STA, DT, WGHT, PHA

This data format is useful when users arrange the cross-correlation data station by station.
5.2 Differential catalog data file (*dt.ct*)

This file has exactly the same format as **hypoDD** code. Each event pair is listed by a header line, followed by *nobs* lines of observations.

#, ID1, ID2
STA, TT1, TT2, WGHT, PHA
…

This file can be produced using the package ph2dt released with hypoDD code (Waldhauser, 2001).

5.3 Absolute catalog data file (*absolute.dat*)

This file is **new** to **tomoDD**. Each event listed by a header line, followed by *nobs* of observations.

#, ID1
STA, TT1, WGHT, PHA
…

The awk file ph2abs.awk can be used to produce the absolute data from the phase file phase.dat that is used to produce the catalog differential data using program ph2dt.

5.4 Station input file (*station.dat*)

STA, LAT, LON, DEP

Each line contains station name, latitude, longitude and depth of a given station. Station depth is in METRES (+ above sea level; - below sea level).

5.5 Event input file (*event.dat*)

One event per line:
DATE, TIME, LAT, LON, DEP, MAG, EH, EV, RMS, ID, TYPE

The only difference between **tomoDD** and **hypoDD** is that *event.dat* in the former algorithm contains additional event type information for each event.

TYPE--- 0=earthquake data; 1=shot data; 2=blast data.

5.6 Starting velocity model (*MOD*).

The file name MUST be *MOD*. It has the following formats (simul2000):

bld, nx, ny, nz
xn(1),xn(2), ..., xn(nx)
yn(1),yn(2), ..., yn(ny)
zn(1),zn(2), ..., zn(nz)
Vp(1,1,1), Vp(2,1,1),… …, Vp(nx,1,1)
Vp(1,2,1), Vp(2,2,1),… …, Vp(nx,2,1)
… …
Vp(1,ny,1),Vp(2,ny,1),… …, Vp(nx,ny,1)
… …
Vp(1,ny,nz), Vp(2,ny,nz),… …, Vp(nx,ny,nx)
Vp/Vs(1,1,1),Vp/Vs(2,1,1),… …,Vp/Vs(nx,1,1)
Vp/Vs(1,2,1),Vp/Vs(2,2,1),… …,Vp/Vs(nx,2,1)
… …
Vp/Vs(1,ny,1), Vp/Vs(2,ny,1),… …, Vp/Vs(nx,ny,1)
… …
Vp/Vs(1,ny,nz), Vp/Vs(2,ny,nz),… …,Vp/Vs(nx,ny,nx)

Parameters

BLD--- Must be 1 or 0.1. Increment size for *ixkms*, *iykms*, and *izkms*.
NX, NY, and NZ---number of grid nodes in X, Y and Z directions.

XN--- grid node positions in X direction.
YN--- grid node positions in Y direction.
ZN--- grid node positions in Z direction.

Note that xn(1), xn(nx), yn(1), yn(ny), zn(1) and zn(nz) are boundary nodes that must be large enough to hold all the events and stations.

6. Output files

6.1 Velocity model output (*tomoDD.vem, Vp_model.dat and Vs_model.datl*)

In the first part of this file, it contains the starting velocity model information. Then it contains P-wave and S-wave DWS and velocity structure after each iteration (the same format as *MOD*). The final velocity models are stored in Vp_model.dat and Vs_model.dat for P and S waves, respectively.

6.2 Initial hypocenter output (*tomoDD.loc*)

It has exactly the same format as *hypoDD.loc* in **hypoDD**.
One event per line
ID, LAT, LON, DEPTH, X, Y, Z, EX, EY, EZ, YR, MO, DY, HR, MI, SC, MAG, CID

6.3 Relocated hypocenter output (*tomoDD.reloc*)

It has exactly the same format as *hypoDD.reloc* in **hypoDD**.
One event per line
ID, LAT, LON, DEPTH, X, Y, Z, EX, EY, EZ, YR, MO, DY, HR, MI, SC, MAG, NCCP, NCTP, NCTS, RCC, RCT, CID

6.4 Station residual output (*tomoDD.sta*)

It has exactly the same format as *hpoDD.sta* in **hypoDD**.
One station per line:
STA, LAT, LON, DIST, AZ, NCCP, NCCS, NCTP, NCTS, RCC, RCT, CID

6.5 Data residual output (*tomoDD.res*)

It has exactly the same format as *hypoDD.res* in **hypoDD**.
One observation per line:
STA, DT, ID1, ID2, IDX, WGHT, RES, WT, DIST

6.6 Takeoff angle output (tomoDD.src)

It has similar format as *hypoDD.src* in **hypoDD** except that there is one more takeoff angle for S waves. The takeoff angle is positive if ray path is downward at the source and negative if the ray path is upward.

For each line, the following parameters are listed:

Event_ID, event_lat, event_lon, station_name, epicental distance, azimuth, Source_lat, source_lon, P-wave takeoff angle, S-wave takeoff angle

6.7 Run time information output

Run time information is stored *tomoDD.log*.

7. Other auxiliary programs (in Util)

Some scripts and corresponding notes can be found in the **scripts/** folder.

References

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