

# FMTOMO Extras

## INTRODUCTION

This brief file briefly describes how to install and operate several programs that allow:

- Fully non-linear source relocation together with velocity inversion
- Direct inversion for  $V_p/V_s$  ratio

It essentially operates as an add-on package to FMTOMO.

## LIMITATIONS

At this point, the code will only work for local earthquake tomography (i.e. sources lies inside model volume), and with media containing no internal interfaces. If this is too restrictive, then you are advised to use FMTOMO, which does allow for source relocation, but under a locally linear assumption.

## ASSUMPTIONS

It is assumed that you are familiar with the FMTOMO package, which you will need to be in order to use FMTOMO Extras. It is assumed that FMTOMO is installed and properly linked on your system.

## INSTALLATION

To install, edit line 2 of the "compile\_all" script so that it points to your favourite Fortran 90 compiler (it is well tested with gfortran). Then simply execute "compile\_all" at the command line. All executables will be placed in the subdirectory "bin", which can then be placed anywhere and accessed by editing your .bashrc file or other startup shell script.

NOTE: Although some programs and their actions are similar to that found in the original FMTOMO package (e.g. grid3dgi, synthdata1, gmtslicei), they have been modified and may have different input requirements. Thus, they have been renamed by placing an "I" at the end. This means that the Extras package can be installed without interfering with the original FMTOMO package, although the Extras package DOES require FMTOMO to be installed in order to work (although not vice versa).

## CODE STRUCTURE

Two examples have been provided with the distribution - "observed" and "synthetic"; in the former case, we are dealing with an observed P-wave and S-wave dataset, and in the latter case, the corresponding checkerboard resolution test. The directory structure of these examples is as follows:

- In the root directory, there are three subdirectories plus a number of files
- invert\_p contains all the FMTOMO files required to do an inversion of the P-wave data for  $V_p$ -structure. However, the additional element is that instead of tomo3d, a script called tomo3di is used, which calls a program called "gridloc" to perform a non-linear inversion for source relocation between each inversion step for velocity structure. Thus, executing tomo3di will invert all P-arrival times for  $V_p$  and source location.
- invert\_s is exactly the same as invert\_p except for S-waves.
- !The subdirectory vpv\_s contains all the files necessary to perform the direct inversion of P and S-times for  $V_p/V_s$  velocity structure.

## RUNNING THE CODE

The following procedure provides a general outline of how to run the new software, once all input files are in place:

1. Under invert\_p/mkmodel and invert\_s/mkmodel, make sure that obsdatai has been run and otimes.dat and src.dat have been created. Copy these files into invert\_p and invert\_s directories, ensuring that otimes.dat is renamed otimesref.dat. Also, receivers.in needs to be copied across too and renamed receiversref.in (these are actually the source locations that will be adjusted during the inversion process). As with FMTOMO, sources.in needs to be copied across, as well as the the velocity/interface grid files and propagation grid information.
2. Once these steps have been done, it should be possible to run tomo3di in either invert\_p or invert\_s to separately carry out inversion and relocation for the P and S-wave data respectively.
3. In order to invert for both Vp and Vs and jointly relocate (otherwise, if only step 2 is done, then the P-sources and S-sources will probably be in different locations when in fact that should not be the case if a receiver detected both a P and S-wave from the same source) move to the root directory, and execute jointimes; this will create src.dat in the root directory, with contains association information for P and S times. Now execute the script tomo3dj, which will jointly invert for Vp, Vs and source locations.
4. The traveltime misfit as a function of iteration will be listed in residuals.dat in invert\_p (for P-times) and invert\_s (for S-times); this is exactly the same as for the standard FMTOMO package. Likewise, Vp can be visualised using gmtslicei in invert\_p/gmtplot, and Vs can be visualised using gmtslicei in invert\_s/gmtplot.
5. Once tomo3dj has completed, you can then invert for Vp/Vs ratio. A linear approach is used based on the output of tomo3dj. It therefore runs much more quickly than tomo3dj. To do this, enter the directory vpv, run the script cp\_script, and then tomo3dps. The data residual information is contained in vpvresids.out, and the Vp/Vs ratio can be visualised in the standard way in the subdirectory gmtplot. Note that the starting Vp/Vs ratio is assumed to be constant throughout the model.

## NOTES ABOUT VISUALISING THE RESULTS

FMTOMO uses gmtslice to extract vertical and horizontal slices through the model for visualisation by GMT. With the Extras package, this is done in exactly the same way, but now an option for plotting % perturbation now exists. Hence, the code has been renamed gmtslicei to avoid confusion. To plot percentage perturbation, edit line 59 of gmtslicei.in. Then, rather than using the scripts plotd, plotew and plotns, you can use plotd, plotewp and plotnsp. Note that the code can also be set to produce estimates of location uncertainty. This can be done in gridlocj.in, and a file "error.dat" is produced. Note that the plotting scripts don't currently include an option for plotting uncertainty, but this could be added quite easily. For example, to plot the EW error, you could include in the GMT script something like the following (after copying "error.dat" to the current directory):

```
sort -n -r -k 6,6 error.dat >! temp.dat
awk '{print $3,$1,$6}' temp.dat >! serrorrew.dat
psxy serrorrew.dat $bounds1 $proj -Sc0.33 -Ccolor.cpt -W1 -O -K -P >> $psfile
```

For NS error, the equivalent is

```
sort -n -r -k 5,5 error.dat >! temp.dat
awk '{print $2,$1,$5}' temp.dat >! serrornrns.dat
psxy serrornrns.dat $bounds1 $proj -Sc0.33 -Ccolor.cpt -W1 -O -K -P >> $psfile
```

For depth error, it would be

```
sort -n -r -k 4,4 error.dat >! temp.dat
```

```
awk '{print $2,$1,$4}' temp.dat >! serrord.dat  
psxy serrord.dat $bounds1 $proj -Sc0.33 -Ccolor.cpt -W1 -O -K -P >> $psfile
```

## SETTING UP A SYNTHETIC TEST

In order to set up a synthetic test, do the following (here it is assumed that you have a real data example, and now want to run a resolution test):

1. In invert\_p/mkmodel, edit grid3dgi.in! so that that synthetic structure is created (be it checkerboard, spikes or random structure).
2. Copy the grid files to invert\_p and run fm3d, which creates arrivals.dat
3. In invert\_p/mkmodel, copy the newly created arrivals.dat to the current directory and execute synthdatai. Then copy src.dat and otimes.dat to invert\_p, ensuring that in the latter case the file is renamed to otimesref.dat.
4. Repeat steps 1-3 for the S-wave data i.e. under invert\_s
5. Move to the root location of the synthetic test, execute jointimes and then tomo3dj
6. For Vp/Vs ratio, enter vpv and execute cp\_script followed by tomo3dps. Note that the file vgridvpvs.in that is also created - in addition to the solution that comes from the direct inversion for Vp/Vs which is located in vgrids.in - contains the result of simply dividing the Vp solution (from invert\_p) with the Vs solution (from invert\_s). This is useful for the purposes of comparison.

## SELECTION OF PAPERS THAT HAVE USED FMTOMO EXTRAS

- Pilia S., N. Rawlinson, N. G. Direen, P. R. Cummins, and N. Balfour (2013), Structural controls on localized intraplate deformation and seismicity in southern Australia: insights from local earthquake tomography of the Flinders Ranges, *Journal of Geophysical Research: Solid Earth*, 118, 2176–2190, doi:[10.1002/jgrb.50168](https://doi.org/10.1002/jgrb.50168).
- Wilks M., Rawlinson N., Kendall J.-M., Nowacki A., Biggs J., Ayele A. and Wookey J. (2020). The Coupled Magmatic and Hydrothermal Systems of the Restless Aluto Caldera, Ethiopia. *Frontiers in Earth Sciences*, 8, doi:[10.3389/feart.2020.579699](https://doi.org/10.3389/feart.2020.579699)
- Zenonos, A., DeSiena, L., Widiyantoro, S., Rawlinson, N. (2020). Direct inversion of S-P differential arrival times for Zenonos, A., DeSiena, L., Widiyantoro, S., Rawlinson, N. (2020). Direct inversion of S-P differential arrival times for Vp/Vs ratio in SE Asia. *Journal of Geophysical Research: Solid Earth*, 125, e2019JB019152. <https://doi.org/10.1029/2019JB019152>
- Gauntlett, M., Hudson, T., Kendall, J.-M., Rawlinson, N., Blundy, J., Lapins, S., et al. (2023). Seismic tomography of Nabro caldera, Eritrea: Insights into the magmatic and hydrothermal systems of a recently erupted volcano. *Journal of Geophysical Research: Solid Earth*, 128, e2022JB025742. <https://doi.org/10.1029/2022JB025742>
- Han, J., Rawlinson, N., Greenfield, T., White, R. S., Brandsdóttir, B., Winder, T., & Drouin, V. (2024). Evidence of a shallow magma reservoir beneath Askja caldera, Iceland, from body wave tomography. *Geophysical Research Letters*, 51, e2023GL107851. <https://doi.org/10.1029/2023GL107851>