Brief manual of using the code for repeated tomography

This manual gives a brief description of the main steps allowing reproducing the results contained in the paper "Causes of volcanic unrest of Mount Spurr in 2004-2005 inferred from repeated seismic tomography," by I. Koulakov, S.Z. Smirnov, V. Gladkov, E. Kasatkina, M. West, S. El Khrepy, N. Al-Arifi.

General information

The calculations are based on the LOTOS code. This code uses arrival times of P and S waves from local earthquakes and performs iterative inversion for source coordinates, P and S wave velocities. The details of the code can be found at the web site (www.ivan-art.com/science/LOTOS) and in the paper Koulakov (2009). All the codes are written in Fortran-90 and compiled under Windows OS.

1. The present version of the code presumes the workflow as follows:

1.1. All the sources in the initial data base are localized using the same 1D model as will be used for repeated tomography. At this step a grid search method is used. To speed up the calculations, the travel times are computed along the straight rays. The only difference from the regular location step in the LOTOS code is that the information about absolute times of events is kept in the input and output files.

1.2. For two predefined time intervals, we select events located close to each other and having identical phases (same stations and types of waves, P or S). The selected subsets are used as input data for the tomographic inversion.

1.3. Tomographic inversion of two data subsets using the LOTOS code. It performs generally same steps as in the case of the regular workflow. An only exception is that after computing the 1st model, all the files with parameterization grids are copied to the second model. Thus, the second model is computed on the basis of the same parameterization nodes as the first model.

1.4. The differences between the results are computed for the P, S velocities and Vp/Vs ratio in the same vertical and horizontal sections as used for presenting the main results.

2. Main steps to repeat the calculations of the models presented in the paper:

2.1. Download the file **www.ivan-art.com/science/LOTOS/repeat_spurr.zip.** Unpack it and copy to any location of the computer. It is better to avoid system folders like "**Program Files**" or "**My Documents**" etc. It's better to use simple paths, like: "**c:/science/repeatomo/**" or similar.

2.2. In the DATA folder, there are two major group of data "**SPUR_1__**", and "**SPUR_2__**" corresponding to two series: 1996-2001 vs 2002-2004, and 2002-2004 vs 2005-2012. The corresponding folders with names ending with "**A**" and "**B**" include the data for each of two subsets in the same series. For example, "**SPUR_1_A**" corresponds to the interval of 1996-2001, and "**SPUR_1_B**" – 2002-2004. If these two folders do not exist, they will be automatically created during calculations.

2.3. In the root folder, open the file "**area_repeated.dat**" and define the names of the Series ("**SPUR_1__**") and of the model ("**MODEL_01**"), as well as the number of iterations ("**5**" in our case), and keys for performing steps of preliminary location of the entire dataset (Step 1.1, see above) and data selection (Step 1.2). In cases of zero values corresponding to a step, it will be skipped. The format should be respected: between each item in the line, there should be one space.

Example of "**area_repeat.dat**" file:

```
1: name of the area (any 8 characters)
2: name of the model (any 8 characters)
3: number of iterations
4: perform the initial source locations (1-yes, 0-no)
5: perform the selection of data subsets (1-yes, 0-no)
 ******************************************
SPUR_1__ MODEL_01 5 1 1
```

2.4. Run the calculations using the "START_repeated.BAT" file. In a case of selecting "1" for the source location of the entire initial dataset, only this step may take approximately one hour. The remaining calculations may take another hour.

2.5. After completing the calculations, the main results can be previewed at the folder "PICS", in subfolders corresponding to the current subset (e.g. SPUR_1_A) and model (MODEL_01), where there are PNG images of the results including P- and S anomalies in horizontal and vertical sections for each of the iteration (folders IT1 to IT5) and results of source locations (folder LOC).

2.6. The values of the residual deviations in L1 norm and variance reduction can be found in the file "info_resid.dat" in the corresponding subfolder of "PICS".

2.7. The ray paths and parameterization node distributions in vertical and horizontal sections can be visualized by running the batch-file "visual_grid_raypath.bat" from the root folder. The resulting PNG files will be stored in "RAYS_GRIDS" in the corresponding subfolder of "PICS".

3. Major resulting files for visualization

All figures presented in the paper were created using Surfer-13. All the calculation results are created in formats that can directly visualized in Surfer. Here are the main files used for visualization with brief explanations and locations:

3.1. Resulting velocity anomalies and Vp/Vs ratio in horizontal sections:
TMP_files/hor/dvAB C.grd, velocity anomalies,
TMP_files/hor/vpvsB C.grd, Vp/Vs ratio,
where A is 1 for P and 2 for S, B is the number of iteration and C is the number of depth level. Note that running every new subset overwrite the previous grids. To re-calculate the results of the previously computed model, it is necessary to perform the following steps:

- In file "model.dat" in the root folder type the required names of the subset and the model, and the number of iteration.
- Run "visual_result.bat", which replace all the grid files according to the defined parameters.

3.2. Resulting velocity anomalies and absolute velocities and Vp/Vs ratio in vertical sections:
TMP_files/vert/ver_AB C.grd, anomalies
TMP_files/vert/abs_AB C.grd, absolute velocities
TMP_files/vert/vpvs_B C.grd, Vp/Vs ratio
where A is 1 for P and 2 for S, B is the number of iteration and C is the number of depth level. To reproduce the grids corresponding to one of the previous model, repeat the steps in 3.1.

3.3. Events in map view in a depth interval corresponding to the horizontal section:
TMP_files/hor/ztr C.grd, where C is the number of depth level.

3.4. Events in the vertical section:
TMP_files/vert/ztr_ C.grd, where C is the number of section.

3.5. Topography in the vertical section:
TMP_files/vert/topo_ C.grd, where C is the number of section.

3.6. Location of the profile in the map view:
TMP_files/vert/mark_ C.bln, profile line

TMP_files/vert/mark_ C.dat, marks
where C is the number of section.

3.7. Differences between velocities and Vp/Vs ratio between models in one series (for example "SPUR_1__") and model ("MODEL_01") in horizontal and vertical sections:
DATA/SPUR_1__/MODEL_01/data/diff_dv_AB C.grd, velocity difference in horizontal section;
DATA/SPUR_1__/MODEL_01/data/diff_vpvs_AB C.grd, Vp/Vs ratio difference in horizontal section;
DATA/SPUR_1__/MODEL_01/data/diff_ver_dv_AB C.grd, velocity difference in vertical section;
DATA/SPUR_1__/MODEL_01/data/diff_ver_vpvs_AB C.grd, Vp/Vs ratio difference in vertical section;
where A is 1 for P and 2 for S, B is the number of iteration and C is the number of depth level or vertical section.

3.8. Path of P and S rays in the initial catalogue of a subset (for example "RUIZ_1_A") in map view:
DATA/SPUR_1_A/inidata/ray_p.bln;
DATA/SPUR_1_A/inidata/ray_s.bln;

3.9. Lines indicating the distances between corresponding events in subsets A and B (for the Series "RUIZ_1_A") in map view:
DATA/SPUR_1__/MODEL_01/data/dist_AB.bln;

3.10. Sources and involved stations in the initial catalogue of a subset (for example "RUIZ_1_A") in map view:
DATA/SPUR_1_A/inidata/sources_ini.dat;
DATA/SPUR_1_A/inidata/stat_actual.dat;

3.11. Sources relocated during the iterative inversion (for example for "RUIZ_1_A" and "MAIN_MOD") in map view:
DATA/SPUR_1_A/MODEL_01/data/srcesB.dat;
where B is the number of iteration.

3.12. Ray path (as dots) around a current depth level and nodes of parameterization grids in horizontal and vertical sevtions (available after running visual_grid_paypaths.bat):
TMP_files/rays/rays_horAC.dat;
TMP_files/rays/nodes_horDAC.dat;
TMP_files/rays/rays_verAC.dat;
TMP_files/rays/nodes_verDAC.dat;
where A is 1 for P and 2 for S, D is the number of grid and C is the number of depth level or vertical section.

4. Creating another model for an existing pair of data subsets

In some cases, it is useful to play with inversion parameters and reference model to assess the stability of the results. This can be done using the following steps:

4.1. For an existing series (for example, SPUR_1__) using copy-paste functions create a copy of the existing model (MODEL_01) and rename it using any 8 characters (for example, MODEL_02).

4.2. Make any changes in the file of parameters MAJOR_PARAM.DAT or in the reference model. Details on the formats of these files can be found in the LOTOS code description.

4.3. The corresponding folders and all necessary files in subsets SPUR_1_A and SPUR_1_B will be created automatically. There is no need to create them manually.

4.4. In the root folder, open the file "area_repeated.dat" and define the name of the new model ("MODEL_01"), as well as the number of iterations ("5" in our case). In this case, we do

not need performing the location of the initial sources and selection of data; therefore, we put 0 for the corresponding keys:

```
1: name of the area (any 8 characters)
2: name of the model (any 8 characters)
3: number of iterations
4: perform the initial source locations (1-yes, 0-no)
5: perform the selection of data subsets (1-yes, 0-no)
 ********************************************
SPUR_1__ MODEL_02 5 0 1
```

4.5. Run the calculations using the "START_repeated.BAT" file. In this time, the calculation will be much faster as they will not require source locating for the full catalogue.

4.6. Check the results using the preview files of construct figures in Surfer.

5. Creating a synthetic model

A synthetic model should be created for existing data subsets (for example SPUR_1_A and SPUR_1_B). Preparing data and running the calculations requires the following steps:

5.1. In the existing data subsets (for example SPUR_1_A and SPUR_1_B) create the folders for the synthetic model (or just take on of the examples as template, for example, BOARD_01). Note that the number of characters in the model name should be 8.

5.2. In each of the subfolders create the files anom.dat and ref_syn.dat determining the synthetic model. The detailed description of synthetic model definition is contained in the LOTOS code manual. For some cases, it is necessary to define polygons for free-shaped anomalies for which it is necessary to create a folder forms. Note that the synthetic models in two subsets should defined manually and can be different.

5.3. In the series folder SPUR_1__ create the subfolder with the name of the synthetic model (BOARD_01). Within this folder there should be two files: MAJOR_PARAM.DAT and ref.start.dat. These files will be automatically copied to the corresponding model folders in subsets A and B.

5.4. Check that definition of the MAJOR_PARAM.DAT presumes the workflow for the synthetic model. The difference in respect to the real data case is highlighted with red:

```
*******************************************************
GENERAL INFORMATION :
2     KEY 1: REAL; KEY 2: SYNTHETIC
1     KEY 1: Vp and Vs; KEY 2: Vp and Vp/Vs
0     KEY 0: all data, KEY 1: odd events, KEY 2: even events
0     Ref. model optimization (0-no; 1-yes)

*******************************************************
SYNTHETIC MODELING PARAMETERS :
inidata         name of the model or "inidata ", source where S-R pairs are taken to compute
synthetic rays
0           iteration of the real data model; in case of "inidata " this line
is ignored
1           type of noise 1: random generator, 2: from real data (2 cannot be
for "inidata "!!!)
_____________________________________
0.02 0.04  level of noise for P and S data. In case of real data, reduction
of remnant residuals, e.g. 0.8 0.8 (80%)
0              in percents, partition of outliers
2.             times larger than the normal noise
```

Set file "area_repeated.dat"

```
1: name of the area (any 8 characters)
2: name of the model (any 8 characters)
3: number of iterations
4: perform the initial source locations (1-yes, 0-no)
5: perform the selection of data subsets (1-yes, 0-no)
 ********************************************
SPUR_1__ BOARD_01 5 0 0
```

5.5. In the root folder, open the file "area_repeated.dat" and define the name of the new model ("BOARD_01"), as well as the number of iterations ("5" in our case). In this case, we do not need defining keys for location and selection. They can remain zero.
5.6. Run the calculations using the "START_repeated.BAT" file.
5.7. Check the results using the preview files of construct figures in Surfer.

6. Creating a series with other time intervals

In case of creating a new series with other time intervals for the pairs of subsets, the following steps should be performed:

6.1. Create a folder for a new series (for example, make a copy of SPUR_2__ and rename it to SPUR_3__).
6.2. Open the file SET.SET and change the time intervals (in the format MMYYYY) as indicated below:

```
011996 122001      1st period
012005 122012      2nd period
-77.35 1.22      Fi0, tet0, Center of conversion to XY
1              Max distance for the pair
5.             Min number of common phases
```

6.3. In the root folder, open the file "area_repeated.dat" and define the name of the new series ("SPUR_3__") and the current model ("MODEL_01"), as well as the number of iterations ("3" in our case). In this case, we do not need performing the location of the initial sources but we should set 1 for the selection key:

```
1: name of the area (any 8 characters)
2: name of the model (any 8 characters)
3: number of iterations
4: perform the initial source locations (1-yes, 0-no)
5: perform the selection of data subsets (1-yes, 0-no)
 ********************************************
SPUR_3__ MODEL_01 5 0 1
```

6.4. Run the calculations using the "START_repeated.BAT" file.
6.5. Check the results using the preview files of construct figures in Surfer.