Short Readme and Description of Simulps14

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Introduction

Simulps14 is an extension to the widely used & well tested Simul-code family, originating from Thurber (1983) and further developed by Um & Thurber (1987) and Eberhart-Phillips (1986, 1990) among others. Simulps14 is based on Simulps13q (Eberhart-Phillips, pers. comm., 1998) which in addition to the usual velocity inversion also incorporates a t* inversion routine to determine 3D distribution of damping values (Rietbrock, 1996).
The new feature in Simulps14 is the incorporation of an alternative forward solution method (ray tracer). Accurate and fast ray tracing in inhomogeneous media is a crucial factor for a successful tomographic inversion. The original ray tracing routine in Simulps, approximate ray tracing + pseudo-bending, ART_PB, is well tested and fast. But it was often noted that, depending on velocity model heterogeneity, ART_PB results may be inaccurate for ray lengths exceeding approx. 60 km. With the increasing amount of data from relatively large & dense temporary networks complementing the permanent installations it becomes important to develop means to evaluate possible defects in tomographic results due to inaccurate ray tracing. A very intuitive way is the comparison of tomographic inversions using two totally different forward solution techniques. A 3D shooting method using paraxial rays and perturbation theory (Virieux, 1991), RKP, was therefore implemented. To enable the meaningful comparison between tomographic results, great care was taken to adequately parametrize the 3D velocity model. This ensures that rays are really computed on physically (seismically) equivalent velocity models, although each ray tracer requires a specific representation of the velocity field. (For details see the appended excerpt from Haslinger, 1998.) Ideally ART_PB and RKP should, therefore, yield identical ray paths and travel times, in contrast to recent work where the physical velocity field depends significantly on the choosen ray tracer (e.g Masson & Delouis, 1997; Le Meur et al., 1997). Here it should be noted that it is quite impossible to decide which velocity model representation better resembles the real earth structure in the study volume, and that one of the main objectives in analyzing tomographic results must be to take into account the specific filter used to image the earth’s structure.

RKP ray tracing requires that velocities are defined on a regular even grid an interpolated in between by 3D cubic b-splines. For ART_PB the velocity model is defined on a possibly uneven grid and linearly interpolated. This grid is also the velocity model used in the inversion. Details of how to ensure the equivalence of the velocity models for ray tracing, and at the same time retaining the model grid for the inversion are given in Haslinger (1998) (see appendix). Basically the original Simulps ART_PB velocity model representation is used to define the model. If using RKP ray tracing, this grid is linearly interpolated down to a regular even grid. In order to correctly represent the linear velocity gradients this grid should be finer by a factor of 3-5. This fine grid then represents the control points for the cubic b-spline interpolation.

Specialities of RKP ray tracing

Shooting

RKP ray tracing is a shooting method, and therefore initial take-off angles (azimuth tet and vertical take-off angle phi) must be calculated. This is done using ART_PB ray tracing on the first occurrence of a ray to be calculated. For very heterogeneous velocity models and/or specific geometries, ray shooting may not be successful. A warning message is then written to file ‘rkpfail’ and ART_PB ray tracing is again used for this ray. For any subsequent ray tracing again RKP is used. Shooting failure may be caused by two reasons: the ray somewhere intercepts the model boundary during the ray adjustment phase; or the specific source-receiver geometry leads to instabilities due to the presence of caustics or shadow zones. To chech this one may use the option of a more descriptive output to file ‘rkplog’. Take-off angles could also be set manually in the specific angle-file (see below).

Speed
Due to the increased computational burden, RKP ray tracing is significantly slower than ART_PB ray tracing. One should count on a 10-fold increase in CPU-time. Still, on modern workstations (e.g. Sparc Ultra 60) a moderatly sized tomographic inversion (grid 200x200x50 km, 7’000 observations) takes about 20 hours with 4 iterations using RKP.

How to use RKP ray tracing in Simulps14
As noted above, Simulps14 is based on Simulps13q. Please read the notes at the beginning of the source-code and Evans et al. (1994) if you are not familiar with that code.
No changes are neccessary to the model file (MOD), earthquake data (EQKS, SHOT) and station list (STNS). In the control file (CNTL) the switch *i3d* now controls the use of RKP or ART_PB ray tracing (*i3d* = 4 to use RKP). Specific control parameters for RKP raytracing are read from file RAYTRAC. A directory ‘angle’ must exist in the directory from which Simulps14 is run when using RKP ray tracing. In this directory the current take-off angles are stored, one file per event.

Description of file RAYTRAC
line 1 - free format
iheter, epsob, epsca, ides, ampr, iterrai

iheter: maximum number of trial iterations to reach the station from a source with RKP shooting. Around 20 is suggested for average heterogeneous velocity models. To calculate synthetic data, use *iheter* = 3, 13, or 23 in addition to the settings in CNTL.

epsob: precision in km^2 with which the station has to be reached within iheter iterations. A value which corresponds to the station position accuracy makes sense (e.g. 0.01 for 100 m).

epsca: tolerance in km^2 to keep the result after iheter iterations. If after *iheter* iterations the ray still is more than *epsob* away from the station, but less than *epsca*, the raytracing is taken to be successful (travel time is anyway adjusted by continuation). The use of this option may be controversial. To force the ray to be precise within *epsob*, use the same value for *epsob* and *epsca*.

ides: output to file ‘rkplog’: *ides* = 0: very brief output; *ides* = 1: descriptive output; *ides* = 2: VERY descriptive output - use only if testing with a few rays!

ampr: parameter for the integration step along the ray. Units distance * velocity [km**2/s]. For local earthquake data 1.0 is a good value. Larger *ampr*-values speed up the ray tracing but also lead to greater inaccuracies in the travel-time computation.

iterrai: flag to read initial angles from files in directory ‘angle’. *iterrai* = 1: calculate angles on first interation using ART_PB; *iterrai* = 2: angles already exist (from previous inversion runs or manually defined).

line 2 - free format (3 float)
dxrt, dyrt, dzrt

grid spacing for the ray-tracing grid (linearly interpolated down from the input velocity grid). In units of *bld* (in CNTL, whole km or .1 km). Make sure that with the choosen grid spacing the input model grid nodes are also used as control points in the ray-tracing grid. (e.g. use 1.0, makes quite large grids but allows the most flexibility in defining the velocity model).

Format of angle-files
The currently valid shooting angles are stored in the directory ‘angle’, in files *angle.xxxx*, where *xxxx* is the sequential event-number. In each file every observation has 3 values: tet, phi, station_number, where tet and phi are the azimuth and vertical take-off angle respectively, both in radians (mutiply by $180/\pi$ to get degrees). If tet and phi are ‘999.00’ then shooting was not successful for this ray in the last forward-calculation loop.

Final remarks

Simulps14 was developed within a Ph.D thesis (Haslinger, 1998), mainly for the testing of forward-solution effects on tomographic results. An analysis of the results can be found in this thesis. The RKP ray tracing was adopted from a code by J. Virieux. This may explain some french leftovers in the comments and variable names. Simulps14 has been successfully used, but definetly no guarantee can be given for bug-freeness. Any user of Simulps14 is encouraged to improve the code in any possible way. Please report any bugs, changes to the code, or suggestions to the author, as development is still ongoing.

One last note: Unfortunately seismic tomographic inversion is a very complex procedure, and the experience shows that no tomography-code can be used as a black box. Any unexperienced user is encouraged to make himself familiar with the code by parsing the source and in addition have a close look at Evans (1994) and the references therein. And a careful examination of the output-files may reveal a great deal about peculiarities in the inversion, which do not neccessarily show up in the final results.

Together with S. Husen the author has developed a program to read the main Simulps '*output*' file and reformat it for use with GMT (Wessel & Smith, 1995) to display the results. This program '*sim2gmt*' can be obtained from the author, together with some sample-GMT scripts.

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