Model parametrization in seismic tomography: a choice of consequence for the solution quality

E. Kissling*, S. Husen, F. Haslinger

Institute of Geophysics, ETH Hoenggerberg, CH8093 Zurich, Switzerland

Abstract

To better assess quality of three-dimensional (3-D) tomographic images and to better define possible improvements to tomographic inversion procedures, one must consider not only data quality and numerical precision of forward and inverse solvers but also appropriateness of model parametrization and display of results. The quality of the forward solution, in particular, strongly depends on parametrization of the velocity field and is of great importance both for calculation of travel times and partial derivatives that characterize the inverse problem.

To achieve a quality in model parametrization appropriate to high-precision forward and inverse algorithms and to high-quality data, we propose a three-grid approach encompassing a seismic, a forward, and an inversion grid. The seismic grid is set up in such a way that it may appropriately account for the highest resolution capability (i.e. optimal data) in the data set and that the 3-D velocity structure is adequately represented to the smallest resolvable detail apriori known to exist in real earth structure. Generally, the seismic grid is of uneven grid spacing and it provides the basis for later display and interpretation. The numerical grid allows a numerically stable computation of travel times and partial derivatives. Its specifications are defined by the individual forward solver and it might vary for different numerical techniques. The inversion grid is based on the seismic grid but must be large enough to guarantee uniform and fair resolution in most areas. For optimal data sets the inversion grid may eventually equal the seismic grid but in reality, the spacing of this grid will depend on the illumination qualities of our data set (ray sampling) and on the maximum matrix size we can invert for.

The use of the three-grid approach in seismic tomography allows to adequately and evenly account for characteristics of forward and inverse solution algorithms, apriori knowledge of earth’s structure, and resolution capability of available data set. This results in possibly more accurate and certainly in more reliable tomographic images since the inversion process may be well-tuned to the particular application and since the three-grid approach allows better assessment of solution quality.

Keywords: Seismic tomography; 3-D-grid

1. Introduction

With the growing availability of high-performance computing power and the increase of digital seismologic data sets, seismic tomography currently sees a boost in number of applications and publications. Besides mainly interpretative studies, competition for the “best method” is wide open. Problems arise from the fact that even the highest quality data available is incomplete, inconsistent, and erroneous, and that there exists apriori and a posteriori information about the three-dimensional (3-D) earth structure which somehow have to be incorporated in the modeling process. In addition, the inverse procedure itself is complex, as
it normally includes independent calculations of the forward problem, the coupled inverse problem, and resolution and reliability estimates. The goal of this paper is to study the effects of the coupling between the various elements involved in seismic tomography, in particular, with regard to model parameterization, and, consequently, to suggest some improvements to the tomographic inversion process.

Since the first applications of seismic tomography the dominant factors in the choice of a particular model parameterization have always been forward and inverse solution algorithms, apriori knowledge of earth’s structure, and resolution capability of available data set. Limitations in computing power, however, made it impossible to evenly account for all those factors and demanded that priorities were set. Dividing a layered earth model in blocks of 10–15 km lateral extension with uniform velocity (Aki et al., 1977; Roecker, 1981; Ellsworth, 1977; and later users of the ACH method, see f.e., Evans and Achauer, 1993) is an appropriate choice with regard to the resolving power of teleseismic travel time data. This kind of model parametrization, however, is clearly not applicable to crystal studies to account for apriori known structure such as, sedimentary basins (compare, f.e., application of teleseismic tomography to Long Valley Caldera in California by Steeples and Iyer, 1976; and by Weiland et al., 1995) and surface fault structures. Spherical harmonics, on the other hand are an excellent tool to represent smooth broad mantle structure (e.g. Dziewonski and Woodhouse, 1987; Hager and Clayton, 1988) and to accommodate the inverse problem with strongly unevenly distributed data of large wave lengths. While ray tracing with this approach accounts for the sphericity of the 1-D earth model, local 3-D path effects are either neglected or only approximately corrected for. In addition, the usage of spherical harmonics makes it hard to assess resolution in specific regions and reliability of the 3-D model.

Alternative approaches were based on 3-D grid models of the velocity field. Representing the velocity field by grids of variable node spacing (see Thurber, 1983; Eberhart-Philips, 1986) is widely recognized as the most promising approach in local source tomography to accommodate strong lateral variations in the near-surface structure (f.e., sedimentary basins) and at the same time enabling efficient 3-D ray tracing. With respect to the inverse problem and the non-uniform sampling by real data, however, approaches with block models of variable cell sizes (e.g. Kissling, 1988; Bijwaard et al., 1998) but of uniform velocity within each cell yield superior results, in particular, with regard to resolution and reliability assessment.

The above mentioned and other studies document that presently no model representation exists that may account appropriately for all boundary conditions of a seismic tomography application with real data. Comparisons between these studies, however, also show how particular model representations may favorably accommodate one or two boundary conditions and that different model representations potentially lead to different results, resolution, and reliability estimates (see also Haslinger and Kissling, 2000; Husen and Kissling, 2000). With the availability of efficient and high-precision 3-D forward solvers, high-performance inverse algorithms, and higher quality data sets — see effects of improved data quality on global tomographic images (van der Hilst et al., 1997), resolution and solution quality assessment unbiased by model representation have become increasingly important in seismic tomography. In this study we present a new approach to model parametrization that allows to evenly accommodate the requirements of forward and inverse solution algorithms, of apriori knowledge of earth’s structure, and of the resolution capability of the available data set. In addition, we show how the velocity model may be adjusted to compensate for usage of different forward solvers to yield identical results and we document how strongly resolution estimates depend on model parameterization and forward solver. The problems are similar for any kind of seismic tomography, here we will focus the discussion on results from local earthquake tomography (LET).

2. Model parameterization and forward solvers

Theoretically, high-precision forward solutions for complex velocity structure may be obtained by many methods (Thurber and Kissling, 2000). Practical applications, however, are often limited by specific model representation of velocity structure demanded by the applied forward method and by apriori knowledge. The approximate ray tracing (ART) with pseudo bending implemented in the widely used SIMULPS (Thurber, 1983; Eberhart-Philips, 1986), for example,
very efficiently handles 3-D velocity models with uneven gridding. Uneven gridding is a powerful model design easily allowing to adopt to a priori knowledge such as, e.g., sedimentary basins or tectonic lineaments (Eberhart-Phillips and Michael, 1993). Most higher precision forward solvers though demand fine resampling of such a velocity grid. Recently, Haslinger (1998) introduced the 3-D shooting ray tracing algorithm (RKP) by Virieux and Fara (1991) to the SIMULPS code and documented how this problem of regridding and of different model representations of a complex velocity structure may be tackled. Haslinger’s (1998) results show that travel times calculated with two different ray tracers with optimal regridding and interpolation schemes might not differ significantly with respect to normal observation errors. While different ray paths calculated with RKP and with ART for most cases lie within the Fresnel volume and, hence, do not strongly affect the tomographic inverse solution in well-resolved regions, the differences in the take-off angles of the rays at the source might be significant for high-precision earthquake location (Haslinger and Kissling, 2000).

Resolution estimates obtained with the two different ray tracers differ notably in regions of fair to poor resolution. Such excellent correlation of the tomographic results obtained with two different ray tracers, however, may only be achieved for optimal regridding.

To better understand the influence of the forward solution on tomographic results and resolution estimates we further compare the above mentioned two 3-D ray tracing schemes with a 3-D finite difference (FD) solver of the eikonal equations (Podvin and Lemconte, 1991). The FD-solver is used to calculate fat rays which approximate the first Fresnel volume of a seismic wave (Husen and Kissling, 2000). Each of these forward solutions represents a different approximation to seismic wave theory and requires its specific parametrization of the seismic velocity field (Fig. 1). Hence, if we want to study the effects of different approximations to wave theory, care has to be taken that different parametrizations of the velocity field do not lead to different solutions.

We achieve the same high level of accuracy and stability for travel time computations with all three 3-D forward solvers (Husen, 1999; Haslinger and Kissling, 2000). Our results, as shown later also demonstrate that effects of the parametrization of the velocity field on travel times and partial derivatives are at least of the same order of magnitude as the effects resulting from the different mathematical or physical approximations. Thus, the characteristics of the model parametrization applied to forward and inverse problems must be considered when assessing the quality of 3-D tomographic results.

As an additional result of these comparisons we note that while the original seismic velocity field was represented by a 3-D grid of uneven node spacing, the actual numerical calculations needed to be performed on different grids. Upon close inspection one realizes, that in many tomographic applications the forward solutions are actually obtained by (locally) regridding the original velocity field to achieve the desired accuracy or simply because the numerical algorithm demands a very fine and evenly spaced grid. We will...
further call such (locally) regridded velocity models numerical (forward) grids as opposed to the seismic grid that denotes the original velocity model.

3. Three-grid approach

The needs to especially define the velocity model during the forward calculation by a numerical grid, to adequately incorporate apriori information, and to adequately account for the variable data density, lead to the introduction of a three-grid approach, which encompasses a forward, a seismic and an inversion grid (Fig. 2). The seismic grid (Fig. 2b) corresponds to the velocity model we normally refer to as representing real earth structure. It is set up in such a way that it may appropriately account for the highest resolution capability (i.e. optimal data) in the data set and that the 3-D velocity structure is adequately represented to the smallest resolvable apriori known detail (Fig. 2). For example, a seismic grid must be fine enough to allow adequate representation of a tectonic lineament like the San Andreas Fault in California. It must further allow to precisely define lateral extension and near-surface velocities of a sedimentary basin which might be very reliably known and to adequately model the topography of the basement below the sediments that might be only locally known or largely in question. In addition, we possess qualitative information about velocity structure of the earth such as, f.e., that the crust–mantle boundary is characterized by a strong velocity gradient and that we generally observe a stronger velocity gradient with depth than in lateral directions. The seismic grid must allow to accommodate such qualitative apriori information on earth structure. To meet all these requirements, the seismic grid in general is of uneven node spacing (Fig. 2). A prime example and prototype of a seismic grid is the model parametrization in the widely used SIMULPS program (Thurber, 1983; Eberhart-Philips, 1986). The seismic grid is also the basis for later display and interpretation of tomographic results.

To perform numerically stable and accurate computations of travel times, ray paths, and partial derivatives with respect to the apriori (seismic) velocity model, a numerical (forward) grid has to be designed. It’s specifications are defined by the individual forward solver (Fig. 1) and it will vary for different forward solution techniques. Often even gridding is required and special requirements on smoothness and continuity of the spatial velocity derivatives must be met. While most modern high-performance tomographic inversion packages contain a numerical grid — though usually unnoticed by the user, SIMULPS with its ART forward solver is a notable exception.

The third grid employed in the seismic tomographic inversion process is called the inversion grid and is used during the actual inversion. Even the highest quality and largest possible data set in seismic tomography applications will lead to uneven sampling of the volume under study (Fig. 3). Generally, artifacts in the form of single-cell high-amplitude anomalies cannot be avoided in poorly sampled regions (Kissling, 1988). Poor sampling often corresponds to a lack of crossing ray paths and, hence, to very poor model resolution. In such cases, artifacts might acquire the form of multi-cell high-amplitude anomalies that are undistinguishable from real structure. A simple and effective strategy to improve sampling, in particular, by crossing ray paths, is to combine cells before inversion (e.g. Kissling, 1988). Recently, Bijwaard et al. (1998) have adopted an automated routine adjusting the cell size based on hit count and Thurber and Eberhart-Phillips (1999) promote the idea of a flexible gridding strategy with linked nodes as to obtain more uniform sampling.

The inversion grid is based on the seismic grid but must be large enough to guarantee fair and — as much as possible — uniform resolution in most areas under study. As will be shown later, for interpretation purposes uniformity of resolution within a region is more important than absolute resolution diagonal element values. A locally variable inversion cell size, however, denotes an apriori and effectively variable resolution potential. Hence, inversion cell size should only vary regionally and should be chosen to guarantee uniform fair resolution throughout a certain region of the area under study. For optimal data sets the inversion grid may eventually equal the seismic grid but in reality the spacing of this grid will depend on the illumination qualities of our data set (ray sampling) and on the maximum size of the matrix we can invert for.

With the introduction of three different grids in the inversion process, we must define how to get from one grid to another. The way of extrapolating from the coarser seismic grid to the finer forward grid is
Fig. 2. Three-grid approach for local earthquake seismic tomography. (a) Numerical (forward) grid specifically designed for optimal performance of forward solver. (b) Seismic grid resembling real earth structure. The seismic grid is designed to adequately represent apriori information (i.e., sedimentary basins, Moho topography) and apriori unknown structure of the size resolvable by the data. Generally, the seismic grid is of uneven size. (c) Inversion grid. In optimally sampled regions the inversion grid equals the seismic grid. In poorly sampled regions the inversion cell encompasses a few seismic cells (see text).
generally straightforward with the applied forward algorithm requiring a specific representation of the velocity model, e.g. B-spline interpolation for the 3-D ray tracer (RKP) and blocks with constant velocity for the FD-algorithm (fat ray). A different approach is needed to update the velocities of the seismic grid for the inversion results obtained on the coarser inversion grid. When tomographic results (i.e. relative (percentage) velocity changes for the inversion cells) are obtained by a non-linear procedure, after each inversion step they may easily be appointed to several seismic grid nodes within each inversion cell, though they might represent different velocity values.

4. Effects on tomographic solution

The use of the three-grid approach in seismic tomography allows to adequately and evenly account for characteristics of forward and inverse solution algorithms, apriori knowledge of earth’s structure, and resolution capability of available data set. This results in possibly more accurate and certainly in more reliable tomographic images since the inversion process may be well-tuned to the particular application. Explicit definition of the three grids further allows to better study the effects of specific steps in the tomographic inversion process, such as, different forward solvers, specific damping scheme, or different non-linear inversion procedure.

A still unresolved question in seismic tomography regards the effective lateral resolution capability of seismic waves of a particular frequency content. The best solution to the forward problem by full wave theory at present is not possible for a 3-D spherical velocity field. Ray tubes or fat rays approximating the first Fresnel volume (e.g. Marquering et al., 1999; Dahlen et al., 2000; Husen and Kissling, 2000) denotes one step away from pure ray geometry toward waves. Ray tubes like Fresnel volumes show a different sensitivity to lateral variation of the velocity field than rays and, hence, differences in the resulting tomographic images are expected. The three-grid approach is necessary to study these effects as in pure ray applications the sensitivity of the ray to lateral velocity variations entirely depends on the interpolation scheme of the velocity grid.

In LET damping is introduced to efficiently handle the underdetermined parts of the inverse problem (e.g. Nolet, 1978, 1987). Often the damping parameters are determined on the basis of a trade-off curve between data variance and model variance (Eberhart-Philips, 1990). Actually, this trade-off curve is a simplification, since the underdetermination strongly depends on the sampling of individual inversion cells and, hence, on model parameterization and on the appropriateness to approximate waves with rays. Different from pure ray tomography, fat ray tomography (FATOMO) documents this relation between damping of the inverse problem, fat ray width (Fig. 4) and cell size of the inverse grid (Husen and Kissling, 2000). With a damping parameter of 30 and a fat ray width of 0.07 s, FATOMO yields virtually identical results for a synthetic data set as SIMULPS with damping of 10, both using uniform inversion cell size of 10 km (Fig. 4b). When using the same damping value, however, FATOMO and SIMULPS yield different results.
Fig. 4. Fat ray tomography documenting the relation between fat ray width, cell size of the inversion grid, and damping of the inverse problem (modified from Husen, 1999). (a) Inversion results of synthetic data (top: synthetic structure in this layer) for different fat ray widths using constant damping parameter of 10. (b) Inversion results of same synthetic data for fat ray tomography with damping 10 and 30 (fat ray width = 0.07) and for pure ray tomography with SIMULPS (see text).
and resolution estimates, e.g. larger resolution matrix diagonal elements (RDE) for FATOMO.

The reason for this behavior is the above mentioned relation between damping, fat ray width, and cell size (Fig. 4). In pure ray tomography and in cases of uniform gridding, the sampling of an individual inversion cell by, for example three crossing rays, depends entirely on the interpolation scheme of velocity partial derivatives for ray segments within the cell and it is, however, independent of the inversion cell size. In the case of fat rays, the sampling depends on the relation between fat ray width and cell size (Husen and Kissling, 2000, their Fig. 3). Since the fat ray represents the first Fresnel volume, its width is a function of the frequency content of the wavelet and of the velocity. The size of the inversion cells on the other hand is defined by the data set and is chosen to obtain best (uniform) resolution. Our three-grid approach allows to assess this relation and to tune the damping, in particular, for models with uneven cell sizes. Damping parameters appropriate to the forward solvers and to the resolution capabilities of the data set are a prerequisite to obtain high-quality and highly reliable tomographic images.

5. Solution quality assessment

Once a solution to the inversion problem has been obtained, different tools exist to a posteriori estimate the solution quality. Analysis of the resolution and covariance matrices provide mathematical resolution estimates, whereas weighted ray lengths (Thurber, 1983; Eberhart-Philips, 1986) or ray density tensors (Kissling, 1988) illustrate the illumination properties by the data set. In principal, however, these resolution estimates only yield information about the quality of the solution assuming appropriate model parametrization. They offer no means of assessing the validity of this parametrization. The chosen model parametrization may possibly be justified by geological and physical plausibility considerations like the consistency of the results with independent data and internal consistency of the 3-D results (how much of the resulting structure is made up by single-cell anomalies?). The best presently available tools to study the effects of particular model parametrization or of a particular choice of forward or inverse solution are synthetic data tests using a synthetic 3-D velocity model that mimics expected or apriori known real structures. Such tests (Husen and Kissling, 2000; Haslinger and Kissling, 2000) clearly document the need for a three-grid approach and the difficulties to apriori choose the model parameterization appropriate to the data set and to the forward and inverse algorithms.

Even the best resolution estimates such as RDE or resolution spread functions (SPR, Toomey and Foulger, 1989; Michelini and McEvilly, 1991) are only relative measures since they depend not only on quantity and quality of the data set but also on model parametrization and on forward and inverse solution parameters, such as damping. Consequently, all resolution estimates — including sensitivity tests such as harmonic or spike checkerboard tests (e.g. Spakman et al., 1993) — need to be calibrated by synthetic data testing using a so-called characteristic synthetic 3-D model (Haslinger et al., 1999). With such calibration, combined resolution estimates (RDE, SPR, ray density tensors, partial derivative weight sums (DWS), total number of hits per cell (HIT)) provide excellent and detailed information about the laterally variable resolving power of the data set for any particular application.

Outlining uniformly well-resolved regions is probably the most important task of resolution estimation with regard to interpretation of tomographic images. The significant difference between the original square velocity structure (Fig. 5a) and the recovered bone-shaped structure in the tomographic image (Fig. 5b) is entirely due to rather minor lateral variations of resolution (Fig. 6). The synthetic model has been represented by a grid of $10 \text{km} \times 10 \text{km} \times \Delta z$ ($\Delta z$ is the layer thickness varying from 3 km at top to 5 km at bottom of model) and, hence, assuming uniform optimal data coverage the same gridding would yield best tomographic results. In our example, however, we deliberately reduced the number of rays in the center of the model (Fig. 6). Lateral variation of resolution due to uneven data coverage are commonly observed in tomographic applications.

Tomographic results obtained for an even $10 \text{km} \times 10 \text{km} \times \Delta z$ grid (Fig. 5b) document excellent recovery of amplitude, shape and extent of the velocity anomaly in well-resolved regions but also show artifacts mainly in form of thin bands of low-velocity regions encircling the positive velocity anomaly in the center. These
Fig. 5. Synthetic data test documenting the effects of non-uniform resolution. (a) Synthetic model; (b) tomographic reconstruction with 10 km × 10 km × Δz grid (Δz is layer thickness varying from 5 km at top to 5 km at bottom of model); (c) tomographic reconstruction with 15 km × 15 km × Δz grid; (d) tomographic reconstruction with locally variable inversion cell size.
are commonly observed edge effects and effects of “overswinging” and leakage problems (see, e.g., layer at 15 km depth). With regard to tectonic interpretation, however, the main defect in these recovered images (Fig. 5b) is the separation of the high-velocity anomaly into two regions, particularly well-developed in the layer at 6 km depth. This is the result of the lateral variation in resolution (Fig. 6). By careful analysis of the non-uniform resolution one may locally introduce large inversion cells. The tomographic results for such a grid (Fig. 5d) show some improvements in the shape of the recovered
high-velocity anomaly in the layer at 10 km depth but no improvement or even worse recovery in the layer at depth 6 km. This clearly documents the danger in applications with locally variable inversion gridding. The best results (Fig. 5c) in layers at 6 and 10 km depths are obtained by a uniform but larger inversion grid with cells of 15 km $\times$ 15 km $\times$ $\Delta z$. Due to horizontally larger grid dimensions for unfavorably thin layers, however, increased vertical leakage is observed in this case. These results underline the importance of accurate resolution estimates and of uniformity of resolution to avoid misinterpretation of tomographic images. In addition, these results clearly document that for real data no ideal but rather a small number of well-adopted model parametrizations exist.

6. Discussion and conclusions

The three-grid approach is necessary to better control parametrization effects of forward solvers, data distribution and inversion routines in the different steps in seismic tomography (forward and inverse solution, resolution and reliability estimates). Such control then allows to separate the influence of different ray tracers from those of model parametrization and of inversion grid dimension. This is of great importance to evaluate any new, improved, or just different approach to each of the elements in seismic tomography, as, for example, the introduction of the fat ray approach, by which we are able to compare two different mathematical approximations (rays and fat rays) to the real physical problem (waves).

The issue of uneven data distribution and potential artifacts is of importance to any application of seismic tomography and popularly dealt with by a different approach than advocated here. In most applications a solution is calculated on an evenly spaced grid designed for the region of best resolution followed by simple smoothing or fancy filtering trying to eliminate artifacts from the tomographic results. Most artifacts, however, denote image deformation that cannot be distinguished aposteriori from real structure. Hence, image filtering eliminates parts of artifacts and parts of real structure likewise, prevents recovery of true anomaly amplitude and sharp velocity gradients, and in general neglects the laterally variable resolution power of the employed data set. For these reasons and in general accordance with the approaches by, e.g. Kissling (1988), Bijwaard et al. (1998), and Thurber and Eberhart-Phillips (1999), we advocate the usage of inversion gridding with larger cells in region of apriori known lower resolution. This approach effectively means trying to get as much and as reliable information as possible out of the data.

With the introduction of the three-grid approach it is possible to parametrize a LET problem such that effects due to different representations of the velocity model for different forward solvers can be avoided. Most modern LET codes internally use a “numerical” grid without explicitly defining its relation to the “seismic grid”. The most widely distributed and most often applied LET code of all, SIMULPS (Thurber, 1983; Eberhart-Philips, 1986) for the approximate ray tracer uses only the seismic grid. A newer version of this code has been updated with an additional 3-D shooting algorithm (Haslinger and Kissling, 2000) and this version does include usage of a numerical grid. Up to now the seismic grid in SIMULPS equals the inversion grid, and due to favorable data distribution and network dimensions, even grid spacing could be used in our tests. Uneven gridding without decoupling seismic and inversion grids greatly complicates matters since one may not accommodate apriori information and uneven sampling by the data set with only one grid.

Whereas in excellently resolved regions differences in seismic tomographic results obtained by different methods (i.e. forward solvers, model parametrization) are insignificant, in regions of only fair or poor resolution application of strict ray theory may lead to distortions in the tomographic images (Husen and Kissling, 2000). Such artifacts are the combined result of model parametrization, ray path distortions, and problems in association of observed seismic phases with calculated ray paths. Contrary to the similarity of the inversion results, the resolution estimates even for excellently resolved regions often show remarkable differences. This documents a strong dependency of the various resolution measures (HIT, DWS, RDE, SPR, ray density tensor) on the employed forward and inverse solvers, on model parametrization and damping parameters.

We conclude that the three-grid approach satisfies the different needs of the entire inversion process: (1) a physically meaningful discretization depending on theoretical resolution capability (i.e. wavelength) of
the data set and on apriori information (seismic grid),
(2) a numerically stable and precise forward solution
(numerical grid), and (3) an appropriate parametriza-
tion of the inversion problem accounting for variable
ray distribution (inverse grid). We further conclude
that a reliable resolution estimation for seismic to-
mography needs the combined estimation of different
resolution measures calibrated by carefully designed
synthetic data tests with the characteristic synthetic
3-D model.

The software packages we used are available on the
internet (see Appendix A).

Acknowledgements

We thank G. Nolet and D. Eberhart-Phillips for
critical and helpful reviews. This work was finan-
cially supported by the Swiss TOMOVES project
BBW 97.0451 as part of the EU research project
Environment ENV4-CT98-0698. Contribution No.
1144 Institute of Geophysics, ETH Zurich.

Appendix A

The main results and the LET programs discussed in
this study are summarized in the form of the software
package 3 DTOMOVES and are available on internet
(www.sg.geophys.ethz.ch/aes).

This software package for seismic tomography
with local sources travel time data has been developed
by several authors — see README files and source
code headers — and continues to evolve. The pack-
age contains source codes, example files, and short
descriptions of the four FORTRAN programs VE-
LEST, SIMULPS14, FATOMO, and TOMO2GMT.
VELEST allows to obtain an iterative solution to the
coupled hypocenter-1-D velocity model problem (and
joint hypocenter determinations), and is mostly used
for the calculation of a Minimum 1-D model with sta-
tion delays for high-precision earthquake location and
for use as initial reference model in 3-D-tomography.
SIMULPS14 is a special version of SIMULPS (origi-

data base code by C. Thurber, 1983 and D. Eberhart-Philips,
1986, addition of Farra- and Virieux-ray tracer by
Haslinger, 1998) and provides an iterative solution to
the coupled hypocenter-3-D velocity problem. This
version includes the original ART and, in addition, a
precise shooting ray tracer. FATOMO again provides
an iterative solution to the 3-D velocity problem using
the fat ray concept. Earthquakes are relocated using a
grid-search algorithm. TOMO2GMT is a reformatting
routine preparing output by SIMULPS and FATOMO
for plotting with GMT commands. In particular, it al-
lows to display horizontal and vertical cross sections
of tomographic results (relative or absolute velocity)
and of resolution estimates (number of hits, DWS,
resolution diagonal elements, resolution spread, etc.).
Ray density tensors may also be displayed.

References

Aki, K., Christofferson, A., Husebye, E.S., 1977. Determination
of the three-dimensional seismic structure of the lithosphere. J.
Geophys. Res. 82, 277–296.


Eberhart-Philips, D., 1986. Three-dimensional velocity structure
in northern California coast ranges from inversion of local

Eberhart-Philips, D., 1990. Three-dimensional P and S velocity
structure in the Coalinga region, California. J. Geophys. Res. 95, 343–363.

velocity structure, seismicity, and fault structure in the Parkfield

Ellsworth, W.L., 1977. Three-dimensional structure of the crust
and mantle beneath the island of Hawaii, Ph.D. Thesis, Massa-
chusetts Institute of Technology, Cambridge.

Evans, J.R., Achauer, U., 1993. Teleseismic velocity tomography
using the ACH method: theory and application to continental-scale

Hager, B.H., Clayton, R.W., 1988. Constraints on the structure of mantle convection using seismic observations, flow models, and
and Breach, New York, pp. 657–763.

Haslinger, F., 1998. Velocity structure, seismicity and seismo-
tectonics of northwestern Greece between the gulf of Arta and
Zakynthos, Ph.D. Thesis, ETH Zürich, Switzerland.

Haslinger, F., Kissling, E., Ansorge, J., Hatzfeld, D., Papadimitriou,
E., Karakostas, V., Makropoulos, K., Kahle, H.-G., Peter, Y.,
1999. 3-D crystal structure from local earthquake tomography
around the Gulf of Arta (Ionian region, NW Greece). Tectonophysics 304, 201–218.
Haslinger, F., Kissling, E., 2000. Investigating the effect of the
applied ray tracing in local earthquake tomography. Phys. Earth
Plan. Int.
Husen, S., 1999. Local earthquake tomography of a convergent
margin, N Chile: a combined On and Offshore study, Ph.D.
Thesis, University Kiel, Germany.
Husen, S., Kissling, E., 2000. Local earthquake tomography bet-
Parkfield. Part I. Simultaneous inversion for velocity structure
Seis. Soc. Am. 81, 524–552.
The Netherlands, pp. 386.
sensitivity kernels for finite-frequency travel times: the
Podvin, P., Lemconte, I., 1991. Finite difference computation of
travel times in very contrasted velocity models: a massive
parallel approach and its associated tools. Geophys. J. Int. 105,
271–284.
Roecker, S.W., 1981. Seismicity and tectonics of the Pamir–Hindu
Kush region of central Asia, Ph.D. Thesis, Massachusetts
Institute of Technology, Cambridge.
Spakman, W., Van der Lee, S., Van der Hilst, R., 1993. Travel
time tomography of the European–Mediterranean mantle down
to 1400 km. Phys. Earth Plan. Int. 79, 3–74.
Valley as determined from teleseismic events. J. Geophys. Res.
81, 849–860.
Thurber, C.H., 1983. Earthquake locations and three-dimensional
crystal structure in the Coyote lake area central California. J.
Thurber, C.H., Eberhart-Phillips, D., 1999. Local earthquake tomo-
calculations for three-dimensional structures. In: Thurber, C.H.,
Rabinowitz, N. (Eds.), Advances in Seismic Event Location.
Kluwer, Dordrecht, The Netherlands, Chapter 4, p. 29, in
press.
earthquake data from the Hengill-Grensdalur central volcano
for deep mantle circulation from global tomography. Nature
386, 578–584.
Virieux, J., Fara, V., 1991. Ray tracing for earthquake location in
Non-linear teleseismic tomography at Long Valley Caldera
using three-dimensional minimum travel time ray tracing. J.
Geophys. Res. 100, 20379–20390.