

Title	A practical on moment tensor inversion using the Kiwi tools
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1 Introduction

This tutorial with exercises introduces to the use of the Kiwi tools (Heimann, 2011; Cesca et al., 2010), an open source seismological software developed at the University of Hamburg and the GFZ Potsdam for the goal of moment tensor inversion and finite source inversion. The following text is accompanied by an electronic supplement, including a virtual machine (KiwiVirtualBox) with a Linux Ubuntu system. The virtual machine includes all required software, manuals, and data examples here discussed. It can be downloaded at [10.5880/GFZ.2.1.2013.001](https://doi.org/10.5880/GFZ.2.1.2013.001).

The aim is to guide the reader through the different modules required to perform a moment tensor inversion. All moment tensor and source inversion routines in seismology require access to the following components: Green's functions, seismological data, inversion framework and results assessment.

The following sections introduce the reader to the Kiwi tools devoted to the Green's function databases handling, data access and visualization, selection of the inversion parameters and inversion process, and results visualization. While describing the most important software tools and their more relevant options, specific examples guide the reader through the different steps of the inversion process. In conclusion, a number of relevant exercises are provided.

2 Green's functions

Green's functions (GFs) describe, on the basis of model assumptions or empirically gained data, the wave propagation from the seismic source to a receiver, in response to specific source excitation. In the framework of source inversion problems, they are used to build synthetic seismograms, which are compared to real surface data records in the moment tensor inversion.

In the current setup of the Kiwi tools, only 1D velocity models are considered. This means, Earth models for which all relevant properties (P and S wave velocities, density, attenuation coefficients) only change with depth. A 1D case presents certain advantages in terms of Green's function computation. First, several codes are nowadays freely available to solve the forward problem. Moreover, because of the symmetry of the model, it is only required to compute a limited number of Green's functions. For any combination of source depth and source-receiver distance, 10 Green's functions have to be computed. These 10 Green's

functions can be combined using proper weighting to compute the response to any moment tensor configuration at any azimuth.

Green's functions are typically stored into databases, which we refer here as Green's function database (GFDB). A GFDB may require a significant computational effort, but is then ready for use and significantly reduces computational time of the inversion. The Kiwi tools currently handle GFDB through HDF5 (the dependence on HDF5 may be removed in future Kiwi versions). The system is independent on the software used to generate GFs, however we have successfully worked so far with Qseis (Wang, 1999) and Gemini (Friedrich and Dalkolmo, 1995). GFDBs are built for any required velocity model with user-defined constraints. In particular, the following parameters have to be chosen when preparing a GFDB:

- Description of the velocity model,
- Range of epicentral distances,
- Range of source depths,
- GF sampling.

When preparing an own GFDB, these parameters have to be chosen carefully with respect to the area of study, network geometry, expected range of magnitudes and source depths, and sensor instrumentation (sampling rate, frequency range). The range of distances and depths limits the possible application of the GFDB, e.g. synthetic seismogram for too far away stations or too deep sources cannot be computed when exceeding the spatial boundary of a GFDB. Epicentral distances and depths should be sampled equidistant. The sampling interval limits the resolution potential of a GFDB: first, because it limits the maximal reproducible frequencies, and second because the inversion framework requires a common sampling of data and GFs.

The KiwiVirtualBox includes a single GFDB. This was generated with the software Qseis (Wang, 1999) for a global velocity model, IASP91 (Kennett & Engdahl, 1991). The available GFDB allows to build synthetic seismograms for sources down to 40 km and stations up to 1000 km epicentral distance with a spatial sampling of 1 km. Thus GFs are available every 1 km in distance and depth and the computation of synthetic seismograms in between grid points can either be done through GFs interpolation or by using the GFs of the closest grid point. The sampling is 0.5 s, so that the spectral fit cannot exceed 1 Hz.

The GFDB is found at the directory */GFDB*; its name is *GFDB/db*.

To get some information on the GFDB type:

```
gfdb_info GFDB/db
```

In turn you get information on the sampling (dt), spatial GF sampling along epicentral distances and source depths (dx, dz), minimal epicentral distance and source depth (firstx, firstz), number of epicentral distances and source depths (nx, nz), number of GFs per source depth-epicentral distance geometry (ng, typically 10), and some additional technical information on the number of files used to allocate GFs (chunks) and the state of filling of a GFDB (for large GFDBs, with significant GF computation time, the available database may still be incomplete). Temporal and spatial units are always given in seconds and meters.

To extract a Green's function (in the example we extract from the database GFDB/db at a distance of 400000 m and source depth of 20000 m the GF number 1, and store it in the file `gf1.d400km.z20km.mseed`) in miniSEED format type (note that using a different extension than `.mseed` provides the GF in the default ASCII format):

```
gfdb_extract GFDB/db <<EOF  
400000 20000 1 gf1.d400km.z20km.mseed  
EOF
```

To view the Green's function with the snuffler visualizer type:

```
snuffler gf1.d400km.z20km.mseed
```

A new GFDB can be created using the Kiwi command `gfdb_build`, while a subset of an existing database can be created using the command `gfdb_redeploy`. Testing these commands with no argument, provide more information on their syntax:

```
gfdb_build  
gfdb_redeploy
```

Further information on other Kiwi tools to generate and handle Green's function databases are available in the enclosed documentation (in the directory *DOCS*).

3 Data

The data, here intended as displacement waveforms, are an obvious prerequisite for any source inversion tool. Their characteristics, e.g., their sampling rate or the limited bandwidth of the flat displacement-proportional frequency response of the recording instrument can severely limit the inversion potential.

Kiwi can currently handle different formats, including the preferred miniSEED (see Chapter 10) and a simple ASCII format (first column time, second column displacement amplitude). Sampling should be common for any single study (e.g., for any treated earthquake case), and common to the adopted GFDB. Amplitudes are given in meters, times in seconds, with respect to the reference system timestamp, January 1, 1970, 00:00:00.

Data preprocessing is not described in detail here (see Scherbaum, 2007). However, displacement traces are typically obtained from velocity seismometers, through data recovery, tapering (see IS 14.1), removal of mean and trend and restitution to displacements, according to instrument response function. Data may also need to be converted to any of the usable data formats.

Displacement files for a single study (earthquake) should be stored in a single event directory, with the following naming:

```
DISPL.$STAT.$CHAN
```

where `$STAT` is the station code, and `$CHAN` the channel code (BHZ: Vertical, BHN: North, BHE: East, BHR: Radial, BHT: Transversal). The adoption of channel "BH" is only a naming convention, and does not limit the application of the Kiwi tools to any instrument type or channel.

The KiwiVirtualBox includes several datasets, which are described in the following paragraphs. All data are stored as miniSEED files, with a sampling of 0.5 s (common to the available GFDB). All data were recorded by velocity broadband sensors, and can be safely analyzed in any frequency band above 0.01 Hz and below 1 Hz.

An example of directory structure for a synthetic dataset can be found at:

```
DATA/SYNTHI
```

which is a synthetic example. Displacement waveforms have been created there for a pure double couple (DC) point source (location, and origin time are given in the last section), with the available GFDB and no noise (therefore they can be perfectly matched in the test inversion).

To visualize the typical content of a data directory type:

```
ls DATA/SYNTHI
```

It indicates files corresponding to displacement traces, plus an additional station file.

To look at the miniSEED waveforms, use the snuffler software:

```
snuffler DATA/SYNTHI/DISPL.*
```

The following command allows to include event information and to perform some data sorting:

```
snuffler DATA/SYNTHI/DISPL.* \  
--stations="META/stations.dat" --event="META/events.txt"
```

An event is then selected by typing “e” when the cursor is on the event label (a rectangle should appear around the label).

A left click on the event label opens a window with possible operations.

For example, it is possible to sort traces according to their epicentral distance from the selected event.

Repeating the operation with the following attribute allows to compare observed waveforms with synthetics for provided focal mechanisms.

```
snuffler DATA/SYNTHI/DISPL.* \  
--stations="META/stations.dat" --event="META/events_w_solutions.txt"
```

It is now possible to modify the frequency filter applied to both the recorded and the synthetic traces, and to visually inspect the effect of frequency filtering on both traces and on their fit.

Apart from the displacement files, the data directory includes one more file: *stations.dat*. This ASCII file, which can be opened with any text editor, is very important; the inversion cannot be performed without it. It include several lines, one per each desired station. Each line is composed by a station number (an increasing integer), the station code, latitude and longitude (in degrees).

Note that, when running the inversion and select a given station file, only stations listed in the station file and for which properly named traces are available in the data directory will be used. This implies that: (a) stations can be temporarily omitted, simply by file renaming (e.g.

removed.DISPL.STAT.BHZ), (b) several station files can be created, to simulate different network configurations, with no need to duplicate data.

4 Inversion setup

We refer to the inversion framework, in the most general sense, as to the combination of inversion software, scripts, input files and the selection of inversion parameters. In the general formulation of a source inversion process, the data and GFs have to be made accessible. Then, a source model is first considered, synthetic seismograms are computed on the basis of a selected source model and the adopted GFs, synthetic seismograms are then compared to observations, and a fit among data and synthetics is estimated. On the base of such a fit, the source model is modified, perturbed or “improved”, and the process iteratively repeated, until certain conditions are met. At the end of the process, the information regarding the best fitting model is released, typically together with amisfit estimation and suitable evaluation plots, such as the fault-plane (“beach-ball”) solution (see., e.g., section 3.4 of Chapter 3), waveform fits, etc..

The inversion process is for sure to some extent non unique, since the results are affected both by the choice of the (usually oversimplified or sometimes even not appropriate) velocity model and of the inversion parameters. E.g., , with respect to the latter only, a specific station selection covering different azimuthal and distance ranges, different frequency bands analyzed, the fitting of body waves only or of full waveforms or the performance of the inversion through either waveform or amplitude spectra fitting, all could contribute to significant differences in the inversion results. If a good quality dataset should ensure a minor deviation between results from different inversion setups, then this requires the reasonable selection of the underlying model and inversion parameters and of the chosen inversion approach. These should be tuned as good as possible to the event size, its depth, the reliability of the available velocity model, the seismic instrumentation, data acquisition and processing, and the source-stations geometry.

Here, we describe how to use the *rapidinv* python code to perform the inversion. *rapidinv* allows the user to customize the inversion procedure, within certain limits, and make use of the Kiwi tools inversion modules without directly dealing with these tools. *rapidinv* acts as a user friendly interface to these tools. Its potential may be further exploited by advanced users. In particular, *rapidinv* internally calls several times the Kiwi tool *minimizer*, which is used to assess source model parameters, generate synthetic seismograms, filter and taper synthetics and observed seismograms, compare them and compute misfits, perform grid search or Levenberg-Marquardt inversion for selected source parameters, and export seismograms in different formats.

rapidinv always performs the inversion in 3 separate steps, as described in Cesca et al. (2010) (DC and finite source inversion), and Cesca et al. (2013) (DC and full MT inversion). The first and second steps have to be carried out to obtain a point source solution, the third step is only required to perform an additional finite, kinematic source inversion.

The first step is typically performed as an amplitude spectra inversion. The pure DC results include strike, dip, rake (4 configurations because of the polarity ambiguity of the focal mechanism), centroid depth, scalar moment and magnitude. The full moment tensor (MT)

results additionally include moment tensor components (2 configurations because of the polarity ambiguity) and moment tensor decomposition (see also IS 3.9 and EX 3.5).

The second inversion step is always performed in the time domain, to resolve the polarity ambiguity and to search for the preferred centroid locations. Previous results are improved through the solution of the polarity ambiguity. Additionally, the relative epicentral location and time of the centroid are found. Location and times are defined with respect to the hypocentral location (in terms of spatial shift along North/South and East/West) and nucleation time (in terms of relative time). Both these reference parameters are defined by the user prior to the inversion, and are typically based upon a specific source location result or seismic catalogue information.

After completion of the first and the second inversion step we leave the framework of point source inversion and try to invert for kinematic parameters of the extended source. The background for doing so and the source models used to keep the inversion problem feasible is given in Heimann (2011) and Cesca et al.(2010). The third inversion step for kinematic parameters of the extended source is preferably performed in the frequency domain, including higher frequencies, which should help to estimate finite source parameters. Among the possible resolved parameters are: the preferred rupture plane orientation (discrimination between rupture and auxiliary plane), rupture directivity, rupture velocity, size and duration.

The inversion is preferably performed in the WORK directory, where all local python (<http://www.python.org>) codes (rapidinv, Cesca et al. 2010; mopad, Krieger & Heimann 2013) are locally stored.

The following command gives a list of the initial directory content:

```
ls WORK/*
```

*.py and *.pyc are locally stored python scripts. rapidinv* (* denotes different version which may be available at different stages) is the script to perform the source inversion. mopad is a tool to perform moment tensor decomposition and plotting (see Krieger and Heimann 2013), which is internally used for these purposes.

```
rapidinv.inp.* are example of input files, for different events or inversion setups;  
rapidinv.defaults includes the default setup of inversion variables;  
rapidinv.acceptables is a control file to verify very roughly the inversion variables  
choice.
```

5 Selection of inversion parameters

The inversion is customized after building an own input file. To have an idea, how such an input file looks like, we can open with an editor the file *rapidinv.inp.synth1*. It can be seen that the file includes a list of variables (first column) and a list of values (second column). The most important variables are described in the following. A complete list of variable definition and accepted values is given in the rapidinv manual in the VirtualBox in the directory *DOCS*.

The input file should be kept as short as possible, and only contains those variables which are specific for the specific event inversion. All other variables, those kept to the defaults values and those common for all studied events, should be stored in the file *rapidinv.defaults*.

5.1 Important global variables:

DATA_DIR: Path to the directory containing all data and station information.

DATA_FORMAT: Expected format of input displacement data (see kinherd.org for more details).

STAT_INP_FILE: (Default: stations.dat): Name of the input file with list of stations to be used. This file, with the proper format, should exist and be saved in the data directory (see DATA_DIR). Specific file format (manual). All stations herein indicated will be considered. If data are missing, the station will be excluded. If data are partially missing, only existing components will be used. If data files exist, but the station name is not included in the list, data will not be used.

INVERSION_DIR: Path to the directory where all output files will be saved.

NUM_INV_STEPS: Number of inversion steps to be realized (1 = only focal mechanism, 2 = focal mechanism and centroid location, 3 = full point and kinematic inversion).

COMP_2_USE: The string should include one letter for each spatial component to consider. Letters follow the convention from kinherd.org (d: down; u: up; n: North; s: South; e: East; w: West; r: transversal, rightward as seen from source to receiver; l: transversal, leftward as seen from source to receiver; a: radial, away from source; c: radial, backward to source).

EPIC_DIST_MIN, EPIC_DIST_MAX: Minimum and maximum epicentral distance to be considered for all steps.

LATITUDE_NORTH, LONGITUDE_EAST: Original latitude and longitude (deg) of the epicenter. Further relocation will be relative to this value.

SW_FILTERNOISY: Switch to detect and remove noisy traces.

SW_WEIGHT_DIST: Apply a distance-dependent weight, w: $w = \text{station_epicentral_distance} / \text{maximal_epic_distance}$.

SW_FULLMT: Switch to additionally run full moment tensor inversion

5.2 Important variables for inversion step 1:

BP_F1_STEP1, BP_F2_STEP1, BP_F3_STEP1, BP_F4_STEP1: Bandpass frequency (e.g. 0.009 0.01 0.1 0.11) at inversion step 1.

DEPTH_BOTTOMLIM, DEPTH_UPPERLIM: Minimum and maximum accepted depth (km) after inv. step 1 (all other solutions will be removed)

DEPTH_1, DEPTH_2, DEPTH_STEP; SCAL_MOM_1, SCAL_MOM_2, SCAL_MOM_STEP; STRIKE_1, STRIKE_2, STRIKE_STEP; DIP_1, DIP_2, DIP_STEP; RAKE_1, RAKE_2, RAKE_STEP: Min, Max, Increment of depth (km), moment (Nm) and fault angles (deg) to define starting configurations, during inversion step 1.

SW_RAPIDSTEP1: If set TRUE will ignore STRIKE_1, STRIKE_2, ... and test 10 default configurations of strike-dip-rake.

INV_MODE_STEP1: Defines the strategy to carry out inversion step 1. The following possibilities are allowed (e.g. invert_dmsdst: gradient inversion of invert strike, dip, rake, moment, depth)

MISFIT_MET_STEP1: Defines the misfit definition for inversion step 1 (ampspec_l1norm: amplitude spectra will be compared, using L1 norm; ampspec_l2norm: amplitude spectra will be compared, using L2 norm; l1norm: time traces will be compared, using L1 norm; l2norm: time traces will be compared, using L2 norm).

PHASES_TO_USE_ST1: Seismic phases to be used for inv. Step 1 (p: P phases on all used components, as defined in COMP_2_USE; b: Bodywaves, P on vertical component, S on remaining components; a: Full waveform on all used components, as defined in COMP_2_USE).

WEIGHT_A_ST1, WEIGHT_P_ST1, ...: Defines a weight for the time window for phase a (p, ...) during inversion step 1. It is used only if the phase is activated in PHASES_TO_USE_ST1.

WIN_LENGTH_A_ST1, WIN_LENGTH_P_ST1, ...: Defines the length (s) of the time window for phase a (p, ...) during inversion step 1.

WIN_START_A_ST1, WIN_START_P_ST1, ...: Defines the starting time of the time window for phase a (p, ...) during inversion step 1. The value indicates the position of theoretical first P (or S) phase within the time window, defined as percentage of the window length (e.g. 0.02 for a window length of 100s, indicates that the window will start to have the theoretical first P phase arrival time at 2% of the window length).

WIN_TAPER_A_ST1, WIN_TAPER_P_ST1, ...: Defines the tapering of the time window for phase a (p, ...) during inversion step 1. A taper is applied in the time domain, smoothing the time window at both sides. The length of the smoothed part of each side is defined by the given real value, which is defined as a percentage of the time window length.

5.3 Plotting variables for inversion step 1:

DATA_PLOT_STEP1: Define if data format for plotting result after inversion step 1 is amplitude spectra or displacements). Acceptable values are amsp or seis.

AMPL_PLOT_STEP1: Amplitudes of plotted spectra/waveforms (amax: amplitudes of different traces have the same scale; norm: amplitudes are normalized, they are enlarged to the maximal possible scale).

FILT_PLOT_STEP1 Defines the format (plain = unfiltered, filtered, tapered) of time series for plotting results after inversion step 1.

START_PLOT_STEP1, LEN_PLOT_STEP1, TICK_PLOT_STEP1: Defines the start, length and tick interval (s) of time series for plotting results after inversion step 1. These are used only if DATA_PLOT_STEP1 is seis.

5.4 Important (and plotting) variables for inversion step 2:

EPIC_DIST_MAXLOC: Additional constraint on maximum epicentral distance to consider for inversion step 2 (where maximum distance will be the minimum between EPIC_DIST_MAX and EPIC_DIST_MAXLOC).

GFDB_STEP2: GFDB used to calculate synthetic seismogram during inversion step 2.

MISFIT_MET_STEP2: Defines the misfit definition for inversion step 1 (l1norm: time traces will be compared, using L1 norm; l2norm: time traces will be compared, using L2 norm)

REL_EAST_1, REL_EAST_2, REL_EAST_STEP; REL_NORTH_1, REL_NORTH_2, REL_NORTH_STEP: Min, max and increment of relative location along East and North direction (meters) to define the group of starting configuration, during inversion step 2.

REL_TIME1, REL_TIME_2, REL_TIME_STEP: Min, max and increment of relative time offset (seconds) to define the group of starting configuration, during inversion step 2.

PHASES_TO_USE_ST2; WEIGHT_*_ST2, WIN_LENGTH_*_ST2, WIN_START_*_ST2, WIN_TAPER_*_ST2: Analogous to the case as for inversion step 1.

BP_F1_STEP2, BP_F2_STEP2, BP_F3_STEP2, BP_F4_STEP2: Bandpass inversion step 2.

DATA_PLOT_STEP2: Define if data format (amsp, seis) for plotting result after inversion step 2 (amplitude spectra/displacements)

5.5 Important (and plotting) variables for inversion step 3:

EPIC_DIST_MAXKIN: Additional constraint on maximum epicentral distance to consider for inversion step 3 (where maximum distance will be the minimum between EPIC_DIST_MAX and EPIC_DIST_MAXKIN).

GFDB_STEP3: Defines the GFDB used to calculate synthetic seismogram during the inversion step 3.

MISFIT_MET_STEP3: Defines the misfit definition for inversion step 3 (amspec_l1norm: amplitude spectra will be compared, using L1 norm; amspec_l2norm: amplitude spectra will be compared, using L2 norm; l1norm: time traces will be compared, using L1 norm; l2norm: time traces will be compared, using L2 norm).

REL_RUPT_VEL_1, REL_RUPT_VEL_2, REL_RUPT_VEL_S: Min, max, increment of relative rupture velocity for starting configurations of inv. Step 3.

PHASES_TO_USE_ST3; WEIGHT_*_ST3, WIN_LENGTH_*_ST3, WIN_START_*_ST3, WIN_TAPER_*_ST3: Analogous as for inversion step 1 (use of bodywaves may work better for location)

BP_F1_STEP3, BP_F2_STEP3, BP_F3_STEP3, BP_F4_STEP3: Bandpass inversion step 3.

DATA_PLOT_STEP3: Define if data format (amsp, seis) for plotting result after inversion step 2 (amplitude spectra/displacements)

SW_APPDURATION: Activate fast directivity inversion (uses BP and taper from inversion step 3)

Once all parameters are modified we are ready to perform the inversion

6 Moment tensor inversion step by step

The inversion procedure is here described for the case of the SYNTH1 event, according to the original rapidinv.inp.synth1 inversion setup.

Go to the working directory and open the chosen input file.

Check DATA_DIR points to the correct data directory

Check GFDB_STEP1, GFDB_STEP2, GFDB_STEP3 point to the correct database

Adapt inversion parameters to user wishes.

Check that specific relevant parameters are fixed, in particular those defining the source parameters which are considered to be known, when starting the moment tensor inversion, This include the event origin time, its hypocentral location, and a first moment estimate. Both depth and moment will be . This information is typically available from global catalogue, such as NEIC or GCMT for earthquakes above Mw 5.5, or from local agencies in the case of smaller magnitude events of regional interest. These parameters are provided for all test datasets. For synthetic dataset, the true source parameters are given, while for real dataset, source parameters were chosen according to the information provided either by NEIC, GCMT or EMSC-CSEM.

Known source parameters for the event SYNTH1 are as follows:

Date/Time	2012-03-15 15:00:00
Lat N	47.6667
Lon E	12.0167
Depth (rough)	15km
Mw (rough)	6.0
M ₀ (rough)	1e18Nm

We are now ready to run the inversion. This is done by typing in the working directory:

```
python rapidinv12.py rapidinv.inp.synth1
```

The code first read rapidinv.defaults and assign default values to all variables.

Then it reads the input file and overwrites all selected variables (repeated variable assignment imply the last assignment will overwrite previous ones)

Finally, a rough control on variable values is performed using the file rapidinv.acceptables

Then, the following tasks are performed:

- Create/overwrite results directory;
- Filter stations according to selected epicentral distance ranges;
- A number of starting source configuration for the DC inversion is built, according to input parameters, and the DC inversion is then performed.
- The best DC solution, together with a number of non-DC solutions, constitute the starting source configurations for the full MT inversion, and the MT inversion is then performed.
- The first inversion step is successfully completed when two GMT scripts are created, executed and two postscript files generated: step1.ptsolution.ps and step1.mtsolution.ps

step1.ptsolution.ps (see Figure 1, obtained for event SYNTH1) shows the results of the pure DC inversion after inversion step 1. Source parameters, including location, depth, moment, magnitude, strike-dip-rake configurations and misfit are given in the top left section of the figure. The top right section is dedicated to the relative misfit variations with respect to the best solution, when perturbing single source parameters (depth, strike, dip, rake). These curves are expected to have a minimum in correspondence of the preferred solution, the variability of the minima broadness provides information on the relative resolution of different source parameters (e.g. strike vs. dip vs. rake).

The bottom panel of *step1.ptsolution.ps* is dedicated to waveform or spectra comparison (red colors are used for data, black for synthetics). Waveform plots additionally show a gray area denoting the applied time domain taper. Stations are sorted on the base of epicentral distances, with station name, distance, azimuth and maximal amplitudes provided on the left side.

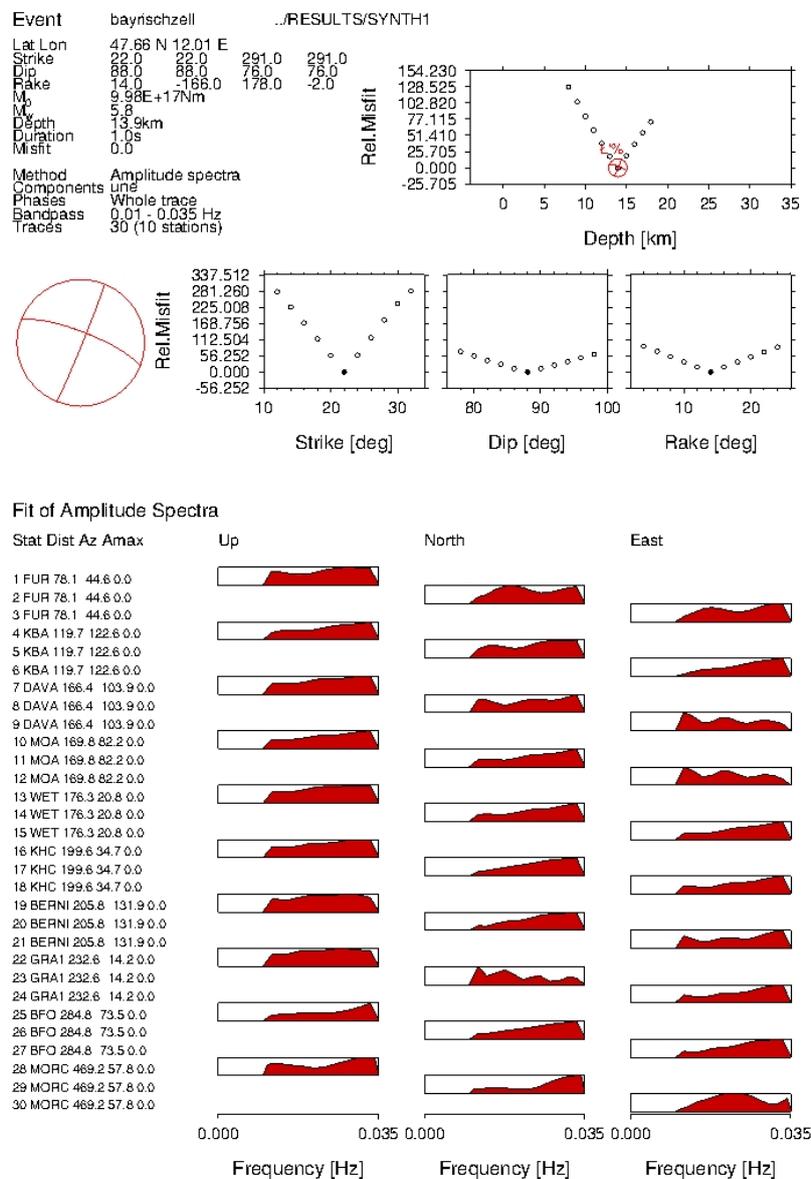


Figure 1 *step1.ptsolution.ps*

step1.mtsolution.ps (figure 2, obtained for event SYNTH1) provides a similar representation for the full MT inversion results (for the definition of the full MT parameter set (centroid location and time, CLVD, isotropic components etc. see IS 3.9):

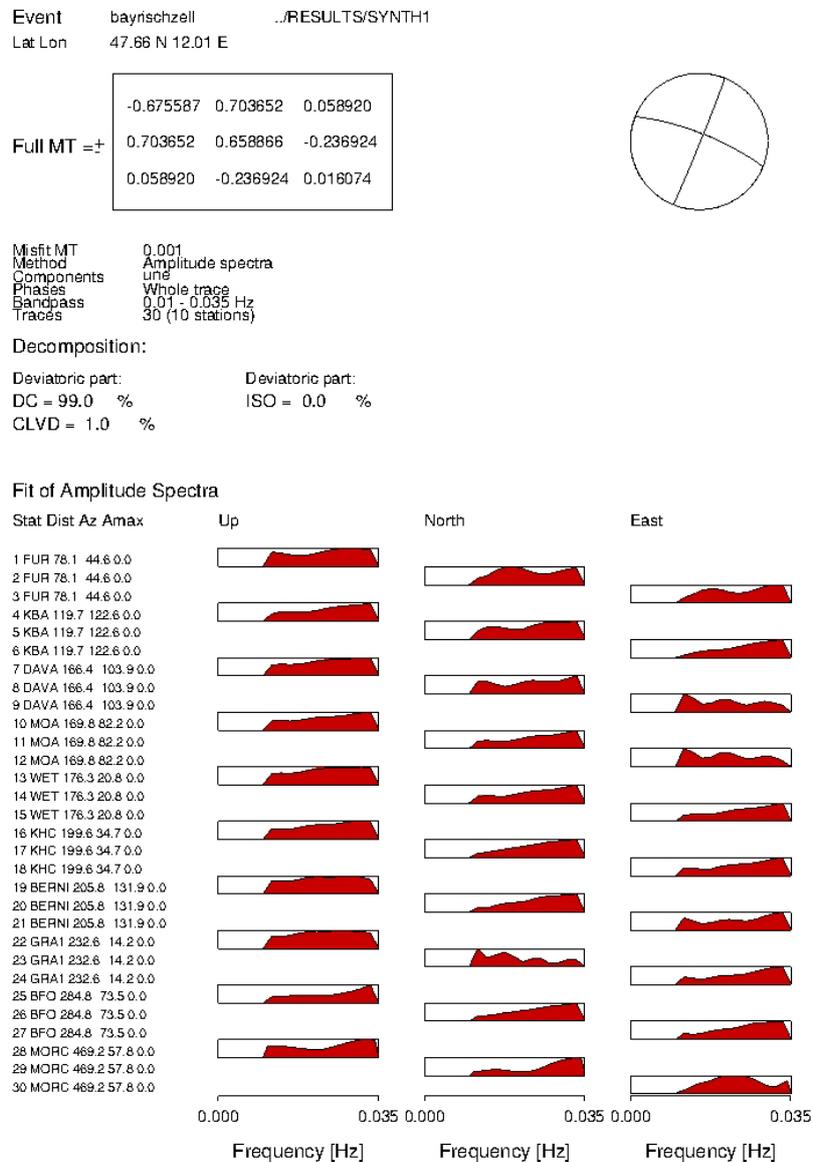


Figure 2 *step1.mtsolution.ps*

The second inversion step is carried out in the time domain, by comparing observed and synthetic displacement waveforms, for a reduced set of focal mechanisms, decided upon results of inversion step 1. The inversion step 2 for DC solution is performed as follows:

- Two possible DC focal mechanisms, with opposite polarities are used to build synthetics. After waveform cross-correlation, waveforms fits are evaluated and the polarity chosen.
- A grid search for the centroid location and centroid time (as relative location and time

with respect to the original epicentral location and origin time respectively) is performed, and best centroid location/time found.

- Polarities are also tested for the best location also for the best full MT solution, and the polarity chosen. A full MT decomposition, through DC, compensated linear vector dipole (CLVD) and isotropic components is then performed.
- The second inversion step is successfully completed when two GMT scripts are created, executed and two postscript files generated: *step2.ptsolution.ps* (figure 3) and *step2.mtsolution.ps*

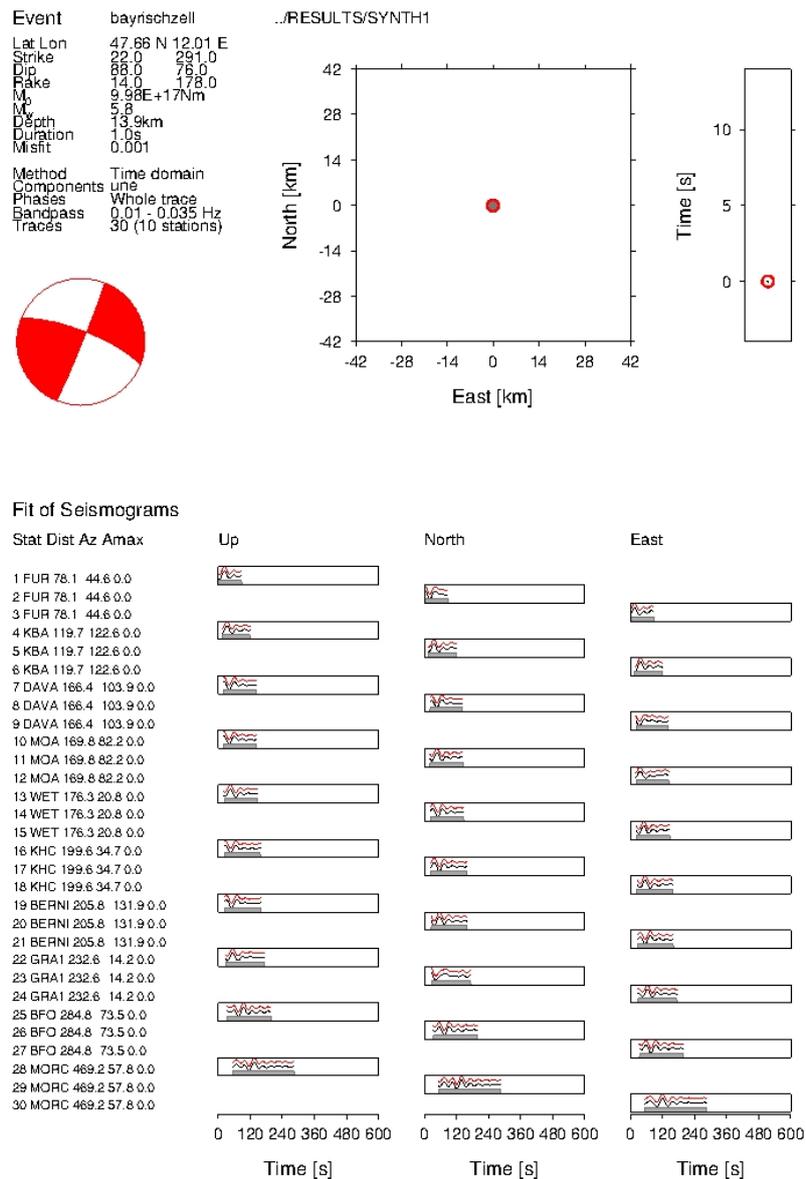


Figure 3 *step2.ptsolution.ps*

step2.ptsolution.ps shows the results of the pure DC inversion after inversion step 2. Improved source parameters are given in the top left section of the figure. The top right section is dedicated to the relative misfit variations for the centroid location and centroid time

grid search (reference location is at 0, 0; reference time at 0). Larger circle sizes correspond to lower misfits. Red circles denote best solutions. The bottom panel is again dedicated to waveform (or spectra) comparison (red colors are used for data, black for synthetics). Waveform plots additionally show a gray area denoting the applied time domain taper. Stations are sorted on the base of epicentral distances, with station name, distance, azimuth and maximal amplitudes provided on the left side.

The moment tensor polarity is similarly obtained, by comparing waveform fits for both full MT solution with opposite polarity. The resulting plot (step2.mtsolution.ps, shown in figure 4 for event SYNTH1) illustrates the result of moment tensor decomposition, according to DC, compensated linear vector dipole (CLVD) and isotropic (ISO) components.

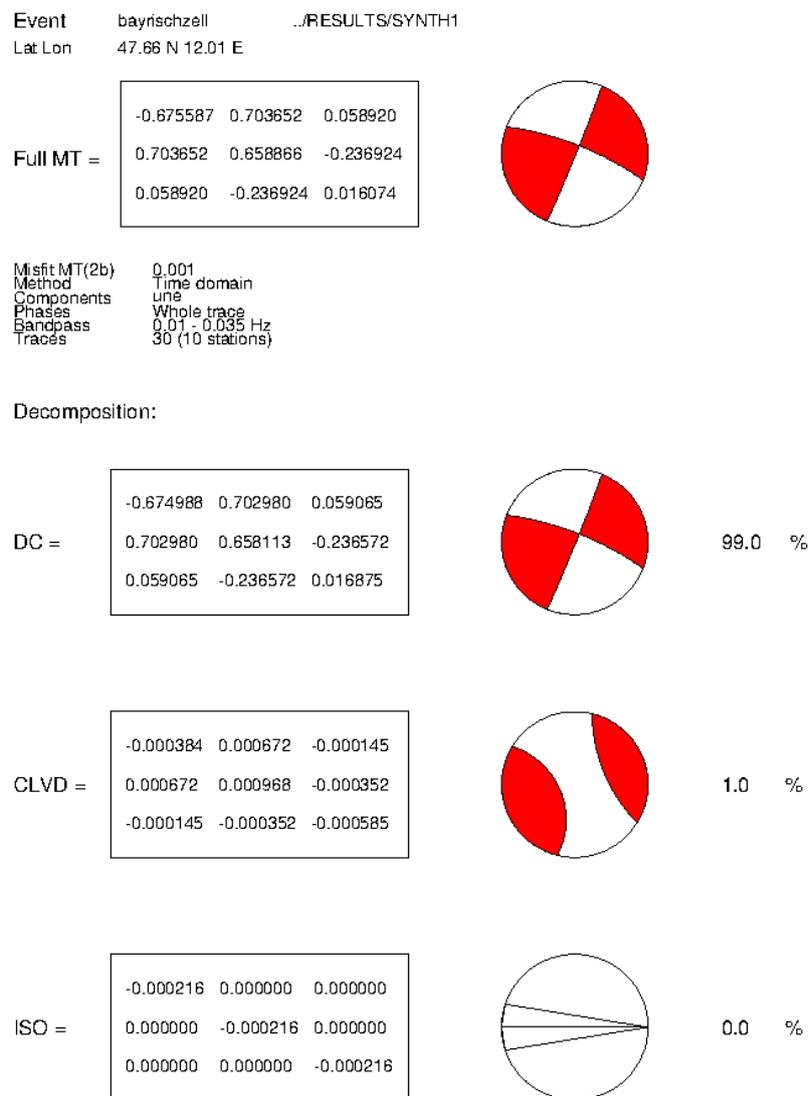


Figure 4 *step2.mtsolution.ps*

Prior to the complete finite source inversion, a quick directivity inversion is carried out (see Cesca et al. 2011 for details), by inverting the apparent source duration at single stations, and plot its dependence on the station azimuth. Results can be seen in the file *apparentdurations.ps*. This file shows the results of the quick directivity detection analysis. The map on the right side of the plot illustrate the study region, the epicenter (star), and the station locations (circles). Circle colors denote the apparent duration seen at that station, according to the color bar. The azimuthal distribution of the apparent durations are shown on the left graphs, and fitted through a preferred directivity model (more details on expected curve shapes are discussed in Cesca *et al.*, 2011), or through a common, average source time function length (bottom).

Figure 5 shows an example of the file *apparentduration.ps* for event SYNTH8 where rupture directivity towards NNE is correctly resolved.

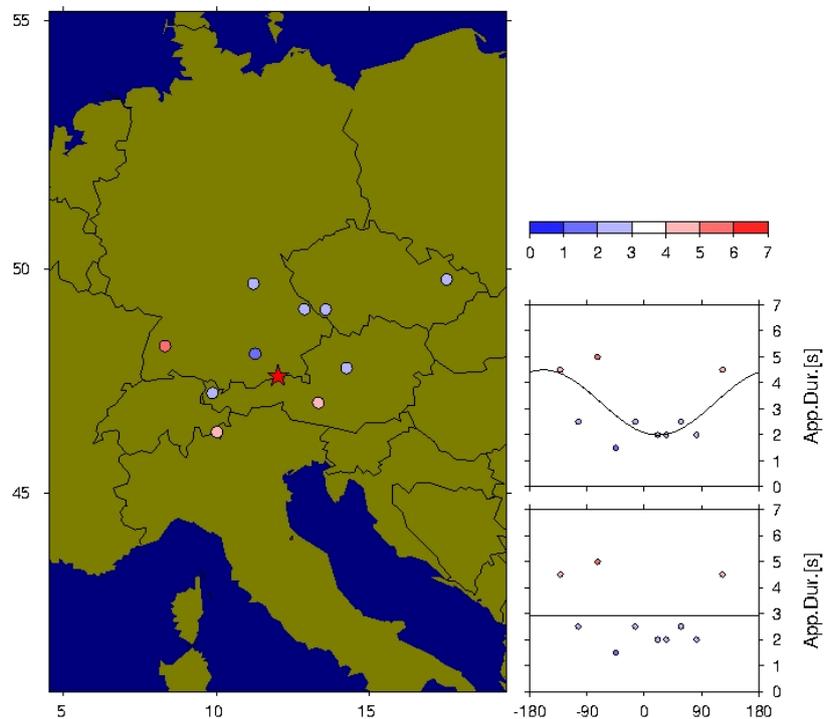


Figure 5 *apparentdurations.ps*

- A range of tested found source solutions is built, with two possible fault plane orientations, variable size and directivity (currently hardcoded, and link to the event magnitude), and possibly variable rupture velocity.
- Finally, performs the third inversion step, which is carried out by grid search, evaluating the misfits for all considered finite source solutions. This last step is successfully completed when a GMT script is created, executed and a postscript file generate: *step3.eiksolution.ps*

step3.eiksolution.ps (see figure 6, obtained for event SYNTH8) shows the results of the finite source inversion after inversion step 3. Point and finite source parameters (e.g. Fault plane orientation, radius, area, average slip, etc.) are given in the top left section of the figure. The top right section is dedicated to the rupture propagation (color denote times of excitation,

lines correspond to rupture isochrones) along the rupture plane (x axis: along strike; y axis: along dip) and relative misfit variations for solutions of different radius and relative rupture velocity).

The bottom panel is again dedicated to waveform (or spectra) comparison (red colors are used for data, black for synthetics). Waveform plots additionally show a gray area denoting the applied time domain taper. Stations are sorted on the base of epicentral distances, with station name, distance, azimuth and maximal amplitudes provided on the left side.

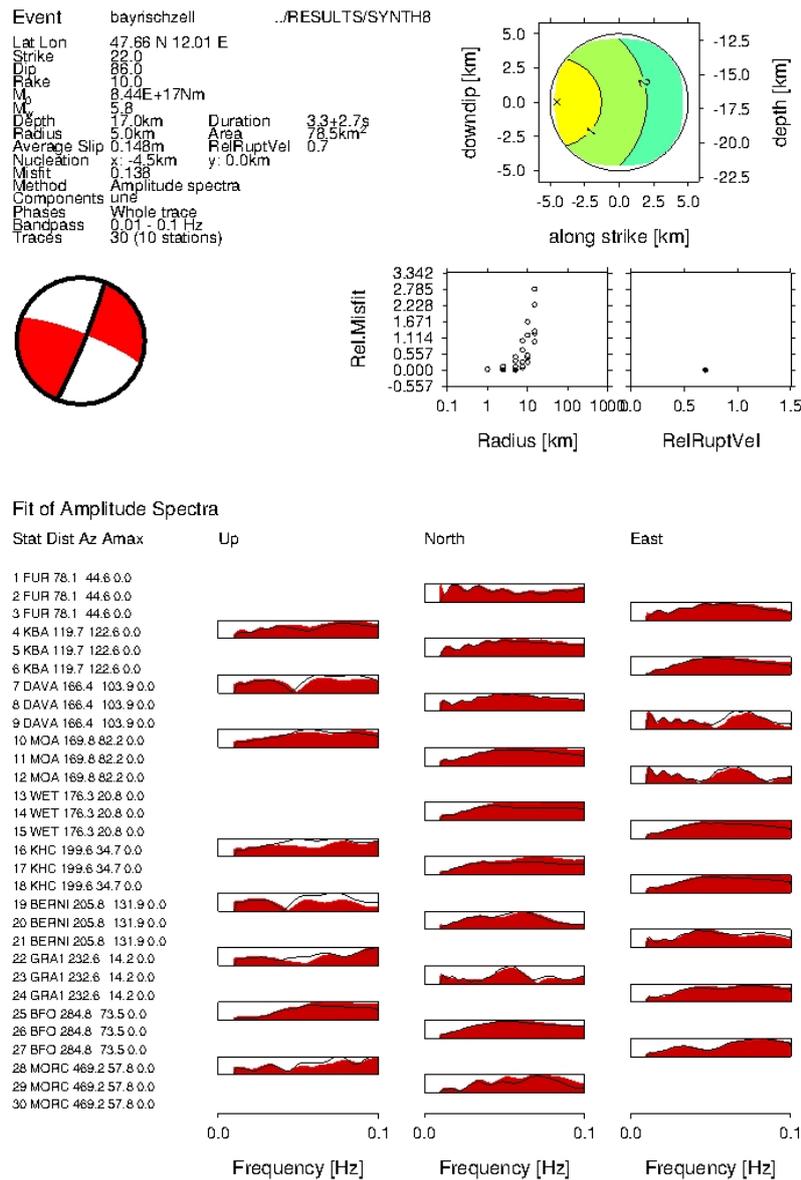


Figure 6 *step3.eiksolution.ps*

7 Testing cases/exercises

Data, including displacement waveforms and metadata, are provided for 20 earthquakes: 8 of them are synthetic events, the remaining 12 are real earthquakes. Because of the spatial

limitations of the here presented available GFDB all events are shallow (crustal) earthquakes, with an hypocentral depth between 1 and ca. 30km. For the same reason only data for stations at local/regional distances up to a maximum of 1000 km are available. Magnitudes of the events range between Mw 4 and 7.

Real datasets have been selected in order to illustrate possible inversion targets, such as the inversion of pure double couple solutions (moderate magnitude natural earthquakes), full moment tensor solutions (mine collapse induced event), and finite source inversion (larger magnitude earthquakes).

The following events (and directories) are available for the reader to test:

<i>Directory</i>	<i>Event name</i>	<i>Dataset short description</i>
SYNTH1	Bayrischzell_D	Synthetic data (DC point source)
SYNTH2	Bayrischzell_D	Synthetic data (MT point source)
SYNTH3	Bayrischzell_D	Synthetic data (kinematic bilateral model)
SYNTH4	Bayrischzell_D	Synthetic data (kinematic unilateral model)
SYNTH5	Bayrischzell_D	Synthetic data, wrong model (DC point source)
SYNTH6	Bayrischzell_D	Synthetic data, wrong model (MT point source)
SYNTH7	Bayrischzell_D	Synthetic data, wrong model (kinematic bil. model)
SYNTH8	Bayrischzell_D	Synthetic data, wrong model (kinematic unil. model)
GER110996A	Teutschenthal_D	Real data, Local distances, Potash mine collapse
GER220203A	St_Die_Vosges_F	Real data, Local distances
GER201004A	Rotenburg_D	Real data, Local distances, Reservoir induced
GER051204A	Waldkirch_D	Real data, Local distances
GRE110406A	Zakynthos1_GR	Real data, Regional distances
GRE110406B	Zakynthos2_GR	Real data, Regional distances
GRE120406A	Zakynthos3_GR	Real data, Regional distances
GRE080608A	Andravidia_GR	Real data, Regional distances, Directivity
ITA060409A	L'Aquila_I	Real data, Regional distances
ITA250112A	Emilia_I	Real data, Local distances, Dense network
TUR231011A 2011	Van1_TR	Real data, Regional distances, main event Van
TUR091111A 2011	Van2_TR	Real data, Regional distances, aftershock Van

Details for each event are provided on the following pages. Together with the event reference name and a short description, the reader should make use of the “Known source parameters”, which are the only needed parameters to build a proper input file for the inversion.

SYNTH1

Event Name: Bayrischzell, Germany Description:

Description:

Synthetic dataset for local inversion. The IASP91 GFDB was used to create synthetic seismograms and no noise is included. Seismograms are obtained for a pure DC point source model.

Known source parameters:

Date/Time	2012-03-15 15:00:00
Lat N	47.6667
Lon E	12.0167
Depth (rough)	15km
M _w (rough)	6.0
M ₀ (rough)	1e18Nm

Network configuration:

Stations number	10
Station distances	up to 500km

SYNTH2

Event Name: Bayrischzell, Germany

Description:

The IASP91 GFDB was used to create synthetic seismograms and no noise is included. Seismograms are obtained for a full MT point source model (DC term similar to SYNTH1).

Known source parameters and network configuration: see SYNTH1

SYNTH3

Event Name: Bayrischzell, Germany

Description:

The IASP91 GFDB was used to create synthetic seismograms and no noise is included. Seismograms are obtained for one extended source model (DC similar to SYNTH1).

Known source parameters and network configuration: see SYNTH1

SYNTH4

Event Name: Bayrischzell, Germany

Description:

The IASP91 GFDB was used to create synthetic seismograms and no noise is included. Seismograms are obtained for a different extended source model (DC similar to SYNTH1).

Known source parameters and network configuration: see SYNTH1

SYNTH5

Event Name: Bayrischzell, Germany

Description:

A different crustal model was used to create synthetic seismograms and no noise is included. Seismograms are obtained for a pure DC point source model (same as SYNTH1).

Known source parameters and network configuration: see SYNTH1

SYNTH6

Event Name: Bayrischzell, Germany

Description:

A different crustal model was used to create synthetic seismograms and no noise is included. Seismograms are obtained for a full MT point source model (same as SYNTH2).

Known source parameters and network configuration: see SYNTH1

SYNTH7

Event Name: Bayrischzell, Germany

Description:

A different crustal model was used to create synthetic seismograms and no noise is included. Seismograms are obtained for one extended source model (same as SYNTH3).

Known source parameters and network configuration: see SYNTH1

SYNTH8

Event Name: Bayrischzell, Germany

Description:

The IASP91 dataset was used to create synthetic seismograms and no noise is included. Seismograms are obtained for a different extended source model (same as SYNTH4).

Known source parameters and network configuration: see SYNTH1

GER220203A

Event Name: St. Die, Vosgian_Mts, France

Description:

Real data (GRSN, MEDNET, GEOSCOPE networks).

Local earthquake with good quality data.

Point source (DC and MT) inversion should be well constrained and easily retrieved.

Kinematic models are not easily resolved, because the rupture model is likely very small for such moderate event.

Known source parameters:

Date/Time	2003-02-22 20:41:01
Lat N	48.33
Lon E	6.67
Depth (rough)	12km
Mw (rough)	4.5
M ₀ (rough)	1e16Nm

Network configuration:

Stations number	17
Station distances	up to 500km

GER051204A

Event Name: Waldkirch, Black Forest, Germany

Description:

Real data (GRSN networks).

Local earthquake with good quality data, but poor azimuthal coverage.

Point source (DC and MT) inversion should be well constrained and easily retrieved.

Kinematic models are not easily resolved, because the rupture model is likely very small for such moderate event.

Known source parameters:

Date/Time	2004-12-05 01:52:37
Lat N	48.115
Lon E	8.077
Depth (rough)	10km
Mw (rough)	4.5

M_0 (rough) 1e16Nm
Network configuration:
Stations number 8
Station distances up to 500km

GER110996A

Event Name: Teutschenthal Collapse, Germany

Description:

Real data (GRSN network) from 1996.

Local earthquake with challenging dataset. A complex rupture model is expected, with energy released in different subevents. The collapse of the mine is expected to show relevant implosive components and CLVD.

Point source (DC and MT) inversion should be well constrained and easily retrieved.

Kinematic models are not easily resolved, because the rupture model is very small (≤ 1 km radius).

Known source parameters:

Date/Time 1996-09-11 03:36:35
Lat N 51.48
Lon E 11.79
Depth 1km
Mw (rough) 4.5
 M_0 (rough) 1e16Nm

Network configuration:

Stations number 10
Station distances up to 500km

GER201004A

Event Name: Rotenburg, induced event, Germany

Description:

Real data (GRSN network). Local earthquake.

Point source (DC and MT) inversion should be well constrained and easily retrieved.

Kinematic models are not easily resolved, but perhaps possible, because the rupture velocity was reported as very slow.

Known source parameters:

Date/Time 2004-10-20 06:59:18
Lat N 53.01
Lon E 9.63
Depth 5km
Mw (rough) 4.5
 M_0 (rough) 1e16Nm

Network configuration:

Stations number 20
Station distances up to 500km

GRE110406A

Event Name: Zakynthos_1, Greece

Description:

Real data (GEOFON, MEDNET, IRIS networks). The earthquake is part of a seismic sequence close to Zakynthos, Greece (other events from the sequence are available).

Regional earthquake.

Point source DC (and MT) and kinematic inversion can be performed.

Known source parameters:

Date/Time	2006-04-11 00:02:40
Lat N	37.64
Lon E	20.75
Depth	20km
Mw (rough)	5.5
M ₀ (rough)	1e17Nm

Network configuration:

Stations number	17
Station distances	up to 1000km

GRE110406B

Event Name: Zakynthos_2, Greece

Description:

Real data (GEOFON, MEDNET, IRIS networks). The earthquake is part of a seismic sequence close to Zakynthos, Greece (other events from the sequence are available).

Regional earthquake.

Point source DC (and MT) and kinematic inversion can be performed.

Known source parameters:

Date/Time	2006-04-11 17:29:27
Lat N	37.64
Lon E	20.75
Depth	20km
Mw (rough)	5.5
M ₀ (rough)	1e17Nm

Network configuration:

Stations number	15
Station distances	up to 1000km

GRE120406A

Event Name: Zakynthos_3, Greece

Description:

Real data (GEOFON, MEDNET, IRIS networks). The earthquake is part of a seismic sequence close to Zakynthos, Greece (other events from the sequence are available).

Regional earthquake.

Point source DC (and MT) and kinematic inversion can be performed.

Known source parameters:

Date/Time	2006-04-12 16:51:59
Lat N	37.63
Lon E	20.74
Depth	20km
Mw (rough)	5.5
M ₀ (rough)	1e17Nm

Network configuration:

Stations number	17
Station distances	up to 1000km

GRE080608A

Event Name: Andravida, Greece

Description:

Real data (GEOFON, MEDNET, IRIS networks) with very good quality.
Magnitude 6.3 earthquake in NW Peloponnese, Greece, with stations at regional distances.
Point source DC (and MT) and kinematic inversion can be performed.
Directivity effects can be clearly seen.

Known source parameters:

Date/Time	2008-06-08 12:25:27
Lat N	37.93
Lon E	21.63
Depth	25km
Mw (rough)	6.3
M ₀ (rough)	4e18Nm

Network configuration:

Stations number	20
Station distances	up to 1000km

ITA250112A

Event Name: Emilia, Italy

Description:

Real data from different networks (MEDNET, IRIS, GEOFON, INGV, Univ.Genova).
The event is relatively weak but the stations distribution unusually dense (inversion may be time consuming if all stations are used).
Stations are at local distances, most below 200km.
Point source (DC and MT) inversion should be well constrained and easily retrieved.
Kinematic models are not easily resolved, because of the small earthquake size/magnitude.

Known source parameters:

Date/Time	2012-01-25 08:06:36
Lat N	44.85
Lon E	10.54
Depth	20km
Mw (rough)	4.5
M ₀ (rough)	1e16Nm

Network configuration:

Stations number	38
Station distances	up to 300km

ITA060409A

Event Name: L'Aquila, Italy

Description:

A well-known earthquake for (Italian) seismologists.
Real data from different networks (MEDNET, IRIS, GEOFON, GEOSCOPE, GRSN) are available at regional distances.
Point source (DC and MT) and kinematic inversions can be tested.

Known source parameters:

Date/Time	2009-04-06 01:32:41
Lat N	42.33
Lon E	13.34
Depth	5km

M _w (rough)	6.2
M ₀ (rough)	3e18Nm
Network configuration:	
Stations number	15
Station distances	up to 1000km

TUR231011A

Event Name: Van, Turkey

Description:

The largest event in the dataset. This event has recently affected Eastern Turkey, the epicenter close to the city of Van.

Real data from different networks are available at regional distances.

Station distribution is poor and uneven.

Point source (DC and MT) and kinematic inversions can be tested.

Known source parameters:

Date/Time	2011-10-23 10:41:22
Lat N	38.67
Lon E	43.58
Depth	5km
M _w (rough)	7.0
M ₀ (rough)	5e19Nm

Network configuration:

Stations number	5
Station distances	up to 1000km

TUR091111A

Event Name: Van, Turkey

Description:

The strongest aftershock of the 23.10.2011 earthquake (see TUR231011A).

Real data from different networks are available at regional distances.

Station distribution is poor and uneven. The azimuthal gap is very large.

Point source (DC and MT) and kinematic inversions can be tested.

Known source parameters:

Date/Time	2011-11-09 19:23:35
Lat N	38.35
Lon E	43.40
Depth	20km
M _w (rough)	5.7
M ₀ (rough)	5e17Nm

Network configuration:

Stations number	6
Station distances	up to 1000km

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References

- Cesca, S., Heimann, S., Stammer, K., and Dahm, T. (2010). Automated procedure for point and kinematic source inversion at regional distances. *J. Geophys. Res.*, . **115**, B6304; doi: 10.1029/2009JB006450
- Cesca, S., Heimann, S., and Dahm, T. (2011). Rapid directivity detection by azimuthal spectra inversion. *J. Seismol.*, **15** (1), 147-164; doi: 10.1007/s10950-010-9217-4
- Cesca, S., Rohr, A., and Dahm, T., (2013). Discrimination of induced seismicity by full moment tensor inversion and decomposition. *J. Seismol.*, **17** (1), 147-163; doi: 10.1007/s10950-012-9305-8
- Friedrich, W., and Dalkolmo, J. (1995). Complete synthetic seismograms for a spherically symmetric earth by a numerical computation of the green's function in the frequency domain, *Geophys. J. Int.*, **122**, 537-550.
- Heimann, S., 2011. A Robust Method to estimate kinematic earthquake source parameters. PhD thesis, University of Hamburg, Hamburg, Germany. <http://ediss.sub.uni-hamburg.de/volltexte/2011/5357/>
- Kennett, B. L. N., and Engdahl, E. R. (1991). Traveltimes for global earthquake location and phase identification. *Geophys. J. Int.*, **105**, 429-465; [doi:10.1111/j.1365-246X.1991.tb06724.x](https://doi.org/10.1111/j.1365-246X.1991.tb06724.x).
- Krieger, L., and Heimann, S., 2013. MoPaD – Moment Tensor Plotting and Decomposition: a Tool for Graphical and Numerical Analysis of Seismic Moment Tensors, *Seismol. Res. Lett.*, doi: 10.1785/gssrl.83.3.589
- Scherbaum, F. (2007). *Of poles and zeros; Fundamentals of Digital Seismometry*. 3rd revised edition, Springer Verlag, Berlin und Heidelberg.
- Wang, R. (1999). A simple orthonormalization method for the stable and efficient computation of Green's functions. *Bull. Seismol. Soc. Am.*, **89**, 733-741.
- Wessel, P., and Smith, W. H. F. (1998). New, improved version of the generic mapping tools released, *Eos Trans. AGU*, **79**, 579; doi:10.1029/98EO00426.