Time-Domain Moment Tensor INVerse Code (tdmt_invc_iso)
Release 3.1

By

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Introduction

This seismic moment tensor inverse software package has been in use at the University of California, Berkeley Seismological Laboratory (BSL) since 1993 and is employed to automatically investigate all M_L>3.5 events in northern California (e.g. www.seismo.berkeley.edu/~dreger/mtindex.html). The package has been successfully implemented at the Japan National Research Institute for Earth Science and Disaster Prevention (NIED), Caltech, University of Alaska (AEIC), University of Utah, Aristotle University, ETH, and has been used by individual researchers in the United States, Europe and Asia. This distribution includes a set of programs for calculating a library of Green's functions, inverting broadband data for the seismic moment tensor, various data processing utilities and shell scripts, and code and scripts demonstrating how to automate the procedures. Complete source code is provided. The frequency-wavenumber integration program (FKRPROG) written by Chandan Saikia is included with his permission. This software may be distributed only by means of its gzipped tar file. There is no warranty either expressed or implied, and the author is not responsible for damages due to misinterpretation of results and misuse of the software. **Finally, this software is freely distributed for non-commercial use. The reporting of seismic moment tensor solutions obtained using this software on the WWW and in the technical literature should include the following acknowledgement statement. "Moment tensors were computed using the mtpackagev3.1 package developed by Douglas Dreger and Sean Ford of the Berkeley Seismological Laboratory, and Green's functions were computed using the Computer Programs for Seismology software developed by Robert Herrmann."**

In the following the user manual documents how to build the software package, demonstrates usage through a series of examples, provides references to studies illustrating how suitable velocity models may be determined, and describes how the method may be automated.

Building the Program

Download the package compressed tar file from the Table of Contents (or the current version) from **http://www.seismo.berkeley.edu/~dreger/PASI-MT-ShortCourse**. Uncompressing and extracting the files will produce a subdirectory structure that includes a BIN (binaries), UTILITIES (various supporting programs), and TDMT-GMTPLOT (waveform moment tensor inversion code using GMT plotting). You will need to execute 'make all' in the UTILITIES, FKRPROG and TDMT-GMTPLOT directories. The executables will be placed in the BIN directory. Update your path to include BIN.

You will also need to download and install Professor Herrmann's Computer Programs for Seismology (CPS3.3), GMT (Generic Mapping Tools), and Seismic Analysis Code (SAC) from IRIS. CPS3.3 can be obtained from http://www.eas.slu.edu/eqc/eqccps.html, and SAC can be obtained from https://ds.iris.edu/ds/nodes/dmc/software/downloads/sac/. GMT should be obtained from one of the MacOS (Fink,Homebrew, Macports) or Linux package installers.

Included Programs

1. tdmt_invc_iso <time domain waveform inversion for full moment tensor>
2. tdmt_plot, tdmt_plot_gmt5_perl <perl script to create GMT plot of the results>
3. mtmanip <program for reformatting the moment tensor>
4. run_cps
5. run_cps_2_helm
6. run_filtsyniso <csh script to filter Green's functions using SAC>
7. There are also a number of formatting and file manipulating codes that are executed by the csh scripts.

Note that all of the run_* codes are csh scripts that call various programs. You will need to make sure that the paths to the various executables are defined either globally (preferred) or within the scripts.

Basic Methodology and Program Assumptions

The general representation of seismic sources is simplified by considering both a spatial and temporal point-source.

$$U_n(x,t) = M_{ij} \cdot G_{ni,j}(x,z,t)$$

U_n, is the observed n^{th} component of displacement, $G_{ni,j}$ is the n^{th} component Green's function for specific force-couple orientations, and M_{ij} is the scalar seismic moment tensor, which describes the strength of the force-couples. The general force-couples for a deviatoric moment tensor may be represented by three fundamental-faults, namely a vertical strike-slip, a vertical dip-slip, and a 45^0 dip-slip. The indices i and j refer to geographical directions. The above equation is solved using linear least squares for a given source depth. In this distribution only the deviatoric seismic moment tensor is solved for, and the inversion yields the M_{ij} which is decomposed into the scalar seismic moment, a double-couple moment tensor and a compensated linear vector dipole moment tensor. The decomposition is represented as percent double-couple (Pdc), percent CLVD (PCLVD), and percent isotropic (PISO). The tdmt_invc_iso code can be run either for a best fitting deviatoric solution in which the trace is constrained to be zero producing a zero percent isotropic component, or the full six degree of freedom moment tensor. The double-couple component of the moment tensor is further represented in terms of the strike, rake and dip of the two nodal planes. The basic methodology and the decomposition of the seismic moment tensor is described in Jost and Herrmann (1989).

Source depth is found iteratively by finding the solution that yields the largest variance reduction,

$$VR = \left[1 - \sum_i \sqrt{(data_i - synth_i)^2} \Big/ \sum_i \sqrt{data_i^2} \right] * 100,$$

where *data*, and *synth* are the data and Green's function time series, respectively, and the summation is performed for all stations and components.

Another measure that is useful for determining source depth in regions where explosive events are unlikely is the RES/Pdc, the variance divided by the percent double-couple where,

$$RES / Pdc = \sum_i \sqrt{\left(data_i - synth_i\right)^2} \; / \; Pdc$$

Dividing the variance by the percent double-couple tends to deepen the minimum.

It is assumed that the event location is well represented by the high frequency hypocentral location, and a low frequency centroid location is not determined. Second, the simplified representation above assumes that the source time history is synchronous for all of the moment tensor elements and that it may be approximated by a delta function. These assumptions are generally reasonable for M_w<7.5 events since long period waves (>10-20s) are used. It is noted however, that for larger events these point-source assumptions break down in the period range employed and alternative finite fault approaches (e.g. Dreger and Kaverina, 2000) or longer period waves and larger source-station distances for point-source applications (e.g. Fukuyama and Dreger, 2000) are required.

Finally, it is assumed that the crustal model is sufficiently well known to explain low frequency wave propagation. This software package will not work in a region if calibrated velocity models are not available. Calibrating velocity models to obtain a robust catalog of Green's functions is singly the most important step in successful seismic moment tensor applications.

In California, we have found that three 1D velocity models are adequate for the recovery of the seismic moment tensor. Different monitoring regions may require fewer or more crustal velocity models. Crustal velocity models that are sufficient for moment tensor analysis may be derived from models used to locate earthquakes, or by modeling of the broadband seismograms. There are numerous papers in the literature that describe how to model 3-component waveforms to constrain velocity structure and these (e.g. Dreger and Helmberger, 1990, 1993; Dreger and Romanowicz, 1994; Rodgers et al., 1999; Zhao and Helmberger, 1991; Song et al., 1996) are some examples for getting started. Two- and three-dimensional models may be used provided that the codes used to synthesize the Green's functions produces the full compliment of fundamental-fault responses.

In the following the usage of the software is demonstrated through a series of three examples.

EXERCISE 1

The objective of exercise 1 is to become familiar with computing Green's function files, performing post-processing filter operations, and using the seismic moment tensor inversion code by inverting synthetic waveform data. The files necessary for exercise 1 are found in MT-EXERCISES/EXERCISE1. You should use this directory as your working directory. In this directory you will find the following files; model_gil7.d, dfile, run_cps, run_cps_2_helm, run_mksyndata, run_mksyndatanoise, run_filtsyniso, mt_inv.in, and b2s.par.

model_gil7.d	<CPS3.3 velocity model input file>
dfile	<CPS3.3 station distance, npts, dt, input file>
run_cps	<csh script to run the CPS3.3 FK-Integration Software>
run_cps_2_helm	<csh script for reformatting CPS3.3 output files>
run_filtsyniso	<csh script to filter the Green's functions and place them in a single 10-component ascii file used by tdmt_invc_iso>
run_mksyndata	<csh script to generate synthetic data for four stations for an arbitrary double-couple mechanism>
run_mksyndatanoise	<same as run_mksyndata except random noise of varying levels is applied?
mt_inv.in	<tdmt_invc_iso input file>
b2s.par	<input file for Green's function processing program bin2sac>

Step 1: Compute Green's functions

The Green's function computation is the same is in Labs 1 and 2. We will be using the Herrmann (2013) CPS3.3 codes. The velocity model file is model_gil7.d and the scripts used to run the CPS3.3 codes and post-process them are run_cps and run_cps_2_helm. Please see the previous labs for usage.

These versions of the scripts are hardwired to produce four Green's functions files, gil7_100d8.disp, gil7_200d8.disp, gil7_300d8.disp, and gil7_400d8.disp.

The Green's functions are in units of displacement (cm). The ordering of the Green's functions in each *.disp file follows the Jost and Herrmann (1989) convention. There are 10 Green's functions as follows:

tss	<transverse-component, vertical strike-slip>
tds	<transverse-component, vertical dip-slip>
rss	<radial-component, vertical strike-slip>
rds	<radial-component, vertical dip-slip>
rdd	<radial-component, 45-degree dip-slip>
zss	<vertical-component, vertical strike-slip>
zds	<vertical -component, vertical dip-slip>
zdd	<vertical -component, 45-degree dip-slip>
rexp	<radial-component, explosion>
zexp	(vertical-component, explosion>

In Labs 1 and 2 you have been using the putmech program in the run_mksynth script to sum these fundamental fault Green's functions into a synthetic with arbitrary focal mechanism.

Step 2: Filter Green's functions
Once the *.disp files have been created it is necessary to perform bandpass filtering using the run_filtsyniso script. The usage of run_filtsyniso is:

```
run_filtsyniso  infile_name outfile_name
```

The following is an example processing all four stations:

```
foreach n (100 200 300 400)
run_filtsyniso gil7_{$n}d8.disp gil7_{$n}d8
end
```

The infile_name is the output filename from the run_cps_2_helm script. The outfile_name can be anything, but typically the infile_name with the '.disp' truncated is used. Read the run_filtsyniso csh script to see how to change the Butterworth bandpass filter corners. In this exercise the lowpass corner is 0.05 Hz, and the highpass is 0.02 Hz. We will review this script at the workshop. You will notice the run_filtsyniso script has embedded SAC commands for the signal processing.

If you pre-compute a catalog of Green's functions for a range of distances and source depths all can be processed by adding a second foreach loop over depth.

Step 3: Generate Synthetic Data

The run_mksyndata csh script calls the putmech program to generate synthetic data for a given double-couple mechanism. putmech is called for times for stations located at 100, 200, 300 and 400 km at four different azimuths. Read putmech to learn how the mechanism and azimuth are set. You have been using putmech for Labs 1 and 2.

The usage is:

```
run_mksyndata
```

Successful execution of run_mksyndata will generate four data files stat1.dat, stat2.dat, stat3.dat and stat4.dat.

Step 4: Generate Synthetic Data with Added Random Noise

The run_mksyndatanoise csh script calls the putmech program to generate synthetic data for a given double-couple mechanism. Putmech is called for times for stations located at 100, 200, 300 and 400 km at four different azimuths. Random noise time histories are generated using SAC and added to the synthetic data. The default level of noise is 35% of the maximum synthetic amplitude. We will review this script at the workshop.

The usage is:

run_mksyndatanoise

Successful execution of run_mksyndata will generate four data files stat1noise.dat, stat2noise.dat, stat3noise.dat and stat4noise.dat.

Step 5: Run Moment Tensor Inversion

Once the filtered Green's function files have been computed you can use them to invert test synthetic data created in step 4.

mt_inv.in, tdmt_invc_iso input file, has the following format

4 8 1 5 1	<number of stations, source depth, distance weighting flag, 5-dev or 6-full, plotting flag>
stat1.dat 100 0.0 0 120	<data_filename, distance (km), azimuth (deg from north), sample-offset (Zcor), number_of_samples>
stat2.dat 200 83.0 0 120	<ditto for station 2>
stat3.dat 300 202.0 0 120	<ditto for station 3>
stat4.dat 400 233.0 0 120	<ditto for station 4>
gil7_100d8 0 120	<filtered GF_filename, zero-offset (always zero), number_of_samples (same as corresponding data>
gil7_200d8 0 120	<ditto for station 2>
gil7_300d8 0 120	<ditto for station 3>
gil7_400d8 0 120	<ditto for station 4>
mtinv.dat	<ascii output file for plotting>

To run the moment tensor code execute the following command:

tdmt_invc_iso

When tdmt_invc_iso is run the following information is output to the screen, and to a log file (mt_inv.out).

```
isoflag=5 Depth=8
Station Information
Station(0): stat1.dat  R=100.0km  AZI=0.0  W=1.000  Zcor=11
Station(1): stat2.dat  R=200.0km  AZI=83.0  W=2.000  Zcor=10
Station(2): stat3.dat  R=300.0km  AZI=202.0  W=3.000  Zcor=9
Station(3): stat4.dat  R=400.0km  AZI=233.0  W=4.000  Zcor=7
isoMo: 0
Mo=1.06249e+24  (1.20672e+24)
Mw=5.29
Strike=271 ; 25
Rake=139 ; 39
Dip=58; 56
Pdc=52
Pclvd=48
Piso=0
Station(0)=97.806221  0.00141357
Station(1)=97.304642  0.000503136
Station(2)=99.024948  0.000462836
```

```
Station(3)=49.610275  3.3313e-05
VAR=4.59353e-08
VR=97.27  (UNWEIGHTED)
VR=96.48  (WEIGHTED)
Var/Pdc=8.802e-10
Quality=4
```

Most of the output information is self-explanatory. W is the applied inverse distance weight. Zcor is the sample offset that the code obtains from cross-correlating the data with the fundamental fault Green's functions (tss, tds, etc.). Zcor is a very important parameter that is used to align the data with the Green's functions prior to inverting the data. Because the cross-correlation is against fundamental fault Green's functions its value should be checked. Typically testing values that are +- 3 samples from the value obtained automatically is sufficient for finding the optimal value, but sometimes when the data is noisy or the velocity model used to construct the Green's functions is very approximate a larger search may be necessary.

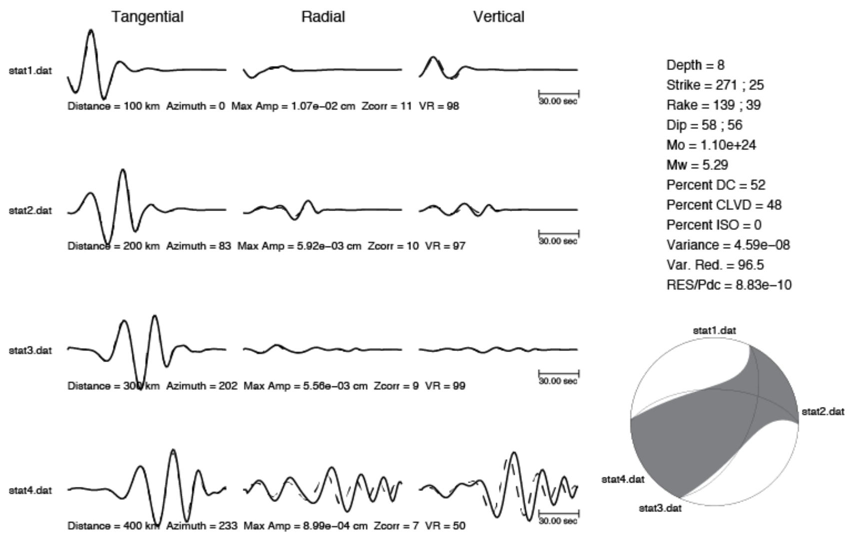

Figure 1. ***tdmt_invc_iso*** graphical output for exercise 1. The data are shown as solid lines, the synthetics are dashed. For each station three-component data and synthetics are compared, and the azimuth, the maximum three-component trace amplitude, cross-correlation samples (Zcorr), and variance reduction (VR) are provided. Solution information includes the strike, rake and dip for the two possible double-couple planes, the scalar seismic moment, and Mw. Information about the moment tensor decomposition in terms of percent double-couple (DC), CLVD, and isotropic (ISO) are also listed. Fitting parameters such as the variance, the variance reduction (Var. Red), and the variance modulated by the percent double-couple (RES/Pdc).

The ascii outfile, mtinv.dat can be processed into a postscript plot file (Figure 1) by executing the tdmt_plot command:

```
tdmt_plot mtinv.dat                  for users with GMT version 4.x
tdmt_plot_gmt5.perl mtinv.dat        for users with GMT version 5.x
```

Note that the weighted VR is only 96.48% where it should be 100% for the noise-free synthetic data inversion that was performed. This is due to the cross-correlation of the synthetic data against the fundamental fault Green's functions yielded slightly incorrect time shifts. The correct time shifts are 10 samples (zcor=10) for all four stations. Make this change in mt_inv.in and rerun tdmt_invc_iso to verify that you are able to fit the synthetic data exactly, and recover the input mechanism (strike=23, rake=45, dip=67, moment=1.2e25 dyne cm). Figure 2 shows the solution obtained with the correct zcor values.

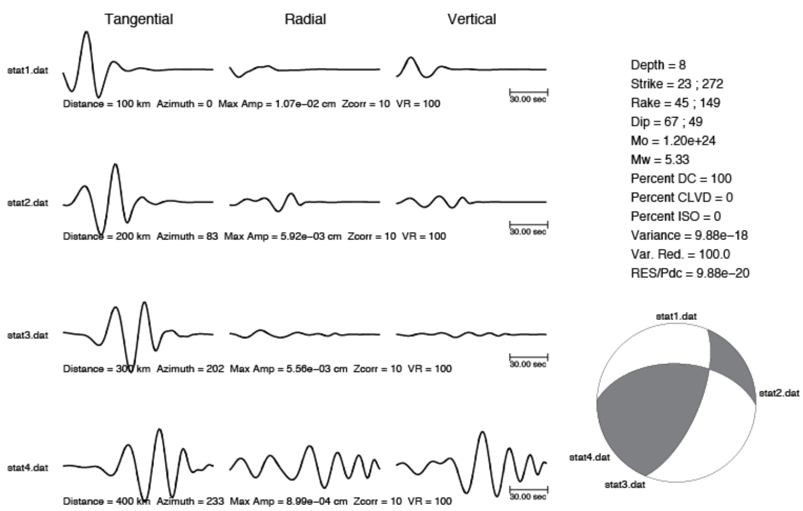

Figure 2. Plot showing the fit and solution for the correct Zcor values.

The output parameters VAR, VR, Var/Pdc and Quality are used to gauge the success of the inversion. VAR is the overall variance estimate, VR is the variance reduction (both unweighted and distance weighted estimates), Var/Pdc is the ratio of the variance to the percent double couple, quality is a subjective measure where 4 is the best and 1 is the worst. The higher the value of VR the better the solution. The Var/Pdc measure can also be very useful for areas where non-double-couple solutions are not expected.

Noisy Data Example

Use the run_mksyndatanoise (see step 5) to generate the noisy data. The noise level is set at 35% of the peak amplitude giving a signal to noise ratio of 3 to 1.

Compare the cases for zcor=0 (cross-correlation alignment), and zcor=10 correct alignment with the no-noise cases.

EXERCISE 2

The objective of this exercise is to apply the data processing scripts to broadband data for a real earthquake, generate suitable Green's functions, and invert the data for the seismic moment tensor. In the MT-Exercises/EXAMPLE2 subdirectory you will find the following files; 1998* (raw sac data files), *zp (sac polezero files), b2s.par, README, mt_inv.in, MODEL_gil7, run_mkdatafile script, and the run_fkrsortiso, and run_filtsyniso scripts.

Data has been provided for 10 broadband stations for a moderate northern California earthquake. The following lists the station names, source station distance, and azimuths.

Station	Distance(km)	azimuth(deg from north)
BKS	142.	331.5
CMB	171.	33.6
HOPS	286.	330.8
JRSC	99.6	316.5
KCC	201.	71.1
MHC	67.	346.4
ORV	311.	359.4
PKD	122.	137.0
SAO	2.0	56.8
YBH	563.	349.3

Step 1: Instrument correct and filter waveform data and write data to ascii files
The first step is to produce the ascii, three-component data files used by tdmt_invc_iso. This step involves acquiring the pole-zero instrument response, using SAC to demean, deconvolve instrument response, integrate to displacement (cm), rotate to transverse and radial components, bandpass filter, resample to 1 sps, and finally write the ascii data files. The run_mkdatafiles accomplishes these tasks.

Edit the run_mkdatafile script to set the station name, and then execute the script. You will need to do this for each station separately.

Do this for stations BKS, CMB, JRSC, KCC, ORV and PKD.

Step 2: Generate Green's functions for a suite of distances and source depths

The next step is to generate a suite of Green's functions over a range of source depth for each source-station distance. The files model_gil7.d and run_cps_2_helm have been setup to generate Green's functions for 9 distances.

Compute the Green's functions for source depths of 2, 6, 8, 11, 14, 18, 21, 24, and 27 km. Use nested foreach loops over distance and then depth to use the run_filtsyniso script to filter the Green's functions.

Step 3: Single Station Moment Tensor Inversion

Edit the mt_inv.in for a single station inversion using the BKS data. Figure 3 shows the result that you should obtain.

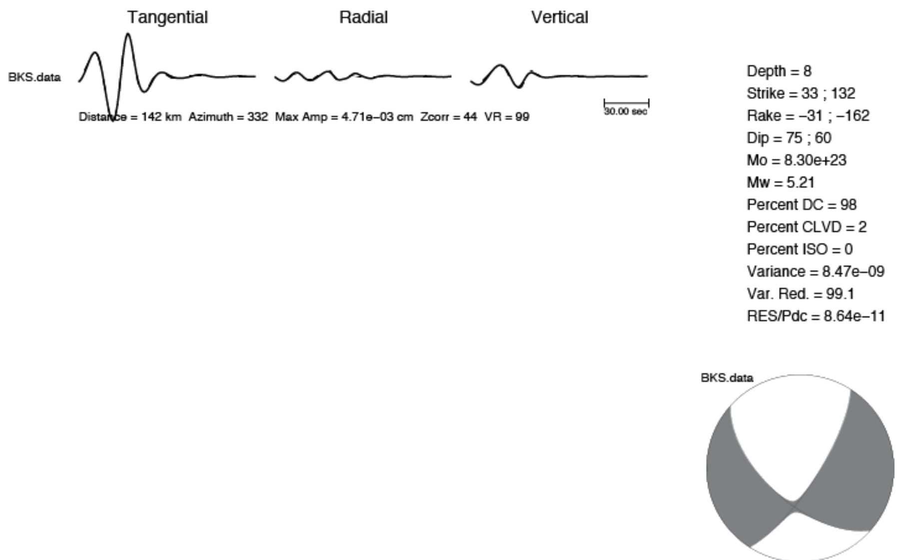

Figure 3. Single station inversion for BKS assuming a source depth of 8 km.

Step 4: Three Station Moment Tensor Inversion

Figure 4 shows an example of a three-station inversion. See if you can improve on this solution by examing the Zcor parameter.

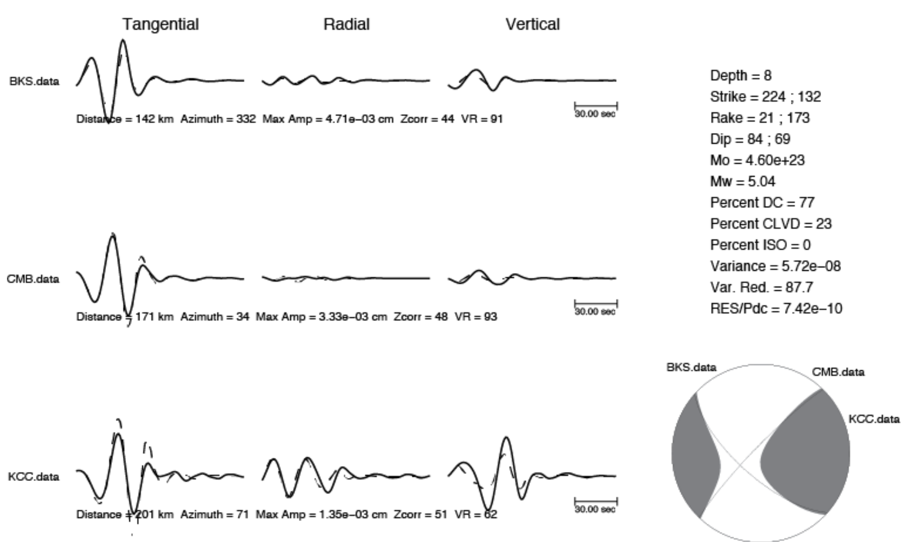

Figure 4. Three station inversion for BKS, CMB and KCC assuming a source depth of 8 km.

Step 5: Six Station Moment Tensor Inversion

Next try adding the other stations. Examine combinations of two and three stations to examine the sensitivity of the solution to the station geometry. For the 6 station case (BKS, CMB, JRSC, KCC, ORV, PKD) find the best depth considering both the VR and the var/PDC measures. Figure 4 shows our preferred 6 station solution.

Bring plots showing your moment tensor inversion results using six stations, and the source depth and station sensitivity tests to class.

EXERCISE 3

In this exercise you will model two events located near Long Valley California, a volcanic center located in eastern California (Figure 5). In the directory EXERCISE3 there are three subdirectories, GFS, EVT1, and EVT2. In GFS there there input files and scripts to generate a catalog of Green's functions. EVT1 and EVT2 contain SAC datafiles and polezero response files for an event that has a large non-double-couple mechanism, and a nearby event that is a pure double-couple. You will generate Green's functions for source depths of 5, 8 and 11 km to find the best source depth for each event assuming a deviatoric moment tensor solution. Then for the best source depth you will invert the data for a full moment tensor solution to test for possible isotropic or volumetric source radiation.

Step 1: Compute Green's functions

Compute Green's functions for a source depth of 5 km for 61 distances every 5 km between 40 to 340 km. Repeat the processing for source depths of 8 and 11 km. You should then bulk filter the Green's functions with a passband of 0.02 to 0.05 Hz. This will be same filter applied to the data.

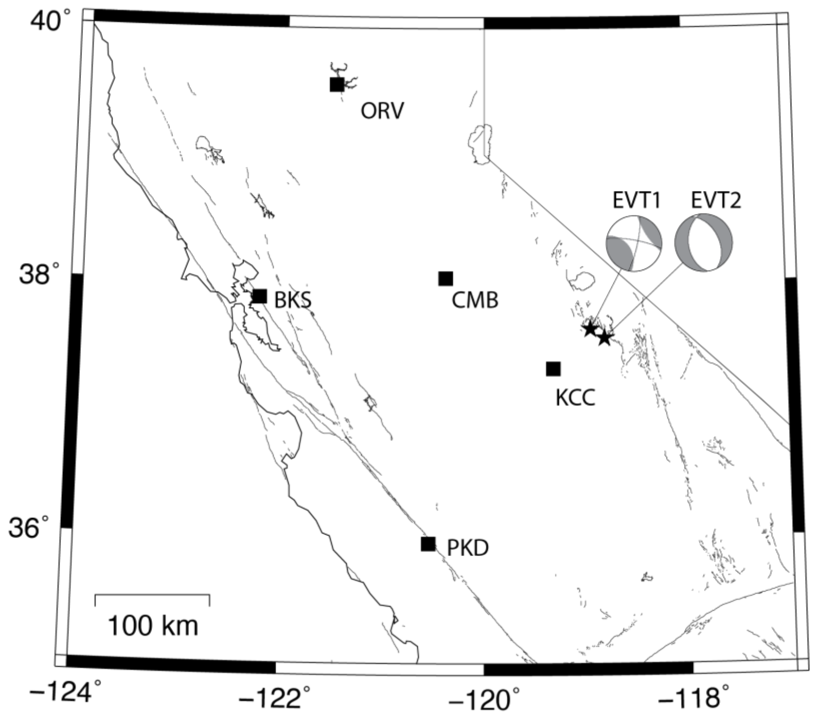

Figure 5. Map showing the locations of 5 BDSN stations and the two study events located near Long Valley, California. The deviatoric moment tensor solutions are plotted. One event has a large non-double-couple component, and the other is nearly a pure double-couple.

Step 2: Compute Moment Tensor for EVT1

Use the run_mkdatafiles script to process the sac data files and create the filtered data ascii files used by the moment tensor code.

The azimuth and distance are obtained from the SAC header, and have already been included in the moment tensor input file, mt_inv.in.

Find the best fitting moment tensor solution for each source depth by adjusting the zcor values.

Compare the deviatoric and full moment tensor solutions and the variance reduction goodness of fit parameter.

Step 3: Compute Moment Tensor for EVT2

Use the run_mkdatafiles script to process the sac data files and create the filtered data ascii files used by the moment tensor code.

The azimuth and distance are obtained from the SAC header, and have already been included in the moment tensor input file, mt_inv.in.

Find the best fitting moment tensor solution for each source depth by adjusting the zcor values.

Compare the deviatoric and full moment tensor solutions and the variance reduction goodness of fit parameter.

Concluding Remarks

We hope that you find this seismic moment tensor package helpful for your seismic monitoring and scientific needs.

Send comments, bug reports and other inquiries to ddreger@berkeley.edu

Updates to this package will be posted to www.seismo.berkeley.edu/~dreger.

Please add the following acknowledgement to any WWW or technical journal publications that use moment tensor results obtained using this software. "Moment tensors were computed using the tdmt_invc_iso package developed by Douglas Dreger and Sean Ford of the Berkeley Seismological Laboratory. Green's functions were computed using CPS3.3 (Herrmann, 2013)."

References and Supplemental Reading

Papers illustrating velocity model calibration:

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