Regional Long-Period Moment Tensor Inversion Best Practices

Version 1.0 – November 15, 2021

Gene A. Ichinose, Andrea Chiang, Sean R. Ford, and Mike Pasyanos

Lawrence Livermore National Laboratory - *Moment Tensor Team*

LLNL Release #: LLNL-SM-829825

Lawrence Livermore National Laboratory is operated by Lawrence Livermore National Security, LLC, for the U.S. Department of Energy, National Nuclear Security Administration under Contract DE-AC52-07NA27344.

Introduction

Prerequisites

This document is for those who are new to moment tensor inversion, want to use software tools like ***MTINV*** or ***MTTIME***, have a basic understanding of seismology, but have little to no experience with geophysical inversion. The best practices in moment tensor inversion are applicable to any moment tensor inversion software available that uses regional distance long-period seismic waves but the details here are loosely oriented around the freely available software toolkit ***MTINV*** available on Source Forge and the ***MTTIME*** python-based software available on GitHub. The following sections provide an overview for the basic theory in moment tensors, Green's functions, and linear inversions; however, it is not necessary, and the reader can skip to the section titled "Moment Tensor Inversion Strategies" which provides answers to frequently asked questions.

***MTINV* requirements and optional software**[1]

https://sourceforge.net/projects/mtinv/	
Un*x type OS	Mac OS-X, Fedora Core, RedHat, Ubuntu, or SUSE
Terminal and X11 (optional)	C-shell csh or tcsh and XQuartz or X11
A text editor	Any, e.g., Vim, emacs, or textedit
GCC and gFortran compilers	http://hpc.sourceforge.net (clang works too)
Ghostscript - Postscript toolkit	https://www.ghostscript.com (optional to convert PS)
GMT version 4.x.x or 5.x.x	http://gmt.soest.hawaii.edu/projects/gmt (for plotting)
PDF/JPG viewers	e.g., MacOSX preview, Gnome eog, xv, Image Magik display
Seismic Analysis Code (SAC)	https://ds.iris.edu/files/sac-manual/ (optional)

***MTTIME* requirements and optional software**

https://github.com/LLNL/mttime	
OS	Any machine that can run Python
Python distribution	Anaconda, miniconda, obspy, numpy
Python Versions	
Computer Programs in Seismology (Green's functions)	http://www.eas.slu.edu/eqc/eqccps.html

What is a Moment Tensor?

The moment tensor (MT) is a mathematical representation of a generalized seismic source (e.g., earthquakes, explosions, mine collapses) that quantify a set of forces and orientations based on the source's radiation pattern. The MT is mathematically represented as a 2nd-order symmetric tensor expressed as a 3-by-3 matrix (i.e., as three shear force couples and three linear vector dipole forces). In a Cartesian coordinate system (i.e., x-axis: +east/-

[1] Typographical conventions: software package names (***MTINV)***; applications, files (`mtinv`, `mtinv.par`, `mtinv.c`); code or scripting instructions `(set mtinv=1,0)`

west, y-axis: +north/-south, z-axis: +up/-down), the dipole forces are contained along the diagonal M_{xx}, M_{yy}, and M_{zz} of the tensor. The off-diagonal elements M_{xy}, M_{xz}, and M_{yz} contain the shear force couples. Through the conservation of angular momentum, there are two force-couples (a.k.a. the double-couple), with one acting in the opposite direction to the other. The MT is symmetrical and therefore $M_{xy}=M_{yx}$, $M_{xz}=M_{zx}$, and $M_{yz}=M_{zy}$ resulting in only six of nine unique tensor elements, that can also be in vector form $\vec{M}$ (Figure 1).

$$M = \begin{bmatrix} M_{xx} & M_{xy} & M_{xz} \\ M_{yx} & M_{yy} & M_{yz} \\ M_{zx} & M_{zy} & M_{zz} \end{bmatrix}$$

$$\vec{M} = \left(M_{xx}, M_{xy}, M_{xz}, M_{yy}, M_{yz}, M_{zz}\right)$$

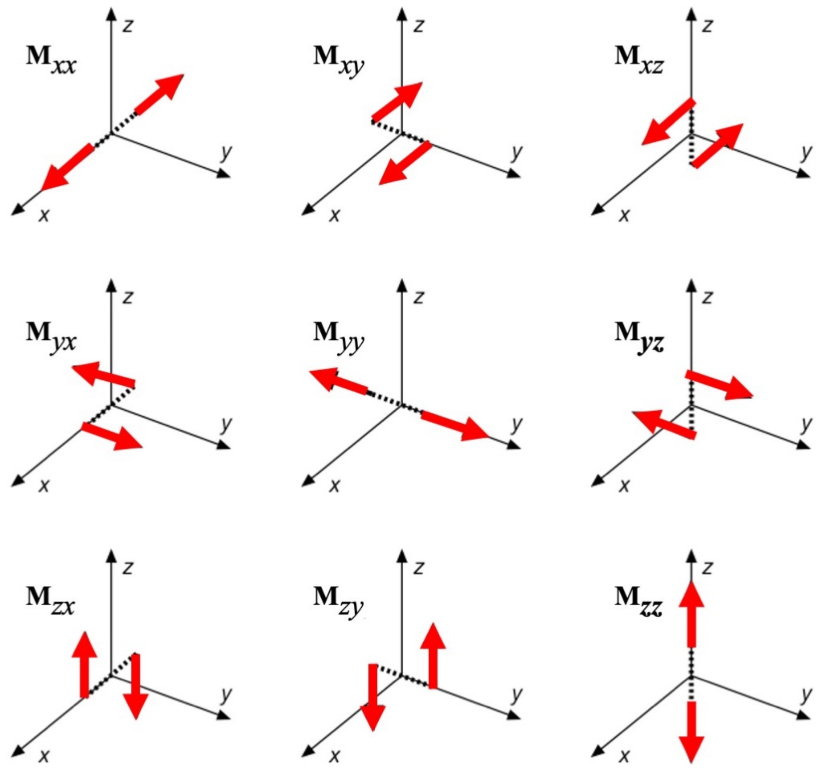


Figure 1. The mathematical representation of the moment tensor is a 3-by-3 matrix. In the Cartesian coordinate system, the diagonal of this matrix represents the 3 linear vector dipole forces (Mxx, Myy, Mzz), and the off-diagonal elements represents the 3-shear force couples. Due to the conservation of angular momentum, there requires two force couples, (e.g., Mxy and Myx) that lends itself to the term double-couple. Therefore, the moment tensor is symmetrical, and it can also be represented as a vector of its unique 6-elements.

Global CMT (https://www.globalcmt.org) reports MT solutions in spherical coordinates rather than in Cartesian coordinate for compatibility with whole Earth normal modes. Since most MT inversion codes generate output for ***GMT*** `psmeca` plotting, the MT is usually provided in both coordinate systems. The following table provides the conversion defined by Aki and Richards (2009) (Box 4.4) for Cartesian (x,y,z), `psmeca` (r,t,f), and spherical (r,Δ,ϕ) coordinate systems.

(x,y,z)	$\mathbf{M}_{zz}$	$\mathbf{M}_{xx}$	$\mathbf{M}_{yy}$	$\mathbf{M}_{zx}$	$-\mathbf{M}_{zy}$	$-\mathbf{M}_{xy}$
(r,t,f)	$\mathbf{M}_{rr}$	$\mathbf{M}_{tt}$	$\mathbf{M}_{ff}$	$\mathbf{M}_{rt}$	$\mathbf{M}_{rf}$	$\mathbf{M}_{tf}$
(r,Δ,ϕ)	$\mathbf{M}_{rr}$	$\mathbf{M}_{\Delta\Delta}$	$\mathbf{M}_{\phi\phi}$	$\mathbf{M}_{r\Delta}$	$\mathbf{M}_{r\phi}$	$\mathbf{M}_{\Delta\phi}$

A moment tensor can be reduced to a scalar seismic moment (e.g., Bowers and Hudson, 1999) reported in either units of dyne-cm or N-m (1 N-m = 10^{-7} dyne-cm) and by Eigenvalue decomposition into its 3 Eigenvalues and 3 Eigenvectors. Eigenvalues and Eigenvectors are presented visually as a focal mechanism (https://en.wikipedia.org/wiki/Focal_mechanism) nicknamed as beachballs (Figure 2) due their alternating bright colored quadrants on a sphere (see Jost and Herrmann, 1989 for review). Eigenvalues can also be reported in the same units of scalar seismic moment or normalized by moment. A fault plane solution or focal mechanism has two orthogonal nodal planes, primary and auxiliary, both represented by a strike, dip, and rake. There is an ambiguity in determining the ruptured fault plane between the primary and auxiliary fault planes, and both are indistinguishable without additional information. The largest positive Eigenvalue and associated Eigenvector represents the T-axes in the extensional quadrant (red), the largest negative Eigenvalue and associated Eigenvector represents the P-axes in the compressional quadrant (blue), and the Eigenvalue closest to zero is the null-axes which the Eigenvector represents the intersection between the 2 nodal planes.

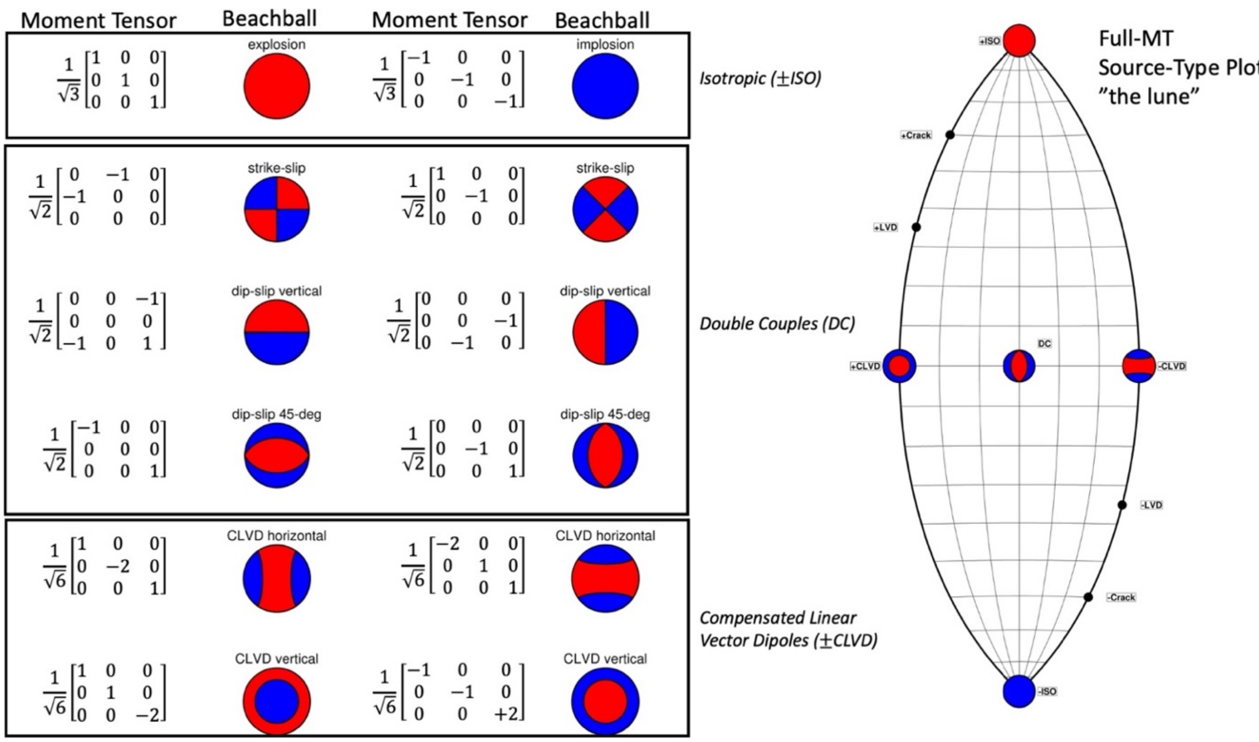


Figure 2. Beachball representations of various moment tensors created using GMT version 6 *psmeca* software (see Figure 4.4-6 pg. 244 of Stein and Wysession, 2003).

In Figure 3, a full-MT can be decomposed into a deviatoric MT or component by removing the mean of the eigenvalues (isotropic component). The deviatoric MT can then be decomposed into any non-unique combination of major and minor double-couples or any combination of linear vector dipoles and double couples; however, the most important unique decomposition of a full-MT is into its deviatoric and isotropic components. Full-MTs can be characterized by plotting their Eigenvalues using a linear or spherical equal area projection otherwise known as source-type plot (e.g., Hudson et al., 1989; Vavrycuk, 2015; Tape and Tape, 2012). In Figure 2, all full-MTs that are completely double-couple locate at the origin of the source-type plot (DC), while MTs that are entirely isotropic plot at the poles. MTs with increasing isotropic components plot away from the origin along lines of latitude. MTs with increasing CLVD components plot away from the origin along lines of longitude (Figure 2). Source-type plots have a potential for framing a physics-based discrimination between “double-couple” earthquakes at the origin and non-double couple sources like mining collapses, and explosions plotting away from the origin. Details and theory in producing NSS or lune plots is beyond the scope of this document; however, we provide some comments later for current practices used. In the future, we will add to this document with best-practices for MT yield estimation, event screening and event discrimination once the community comes together with a consensus for these best practices.

Additional Web Resources on MT:
https://sites.google.com/alaska.edu/carltape/home/research/beachball
http://gfzpublic.gfz-potsdam.de/pubman/item/escidoc:272892/component/escidoc:541895/IS_3.9.pdf
https://ds.iris.edu/media/workshop/2015/09/iris-international-development-seismology/files/presentations/16-September-2015_Herrmann_ASI_MTintro.pdf

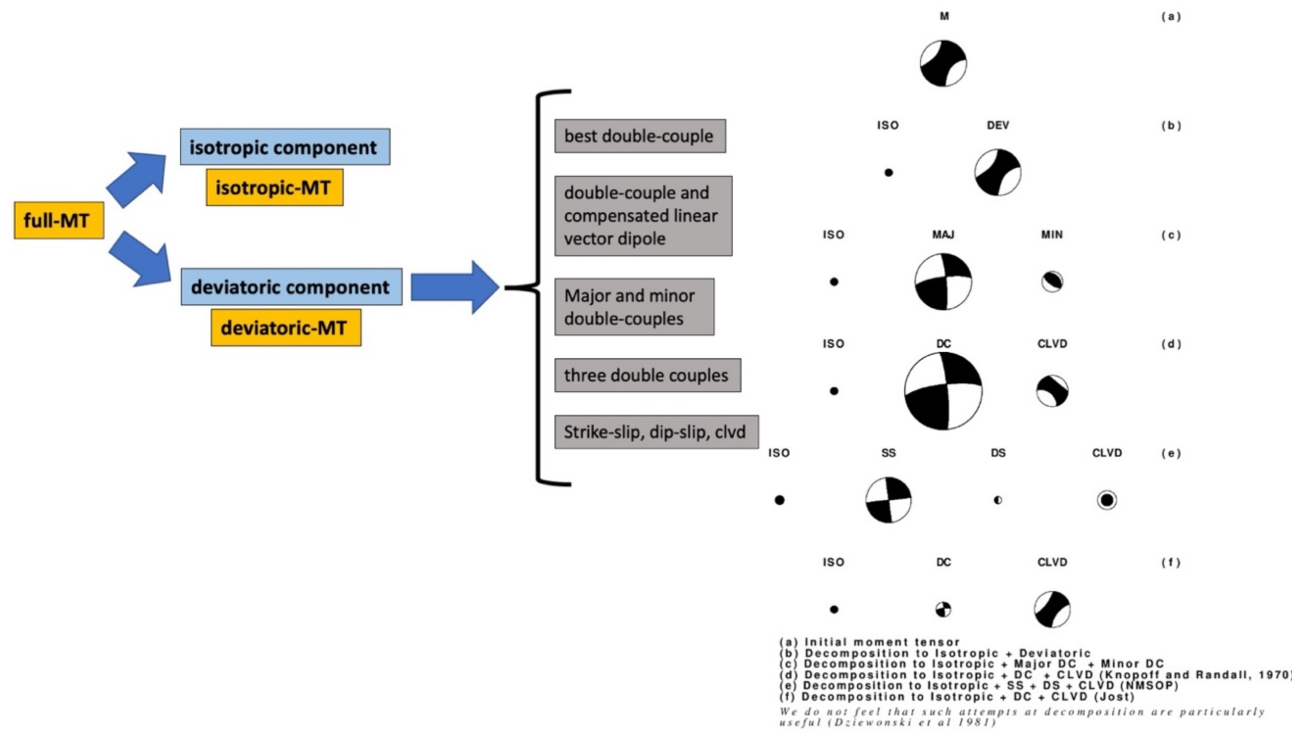


Figure 3. (modified from R. B. Herrmann). A full-MT can be decomposed into isotropic and deviatoric components (a.k.a. dev-MT). Most software codes will allow options to invert for only deviatoric MT and also simple isotropic only MT. The decomposition of the deviatoric MT is non-unique and not particularly meaningful. Therefore, care should be taken not to over emphasize the deviatoric, double-couple, and isotropic components or overly complicate the decompositions particularly when they are small relative to majority of the moment release.

The moment tensor inversion methodology originated from Gilbert (1970). Since then, there have been numerous studies extending the method into the time-domain, for solving higher order source terms and more recently the use of three-dimensional Earth models. For a general review please see Jost and Herrman (1989). ***MTINV*** and ***MTTIME*** employ the time-domain method that uses waveforms instead of the frequency-domain, which only uses spectral amplitudes to estimate the moment tensor. The advantage of the time-domain method is the ability to differentiate between normal and reverse faulting mechanisms without the need of additional information (e.g., historical tectonic deformation or first motion polarities) due to the use of the time-domain phase and amplitude (i.e., both mechanisms have the same spectral amplitudes, but waveform polarities are 180 degrees out of phase). The disadvantage of the time-domain method is that in modeling the phase part requires a decent representation of the Earth 1-D velocity structure, which in most cases for a real-3-D Earth, requires some user finesse with addition of time-shift station corrections. More explanations on model selection, bandpass filtering, and time-shifting strategies later.

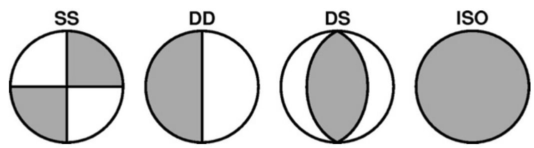
We solve for a generalized moment tensor with a simple constraint added so that the source has no isotropic component although this constraint can be lifted for estimating the moment tensor with an isotropic component for mining or cavity collapses and explosion sources. The deviatoric MT inversion solves for only a 5-degree of freedom MT elements (Mxx, Myy, Mxy, Mxz, and Myz) with the constraint that Mzz = -(Mxx + Myy), therefore this MT is assumed to have no net volumetric component (Mxx + Myy + Mzz = 0). A full-MT inversion solves for all six MT elements. ***MTTIME*** and ***MTINV*** both implement the corrections based on Herrmann and Hutchensen (1993), (also see Herrmann (2013)-Computer Programs in Seismology manual on Source Inversion, and Minson and Dreger (2008)) needed to compute a full moment tensor (6-degree of freedom) that include isotropic components.

Green's Functions

A Green's function (GF) is defined in mathematics and engineering as an impulse response to a linear system. In MT inversion, a GF is a synthetic seismogram, computed for a particular distance and depth (source-to-receiver), and is an impulse response represented as a fundamental fault. When individually scaled and combined linearly with other GFs, provides a full waveform synthetic seismogram comparable to those recorded by seismometers. GFs are related to MTs using a combination of these fundamental faults and scaling coefficients are the MT elements. Helmberger and Langston (1975) developed the 3 fundamental faulting orientations including the isotropic (Figure 4). Kikuchi and Kanamori (1991) developed another MT formulation using 5 fundamental faults and isotropic (Figure 4). These fundamental faults allow for the linear relationships between GFs and MT elements to displacements. With Helmberger and Langston (1975), there are ten GFs commonly noted as: ZSS, ZDS, ZDD, ZISO, RSS, RDS, RDD, RISO, TSS, and TDS. The first character is the component (Z=vertical, R=radial, T=transverse), therefore there are four GFs for the vertical component, four for the radial, and only two for the T component because there are no motions on T components from DD and ISO sources.

GFs for the fundamental faults are simply computed using these DC mechanisms (e.g., SS: Strike=0, dip=90, rake=0). The observation receiver point is at an azimuth of 45 degrees from the event source. We use the 3 fundamental faulting orientations because it results in a total of ten GFs instead of 16 GFs for a Mij formulation (e.g., The six MT elements combined with 3-components Z, R, & T results in 3 x 6 = 18 GFs; however, T is zero for Mzz component for a receiver at the free-surface, so the total is really 15 GFs. Also note that these 15 GFs are no longer linearly related, therefore a non-linear inversion is required.

Fundamental Faulting Orientations (Helmberger and Langston, 1975; Langston, 1981)



Elementary Moment Tensors (Kikuchi and Kanamori, 1991)

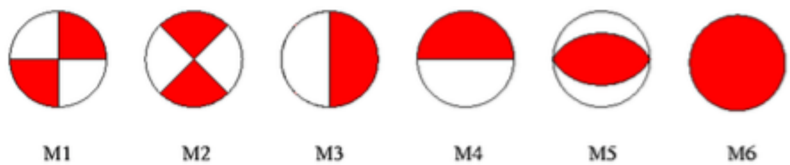


Figure 4. Fundamental faulting orientations and elementary moment tensors used in the calculation of Green's functions. *MTINV* uses H&L 1975 and *MTTIME* uses K&K 1991.

Linear Inversion Basics

There are advantages and disadvantages between linear and non-linear inversion. Geophysical non-linear inversion requires, an initial starting solution, a step size for each solution parameter, and a convergence criterion to know when to stop unless the entire solution and error space is searched. There may be no guarantees that a convergence path to the best fit solution is achievable and sometimes the path to the solution may not be repeatable. A MT inversion can be performed using nonlinear methods, and it is a good learning experience to try this in either a brute force manner or elegantly using partial derivatives. This can be time consuming but an ideal way to explore the solution and error space. A linear inversion is a more hands-off and repeatable approach to inversion lending itself as a best option for operational settings (e.g., see links to real-time MT solution catalogs published online).

The linearized (and nonlinear) MT inversion method starts with the forward problem, $\vec{u} = \boldsymbol{G}\vec{m}$ where $\vec{u}$ is the ground motion vector, $\boldsymbol{G}$ is the GFs matrix, and $\vec{m} = [M_{xx}, M_{xy}, M_{xz}, M_{yy}, M_{yz}, M_{zz}]$ are the six MT elements that are the weights to the GFs matrix columns. The GFs matrix columns are formulated to be linearly related to the MT elements and the rows depend upon the ordering of the data (stations and components) through time. The ground motion vector can be in any units: displacement, velocity, acceleration, or rotation as long as it matches the units of the GFs. The data and GFs are stacked in any order as long as they match along rows of the GFs. The forward equations are shown by Jost and Herrmann (1989) in Appendix V, Minson and Dreger (2008) in section 2.2, and appendix B of Herrmann (2013) in "An overview of synthetic seismogram computation". The ***MTINV*** toolkit uses singular value decomposition to perform the inversion of the forward equations; however, this is overkill, and any numerical inverse technique should work. There is no starting solution, no step size, and if run twice will produce the same answer. We do not solve for source depth or location while these values are fixed in the linear inversion, unlike the GCMT which uses partial derivatives of the source including location and depth. However, we can vary the location and depth through multiple iterations and the best fit can be selected based on overall fit like percent variance reduction (%VR).

Moment Tensor Solution Catalogs
USGS MT, https://earthquake.usgs.gov/earthquakes/search/
GCMT, https://www.globalcmt.org
ISC, http://www.isc.ac.uk/iscbulletin/search/fmechanisms/
UCB, http://www.ncedc.org/ncedc/catalog-search.html

What can I get out of MTs and why are they Important?

Seismic Hazard, Seismotectonics, Nuclear Explosion Monitoring

The MT has many uses in seismology. For seismic hazard, the scalar seismic moment (M_0) and moment magnitude (M_w) is the preferred magnitude scale used in hazard assessment. Magnitude scaling relations are created between a small handful of moment magnitudes to other magnitude scales like local magnitude M_L. M_0 is preferred because of its linkage between amplitudes and physical relationships with fault area and slip. M_0 and M_w also do not saturate like with body-wave (m_b) or surface-wave magnitudes (M_s) at higher magnitude ranges due to the band limited nature of these magnitude measurements. M_0 and M_w represents the amplitude level as the source spectra asymptotically approaches zero frequency (flat displacement spectra at low frequency). The coda magnitude method also calculates magnitudes in M_w; however, it requires a calibration of coda envelope amplitudes using a small set of moment magnitudes determined using MT inversion approach or by other means and is an ideal way to extend M_0 and M_w down to lower magnitude levels beyond MT inversion limitations.

MT solutions play an important role in understanding the relationships between earthquakes and active neo-tectonics in seismotectonic studies (e.g., D'Amico, 2018). Seismic moment provides a tie between geodetic, geologic, and seismically determined strain rates. Focal mechanisms from MT solutions also provide style of faulting when surface rupture is not available. A local or regional MT dataset with a variety of mechanisms can also provide stress-field information that can be compared with direct stress measurements from borehole break outs or geologic slip indicators.

Nuclear Explosion Monitoring has utilized MT as a tool for calibration and special event analysis. For example, the aftershock 8.5 minutes after the 6th North Korean underground nuclear test on 2017-09-03 at 03:30:01 UTC was identified as a cavity collapse instead of another explosion or triggered aftershock (e.g., Chiang et al, 2018). Research into using MT as an explosion discriminant or screening has been applied (e.g., Ford et al., 2010; Ford et al., 2020). MT decomposition into Eigenvalues is used to produce source type plots showing the isotropic and deviatoric components in either Hudson (equal area projection) or more natural spherical projection based on (Tape and Tape, 2012) or the MT elements can directly be used for screening on the hypersphere (Ford et al., 2020).

Seismic Waveform Quality Control

Full-waveform predictions and comparisons to observed data using synthetic seismograms (phase timing and amplitude) provide a very useful means of examining instrument response and metadata quality control issues. When a MT solution is known or well determined using an adequate number of stations (e.g., ~3 or more stations), the ***MTINV*** prediction feature can reveal stations with incorrect metadata or instrument response information. In some cases, these data quality issues present themselves during the inversion process. In the comparison between data and synthetics, the Z, R, or T components may have the correct amplitude but the reversed polarities (180° out of phase). The metadata for the component orientations CMPAZ or CMPINC (for SAC) or HANG and VANG (in CSS) may be reported in error by $\pm\pi$. Another common issue is with gain or unit conversions (Figure 5). There is a feature in ***MTINV*** which allows the user to add a multiplication factor to any station, and or the values can be added to the SAC Pole-zero instrument response files directly.

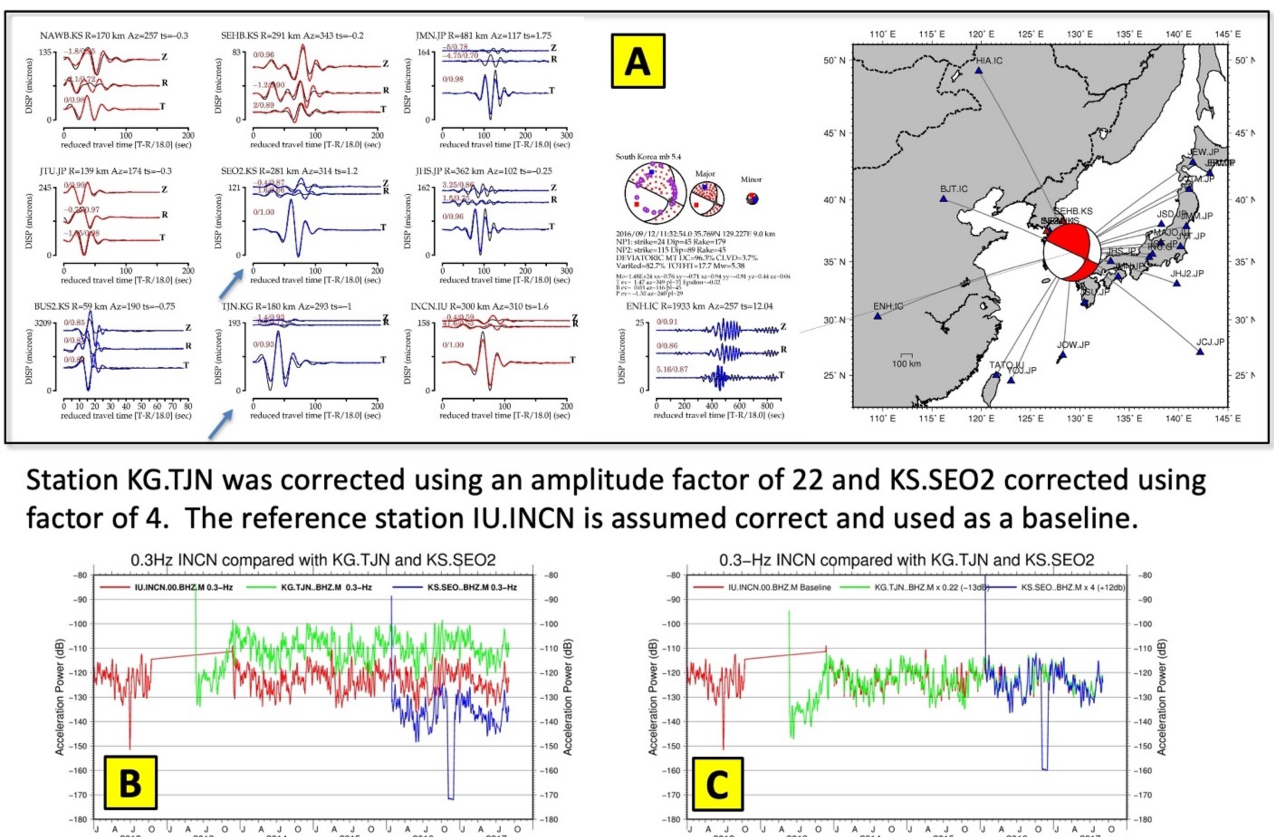


Figure 5. (A) MT inversion reveals incorrect gain for stations KG.TJN and KS.SEO2 (see blue arrows). The inversion used stations in red and predicts the fits in blue after corrections applied to metadata retrieved from IRIS. These gain errors are confirmed using Power

Spectral Density (PSD) time histories in (B) where the background 0.3 Hz amplitude for KG.TJN and KS.SEO2 are offset from IU.INCN, used as a baseline reference station. (C) After the gain corrections are applied, the 0.3Hz amplitudes now overlie each other as expected given the MT analysis and since these nearby stations share the same background noise.

Why does it work?

The trick that makes MT inversion work is mainly from the use long-period regional distance seismic waves. When the wavelengths of the seismic waves are significantly larger (10 to 100 times larger) than the asperities of the fault rupture then the whole complex source process can be reduced to a simple delta function in space and time. Table 1 shows earthquake fault dimensions in km for two magnitudes, 4.3 and 6, respectively and wavelengths computed from the two associated frequency bands assuming a surface wave phase velocity of 3.2 km/sec. The wavelength of the surface-waves are about 10 times longer than the fault length thereby the propagating waves do not carry any fine details from the complex fault rupture.

Table 1. Two same earthquake source parameters based on scaling relations compared to the radiated surface-wave wavelengths

Frequency Range (Hz)	0.03-0.1 Hz	0.01-0.05 Hz
Period (sec)	33-10 sec	20-100 sec
Moment Magnitude M_w (1)	4.3	6.0
Moment M_0 (N m) (2)	3.3e+15	1.0e+18
u - Average Slip (meters) (3)	0.1 m	0.3 m
A - Fault area (L x W) (km^2)	1-9 km (L or W ~ 1 – 3 km)	100-900 km (L or W ~ 10 – 30 km)
Wavelength (km)	32-106 km	64-320 km

(1) $M_w = {}^2/_3 \log_{10}(M_0) - 9.1$
(2) $M_0 = \mu \cdot A \cdot u$
(3) Shear Modulus or Crustal Rigidity μ = 3.3e11 dyne x cm^{-2} (~ 33 GPa)

Another major contribution to the success of MT inversions is that the wave propagation is simplified because filtering regional seismograms to longer periods result in waves that have only propagated for a few wavelength cycles over the distance between the source and receiver. Seismic waves, with wavelengths that are significantly larger than the Earth heterogeneities and propagate for only a few cycles are easily predicted using simple one-dimensional layered Earth models. Canceling out all these complex source and propagation effects leaves the robust extraction of the radiation pattern and thereby results in a robust MT solution. For stations within 300 km, the propagating waves only have 1-10 wavelength cycles (Table 1). With larger earthquakes, it is ideal to use farther-distance stations in order to get at least 1 complete cycle; however, the theory still works, and some very sensitive broadband sensors can nearly record static displacements.

There is also another reason to use surface-waves filtered between frequencies of 0.01-0.05 Hz (100-20 sec period), because this frequency range is the quietist. The Probability Density Function (PDF) shown in Figure 6 is composed of Power Spectral Densities (PSDs) over

359 days in 2016 at US.TPNV.00, a seismic station in remote Tonopah Springs, Nevada. Note the -175 dB low noise level between 0.02-0.05 Hz range that is ideal for MT inversion with slightly higher noise from the primary and secondary microseisms at 0.08 and 0.2 Hz. There are higher noise levels for the winter months at frequencies lower than 0.02 Hz. Stations near the coastline have higher noise levels in these ranges particularly in these winter months. The amplitude levels from surface waves depends on magnitude and distance and TPNV typically has adequate signals above noise down to magnitude of Mw 3.5 in the 0.01 to 0.1 Hz range ideal for MT inversion at regional distances (< 1000 km) but also modeling and inversion at shorter periods (20-5 sec) can be attempted at local distances < 100 km. Overall, the 0.01-0.05 Hz band is best for MT inversion because it sits in a PSD valley where the noise is the lowest.

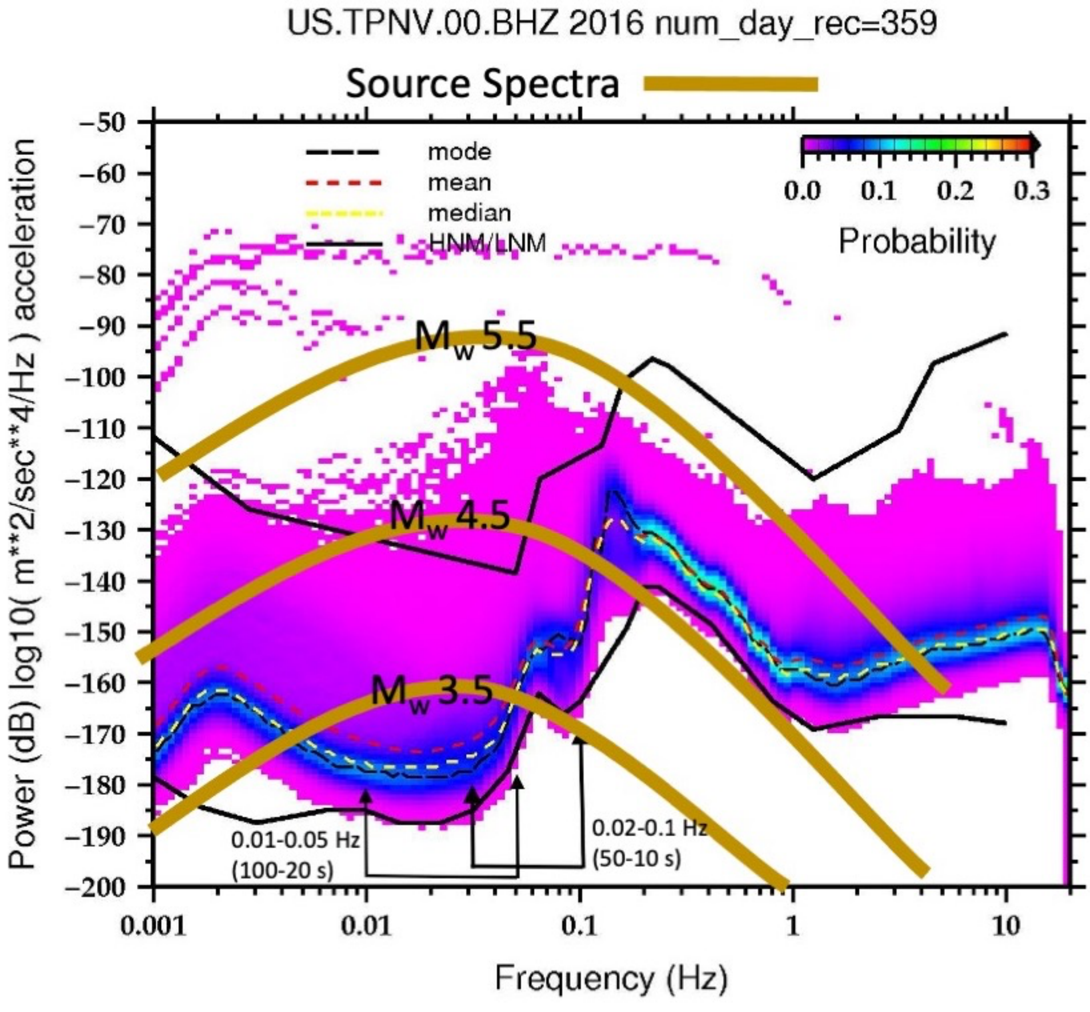


Figure 6. Power Spectral Density (PSD) Probability Density Function (PDF) for Tonopah Springs, Nevada (US.TPNV.00.BHZ). This station is quiet at low frequencies and the noise amplitudes are near the Peterson low-noise model. Arrows point to the frequency ranges of the 0.01-0.05 Hz (100-20 sec), 0.02-0.05 Hz (50-20 sec) and 0.02-0.1 Hz (50-10 sec) bands used for MT inversions. Sample source acceleration spectra overlays are notional for 700 km source-to-receiver distance for 3 different magnitudes.

(http://ds.iris.edu/ds/nodes/dmc/tutorials/waveforms-and-their-power-spectral-density-expressions/)

Moment Tensor Inversion Strategies

Making Green's Functions

What 1D velocity model do I use?

This is by far the most common question when it comes to MT inversion. In some sense, the selection of the velocity model should not matter if only long periods are used so that the wavelengths are much larger than the Earth heterogeneities (see Table 1). However, this is not always possible as crustal scale features like crustal thickness play an important role. For example, the Tibetan Plateau crustal thickness is 60-65 km but is only 20-25 km thick in the Imperial Valley of Southern California, while typical crust is 30 to 40 km thick (see Figure 7). Another extreme are ray paths traversing between continental and oceanic crust e.g., ray paths crossing the Sea of Japan between Japan, Korean Peninsula, and Asian continent. For these ray paths, nothing can be done to improve a 1D model because the source-to-receiver path transitions continental and oceanic crusts. For this case, going to 3D Earth models may be necessary.

In the 0.01-0.05 Hz band (100-20 sec periods) most 1D models work well around the world. Above 0.05 Hz, 1D models may break down and special regionalized 1D or 3D models are required (see Figures 7 and 8). Besides Earth heterogeneities, another limitation is seismic noise. Not all seismic stations are quiet like TPNV (Figure 6), and the portion of the low frequency band best used with 1D models (0.01-0.05 Hz) become noisy particularly at farther distances requiring shorter periods (0.05-0.1 Hz) which makes model selection more important.

The simplest answer to 1D model selection is to select a velocity model by trial and error (see tips in Table 2). If the MT inversion results in a good fit to the data (e.g., percent variance reduction >> 50%), then the model is "good enough" (see Figure 7) with the exception of a small travel-time shift. The best confirmation of a successful model selection is always from the simple visual comparison checking for a wiggle per wiggle fit.

> *"Trial and Error" is a fundamental method of problem-solving. It is characterized by repeated iterations of varied attempts which are continued until success or until all known possibilities are exhausted.*

In my experience, the world can be divided into four 1-D velocity models: (1) tectonically active, (2) stable craton, (3) Tibetan Plateau, and (4) oceanic crust. I have used the western United States (`wus`) model over much the entire world, and it works reasonably well for "tectonically active" regions except for the other three (of course this is for <= 0.05 Hz). The regional "`wus`" model (Ritsema and Lay, 1995) was developed using surface-wave phase velocities in the western US region. Another good regional velocity model is the "`cus`" (central US) model developed by Robert B. Herrmann (SLU) appropriate for stable central and eastern US. The global 1D Earth model IASP91, and its successor, AK135 represents an average of the continental crust, mantle, and core (concentration of seismic stations). It's creator (Brian L. Kennett) once said that it does not realistically represent any one point on Earth. In my experience IASP91 works well for some stable continental regions (Norway and parts of south and western Africa) but are not the best as there have been other detailed regional studies. My best advice is to make an educated guess on a tectonic or geologic environment (Table 2) that characterizes the seismic event or station location and go with the best 1D models provided in the toolkit. If you have more time, then I recommend searching the literature for modeling results from seismic refraction or reflection experiments. Figure 8 shows that a literature search for a south African 1D model results in waveform fits that work much better than IASP91 up to 0.1 Hz.

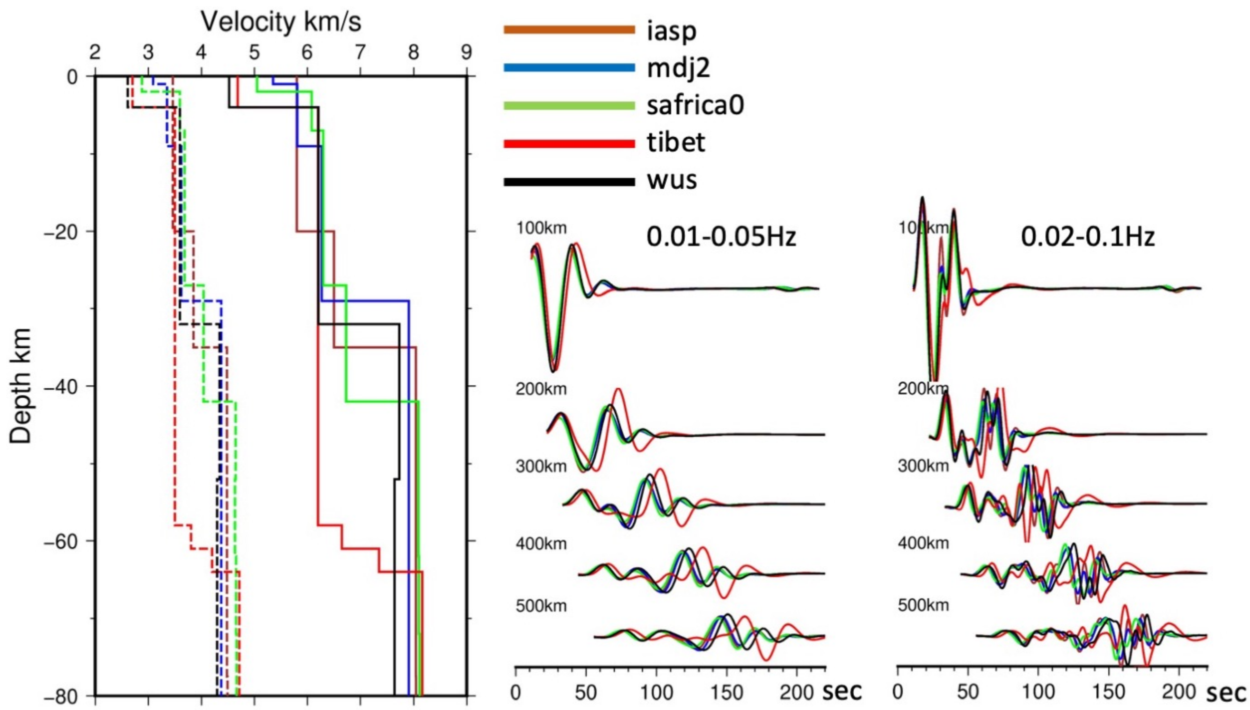


Figure 7. Synthetic seismograms were computed for 5 different velocity models for receivers between 100-500 km distances in 100 km increments. Shown are vertical component displacements for strike-slip mechanism at 10 km depth. For distances <= 100 km, the waveforms look similar regardless of model selection. Also, for frequencies < 0.05Hz (20 s) the displacements are similar in this bandpass except for the "`tibet`" model in red.

Table 2. Summary of Model Selection Tips

Tectonic/Geologic Region of Seismic Event	Model Code (`velmod=`) in `makeglib.csh`
Active Tectonic	`wus, mdj2`
Stable Craton	`cus, iasp, safrica0`
Tibetan Plateau	`tibet`
Oceanic Crust / Mixed Path	Try a mix of 1D models, or try inverting smaller station sets based on region
If all else fails, then search literature for regionalized 1D models	

The point where 1D model's breakdown is very scale dependent. For small source-receiver distances (< 20 km) and normal crustal depth, a layer over a half-space will work up to 1 Hz. Any waveforms from normal crustal depth (> 2 km) earthquakes at local distances, can be characterized by only a few upgoing rays. This will generate a waveform which appears simple with only the direct P- and S-phase up to 1 Hz. However, when the hypocenter depth moves upward closer to the surface, then a simple ideal waveform becomes more complicated requiring many more up and down-going rays (i.e., direct, surface-reflected, reflected, and refracted rays) to synthesize at that same 1 Hz frequency. Also note that at very far regional to teleseismic distances (1200-2500 km) a 1D model will require upper-mantle structure including the gradients for the 210, 410 and maybe the 660 km discontinuities.

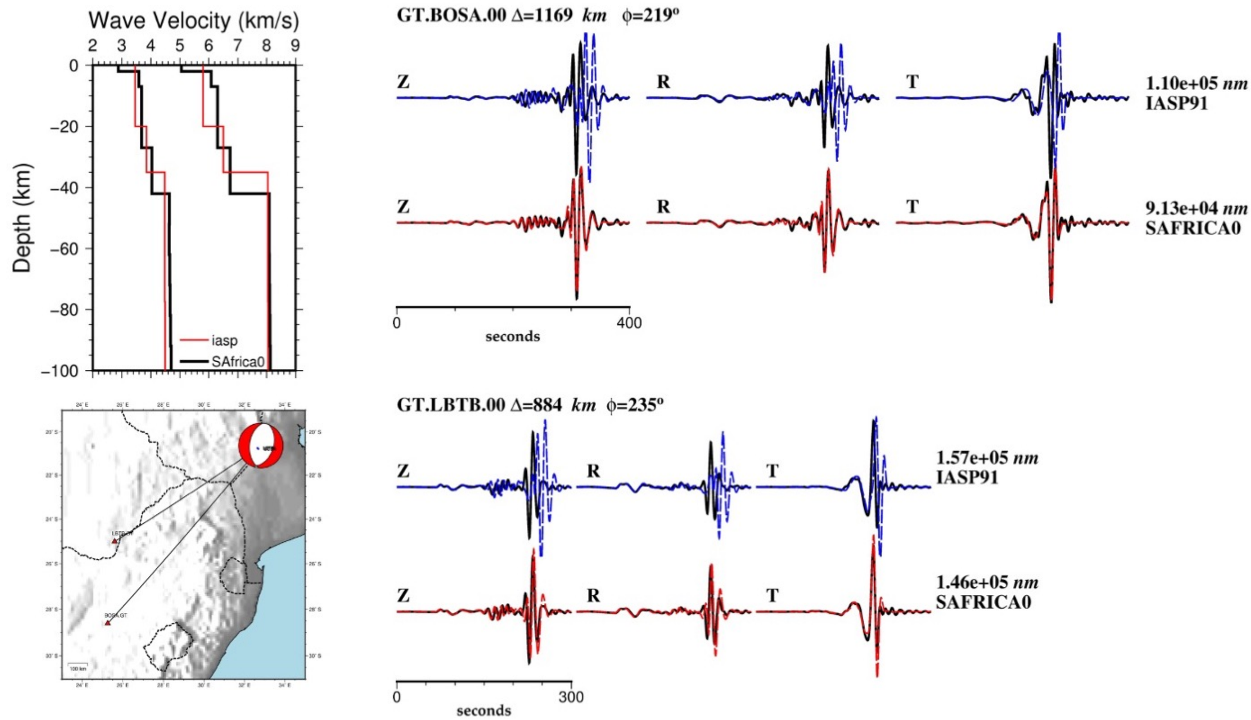


Figure 8. South Africa earthquake example comparing data recorded at stations GT.BOSA and GT.LBTB with synthetics computed using `iasp` and `safrica0` models up to 0.1 Hz. The `safrica0`model is from Table 5 of Qiu et al. (1996), which makes a much better fit to the data. This result of determining which velocity model to use was accomplished by simple trial and error and background literature research.

Besides crustal thickness, deep sedimentary basins can affect MT solutions and the two features of deep basins and think crust can combine like the Imperial Valley of Southern California. There has been a lot of experience with MT inversions of Basin and Range earthquakes showing that narrow shallow basins overall do not affect the waveforms at long periods (> 20 sec). If any significant length of the ray path or when the receiver is in a deep sedimentary basin, then consideration should be given to add a basin or select a 1D model in the literature that includes basin like features. The GIL7 1-D velocity model, with a 1 km thick basin of 3.2 km/s for P-waves, is used by UC Berkeley real-time MT solutions (Pasyanos et al., 1996) for small earthquakes at certain stations around San Francisco Bay. The "GIL7" model works better than "wus" for use with the demonstration dataset in Appendix A in the 0.02 to 0.05 Hz band for extracting higher double-couple components with comparable %VR fits.

Can I use different velocity models for different stations?

There is nothing in the MT codes that prevents the user from using different velocity models for each station and it can be a good practice in cases where the event straddles two tectonic environments. The only point of concern is that the source depth shares the different shear-rigidity modulus from each model, and these different shear rigidities contribute to the total scalar seismic moment. Most codes do not take this difference into account. One test to do if there is concern is to try MT inversions using the same model for all the stations and another with the different models and compare the M_0. It is likely that the this will not vary more than the change in percent difference of the shear wave speed at the source depth (perhaps less than 10%), however, this difference can be much more at shallower depths.

MTINV tip, use setupMT to auto create the script makeglib.csh for computing Green's functions. Type setupMT on the Unix command-line prompt to get the usage.

```
setupMT:
Usage setupMT -z [depth km] -ev [lat lon] -velocity_model wus -ot
["YYYY/MM/DD,hh:mm:ss.ss"] -com ["Comment"] -gmt5 -help -realtime -verbose [sac
files]

This program creates a makeglib.csh file that computes Green functions. Add SAC
files "../Data/*.[BH]HZ*SAC" using wildcards to tell setupMT which stations to use
in the moment tensor inversion
```

What location should be used to compute the Green's functions?

The seismic event catalog hypocenter location and origin-time is usually the best place to start. Seismic networks are reasonably dense world-wide resulting in adequate quality locations. However, if a good MT inversion is not obtained after going through the normal routines, then accounting for location error is one place to start. Model selection could also be a problem. I recommend looking at the International Seismological Center (ISC) website to search the database for other agency location solutions and retry computing the GFs.

Farther stations (> 100-200 km) are relatively immune to location errors, but this depends on the amount of the location error. I've seen one mislocation as large as 50 km. In the worst case you may have to pick the arrival times and use your favorite location code to estimate a new location. This scenario is rare, but I have done this once for a missed event that was not found in any catalog.

In ***MTINV***, the Green's functions are computed using distance between the latitude and longitude of the source (in `mkgrnlib` the parameters `evla` and `evlo` are set with the event location). The receiver latitude and longitude are obtained through a table in a text file (`mkgrnlib` checks the file pointer "`stadb=`" for a file that contains station code and latitude longitude in free format similar to output from ***RDSEED***, see -S option).

How do I set the source-to-receiver distance for computing the Green's functions?

In the normal operating mode of ***MTINV***, the source-to-receiver distance can only be set using latitude and longitude from the event and receiver location and cannot be set explicitly. If you require a specific distance, then one would need to spoof the input with a fictious latitude and longitude locations computed for an exact distance. From these fake coordinates, the source-to-receiver distance and azimuth are computed and stored in the output file for processing and inversion as normal. The only time I see one needing this is for scenario tests and creating figures with GFs or synthetics computed for a range of distances (e.g., Fig. 7).

For computing GFs using `hprep96`, the source-to-receiver distances for each station should be calculated and placed in an input file for `hprep96`.

What depth range do I use?

If the earthquake of interest is a crustal earthquake (<= ~35km), then set the `mkgrnlib` input parameter "`zrange=start,increment,stop`" to go from 2 to 25 km in 1 km increments. This results in calculating 23 Green's functions which is not too time consuming or a heavy lift for a desktop computer. Sometimes I use 3 to 33 km in 3 km increments which covers a wider crustal range with only 11 GF depths. Depth cannot be very well estimated using only long-period waves, but this can be improved using shorter periods. There are regions which frequently have intermediate depth earthquakes between 25-250 km like subduction zones. To keep the number of Green's functions manageable, try changing the depth increment from 1 km to 5-10 km. For ***MTINV***, keep in mind that the multi-threading interface `multithread_mkgrnlib` has a limit of 50 stations.

How shallow or deep can I go?

GF source depth have no limitations but remember the last layer in the model file is a half-space. The MT solution for the Great Bolivian earthquake of 9 June 1994, was estimated at a depth of 620-640 km (e.g., Ekström et al., 2012). Two things to consider, (1) do I need to add structure to the 1D Earth velocity model if I have to go deeper, and (2) what depth increment should be selected so the total number of Green's functions calculated is kept to a reasonable number. My tip is, if the event has a catalog hypocenter depth that goes below the crust, then one should append a global model like the IASP91 upper mantle layers to the bottom of the regional crustal model at least down to the hypocenter. See previous section to select a depth increment for computing Green's functions.

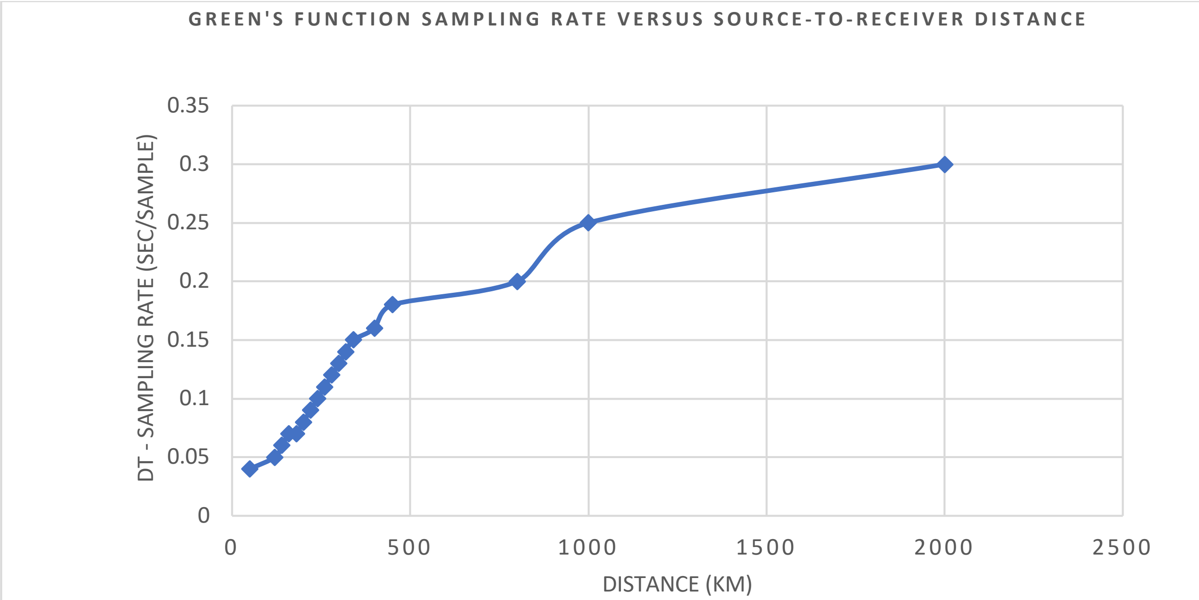
Shallow seismic events with depths < 1 km require a little more attention. More wavenumbers are required for shallow sources to maintain stability. If problems arise, then increase `kmax` and eps in `mkgrnlib`. Unless ground truth is available, I do not recommend using depths less than 1 km, due to increase computation time, stability issues, and lack of benefits at long periods. A regional distance GF computed at a depth of 0.5 km varies very little compared to depth of 1 km at 100-20 sec period. My tip is to start with a 1 km depth with 1 km increments down to 25 km; however, if the shallow isotropic source is not well recorded (poor station coverage), then it is best to fix the depth near the surface (i.e., 1 km) for the full-MT inversion. Also try using hspec96, which tends to be more stable for z < 1 km.

```
#!/bin/csh
#######################
#### makeglib.csh #####
#######################

setenv MTINV_PATH \
/Users/ichinose1/Work/mtinv.v3.0.6

cat >! wus.par << EOF
velmod=wus
zrange=2,1,25
evla=37.8552
evlo=-122.257
dt=0.15
nt=2048
fmax=0.4
t0=0.
redv=18.
damp=1.
kmax=20000
eps=0.0005
smin=0.0005
modeldb=${MTINV_PATH}/data/modeldb/
stadb=../Data/rdseed.stations
noverbose
nodump
EOF
```

<u>What is "`nt`" and "`dt`" for to compute the Green's functions?</u>

The number of time points is "`nt`" and the sampling rate is "`dt`" (seconds per sample). There are two "`nt`" and "`dt`" input parameters (one in `mkgrnlib` and another in `mtinv`) and these are specific only to Green's function calculation (see later for more discussion on the MT inversion). The key here is to make the time window (`twin`) of the synthetic GFs large enough (`twin = nt*dt`) to allow for all of the arrival of body and surface waves. Later in the MT inversion stage, these time windows can be finely adjusted, for both data and synthetics equally, using interpolation/decimation to make fine scale adjustments so here it is only important to select values that allow the calculation of GFs out to enough time given the source-to-receiver distance.

The number of GFs samples, (e.g., `nt=128, 256, 512, 1024, 2048, 4096`) is constrained to powers of 2^n due to the speed optimization in the Discrete Fourier transform algorithms. Any `nt` can be selected; however, to keep this simple we select `nt=2048` and determine the best dt using a formula shown in the chart below. In ***MTINV***, there are parameter file preparation tools "`setupMT`" and "`makepar`" that will set `nt` and `dt` for you automatically.



See file mtinv.v3.0.6/src/setupMT.c

What is `fmax` and `kmax`?

Zeng and Anderson (1995) version of the frequency-wavenumber reflectivity code, used to compute synthetic GFs, can exit early making the computation faster. Typically, the frequency loop of the code continues to the Nyquist frequency determined by the `dt`. A sampling rate of 0.20 sec has a Nyquist of 2.5 Hz but if the filter applied before the MT inversion is only 0.02 to 0.05 Hz then computing up to that frequency is unnecessary. In most cases you never need frequencies greater than fmax=0.4 Hz as long as the high corner of the bandpass filter is below 0.1 Hz. "`kmax`" is the maximum iterations for the wavenumber loop. Do not lower the default value unless you know what you are doing. In most cases increasing "`kmax`" will take longer but improves stability. The f-k reflectivity code by Yeuhua Zeng internally determines the best number of wavenumber loops based on a stability condition so" `kmax`" is for exiting early. Herrmann's `hspec96` and `hprep96` have similar cut-off and stability parameters (e.g., `cmax, cmin, xleng, xfac, alp, arg, k`) but in either case, default values will work the majority of the time.

What is `t0` and reduction velocity and when to use one or the other?

These parameters control the start of the synthetic GFs by two options, option 1: explicitly defining the start time "`t0`" in seconds or option 2: by using a reduction velocity. The simplest condition is `t0=0` and `redv=-1` (reduction velocity off) which starts the synthetic GF at `t0=0` sec, i.e., the origin time of the seismic event. This is adequate at short distances but there are benefits to using reduction velocity at farther distances to allow for the same fixed time windows without significantly increasing `nt` or `dt`. At larger propagation distances, the longer duration dispersed surface waves in the GFs become chopped off at the end of the time window. Even worse, the FFT is cyclic so that these later arriving surface waves wrap around to the front of the signal causing contamination of the P-waves. The fix to this problem is to use a reduction velocity > 9 km/sec, which will shift the start the time window of synthetic from the origin-time to a time closer to the first arrival. The zeros before the start of the signal are not needed for the inversion and that time duration can then be used to capture the slower waves and the end of the time window. The user must ensure that the start and end of the time window are accurate for the synthetic since there are no automatic checks.

The GF is computed in the frequency domain and an inverse FFT brings it back to the time domain. The FFT is cyclic and there is no check or error correction to ensure the time window (start and duration) is adequate for capturing all the propagating synthetic waves. The f-k reflectivity code will wrap around the waves to the start of the synthetics chopped off due to incorrect settings. Caution is recommended and if this condition is encountered, just extend the window by increasing "`nt`" and/or "`dt`" as well as use "`redv`".

Station naming conventions: Network, Station code, Location code, and Channel code (NSLC)

The International Association of Seismology and Physics of the Earth's Interior (http://iaspei.org) station coding standard, adopted by the Federation of Digital Seismograph Networks (http://fdsn.org), standardizes seismic station naming requiring common N.S.L.C identifiers: Network, Station, Location, and Channel. Early versions of ***MTINV*** software toolkit only required network and station. However, it has now become necessary to include location codes, which are typically "01", "02", "00", "10", or "" (null). Location code is a way to identify multiple sensors closely located at the same station. Later versions of ***MTINV*** (version 4+) now include location codes as an extra column for each station row in the par files. Location codes are stored in the ***SAC*** file under "*khole*" header variable extracted from the ***SEED*** blockettes 8 and 35. Intermediate ***MTINV*** output/input files will also contain a NSLC format identification. Channel-code is unnecessary in most of the data processing since we deal with all 3-components. However, it is important to know the distinction of broadband high-gain channels (BH and HH) and in rare cases short period or accelerometer data that can be used (SH or EH). Also, the last character (i.e., Z, N, E, 1 or 2) is important but ***MTINV*** handles this under the hood as long as the ***SAC*** header variables *`cmpaz`*, *`cmpinc`*, and *`kcmpnm`* are correctly populated automatically (via ***RDSEED*** or ***WFDISC_2_SAC***) or manually.

IMS array channels typically use the element designation in the station code portion (e.g., MK01, MK02, …, MK31), although MK31 is the 3-C broadband. However, there are some broadband 3-C arrays and portable arrays which sometimes use the location code to name separate elements.

https://ds.iris.edu/ds/nodes/dmc/data/formats/seed-channel-naming/

The inversion

MTINV tip, use `makepar` to auto-create the `run.csh` and `run2.csh` scripts. Type `makepar` at the Unix command line prompt to get the usage. Modify the `run.csh` script as needed iteratively to remove stations, change frequency bands, and enter time-shifts.

This command is included at the bottom of the `makeglib.csh` script when using the `setupMT` command.

`makepar` will auto-create a `mtbestfit` command at the bottom of the file the `run.csh` script. The application reads the automt.txt output generated by multiple `mtinv` runs and finds the best fit for creating the final plots and database loading scripts.

<u>What is **DEGFREE** and when should I use an isotropic only, deviatoric or Full MT?</u>

`DEGFREE` is a C-shell variable set at the top of the ***run.csh*** script (see box below). It is input for the `mtinv` through a command line parameter `mtdegfree=${DEGFREE}`. The options for this variable are `1, 5, and 6`, where `1` is an isotropic only MT inversion, `5` is a deviatoric only MT inversion, and `6` is for full MT inversion. This controls which type of MT solution is required.

A deviatoric MT (Dev-MT) does not include the isotropic components. Dev-MT inversions are best for any natural earthquake with the expectation to be near 100% double-

```
#!/bin/csh

set DEGFREE=5  ### 1-isotropic_mt 5-deviatoric_mt 6-full_mt

…

mtinv evid=4237645 AutoAuth ts0=${ts0} par=mtinv.par gmt5 mtdegfree=${DEGFREE}
use_snr minsnr=3 shift ctol=0.85 maxshift=10 >> mtinv.out

…
```

couple. An isotropic only MT is best used to help align observed data from explosions or mining collapses to synthetics (see alignment and time shifting later). After alignment, the switch to a full-MT inversion option. Full-MT is what you want for any seismic event where you suspect any volumetric components which is appropriate for both earthquakes and non-earthquakes including bolide impacts (e.g., Antolik et al., 2014).

The best strategy is to always start with deviatoric MT. Find the best fit as much as possible first. While refining the dev-MT, select the best station set, velocity models, bandpass filter settings rerunning the MT inversion. If the %VR and %DC are high, then the fit to the data is very good using just a dev-MT (high confidence double-couple earthquake). At this point, without any additional information or suspicions that the seismic event is an unusual event, then there is no reason to move forward with the full-MT; however, if there are any suspicions then the full-MT is the next step. Clone the best dev-MT work to another directory (copy directory from "`./dev`" to "`./full`") and modify the "`set DEGFREE=5`" to "`set DEGFREE=6`" in the `run.csh` script and rerun.

Compare the %VR for the dev-MT and full-MT. If the event has an isotropic component, then the fit may be the same or improved with some significant increase in isotropic component percentage (> 40% isotropic is significant). The full-MT will generally fit with the same or better %VR given that there is one additional degree of freedom added to the inversion. If there is a significant increase in isotropic for the full-MT, then it may be helpful to do an isotropic only MT inversion to check how well the synthetics fit the data using a very simple 1-degree of freedom inversion. This exercise is akin to going around the source-type space and mapping the %VR for various sources. ***MTINV*** version 4 contains a network sensitivity solution (NSS) application to show the %VR fit for the whole source-type space (e.g., Ford et al., 2010).

In some cases, you will already know the event of interest is a mine collapse or explosion in which case it is ok to go straight to and start work using the full-MT option. In a day-to-day operation of monitoring earthquakes, a full-MT is not necessary for every event and best reserved for occasions of special event analysis. Anytime a good dev-MT solution is achieved, a full-MT can be attempted using the same station set-up and filter settings. To simplify the full-MT we recommend just comparing the full-MT solution for a 1 km depth with the best depth from the dev-MT solution. The 1 km depth GF would need to added if it wasn't included earlier.

How is the origin-time determined and where does it get set?

An initial guess for the origin time is required to window the data. The seismic event catalog origin-time is usually the best place to start. In cases where there is no catalog event available then extra effort is required to search over a longer time range. The MT inversion routine is designed to iterate over a range of relative origin-times (Figure 9).

Origin time is treated like location parameters, they are assumed to be fixed throughout the MT inversion. However, origin time can trade-off with depth just like in seismic hypocenter location determination and also the best fitting OT and depth depends on the selection of velocity model. This trade-off is explored in the run.csh script that is autogenerated (see box). At each origin-time, the moment tensor inversion returns the best fitting depth so that the fit can be tracked over relative origin-time shift. This simple grid search strategy works very well (see Figure 9), and it is useful for tracking the fit improvement peaking and fall-off giving, which gives some confidence on the selection of the best fitting OT and depth.

The text box shows the locations in the C-shell script "`run.csh`" where the origin time is set (0 relative shift represents the absolute time 10:39:38 UTC) and where it iterates through a for loop "`foreach ts0 (…)`" over the range between -8 to +8 sec in 1 second increments relative to the absolute origin-time (i.e., absolute times 10:39:30 to 10:39:46 UTC). Any time interval and decimal seconds are allowed, and minute skipping are correctly handled internally hence the reason for using relative instead of absolute time for shifting.

```
#!/bin/csh
###################
##### run.csh #####
###################

cat >! mtinv.par << EOF
#### REGION COMMENT ############################
CM Berkeley Mw4.4
#### Date and Origin Time ######################
OT 2018/01/04,10:39:38.00
…
EOF

### PROCESS GREENS FUNCTIONS ###
###
glib2inv par=mtinv.par noverbose parallel

### PROCESS DATA ###
###
sacdata2inv par=mtinv.par path=../Data respdir=../Resp noverbose nodumpsac parallel

#### do the inversion (MT at best depths) and iterate over origin-time
####
foreach ts0 ( -8 -7 -6 -5 -4 -3 -2 -1 0 1 2 3 4 5 6 7 8 )
 mtinv evid=4237645 AutoAuth ts0=${ts0} par=mtinv.par gmt5 mtdegfree=${DEGFREE}
use_snr minsnr=3 shift ctol=0.85 maxshift=10 >> mtinv.out
end
```

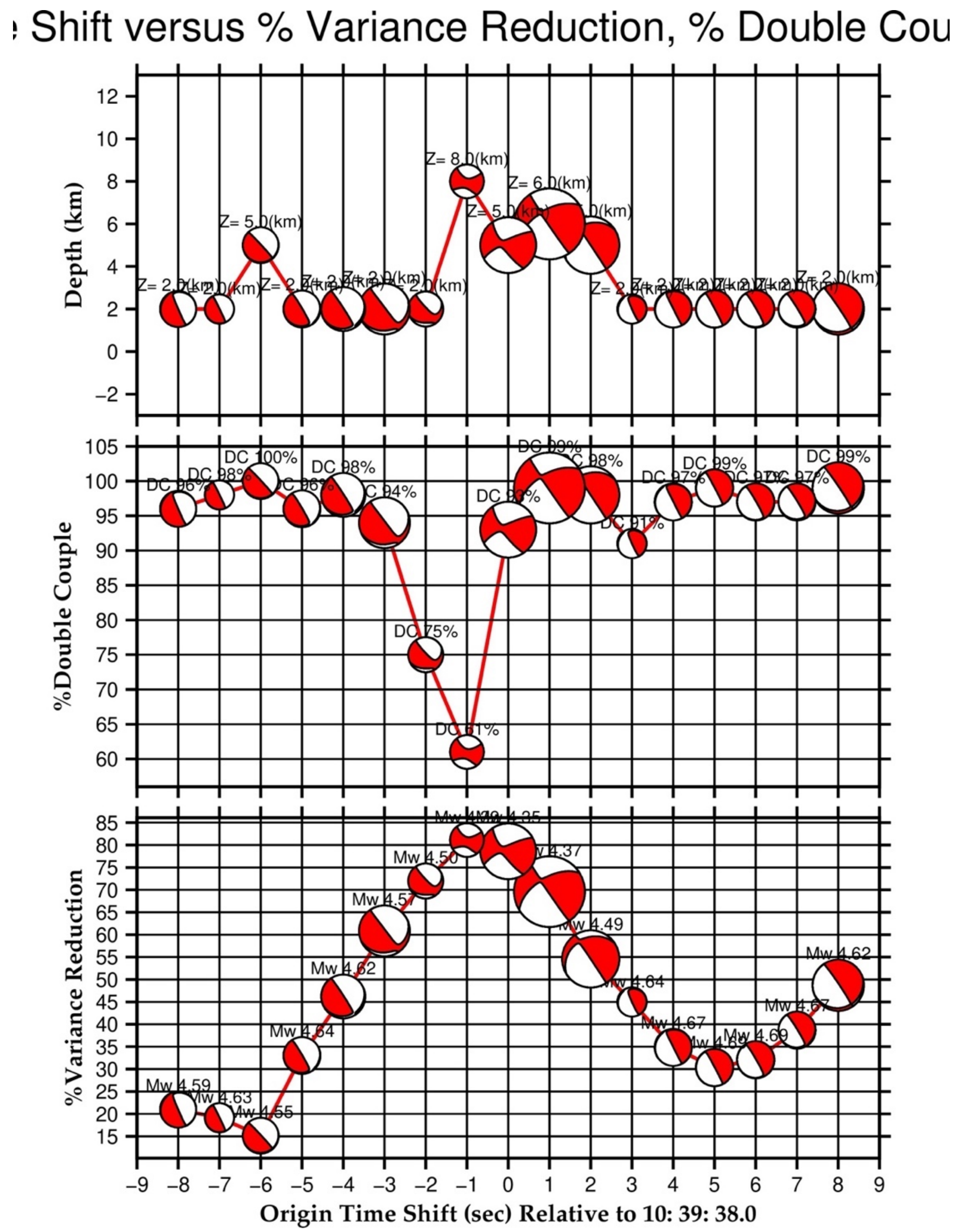


Figure 9. ***MTINV*** **output plot of results.5.jpg. The bottom plot shows that the optimal percent variance reduction (%VR) is at the origin-time shift of -1 sec (10:39:37); however, it only has a 61% double-couple. The MT solution at 0 OT shift has a DC or 93% and also the next highest %VR. This is just meant to be a guide and the final selection should be based on how well the waveforms fit visually. The dev-MT focal mechanisms are approx. scaled by %VR/(100-%DC).**

<u>How many stations should I use?</u>

A well resolved MT inversion only needs 2-4 regional distance stations at different source-to-receiver azimuths. The best strategy here is very similar to those used in any geophysical inverse problem like earthquake hypocenter location. The strategy is to start with the closest stations and typically stations between 50 and 500 km work the best. The next step uses "trial and error" through several iterations specifically defined here as the process of adding or removing defining stations, changing frequency bands, or time shifts and rerunning the inversion and seeing if that small change made any improvement. Improvements can be identified by tracking the %VR which quantifies the fit between data and synthetics; however, the best quality check is visually by eye. To start, fewer data is always better than trying to shove all the data and changes into the first trial run. This approach involves trying to sort out what settings and data are most important to the MT solution (more on this later).

<u>Which stations should I use?</u>

If possible, start with a core of trusted stations like those that are part of the Global Seismic Network (GSN). This is stations from the IU and II networks at IRIS. Start with a few stations (2-4 stations), refine the filters and perhaps the time window durations. then predict the fit for the other stations and add them iteratively one-at-a-time to make sure the additional data helps improve the solution without degrading the overall fit.

Stations less than 50 km may be susceptible to location error. If the seismic catalog location is wrong, then the distance and azimuth error can greatly affect your MT solution. It is best to leave "close-in" stations as non-defining and track the predicted fit over the iterations as MT inversion adjustments progress. Remember the MT inversion is weighted naturally by amplitude, so the "close-in" stations will drive the MT solution. Beware of clipping. If the location is trusted then definitely start with using the closest stations, then bring in the farther distance stations one at a time iteratively on an as-needed-basis and predicted fit indicate a potential benefit to improving the MT solution. Stations farther than 1000 km should be left as non-defining until a good prediction can be achieved (by adjusting filter bands or models) before turning on as defining in the inversion. Stations beyond 1200 km should be removed (comment out using "#") unless the situation requires its use due to poor station coverage. If the %VR fit is greater than 80%, then it may be time for one last iteration for adding and checking the predictions of farther stations, leaving them as non-defining.

Focus on a few stations at first, adjust your frequency bands to remove noise and improve %VR. Remove stations that have bad channels (clipping, spikes, long-period drift transients, recentering artifacts are common on Streckeisen STS-2, Nanometric Trillium, and Guralp CMG-3T sensors). Turn off stations that may have a bad fit due to Earth velocity model error. (e.g., earthquakes along the Eastern Sierras and Walker Lane have slightly different solutions if using all stations from Basin and Range or California only. The California paths are complex crossing the Sierra Batholith and thicker crust and maybe even crossing the thick sedimentary basin of central Great Valley. Keep this in mind when mixing sets of seismic stations crossing two tectonic environments. Use one set or the other at first, then after everything is settled, you can bring in more stations in complex geologic settings as predictions warrant.

What kind of stations should be used?

Try to always start with including one or more trusted stations (typically GSN). These stations have a long operating history, frequently trafficked, and tend to be the best maintained and documented. Instrument responses are well documented for these sites and if something bad happens to the site, then problems usually get fixed quickly. Of course, if all you have is portable deployment data or data from a lesser-known seismic networks, then start with earthquakes that are large enough to be recorded by GSN stations plus may have GCMT solutions and confirm that the stations fit well using predictions and all metadata checks out. This is one very powerful use of the tool in that it can be used to check instrument response and data quality issues.

What is the effect of station distribution on the MT solution?

This is a very common question with many different variations including the question of the effect of station distance, azimuthal gap, and number of stations required to achieve a well constrained MT solution. Theoretically, a MT solution can be determined using a single 3-C station (see Figs A2 and A3); however, in the real world this is not always the case given the uncertainty in the 1D velocity model, event location, and the presence of noise. In practice, at least 3 to 4 stations are recommended to recover a well constrained MT with less than 10 degree variations in strike, dip, and rake compared to a MT solution using 12+ stations (e.g., Ichinose et al., 2003). Satake (1985) suggests that the current distribution of global stations result in MT solution with up to 30% variation on double-couple when more than a single wave-type is used (e.g., P-waves and S-waves or Rayleigh-waves and Love waves). The difference in Mw is typically quoted as +/- 0.1 magnitude units or approximately a factor of two when two different velocity models are used.

Figure 10 shows two earthquakes with two types of mechanisms and associated Rayleigh and Love wave radiation patterns. The radiation patterns are functions of depth and frequency band and does not show the additional effect of phase, only amplitude. Therefore, with just considering amplitudes of surface-waves reveals that the optimal azimuthal station distribution for two stations is ~45-degrees (i.e., S2 and S3 in Figure 10) while two stations with a 90-degree separation may be redundant (i.e., S1 and S3). Redundant in this case means the waveforms look the same.

What is the implication when there is only one or two stations available? When dealing with a sparse seismic network, it really helps to have at least one station within < 500 km or at least one station within 250 km that can provide a wider frequency band 0.01-0.1Hz, with less noise and less model uncertainty. Single station MT inversions may converge to a solution with an excellent fit to the data, but the range of acceptable values in MT, depth, and total moment can be large. In some cases, with a single station or two stations with redundant azimuths, a MT solution can flip back and forth between a normal-slip and strike-slip mechanism with equally good fit to the data. Note in Figure 10 that the two mechanisms share the same Love-wave radiation pattern so noise or model error on the Rayleigh waves can lead to a poorly constrained MT solution without data from additional azimuths. Beware, unless there is at least one station within 500 km (e.g., see demo case in Appendix), there may be large uncertainties in sparse network MT solution at long-periods and stations at farther distances.

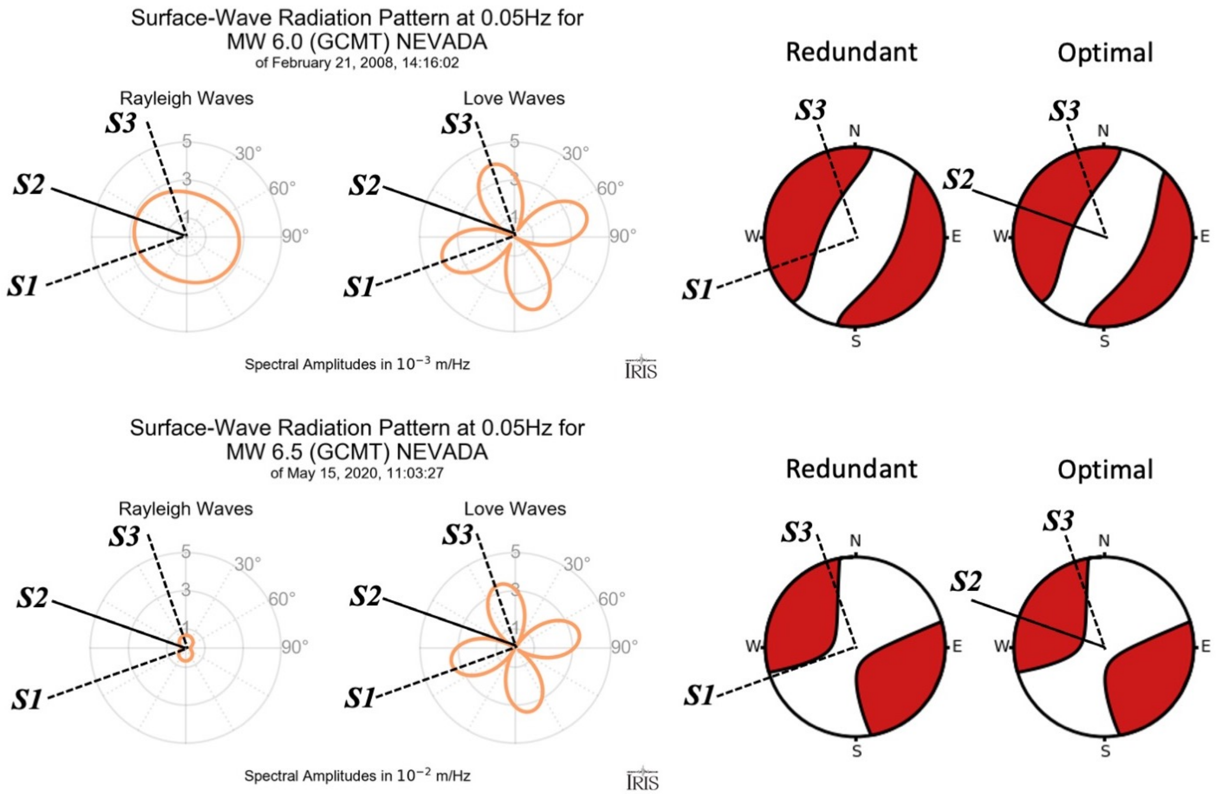


Figure 10. Rayleigh and Love wave radiation patterns (0.05-Hz) for a normal-faulting dip-slip and vertical strike-slip faulting earthquakes with associated global CMT solutions. These patterns have 2- or 4-lobe radiation patterns with peaks and nulls. Two stations S1 and S3, separated by 90 degrees in azimuth would only provide redundant information given these specific source mechanisms and radiation patterns. Stations S2 and S3, separated by 45 degrees is more optimal given these specific source mechanisms and radiation patterns because the information is not redundant.

http://ds.iris.edu/ds/products/surface-wave-radiation-patterns/tools/surface-wave-radiation-patterns/

What frequency bands should I use?

This is where one will spend most of their time iterating between MT inversion runs. Everyone pretty much understands the ends and outs of signal processing and bandpass filtering. The end game here is to use the lowest frequency band that is enhances the signal to noise ratio. I recommend using a trial and error approach starting with the 0.02 – 0.05 Hz (50-20 sec) filter first. After the first iteration of the MT inversion, inspect the waveform fits to determine the next steps. If there is still long-period noise, then move the low frequency corner from 0.02 Hz to 0.025 Hz and iterate the MT inversion leaving the high frequency corner the same. If there is still long-period noise, then increase the low corner from 0.025 Hz to 0.03 Hz. At this point a 0.03-0.05 Hz is a fairly narrow bandpass, therefore if another iteration is necessary, it is best to also move the high-corner to 0.055 Hz (bandpass 0.033-0.055Hz). Try to keep at least a 0.02 Hz difference between the low and high corners for the filter to allow for enough bandwidth.

It helps to arrange the location of terminal windows on the desktop to help with the MT inversion iteration process. Leave the waveform plots from the previous MT inversion iteration placing it next to the text editor with the run.csh C-shell script opened (Figure 11) where the `mtinv.par` file is created so that the frequency band parameters can be changed for as many stations as needed. Typically, the best stable Butterworth filter has 3 poles and is 2-pass. Single pass "acausal filters can be used if it improves signal to noise; however, the user will rarely need to change "np" and "pass" only "lf" and "hf".

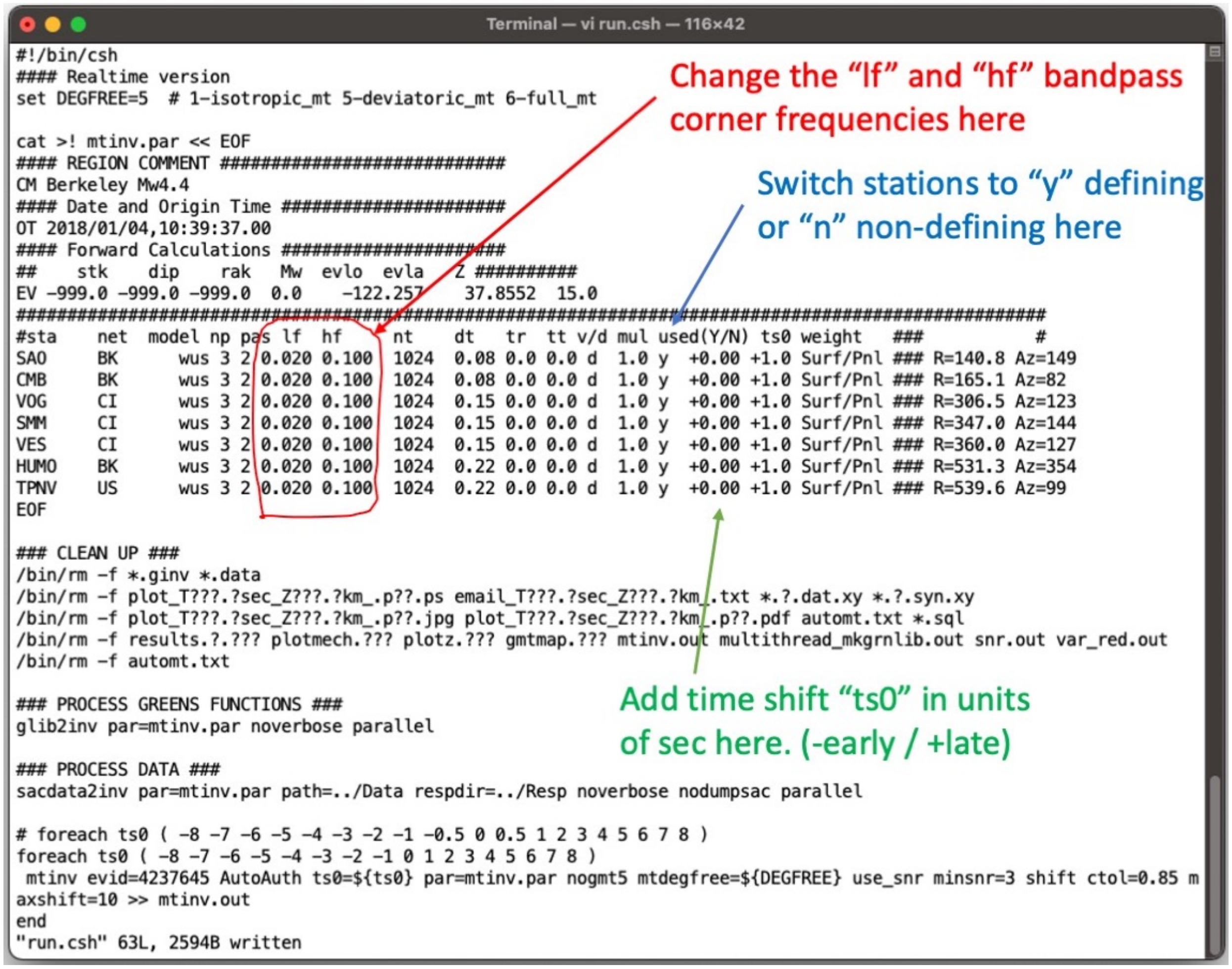


Figure 11. Terminal screen shot of the script "run.csh" used to generate the input file for `mtinv`. The file created named `mtinv.par` will always have the last filters used therefore the script can be modified and upon running will overwrite `mtinv.par`.

Figure 12 shows the transverse component for 11 bandpass filter banks. The 0.02-0.05 Hz or 0.025-0.055 Hz bands appear to be the lowest frequencies with the best signal to noise. The highest SNR is 0.05-0.1 Hz; however, a 1D model may not fit this data at that high of frequency. I recommend leaving the station as non-defining at the next MT inversion iteration to check if a higher frequency band can be predicted before using the higher bands. The lower bands that are noisy, i.e., 0.012-0.04 Hz and 0.015-0.05 Hz are noisy; however, if one is adjusts the time window duration and start-stop times, then the SNR could be improved by windowing out the noise.

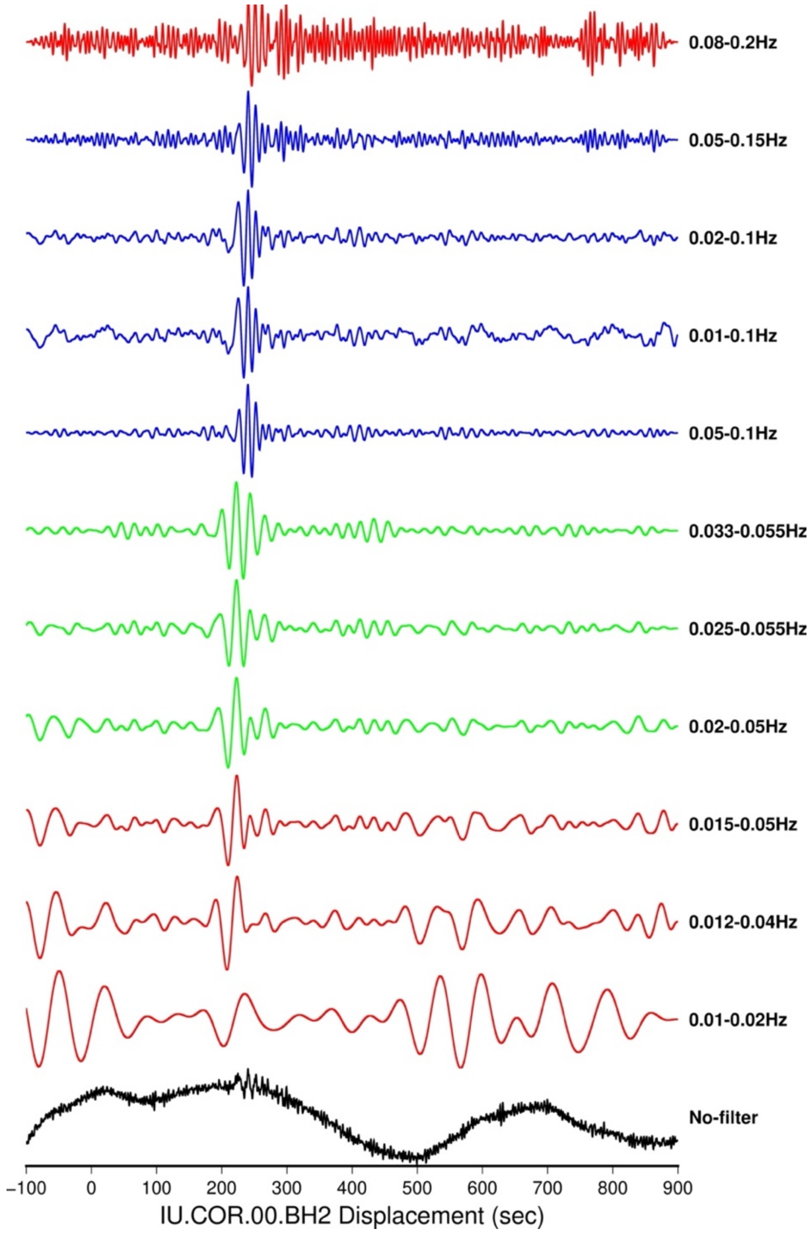


Figure 12. Choosing the best filter band is a balance between achieving the best signal-to-noise ratio at the lowest band possible. The lower frequency bands are noisy because the earthquake displacement spectrum is flat while the noise increases as frequency decreases. The signal-to-noise may be better at higher frequencies; however, the 1-D Earth model used may not be adequate to fit the data. Above is an Mw 3.86 earthquake near Walker, Nevada recorded at IU.COR.00 Corvallis, Oregon, at 743 km distance. The best 3 frequency bands have a low-corner greater than 0.02 Hz (green) while the 3 lowest frequency bands with the low-corner < 0.015 Hz are too noisy (red). The 4 frequency bands with high-corner greater than 0.1 Hz will be difficult to fit using 1D models (blue).

What "nt" and "dt" should I use for the MT inversion?

The variables nt and dt control the time window by the number samples and sampling rate set in the file run.csh in the section creating mtinv.par for each station row. These values are similar to the previous ones used to compute the GF; however, these control the sample rate and window length of both the data and GF for the inversion.

The applications in ***MTINV***, sacdata2inv and glib2inv read the nt and dt station settings in mtinv.par and interpolate the data and synthetics to these new values. It is not allowed for any station with a dt in mtinv.par to be less than the dt in mkgrnlib used to calculate the GFs, and glib2inv will exit with an error. The solution is to increase dt for the stations GFs and recalculate.

These two variables are best set automatically using makepar (calculated internally based on v_{min} and source-to-receiver distance). These automatically set values are usually liberal allowing for larger time windows. Optional additional small adjustments can be made to dt or nt but changing dt allows for more fine scale changes. This is performed during the iteration process in "run.csh" along with fine tuning the lf and hf filter bands that improves %VR by cutting out the noise after the surface waves pass. When the signal is larger than the background noise then this step is unnecessary, but it is some users' preference to use only the signal part of the time window.

See Appendix B for the subroutine used to compute nt and dt in makepar.c: select_nt_and_dt() For example, to compute the time window based on source-to-receiver distance of 500 km, we divide it by the slowest wave of interest (usually ~2.35 km/sec). Therefore, the time window (twin) is, twin = (500 km / (2.35 km/sec)) = 212.7 sec. Most crustal fundamental mode surface waves travel faster than 2.35 km/sec. The best automatic "dt" to use in this case is dt=twin/nt = 212.7 sec/1024 points = 0.208 sec/sample. I recommend rounding up slightly to 0.21 sec.

What is a source time function?

A source time function is a time history of slip along the fault plane, starting from the beginning of a rupture to the end where the fault heals, and slip stops. The theory of LP regional MT inversion method assumes that the source time function is a delta function and in most MT inversion codes this is either the default or is fixed. In MTINV, the source time function can be defined as an average slip along the entire fault plane at its hypocenter or centroid (i.e., there is no spatial slip distribution). The source time function (Figure 13) is defined by a rise time (tr) and top duration (tt). A tt value of zero and tr > 0 results in a triangle source time function while any values of tr > 0 and tt > 0 results in a trapezoid function. The total duration of the source time function will be (tr * 2 + tt).

When to use a source time function?

Typically, a source time function is not necessary. The point source assumption will be adequate up to magnitudes of 5.8 for distances less than 500 km. The point source is good for source-to-receiver distances greater than 500 km below M 6.5, due to Earth attenuation. For a 20-50 sec bandpass filter band, the waveforms will be weighted toward the 20 sec period; therefore, the source time function will need to be longer than 20 sec for it to affect the phase shape and amplitude of the waveforms (like in a Mw 6.5+). For M > 5.8 there is good signal to noise down to 50-100 sec period band (0.01-0.02Hz) out to 1000 km; therefore, it is recommended to use these low frequency bands rather than trying to model in a source-time function. Avoid MT inversions for magnitudes > 6.5 in any conditions unless the user understands the implications of source finiteness.

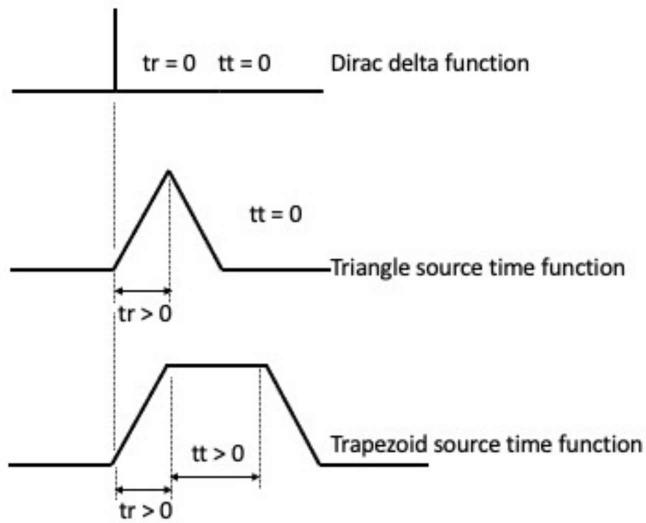


Figure 13. Three source time functions defined by a rise time (tr) and top time (tt) where time is in the x-direction and amplitudes in the y-direction are normalized to 1. The default is a Dirac delta function when tr=0 and tt=0. When tr > 0 and tt = 0, the source time function becomes a triangle shape. When tr > 0 and tt > 0, the function becomes a trapezoid shape.

If dealing with a MT inversion of magnitudes less than 5.8, then don't worry about any of this and leave the default values (tr=0 and tt=0) for a source time function alone. If you are working with larger magnitudes at distances less than 500 km, then it is recommended to shift the filter bands "lf=0.01 hf=0.035" to lower frequencies rather than trying to model in a source time function. The user should have some knowledge about kinematic fault rupture inversion before changing from the point source inversion assumption.

When to switch from displacement to velocity?

There is really only one instance the user might want to use the velocity over displacement. This instance is when the magnitude is < 3.5 or when the data are noisy (low SNR). In signal processing, converting displacement to velocity is equivalent to multiplying the spectrum by frequency. This emphasizes higher frequencies like a high-pass filter. Remember that the MT works best at lower frequencies; therefore, ensure the velocity model will work at higher frequencies. Another instance is when you have a single station available and inverting both displacement and velocity together may seem help, but it is just redundant since both ground motion types share the same radiation pattern although velocity is weighted more toward higher frequencies.

In MTINV, there is a switch between velocity 'v' and displacement 'd' and the default is 'd'. The setting controls the ground motion type for synthetics and data. In most cases leaving the ground motion type in displacement will be best.

What is `Multfact`?

In ***MTINV***, there is a station level input parameter that multiplies the waveforms for all 3-components by a scale factor. By default, this value is 1 and it is most likely that it will never need to change. However, this parameter is useful in cases where the gain is incorrectly reported in the instrument response metadata. This occasion is most apparent when looking at a well constrained MT inversion result and predictions at other stations not used in the inversion reveal that the fit in phase (wiggle per wiggle) is good but not in amplitude. This was the case shown in Figure 5A. Use this feature for testing along with the defining/non-defining option for each station. To avoid confusion, avoid making changes to the station `multfact` parameter without first setting the station non-defining in the MT inversion before testing. The user should also ensure that the MT solution is well constrained without using the station in question. Once the user is convinced that the station gain is wrong, then this `multfact` value can be added to the instrument correction files.

When should I remove a station entirely or just turn it off?

The most useful feature out of all the features in MT inversion or any geophysical inversion technique is the ability to set some data as defining (used=y) and others as nondefining (used=n) in the inversion. This is evident in the inversion of seismic phase arrival times for seismic event location where S-wave phases can be turned off but predicted to allow the user to better find the onset of the S-waves. Is this cheating, or just letting the model help guide you to improve the solution? Even more common is the analyst's ability to remove a single measurement from an inversion but be allowed to compare it to a prediction based on the current or fixed solution. This is an invaluable quality control tactic for any analyst.

The best advice for MT inversion is to start first with the 2-3 closest stations (50 km < source-to-receiver distance < 250 km) as defining and set the other farther stations to non-defining for predictions. After the first MT inversion iteration, review the waveform fits to see which station waveform fit predictions will be best to change from non-defining to defining. Ensure that the current MT solution is reasonable before allowing it to guide you. Visual inspection of the waveform fits is the best criteria, and don't just rely on the numerically calculated variance reduction parameter to judge waveform fits. In ***MTINV***, after the first iteration, check the waveform fit plots for stations that are clipped, have recentering problems, have dead channels, or noisy beyond hope and remove these from the MT inversion entirely by either deleting the station row in `run.csh` where `mtinv.par` is created or just comment it out using a "#" character in the first column.

When the station is set for non-defining is the best opportunity for checking different models, applying time shifts, and applying new filtering settings. Time shifts will be discussed later. Advance users may be able to switch back and forth for groups of stations; however, it is best to perform this step one-station at a time per MT inversion iteration to avoid confusion.

What is the time shift parameter and how do I use it?

In any waveform-based inversion there is a time shift parameter that aligns the observed waveforms with the synthetics. The time shift is required due to the errors in the velocity model used to compute the synthetics and GFs. The closer the model is to the real Earth; the less shifting is required. There are rare cases where the time shift is required for event location errors and even more rare cases to account for GPS clock errors.

At long periods, synthetic surface-waves usually fit the amplitudes well given a close estimate of the MT solution, but the waveforms are usually offset by a simple phase time shift. This time shift is due to cumulative travel-time errors generated from 1D models and build up from a few tenths of a second near the source (< 100 km) to 10-30 seconds at 1000 km distance. A time shift of up to 0.5 sec is tolerated in most deviatoric MT inversion without much effect on the %DC components and total moment. However, small shifts < 1 sec can have an unwanted effect on increasing or decreasing CLVD and isotropic components in full MT inversions.

The following is the recommended strategy for dealing with time shifts. The first few iterations of the MT inversions should focus on testing for the best filter bands and weeding out the noisy or bad stations. As discussed before, only leave defining a few close in distance stations 2-3 in the inversion at the beginning. At this point the MT inversion should return a reasonable MT solution good enough to be able to align the data and synthetics based on time shifts or cross-correlation lag times. The shift times that are more than several tenths of a second are most important and any less than 0.1 sec can be neglected in most cases. Caution should be taken with shifting close in stations that are defining. Shifting data used in the inversion can result in drastic changes in the solution. If this occurs, then just turn the station back to nondefining, reset the time shift to zero and reinvert to get back to the previous or original MT solution. Ideally the shifting should only take place with nondefining stations first before including or reintroducing the data back into the inversion.

MTINV returns the cross-correlation coefficient and lag time between data and synthetics for each channel. These numbers are displayed on each waveform fit plot in the upper left of each of the 3 components. This lag time from the cross-correlation is used to shift the data and align the two waveforms. Each component has a correlation coefficient and lag time calculated but only the lag time from the component with the highest correlation wins. At this point, the value of the time shift in the plot is not used to align the data for the inversion, and only aligns the waveforms in the plot. It is up to the user to copy these values into the par file and reinvert. There is a `maxshift=10` parameter that prevents the time shifts over some threshold from being applied to prevent cycle skipping. This is usually 10 seconds. There is also, a correlation tolerance `ctol=0.85` that prevents time shifting when the correlation coefficient is not high enough.

The time shift values printed in the plots from the cross-correlation can then be entered into the par file and hopefully improves the MT solution. This best works when the station is turned off (non-defining) however it can be determined and applied while the station is on (defining) however care must be taken to ensure the that the change holds. This process is highly non-linear so applying or changing many shifts at once can lead of undesirable effects. Try to minimize the changes to one station at a time and inspect the change while the station is non-defining before turning it back on. ***MTINV*** initially starts with zero-time shifts (15th) column in file `mtinv.par` which is created in the script `run.csh` (see green in Figure 10).

If the %DC, %CLVD, %ISO require scrutiny, then spending some time with fine scale time shift adjustments will be necessary. This is your full-MT explosion, mine-collapse, or suspicious seismic event. A day-to-day dev-MT earthquake may not require the same level of effort with time-shifts and remember the overall goal is highest %DC at highest %VR.

What are weights and when should I use them?

Most geophysical inversion techniques allow for weighting data. This is most common when different data types are inverted together (e.g., geodetic, tsunami, surface-waves, and teleseismic P-waves). The different amplitudes between observed phenomena, sample lengths, and number of samples all factor into the inversion where observations with larger amplitudes and more samples will influence the solution more than other data with lower values. Weights are added by the user to change this influence and so that all the data can be weighted more evenly or allow certain more trusted observed data to have more weight than others.

In MT inversion, all station weights are set by default to 1. All stations have equal user defined artificial weights. However, the effect of Earth attenuation which naturally weights the closet distance stations with higher amplitudes and farther distance stations with lower amplitudes. This type of weight scheme is logical since the closer stations have less error to model uncertainty while the father stations will be more likely to have misfits due to farther propagation. The other condition from natural weighting is from the earthquake source radiation patterns. Rayleigh and Love waves have radiation patterns that have nulls and lobes. Near the nulls some of the 3 components may have no amplitude radiation. This natural amplitude weighting of the different components is the main driver in MT inversion solutions and artificial weighting may interfere; therefore, we do not recommend adding weights.

There are some instances where one might want to up or down weight a single station based on some additional information about a stations geological site conditions, noise quality, or instrument metadata uncertainty and quality. In most operating conditions, it is best to not artificially change from the default weights and weights are best be left for use by more advance users.

How do I plot the source-type on a Tape&Tape lune plot or Hudson plot?

The out parameters of lune latitude and longitude (Tape and Tape, 2012) or eta and k (Hudson et al., 1989) are only computed for full-MT solutions (`set DEGFREE=6`). We recommend that any event first be worked as a Dev-MT (`set DEGFREE=5`) to iterate on best filter setting, station selection, and time window lengths. This provides the best origin-time and depth for a dev-MT. GFs may also need to be added in cases where a shallow <1 depth was not included in dev-MT trial. This allows for a test to see if a full-MT will significantly improve the fit and increase in %VR. In NSS studies, the MT solutions fits in source-type space typically show that an event with a high %VR purely isotropic or opening and closing cracks do not fit well for %DC. However, there is a trade-off in cases caused by poor station coverage or model error where a range of %DC, CLVD and crack MT solutions fit equally well. For ***MTINV***, the source-type plot parameters are output in the waveform fit plots and text E-mail report files. The MTINV toolkit also provides sperate codes and GMT scripts to help with Hudson source-type plots. For the lune source-type plots, GMT already includes a projection that allows for plotting latitude and longitude:

```
gmt psbasemap \
 -R-30/+30/-90/+90 \
-JH0/3i \
-Bxf180g10a180 \
-Byf180g10a180 \
 -Bnsew -P >! lune.ps
```

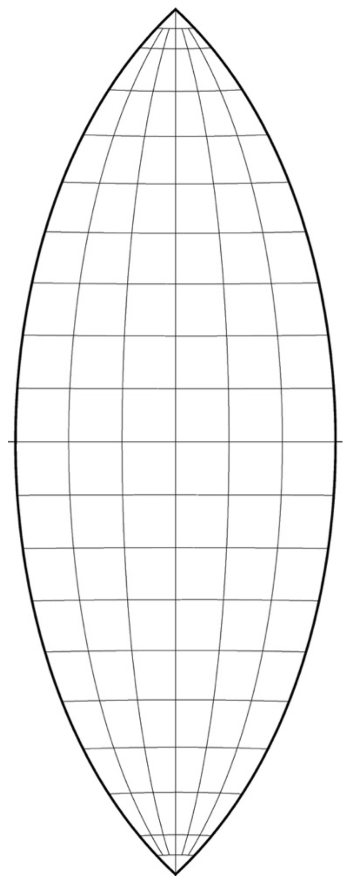


Figure 14. GMT command `psbasemap` is used to create a spherical lune projection for plotting MT solution Eigenvalues transformed to latitude and longitude (see Tape and Tape, 2012).

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Appendix 1. Sample Dataset Demonstration

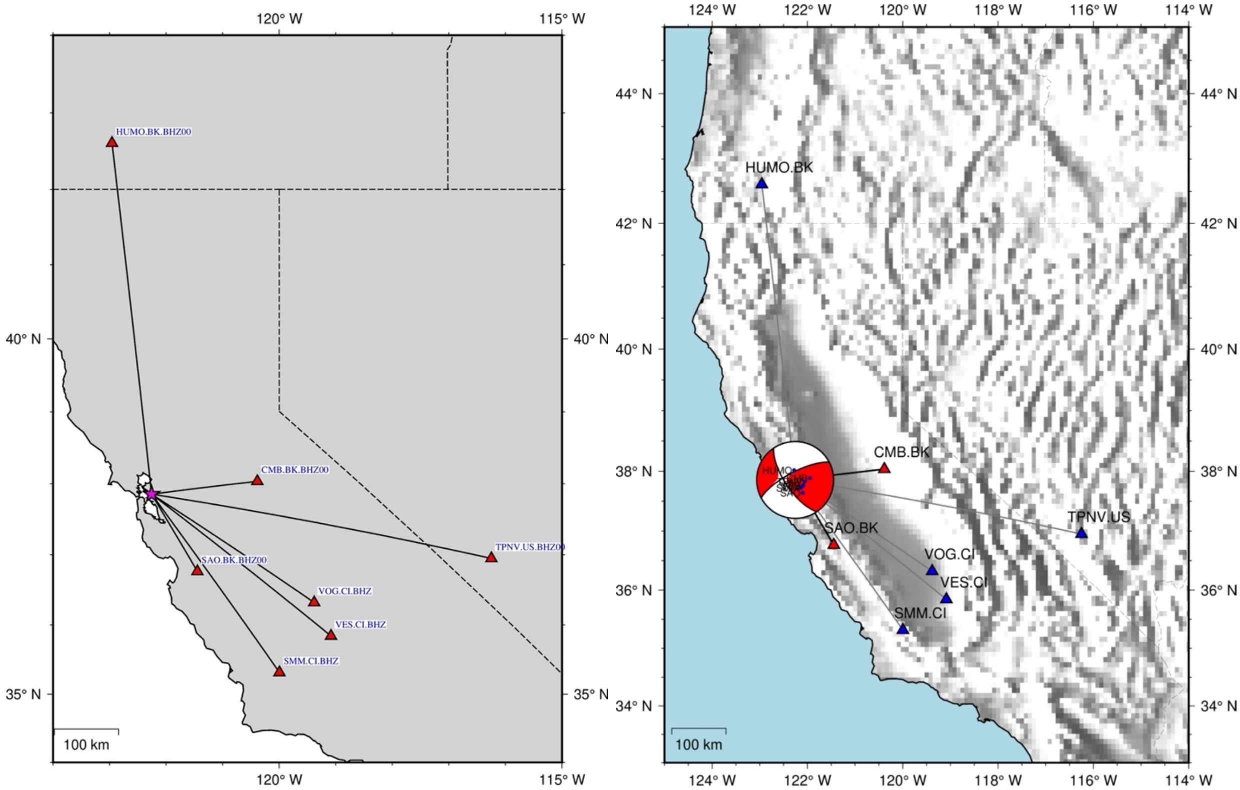

Figure A1. Station map and topography showing that the ray paths from this earthquake to the stations available (note that all the stations available at iris.edu were not included in the demostration dataset due to file size limitations). Station SAO is located along the coast ranges (metamorphosed sediments) and station CMB is located across the Great Valley sedimentary basin.

```
setupMT -z 12 \
        -ev 37.8552 -122.2568 \
        -velocity_model wus \
        -ot 2018/01/04,10:39:37.0000 \
        -com "berkeley demo Mw4.4" \
        -gmt5 \
        -realtime ../Data/*HZ.?.SAC

makeglib.csh

run.csh
```

Note: remove the local flag from makepar at the bottom of the makeglib.csh file

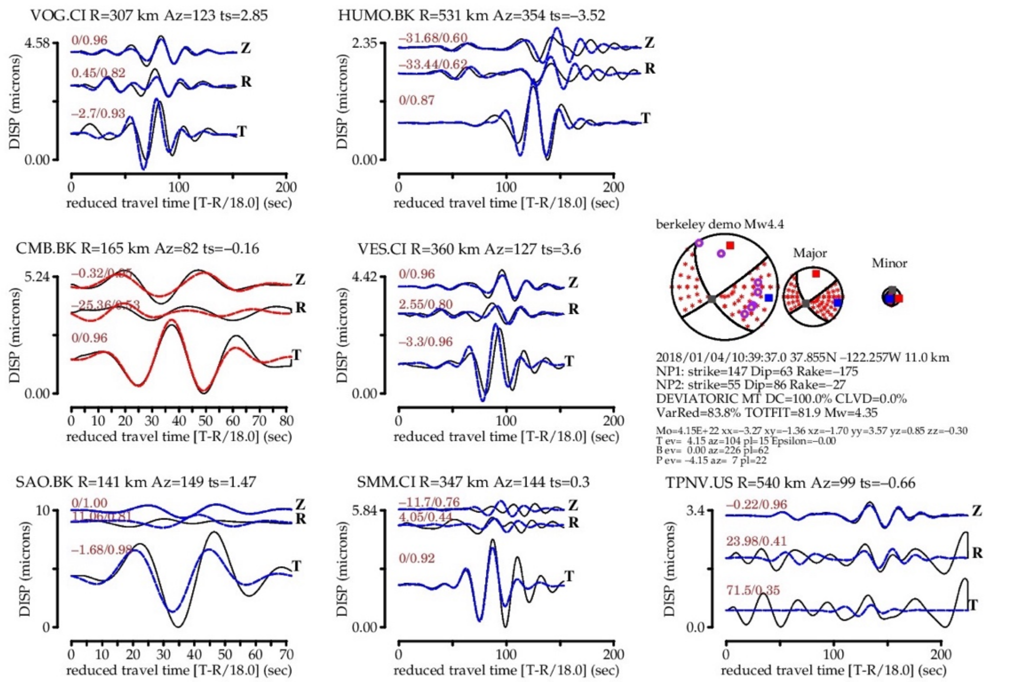

Figure A2. Only station CMB is used in the dev-MT inversion with unchanged default settings.

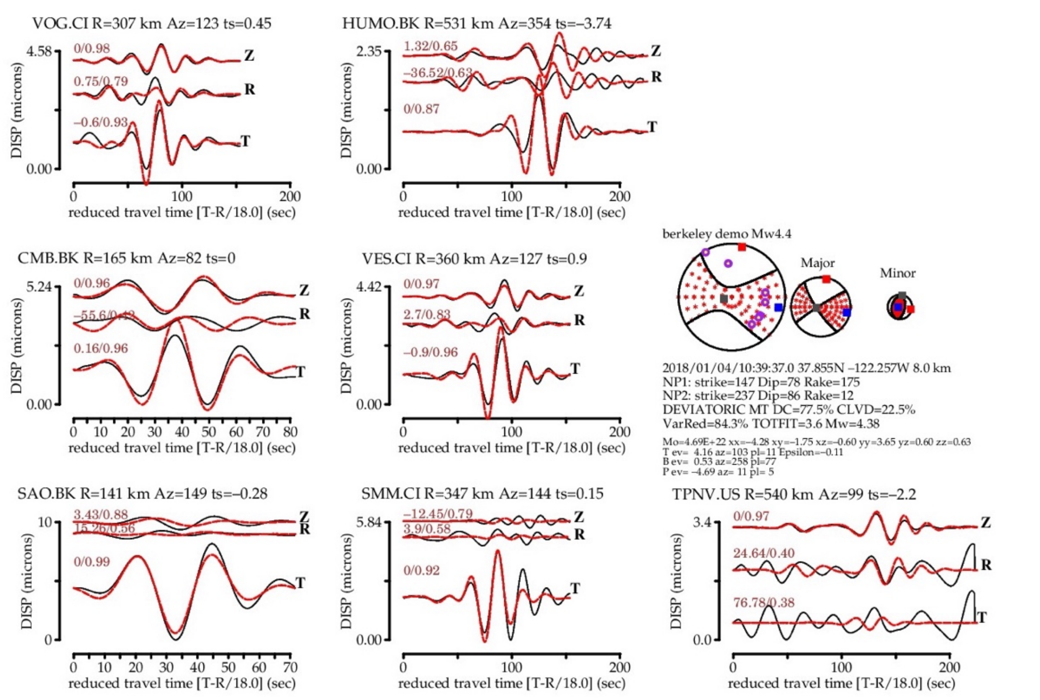

Figure A3. Same as above but now all stations are switched to defining in the dev-MT inversion. The magnitude (Mw 4.35, 4.38), depth (11, 8 km), and %DC (100, 78) are very similar for both inversions with similar %VR fit (83.8, 84.3) despite 1 station versus 7 stations. There were no changes to the default station filters or time window settings. This demonstrates the power of the ability to use just one station with the ability to make predictions.

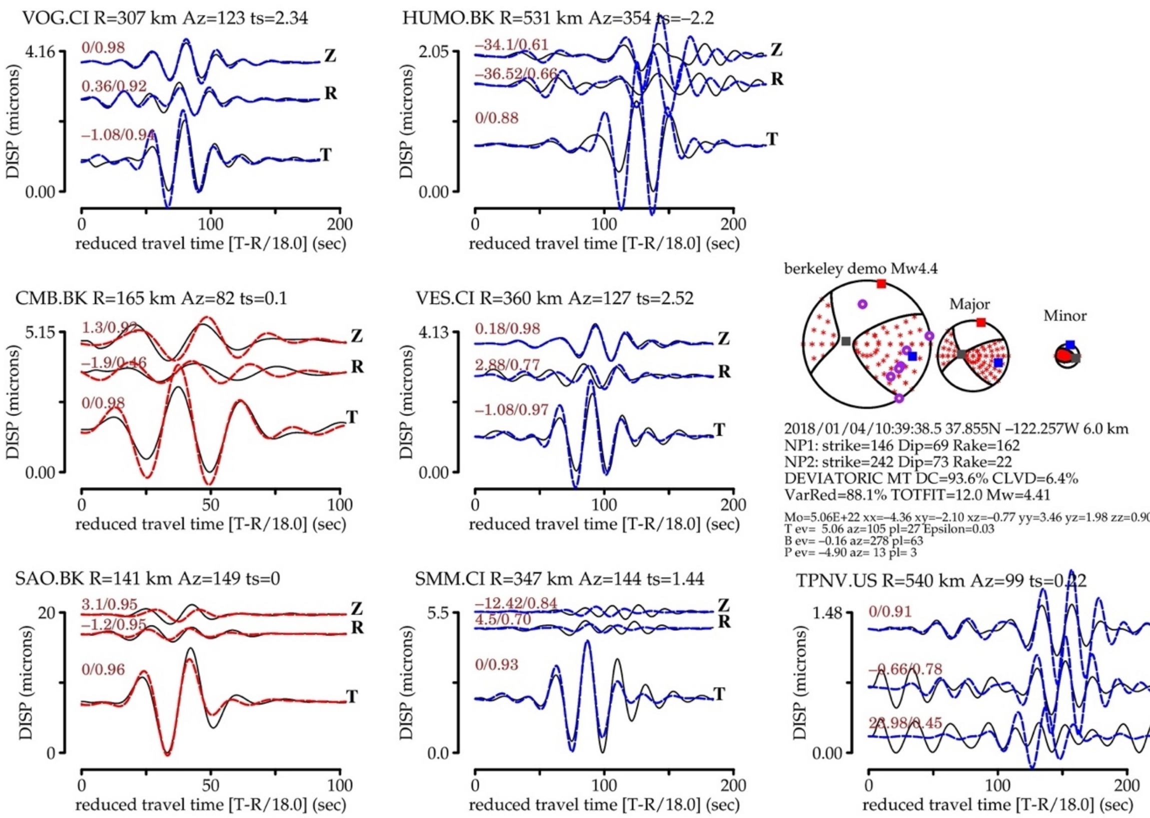

Figure A4. After a review of about 15 minutes with dozens of MT inversion iterations, the best MT solution is achieved because it has the highest fit VR=88.1% at the highest %DC=93.6. Note the origin time changes by 1.5 sec and a time shift of +1.5 sec was applied to CMB. Minor adjustments were made to the filter settings, window lengths, and only the two nearest stations (SAO and CMB) were used in the MT inversion. The solution is not very different from the previous two versions.

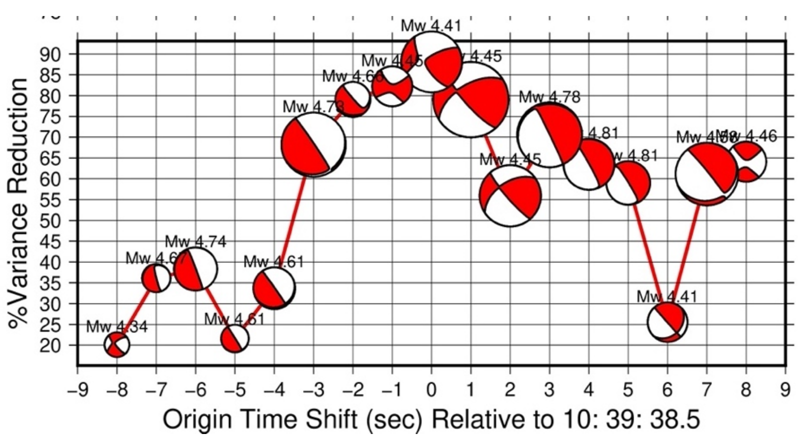

Figure A5. Origin-time versus %VR. Dev-MT focal mechanisms are scale %VR/(100-%DC).

```
#### REGION COMMENT ############################
CM berkeley demo Mw4.4
#### Date and Origin Time ######################
OT 2018/01/04,10:39:37.00
#### Forward Calculations ######################
##    stk    dip    rak   Mw  evlo  evla   Z ##########
EV -999.0 -999.0 -999.0  0.0    -122.257    37.8552  15.0
########################################################################################################
# sta net model  np pas lf  hf  nt  dt   tr  tt v/d  mulfac used(Y/N)  ts0  weight ###             #
SAO     BK      wus 3 2 0.020 0.050  1024  0.07 0.0 0.0 d  1.0 n  +0.00 +1.0 Surf/Pnl ### R=140.8 Az=149
CMB     BK      wus 3 2 0.020 0.050  1024  0.08 0.0 0.0 d  1.0 y  +0.00 +1.0 Surf/Pnl ### R=165.1 Az=82
VOG     CI      wus 3 2 0.020 0.050  1024  0.15 0.0 0.0 d  1.0 n  +0.00 +1.0 Surf/Pnl ### R=306.5 Az=123
SMM     CI      wus 3 2 0.020 0.050  1024  0.15 0.0 0.0 d  1.0 n  +0.00 +1.0 Surf/Pnl ### R=347.0 Az=144
VES     CI      wus 3 2 0.020 0.050  1024  0.15 0.0 0.0 d  1.0 n  +0.00 +1.0 Surf/Pnl ### R=360.0 Az=127
HUMO    BK      wus 3 2 0.020 0.050  1024  0.22 0.0 0.0 d  1.0 n  +0.00 +1.0 Surf/Pnl ### R=531.3 Az=354
TPNV    US      wus 3 2 0.020 0.050  1024  0.22 0.0 0.0 d  1.0 n  +0.00 +1.0 Surf/Pnl ### R=539.6 Az=99
```

Figure A6. Initial `mtinv.par` file with the used flag changed from 'y' to 'n' for all stations except CMB (see dev-MT inversion result in Figure A2).

```
#### REGION COMMENT ############################
CM berkeley demo Mw4.4
#### Date and Origin Time ######################
OT 2018/01/04,10:39:38.50
#### Forward Calculations ######################
##    stk    dip    rak   Mw  evlo  evla   Z ##########
EV -999.0 -999.0 -999.0  0.0    -122.257    37.8552  15.0
########################################################################################################
# sta net model  np pas lf  hf  nt  dt   tr  tt v/d  mulfac used(Y/N)  ts0  weight ###             #
SAO     BK      wus 3 2 0.025 0.070  1024  0.10 0.0 0.0 d  1.0 y  -0.00 +1.0 Surf/Pnl ### R=140.8 Az=149
CMB     BK      wus 3 2 0.025 0.050  1024  0.10 0.0 0.0 d  1.0 y  +1.50 +1.0 Surf/Pnl ### R=165.1 Az=82
VOG     CI      wus 3 2 0.025 0.050  1024  0.18 0.0 0.0 d  1.0 n  +0.00 +1.0 Surf/Pnl ### R=306.5 Az=123
SMM     CI      wus 3 2 0.025 0.050  1024  0.18 0.0 0.0 d  1.0 n  -0.00 +1.0 Surf/Pnl ### R=347.0 Az=144
VES     CI      wus 3 2 0.025 0.050  1024  0.18 0.0 0.0 d  1.0 n  +0.00 +1.0 Surf/Pnl ### R=360.0 Az=127
HUMO    BK      wus 3 2 0.025 0.050  1024  0.22 0.0 0.0 d  1.0 n  +0.00 +1.0 Surf/Pnl ### R=531.3 Az=354
TPNV    US      wus 3 2 0.033 0.055  1024  0.22 0.0 0.0 d  1.0 n  +0.00 +1.0 Surf/Pnl ### R=539.6 Az=99
```

Figure A7. Final `mtinv.par` file for best solution shown in Figure A4 and A5.

```
float LOWEST_VELOCITY = 2.35;
for( ista=0; ista<nsta; ista++ )
{
       ix = index[ista+1]-1;
       select_dt_and_nt(   grn[ix][0].rdist,
                           LOWEST_VELOCITY,
                           grn[ix][0].nt,
                           grn[ix][0].dt,
                           &my_dt,
                           &my_nt,
                           local_setup );
}

void select_dt_and_nt(
              float dist,
              float vel,
              int grn_npts,
              float grn_dt,
              float *dat_dt,
              int *dat_nt,
              int local_setup )
{
        float dt, slow_time;
        int nt;
        float roundoff( float, float );
        slow_time = dist/vel;
        nt = 1024;
        dt = 0.45;
        if( dist < 2000 )
        {
                nt = 1024;
                dt = slow_time/nt;
                dt = roundoff( dt, 100 );
        }
        if( dist < 100 )
        {
                nt = 1024;
                dt = slow_time/nt;
                dt = roundoff( dt, 100 );
        }
        if( dist <= 50 )
        {
                nt = 1024;
                dt = grn_dt + 0.02;
                dt = roundoff( dt, 100 );
        }
        if(local_setup)
        {
                if( dist < 250 ) dt = 0.1;
                if( dist < 180 ) dt = 0.08;
                if( dist < 160 ) dt = 0.07;
                if( dist < 130 ) dt = 0.06;
                if( dist < 100 ) dt = 0.05;
                if( dist <  35 ) dt = 0.05;
        }
        *dat_dt = dt;
        *dat_nt = nt;
}
```

Appendix B. Snippet of source code in makepar.c that computes the nt and dt for mtinv.