IDENTIFYING ISOTROPIC EVENTS USING AN IMPROVED REGIONAL MOMENT TENSOR INVERSION TECHNIQUE

Sean R. Ford¹, Douglas S. Dreger¹, and William R. Walter²

University of California, Berkeley¹ and Lawrence Livermore National Laboratory²

Sponsored by National Nuclear Security Administration
Office of Nonproliferation Research and Development
Office of Defense Nuclear Nonproliferation

Contract No. DE-SC52-05NA26703¹ ²

ABSTRACT

Seismic moment tensor analysis at local, regional and teleseismic distances has become routine practice. Commonly it involves solving for the deviatoric moment tensor, which is suitable for tectonic earthquakes, and characterizing complexity that might be present due to complex fault geometry or fluid processes in volcanic environments. The general seismic moment tensor also allows for recovery of an isotropic component, which is important in nuclear explosion sources, but which has also been shown to be difficult to resolve.

We have recently corrected a regional distance full moment tensor inversion scheme that greatly increases the stability of moment tensor inversions, and has allowed recovery of isotropic components in volcanic events and nuclear explosions that can be shown to be statistically significant with a high level of confidence. These results suggest that the regional distance moment tensor approach may possibly be used for the discrimination of nuclear explosions from earthquakes. Volcanic events and other seismic sources such as mine collapses also produce anomalous radiation patterns and introduce complexity in distinguishing nuclear explosions from such events. Nevertheless, a complete seismic moment tensor method will provide the capability of distinguishing events based on deviation from the expected double-couple for earthquakes and can identify anomalous events for further scrutiny.

We will investigate performance of the improved moment tensor analysis in the presence of noise and using imperfect velocity structure and Green’s functions using both synthetic (controlled experiment) and real data for tectonic and volcanic earthquakes, mine collapses, and nuclear explosions. For nuclear explosions we will test the method for a range of tectonic release strengths, from small up to well known cases where tectonic release seems to dominate and the Rayleigh waves have reversed polarity. We seek to understand the performance of the method under a range of recording conditions from excellent azimuthal coverage to cases of very sparse coverage of one to two stations as might be expected for smaller events of interest. This analysis will be used to determine the magnitude range where reasonably well-constrained solutions can be obtained.
OBJECTIVES

This research seeks to apply a regional distance complete moment tensor approach to tectonic, volcanic and man-made seismic events in order to document performance in the ability to identify and characterize anomalous (non-double-couple) seismic radiation. Identification of events with demonstrably significant non-double-couple components can aid in nuclear event screening and possibly discrimination. The ability of the methodology to characterize the relative amounts of deviatoric and isotropic source components, the similarity of those components with prior events in the source region, and the ability to constrain the source depth all provide utility in investigating events that may appear anomalous using more traditional discrimination techniques.

Large mining collapses, explosions, and volcanic events produce unusual radiation characteristics and seismic moment tensor solutions (see review by Julian et al., 1998). We will apply the regional moment tensor method to a wide range of events in order to characterize the range of moment tensor solutions for different event type and environment. The event populations to be studied include underground nuclear tests, mine collapses, and earthquakes in both the western United States (Walter et al., 2003), and Eurasia, including the 1998 Indian nuclear tests. We will learn what can and cannot be resolved by moment tensor analysis, and what can be found that could help distinguish such mining and natural events from nuclear tests.

Though the full time-domain waveform inversion for the complete moment tensor is a linear operation, there are several choices of parameterization with a nonlinear effect on the solution. For example, the velocity model employed to construct the Green’s function is a large source of solution variability and a several models may produce a well-fit solution (Sileny et al., 1992). Our research will emphasize solution significance, resolution, and error analysis through a series of synthetic and observed sensitivity tests. We will probe the solution space and document the point at which it is no longer possible to recover reliable information.

RESEARCH ACCOMPLISHED

We have implemented the time-domain full regional waveform inversion for the complete moment tensor devised by Minson and Dreger (2006) after Herrman and Hutchensen (1993) based on the work of Langston (1981). In general, synthetic seismograms are represented as the linear combination of fundamental Green’s functions where the weights on these Green’s functions are the individual moment tensor elements. Synthetic displacement seismograms are calculated with a frequency-wavenumber integration method (Saikia, 1994) for a one-dimensional (1-D) velocity model (Table 1) of eastern California and western Nevada (Song et al., 1996). The synthetic data is filtered with a 4-pole acausal Butterworth filter between 0.02 and 0.05 Hz. At these frequencies, where the dominant wavelengths are approximately 100 km, we assume a point source for the low-magnitude \( M_W \leq 5.6 \) regional events investigated in this study. Data are collected from the TERRAscope network stations, ISA, PAS, and PFO (Figure 1). We remove the instrument response, rotate to the great-circle frame, integrate to obtain displacement, and filter similarly to the synthetic seismograms.

Table 1. 1-D velocity model (Song et al., 1996)

<table>
<thead>
<tr>
<th>Thick (km)</th>
<th>( V_\alpha ) (km/s)</th>
<th>( V_\beta ) (km/s)</th>
<th>( \rho ) (g/cc)</th>
<th>( Q_\alpha )</th>
<th>( Q_\beta )</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>3.6</td>
<td>2.05</td>
<td>2.2</td>
<td>100.0</td>
<td>40.0</td>
</tr>
<tr>
<td>32.5</td>
<td>6.1</td>
<td>3.57</td>
<td>2.8</td>
<td>286.0</td>
<td>172.0</td>
</tr>
<tr>
<td>( \infty )</td>
<td>7.85</td>
<td>4.53</td>
<td>3.3</td>
<td>600.0</td>
<td>300.0</td>
</tr>
</tbody>
</table>

We calibrate the algorithm by calculating the full and deviatoric moment tensor for the 1992 Little Skull Mountain event (Figure 1). The deviatoric solution is...
obtained by constraining the trace of the moment tensor to be zero. Our result fits the data very well where goodness 
of fit is measured with percent variance reduction

\[ VR = \left(1 - \frac{(d - s)^2}{d^2}\right) \times 100, \]

where \( d \) is the data and \( s \) is the synthetic sample, and the solution is summed over all samples for each station and 
component. The solution has a \( VR \) of 92.5% and is highly similar to the double-couple solution of Walter (1993), the 
deviatoric solution of Ichinose et al. (2003), and the full solution of Dreger and Woods (2002), where we assume a 
source depth of 9 km. The deviatoric component of the full moment tensor is decomposed to a double-couple and 
compensated linear vector dipole (CLVD) that share the orientation of the major axis. The 1992 Little Skull 
Mountain event is almost purely double-couple and there is little change between the full and deviatoric solutions 
(Figure 2). The best-fit double-couple mechanism produces source parameters of strike 35° and 196°, rake -78° and

Figure 2. Moment tensor analysis of 1992 Little Skull Mountain earthquake. Data (solid line) and synthetics 
(dashed blue line) produced by inversion in the 20-50 s passband and resulting full and deviatoric 
(zero trace) focal spheres with best-fit double-couple planes (black lines), where the size of the 
deviatoric sphere is relative to the total scalar moment contribution.

Figure 3. Moment tensor analysis of 1991 NTS test, BEXAR. See Figure 2 caption for figure details.
-104°, and dip 50° and 42°, for the two focal planes, respectively. The total scalar moment \( M_0 \) is \( 2.92 \times 10^{24} \) dyne-cm, which results in an \( M_W \) of 5.58.

With the same algorithm we calculate the full moment tensor for the 1991 Nevada nuclear test site explosion, BEXAR \( (m_b=5.6 \) and \( M_S=4.2, \) NEIC; Figure 1). The solution has a \( VR \) of 80.5% and is similar to the full solution of Minson and Dreger (2006), where we assume a source depth of 1 km. The moment tensor has a large isotropic component, and the ratio of deviatoric moment \( (M_{DEV}) \) to isotropic moment \( (M_{ISO}) \) is 0.65 (Figure 3), where the \( M_0 \) is \( 4.79 \times 10^{22} \) dyne-cm \( (M_W \) of 4.39). \( M_{ISO} \) and \( M_{DEV} \) are defined according to Bowers and Hudson (1999) and \( M_0 = M_{ISO} + M_{DEV} \).

It is difficult to grasp the source-type from the standard focal mechanism plot. Following the source-type analysis described in Hudson et al. (1989) we calculate \( 2\varepsilon \) and \( k \), which are given by

\[
\varepsilon = \frac{-m_1}{m_3}, \tag{2}
\]

and

\[
k = \frac{M_{ISO}}{|M_{ISO}| + |m_3|}. \tag{3}
\]
where $m_1$ and $m_3$ are the deviatoric principal moments which are ordered $|m_1| \leq |m_2| \leq |m_3|$. $\varepsilon$ is a measurement of the departure of the deviatoric component from a pure double-couple mechanism, and is 0 for a pure double-couple and $\pm 0.5$ for a pure CLVD. $k$ is a measure of the volume change, where +1 would be a full explosion and -1 a full implosion. $\varepsilon$ and $k$ for the Little Skull Mountain earthquake and NTS explosion, BEXAR are given in Figure 4. Error in the values is derived from the standard error in the moment tensor elements given by the estimated covariance matrix obtained in the weighted least-squares inversion. Figure 4 shows that the Little Skull Mountain earthquake is within the error of being a perfect double-couple event ($2\varepsilon = 0$) with no volume change ($k = 0$). The BEXAR test, on the other hand, has a large volume increase with a large variance in the deviatoric source.

Error in the principal axes is analyzed by plotting the best-fit and scatter density of the axes of minimum compression ($T$), maximum compression ($P$) and null ($N$). The scatter density plot is obtained by randomly selecting moment tensor elements assuming a normal distribution for each element described by the standard error (given by the estimated covariance matrix), and diagonalizing the resulting moment tensor to obtain the principal axes. Principal axes plots for the Little Skull Mountain earthquake and NTS explosion, BEXAR are given in Figure 5. The axes for the Little Skull Mountain event are well constrained, while those for the BEXAR test are more variable. However, the BEXAR test axes do not deviate greatly from the axes of for the Little Skull Mountain event, and could both be the result of a similar tectonic stresses.

In an effort to better characterize the source significance we adopt the source convention described in Riedesel and Jordan (1989). Vectors are defined describing the general,

$$MT = \sum_{i=1}^{3} M_i M_i$$

(4)

double-couple,

$$DC = M_1 - M_3$$

(5)

isotropic,

Figure 6. Source vector plot with density plot of general source vector, MT, for the BEXAR test (left) and Little Skull Mountain earthquake (right). See text for definition of vectors. The great-circle line connecting the CLVD1, DC, and CLVD2 vectors defines the purely deviatoric solution space.
ISO = $\sum_{i=1}^{3} M_i$ \hfill (6)

and CLVD sources,

$$CLVD1 = M_1 - \frac{M_2}{2} - \frac{M_3}{2}; \quad CLVD2 = \frac{M_1}{2} + \frac{M_2}{2} - M_3$$ \hfill (7)

where $M_1$, $M_2$, and $M_3$ are the T, N, and P axes, respectively, and $M_1$, $M_2$, and $M_3$ are the principal moments. The source vectors are subspaces of the space defined by the principle axes of the moment tensor. The vectors are plotted on the focal sphere (similar to the T, N, and P axes) for the Little Skull Mountain earthquake and NTS explosion, BEXAR in Figure 6. The general source vector, MT, for the Little Skull Mountain event lies on the great-circle connecting the double-couple and CLVD sources. This great-circle defines the subspace on which MT must lie if the source is purely deviatoric. The MT vector is also collinear with the DC vector, which is to say that the source is almost purely double-couple. The MT vector for the BEXAR test lies well off the line defining the deviatoric solution space. The scatter density of possible MT vectors is also plotted and none of them intersect the deviatoric solution space, which is to say that the solution has a significant isotropic component. Density contours of the distribution will allow for percent confidence statements.

CONCLUSIONS AND RECOMMENDATIONS

The 1992 Little Skull Mountain event is a well-constrained, highly double-couple earthquake with an $M_w$ of 5.6. The 1991 NTS nuclear test, BEXAR ($m_b=5.6$ and $M_S=4.2$, NEIC), has a significant positive isotropic component with an $M_w$ of 4.4. The deviatoric components of both events may be responding to the same general Basin and Range stress field of NW-SE extension. Analysis of $\epsilon$ versus $k$ and the source vectors described above allows for an interpretation of the source with error. There are several sources of error in the moment tensor inversion, and the probabilistic method used in this study has the ability to incorporate those sources and produce empirical probability densities of the analyzed parameters (i.e., $\epsilon$, $k$, and the source vectors). For example, several velocity models could be used to create the Green’s functions for the linear inversion. Each of the moment tensor solutions and their associated scatter density could then be plotted as in Figures 4-6. These types of plots would aid in the understanding of how parameterization choice nonlinearly affects the moment tensor solutions, and help map the solution space of ‘best-fit’ moment tensors.

The analysis presented here shows that high quality solutions can be obtained for sparsely-recorded events at regional distances, and that these solutions have the potential to discriminate between volume changing (explosions) and double-couple (earthquakes) sources. In the future, we will test the sensitivity of the inversion to noise and non-ideal station spacing. We will also increase the population of moment tensors for man-made and natural events that deviate from the well recorded, large magnitude, small tectonic release cases presented here. Only an analysis of a wide range of events in different environments will allow for a true comparison of explosion and earthquake moment tensor populations.

ACKNOWLEDGEMENTS

Figures were made with Generic Mapping Tools (Wessell and Smith, 1998).

REFERENCES


