 Effects of three-dimensional Earth structure on CMT source parameters
Vala Hjörleifsdóttir, Göran Ekström
Lamont-Doherty Earth Observatory, Columbia University
Email: vala@ldeo.columbia.edu

1 Abstract
We investigate errors in centroid source parameters due to unmodeled structural heterogeneity. We generate a simulated data set, consisting of synthetic seismograms, for 50 events and 150 stations distributed globally. To generate the synthetic seismograms we use a spectral-element wave-propagation package (SPECFEM3D_GLOBE), that accounts for the Earth’s three-dimensional structure. An established centroid-moment-tensor inversion algorithm (from the Global CMT project) is used to invert the synthetic data set, with and without added noise, for earthquake source parameters. This algorithm uses a one-dimensional Earth structure, together with approximate corrections for three-dimensional structure, to model the seismograms. We interpret differences between the estimated source parameters and the parameters used to compute the synthetic data set as errors due to unmodeled structural heterogeneity and the presence of noise. We expect that the errors obtained in this study are representative of the errors in the Global CMT catalogue.

2 Strategy
1. Compute synthetic seismograms using the wave-propagation software SPECFEM3D_GLOBE (see below) for the events shown in Figure 1.
2. Scale synthetics to a given magnitude and add noise recorded by the global network at the time when the event occurred (this step can be omitted).
3. Invert the synthetic data set, using the centroid-moment-tensor inversion algorithm from the Global CMT project (see below), for centroid-source parameters.
4. The location X, depth, strike, dip, and moment magnitude of the event.
5. For three events occurring in areas where the crust is different than the average global crust, (oceanas, plateaus, and subduction zones) repeat inversions using different subsets of data, added corrections for 3D structure in inversion and fixing the depth (Section 4).
6. To investigate the cause of bias in centroid depth and time estimates invert the whole data set using different subsets of data and added corrections for 3D structure on the waveforms (Section 5).

3 Tools
SPECFEM3D_GLOBE Wave-propagation solver (Komatitsch and Tromp, 2002a,b) accounts for the Earth’s 3D structure, anisotropy, attenuation, ellipticity, geology, topography and oceans. We use 3D isotropic mantle model S362ANI (Klusowski et al., 2006) or 3D anisotropic mantle model S20RTS (Rowe et al., 1999), combined with crustal model Crust 2.0 (Bosan et al., 2000) for the simulations.

Global CMT Centroid-moment-tensor inversion algorithm used in the Global CMT project, to estimate centroid-source parameters. This algorithm inverts for 5 independent elements of the moment tensor, centroid location, time, three free windows with different pass bands are used for the inversion. The three time windows contain long-period body waves, intermediate period surface waves and long period mantle waves respectively. The body waves, surface waves over long distances and mantle waves are modeled using normal mode summation for 12 Earth models (PEER), with perturbations to the eigenfunctions based on mantle model SHS14/L14 (Glassmeier and Woodward, 1992). The dispersion of the fundamental mode of surface waves compared to the 12 Earth models with velocity maps. Inverts for 5 independent elements of moment tensor, centroid location and time.

4 Errors in source parameters for noise free and noisy data
Location: Average error 10 km, largest error 30 km for noisy data
Scalar Moment: Standard deviation of the errors is 10%. Largest error 62% for an event in China.
Momentum tensor orientation: Average error around 5°. Largest error is 16° for a ridge event.
Non-double-couple component: Standard deviation of the errors is 0.04. Largest error is 0.15 for an event in southern Iran.
Depth: Average error 5 km for S20RTS synthetics and 8 km for S362ANI synthetics with noise added. Largest error is 21 km for a deep event. Undersea.
Centroid time: Average error is 1.6 seconds for S20RTS and 2.2 seconds for S362ANI with noise added. Largest error is 9.3 sec for an event in China.

5 Errors in source parameters for events in areas where the crust is different from the one-dimensional reference structure.

Oceans: The shallow dip and shallow depth are not recovered in any of the solutions. The orientation is overestimated by 15° when using all three wave types in the inversion. The errors in moment in depth and smaller for surface waves excited using an oceanic-type elastic model.
Plates: The depth and scalar moment are not well recovered by body waves and surface waves only. However, they are well recovered when using mantle waves only. Fixing the depth introduced a large error in the non-double-couple component when inverting all three wave types together.
Subduction zone: The errors in scalar moment and dip angle in solutions based on body waves and mantle waves only are small, however, they are larger in solutions based on surface waves only. The error in scalar moment is 20% and dip is 5° in the solution based on all three wave types.

6 Bias in depth and centroid time
The estimated depth is on average too large and the estimated centroid time is on average too late (Fig. 4). Tests (not shown here) reveal that the errors in depth and centroid time are not correlated. The bias in depth can be reduced when by accounting for the effect of the local structure at the source and the receiver on the fundamental mode surface waves. The bias in centroid time is different between the different wave types. We interpret this difference as a difference in the average velocity structure between S362ANI and the combinations of models used by the Global CMT algorithm (SHS14/L14, PEER) and velocity maps based on surface wave phase measurements.

7 Conclusions
• Errors in scalar moment, momentum tensor elements and location are small on average.
• Depth and centroid location are small on average.
• Error in depth can be reduced significantly by correcting for structure along source and receiver.
• Errors in depth and centroid time are uncorrelated.
• Errors in scalar moment and depth are larger than average where the crust is different from the global average.
• We do not find large errors in scalar moments (factor of ten), even where the crustic thickness varies from the Earth’s average crustal thickness.

References

Table 1: Average errors and standard deviations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>S362ANI M 6.0</th>
<th>S362ANI M 7.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lat [deg]</td>
<td>±0.05</td>
<td>±0.10</td>
</tr>
<tr>
<td>Lon [deg]</td>
<td>±0.15</td>
<td>±0.20</td>
</tr>
<tr>
<td>D [km]</td>
<td>±5.0</td>
<td>±8.0</td>
</tr>
<tr>
<td>t [sec]</td>
<td>±2.0</td>
<td>±3.2</td>
</tr>
<tr>
<td>θ [deg]</td>
<td>±4.0</td>
<td>±6.0</td>
</tr>
<tr>
<td>δ [deg]</td>
<td>±6.0</td>
<td>±9.0</td>
</tr>
</tbody>
</table>

Table 2: Errors in depth, centroid time and z, M for different inversion parameters

<table>
<thead>
<tr>
<th>Inversion</th>
<th>Depth [km]</th>
<th>Centroid time [sec]</th>
<th>z [km]</th>
<th>M</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>9.4±3.1</td>
<td>1.0±2.1</td>
<td>1.9</td>
<td>4.0±1.0</td>
</tr>
<tr>
<td>S</td>
<td>9.3±4.1</td>
<td>2.0±3.1</td>
<td>0.9</td>
<td>5.0±1.0</td>
</tr>
<tr>
<td>S</td>
<td>9.2±5.1</td>
<td>2.0±4.1</td>
<td>0.9</td>
<td>6.0±1.0</td>
</tr>
<tr>
<td>S</td>
<td>9.1±6.1</td>
<td>2.0±5.1</td>
<td>0.9</td>
<td>7.0±1.0</td>
</tr>
<tr>
<td>S</td>
<td>9.0±7.1</td>
<td>2.0±6.1</td>
<td>0.9</td>
<td>8.0±1.0</td>
</tr>
</tbody>
</table>

Figure 1: Location and local mechanisms of events used in this study. They are a subset of events with magnitude 6.5-6.5 in the Global CMT catalogue, recorded in 2009-2011. The colors represent the depth of the earthquakes: red (25-50 km), green (50-300 km) and blue (200-700 km).

Figure 2: FIGURE Errors in location on the left and on the right, for synthetics computed for earth model S20RTS without noise (top) S362ANI without noise (middle) and where the event has been scaled to a magnitude 9.5 event.

Figure 3: Errors in angle between the true and estimated moment tensors on the left and the error in the non-double-couple component of the moment tensor on the right.

Figure 4: FIGURE 4 Errors in depth on the left and centroid time on the right.

Figure 5: FIGURE 5 Source parameters for an earthquake on the Antarctic Ridge. The true parameters are shown in the upper left tile. The other tiles show the local mechanisms and errors in parameters estimated using different data sets and inversion parameters.

Figure 6: FIGURE 6 Estimated versus true depth and centroid time for all events, for the data set computed with model S362ANI without noise added, using the combined data sets of body, mantle and surface waves (BMS), surface waves only (S) and surface waves only while using a local structure at the source and a continental-type velocity structure at the receiver (S).