Improving the Resolution of the Isotropic Seismic Moment Tensor using Rotational Ground Motions

S. Donner¹, P. Gaebler¹, M. Mustać², B. Hejrani³, H. Tkalčić³, H. Igel⁴

¹ Federal Institute for Geosciences and Natural Resources (BGR), Hannover, Germany
² Faculty of Science, University of Zagreb, Zagreb, Croatia
³ Research School of Earth Sciences, The Australian National University, Canberra, Australia
⁴ Department of Earth Sciences, LMU München, Germany

P2.1-162
Seismic moment tensors are a great tool to discriminate whether a seismic source has explosive character or not.

\[
\begin{pmatrix}
-0.40 & -0.54 & 0.53 \\
-0.54 & -0.30 & -0.24 \\
0.53 & -0.24 & 0.70 \\
\end{pmatrix}
\]

versus

\[
\begin{pmatrix}
0 & 1 & 0 \\
1 & 0 & 0 \\
0 & 0 & 0 \\
\end{pmatrix}
\]
Seismic moment tensors provide information not only about the geometry of a seismic source (tectonic – DC – part) but also with non-tectonic information such as volume changes (isotropic – ISO – part). This feature is crucial to discriminate an explosive source from others, which can hint to a nuclear test. However, that part is often not very well resolved by standard methods. Measuring rotational ground motions might help to obtain more reliable results.

Six components of ground motion are needed to entirely describe the seismic wave-field, three translational and three rotational. Just recently, portable rotation sensors dedicated for seismological applications are available. In previous studies, we show that by inverting both ground motions together, the resolution of the moment tensor can be improved significantly.

In a synthetic set-up for the Korean peninsula we analysed the 2013 Mw5.8 nuclear test of the Democratic People’s Republic of Korea. Applying a Bayesian inversion method, we tested three frequency bands. We also tested the inversion with Green’s functions based on one- and three-dimensional structural models. The reliability of the source mechanism benefits form both, the three-dimensional structure and rotations, even more in the higher frequency ranges. Thus, also the reliability of the ISO part is increased.
Rotational ground motion $\vec{\omega}$ is composed by space derivatives of translational ground motion $\vec{u}$.

Rotations provide additional information on the vertical displacement gradient.

These information are not available from conventional arrays on the Earth’s surface.

Since recently portable instruments developed for seismology are available. They measure rotations in a broad frequency range with high sensitivity.

Schmelzbach et al. 2018
Bernauer et al. 2021
Izgi et al. 2021
Setting at Korean peninsula:
- Green’s functions calculated with Ses3D (Fichtner et al. 2009)
- 1- and 3-dimensional velocity models (Kim et al. 2011, 2016)

Mw 5.8 DPRK nuclear test of 2013
DC / ISO / CLVD = 21 / 60 / 19 %
\[
\begin{pmatrix}
1.67 & 0.40 & -0.15 \\
1.84 & 0.68 & 3.95 \\
\end{pmatrix}
\]

Mw 5.4 Gyeongju, ROK, earthquake of 2016
DC / ISO / CLVD = 88 / 0 / -12 %
\[
\begin{pmatrix}
3.58 & 3.21 & 1.67 \\
-4.11 & 0.60 & 0.53 \\
\end{pmatrix}
\]
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- time-domain waveform inversion
- synthetic waveform data
- Bayesian approach:

\[
\sigma(m) = k \rho(m) L(m)
\]

Likelihood function

\[
L(m) = k' \exp\left[ - \sum_l \left( \frac{\chi_l(m)}{s_l} \right) \right]
\]

Shannon's measure of information gain:

\[
I(\rho; \sigma) = \int \rho(x) \log \left[ \frac{\rho(x)}{\sigma(x)} \right] dx \quad \text{(unit: bit)}
\]

Bernauer et al. 2014
Donner et al. 2016
Donner 2021 (in print)
Synthetic waveform inversion of Gyeongju seismic event; inverted frequencies: 0.02 – 0.05 Hz (20 – 50 sec)

No big difference in accuracy but significant improvement in precision due to including rotations.

Disclaimer: The views expressed on this poster are those of the author and do not necessarily reflect the view of the CTBTO.
Synthetic waveform inversion of Gyeongju seismic event; inverted frequencies: 0.02 – 0.16 Hz (6 – 50 sec)

No reliable resolution based on 1D Green's functions.

Rotations increase precision.
Synthetics of Gyeongju seismic event

Rotations alone bring great benefit which can be even increased combined with 3D structure.

0.02 – 0.05 Hz (20 – 50 sec)

<table>
<thead>
<tr>
<th></th>
<th>Total Information Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>trans</td>
<td>3C 1D : 9.3 bit</td>
</tr>
<tr>
<td>trans</td>
<td>3C 3D : 14.1 bit</td>
</tr>
<tr>
<td>trans + rot</td>
<td>6C 1D : 12.9 bit</td>
</tr>
<tr>
<td></td>
<td>6C 3D : 15.8 bit</td>
</tr>
<tr>
<td>+ 40 %</td>
<td>+ 70 %</td>
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</table>

0.02 – 0.16 Hz (6 – 50 sec)

<table>
<thead>
<tr>
<th></th>
<th>Total Information Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>trans</td>
<td>3C 1D : 4.6 bit</td>
</tr>
<tr>
<td>trans</td>
<td>3C 3D : 12.1 bit</td>
</tr>
<tr>
<td>trans + rot</td>
<td>6C 1D : 7.1 bit</td>
</tr>
<tr>
<td></td>
<td>6C 3D : 14.8 bit</td>
</tr>
<tr>
<td>+ 55 %</td>
<td>+ 225 %</td>
</tr>
</tbody>
</table>

Donner et al. 2020

Benefits from 6C even higher for vertically rupturing mechanisms. Reinwald et al. 2016
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Synthetic waveform inversion of nuclear test; inverted frequencies: 0.02 – 0.05 Hz (20 – 50 sec)

Especially the ISO part (diagonal moment tensor elements, first row) is problematic, in all cases.
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Synthetic waveform inversion of nuclear test; inverted frequencies: 0.02 – 0.16 Hz (6 – 50 sec)

RESULTS

- No reliable resolution based on 1D Green's functions.
- Rotations increase precision.
Synthetics of nuclear test

Whether 6C or 3D is more supportive depends on the frequency range.

However, both contribute to resolution.

<table>
<thead>
<tr>
<th>Frequency Range</th>
<th>Total Information Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.02 – 0.05 Hz</td>
<td>3C 1D: 10.7 bit</td>
</tr>
<tr>
<td></td>
<td>3C 3D: 10.7 bit</td>
</tr>
<tr>
<td></td>
<td>+ 9 %</td>
</tr>
<tr>
<td></td>
<td>6C 1D: 11.7 bit</td>
</tr>
<tr>
<td></td>
<td>6C 3D: 11.0 bit</td>
</tr>
<tr>
<td></td>
<td>+ 3 %</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Frequency Range</th>
<th>Total Information Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.02 – 0.16 Hz</td>
<td>3C 1D: 12.1 bit</td>
</tr>
<tr>
<td></td>
<td>3C 3D: 15.4 bit</td>
</tr>
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<td></td>
<td>+ 12 %</td>
</tr>
<tr>
<td></td>
<td>6C 1D: 13.5 bit</td>
</tr>
<tr>
<td></td>
<td>6C 3D: 16.7 bit</td>
</tr>
<tr>
<td></td>
<td>+ 38 %</td>
</tr>
</tbody>
</table>

Donner et al. 2020
Rotational Ground motion are defined as the curl of the translational wave-field.

They provide additional information on the vertical displacement gradient.

There is a huge progress in measurement methods and instrumentation.

The resolution of the seismic moment tensor can significantly be increased.

Depth-dependent components have high potential to benefit from rotations.

Inversion results in same or even better resolution with less number of receivers.

There is a high potential to better resolve non-tectonic parts of the source.

3D structural models can increase the benefits but have to be taken with care.