P3.1-353

Benefits of Rotational Ground Motion Measurements for On-Site Inspection (OSI)

S. Donner[1], P. Gaebler[1], J. Lehr[1 2], M. Hobiger[1], and N. Gestermann[1]

[1] Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) Hannover, Germany
[2] now at: GFZ Helmholtz-Zentrum für Geoforschung Potsdam, Germany

BGR
Federal Institute for Geosciences and Natural Resources

INTRODUCTION AND MAIN RESULTS

The seismic wave field is fully described by three components of each, translation and rotation (6 degrees of freedom, 6-DoF or 6C).
Although the methods used for OSI activities are stipulated, we want to show how they might profit from the inclusion of rotational measurements.

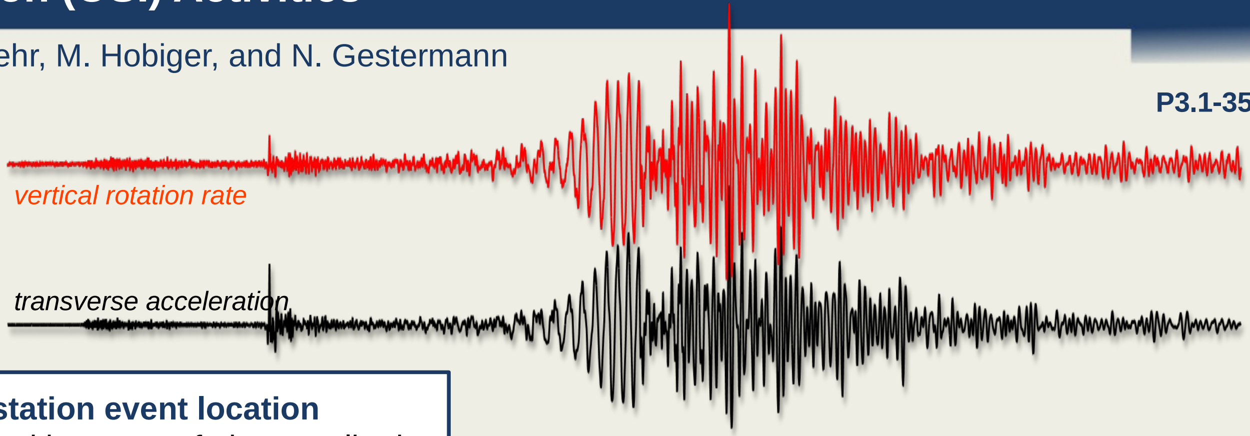
Most importantly, with 6C measurements and adapted processing techniques we can obtain similar information from a single station where traditionally an entire array of translational sensors would be necessary.

SnT 2025
8 SEPTEMBER ONLINE DAY
9 TO 12 SEPTEMBER AT HOFBURG PALACE, VIENNA & ONLINE
CTBT: SCIENCE AND TECHNOLOGY CONFERENCE

Benefits of Rotational Ground Motion Measurements for On-Site Inspection (OSI) Activities

S. Donner, P. Gaebler, J. Lehr, M. Hobiger, and N. Gestermann

P3.1-353



Overview of Benefits from Rotational Ground Motion Measurements

Want to know more to each topic? To each box there is a supplementary slide attatched. At the very back is a list of selected references.

What are rotations?

Next to translations, the „other half“ of the 6-component (6C) seismic wave field, defined as **spatial derivatives of translations**.

$$\omega(\mathbf{x},t) = \frac{1}{2}\left[\nabla \times \mathbf{u}(\mathbf{x},t)\right]$$

A joint **6C analysis improves the results** in all sub-fields of seismology. The **same if not better results** can be achieved **with less number of station or even a single station**.

Challenges of OSI?

A **huge effort** in terms of hardware, logistics, humanpower, and coordination under **time pressure**.

Structural studies

The **amplitude ratio** between certain components of translation and rotation are **directly related to the apparent phase velocity** of specific types of the seismic wave field, e.g. for SH and Love waves:

$$\frac{\ddot{u}_T}{\dot{\omega}_Z} = -2c$$

This feature is frequency dependent and can be used for site characterisation, microzonation and tomography, even **from a single station recording**.

Single station event location

Again making use of the amplitude ratios, the **direction of an incoming wave field (backazimuth, BAz)** can be determined. Together with the **distance and origin time from arrival time differences** between P- and S-waves, the location of an event is reliably deterimined incl. a rough estimate on hypocenter depth.

Influence of heterogeneities and anisotropy

Small-scale structural features **affect rotations much stronger than translations**. This effect might be a **chance to detect cavities**. However, it needs further research.

Inversion for seismic moment tensor

Incorporating rotations into the waveform inversion **improves the resolution of seismic moment tensor components drastically**. Also, the **isotropic source part**, defining an event as earthquake or explosion, benefits clearly. The benefits show **even when reducing the number of stations**.

Wave field separation

Each wave type has a **unique 6C ‚fingerprint’**, hence, supporting wave field separation. As a pre-processing step it helps to **overcome well-known difficulties in active seismic**.

List of (some) references

Data availability

6C waveform data from two locations with ringlasers (BW.RLAS, BW.ROMY) and one, soon two, locations with BlueSeis-3A sensors (PY.BSPF, GQ.WERN) are freely available via FDSN.

BGR Federal Institute for Geosciences and Natural Resources

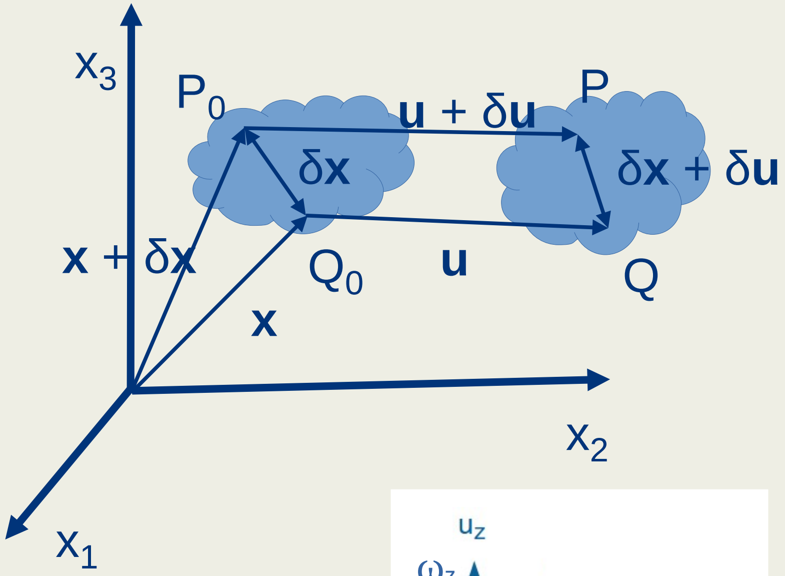
Benefits of Rotational Ground Motion Measurements for On-Site Inspection (OSI) Activities

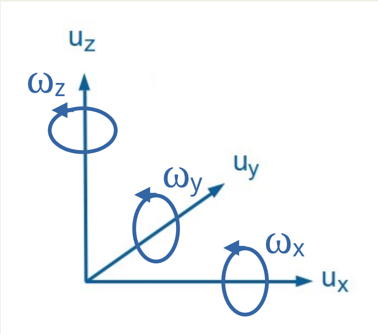
S. Donner, P. Gaebler, J. Lehr, M. Hobiger, and N. Gestermann

P3.1-353

What are Rotational Ground Motions?

We describe the deformation of a point Q_0 related to that of a neighboring point P_0 assuming classical elasticity and infinitesimal deformation.





The entire deformation is then composed by three components of translation **u**, six component of strain **ε**, and three components of rigid body rotation **ω**.

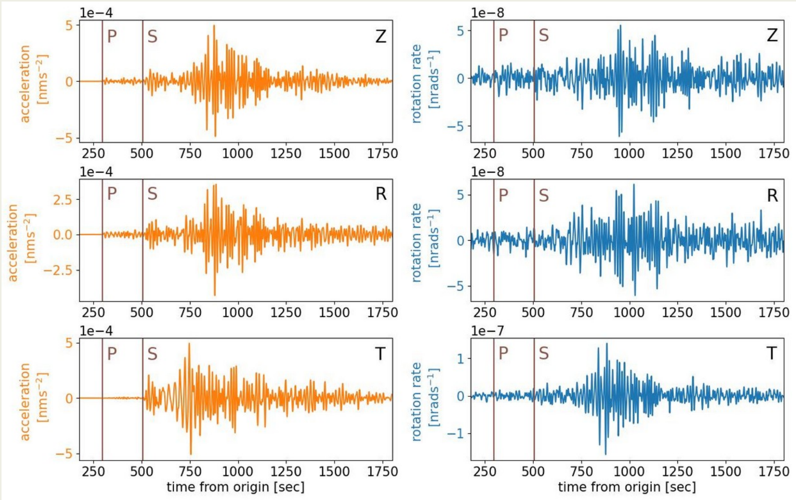
$$\begin{aligned}\mathbf{u}(\mathbf{x}+\delta\mathbf{x}) &= \mathbf{u}(\mathbf{x}) + \mathbf{G}\delta\mathbf{x} \\ &= \mathbf{u}(\mathbf{x}) + \epsilon\cdot\delta\mathbf{x} + \mathbf{\Omega}\delta\mathbf{x} \\ &= \mathbf{u}(\mathbf{x}) + \epsilon\cdot\delta\mathbf{x} + \omega\times\delta\mathbf{x}\end{aligned}$$

The rotational components of the seismic wave field are spatial derivatives of the translational components.

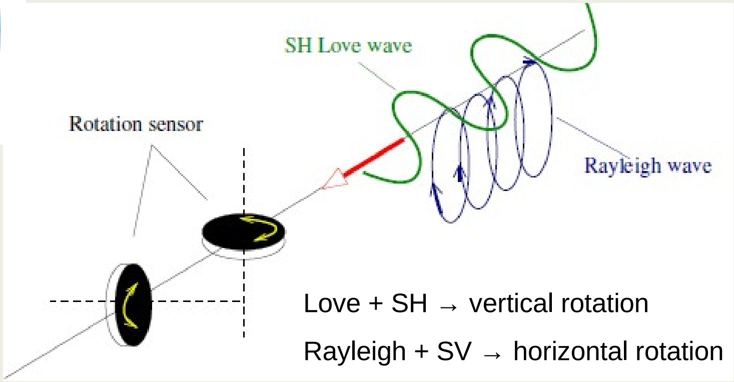
$$\omega(\mathbf{x},t) = \frac{1}{2}\left[\nabla\times\mathbf{u}(\mathbf{x},t)\right]$$

$$\begin{pmatrix}\omega_1\\ \omega_2\\ \omega_3\end{pmatrix} = \frac{1}{2}\begin{pmatrix}\partial_y u_z - \partial_z u_y\\ \partial_z u_x - \partial_x u_z\\ \partial_x u_y - \partial_y u_x\end{pmatrix}$$

Measuring all six components of the seismic wavefield, i.e. translation **u** and rotation **ω**, comes with great benefits for the analysis results.



6 component waveforms of the Mw 7.7 Turkey event on 6th Feb. 2023 recorded at Landwüst, Germany (distance 2440 km).



Aki and Richards 2002; Cochard et al. 2006; Suryanto 2006; Schmelzbach et al. 2018

SnT 2025 8 SEPTEMBER ONLINE DAY 9 TO 12 SEPTEMBER AT HOFBURG PALACE, VIENNA & ONLINE
CTBT: SCIENCE AND TECHNOLOGY CONFERENCE

Benefits of Rotational Ground Motion Measurements for On-Site Inspection (OSI) Activities

S. Donner, P. Gaebler, J. Lehr, M. Hobiger, and N. Gestermann

P3.1-353

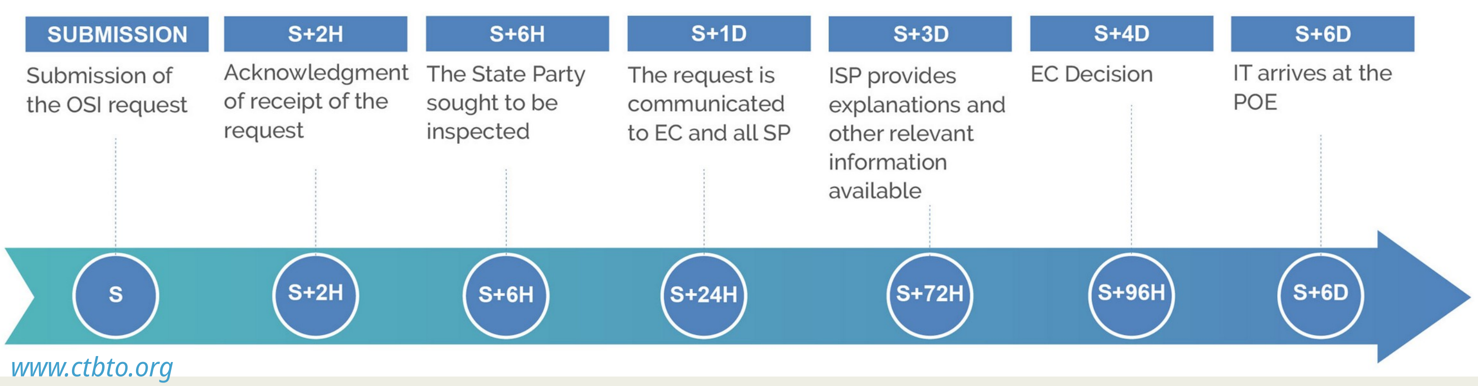
On-Site Inspection tasks and challenges

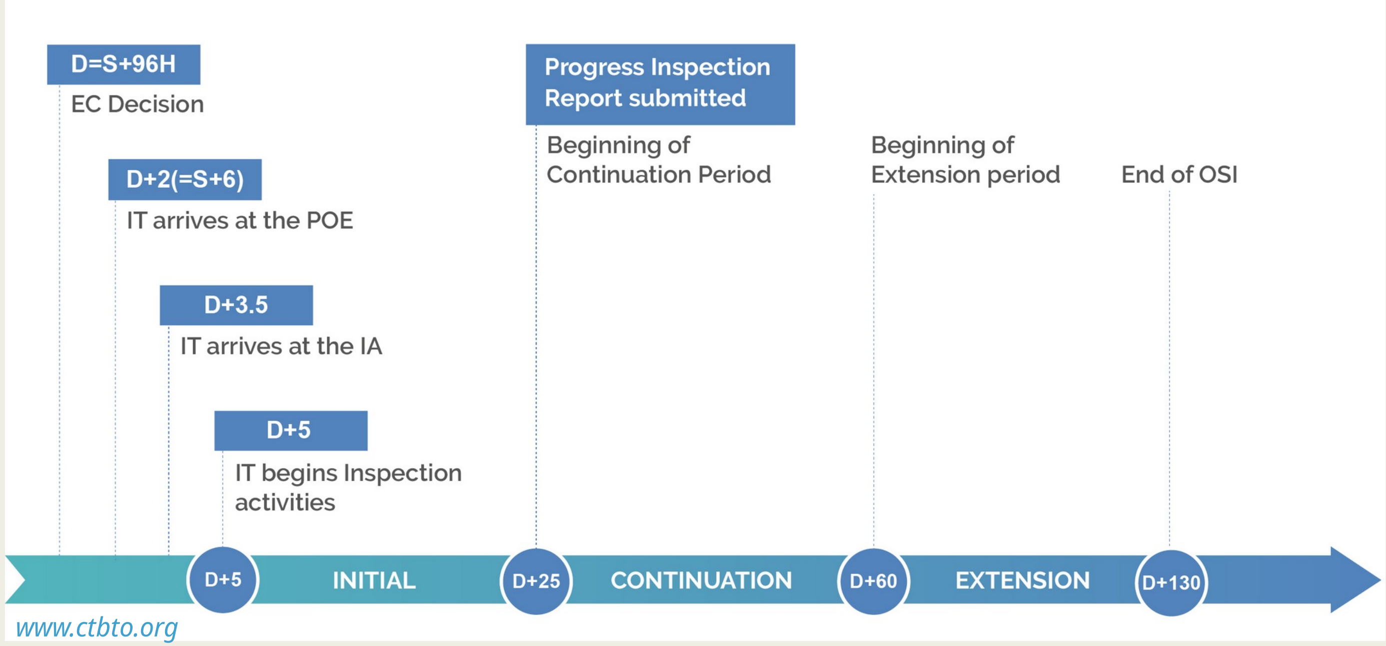
An OSI is the **ultimate measure** in the CTBT verification regime to gather further evidence on the ground whether a nuclear explosion has been carried out. It is a **major mission** that comes with **huge efforts** in terms of logistics, hardware, humanpower, and coordination. In contrast, **speed is a key factor** of OSI.

The launch mission starts with the submission of an **OSI request** from a State Party on the basis of a suspicious triggering event. The Executive Council will make a **decision within 96 hours** (4 days). The inspection **team is deployed to the field within 6 days**. The **pre-inspection phase lasts 72 hours**.

The **inspection phase** is subdivided in an initial phase (25 days), a continuation period (60 days), and an optional extension period (max. 70 days). **Applied methods** include:

- visual observations, multi-spectral imaging for surface changes
- **seismic aftershock monitoring**
- radiation monitoring, environmental sampling
- **seismic surveys (reflection/refraction seismic, tomography)**
- **resonance seismometry to search for underground anomalies**
- ground penetration radar
- drilling for RN samples





BGR Federal Institute for Geosciences and Natural Resources

Benefits of Rotational Ground Motion Measurements for On-Site Inspection (OSI) Activities

S. Donner, P. Gaebler, J. Lehr, M. Hobiger, and N. Gestermann

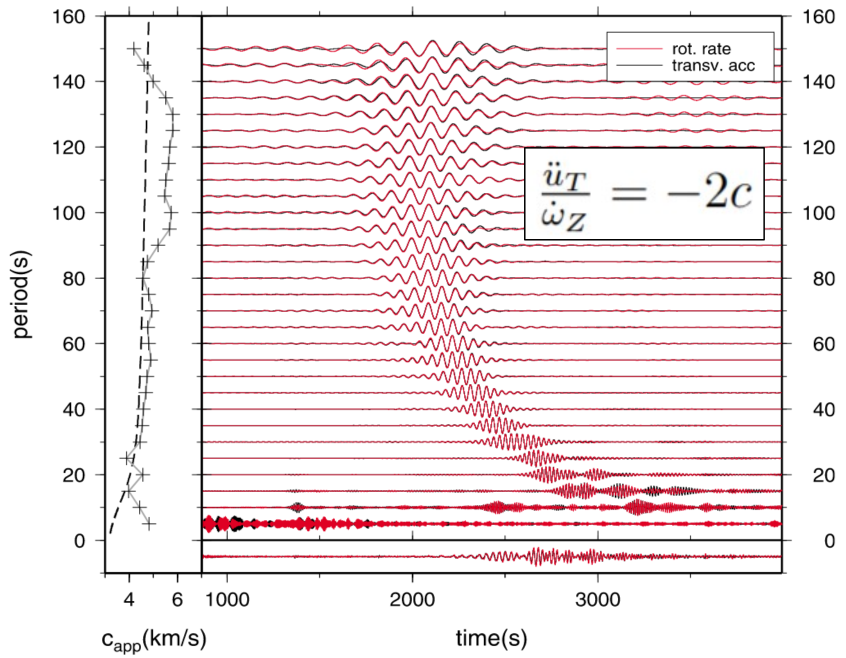
P3.1-353

Single station site characterisation, microzonation, and tomography

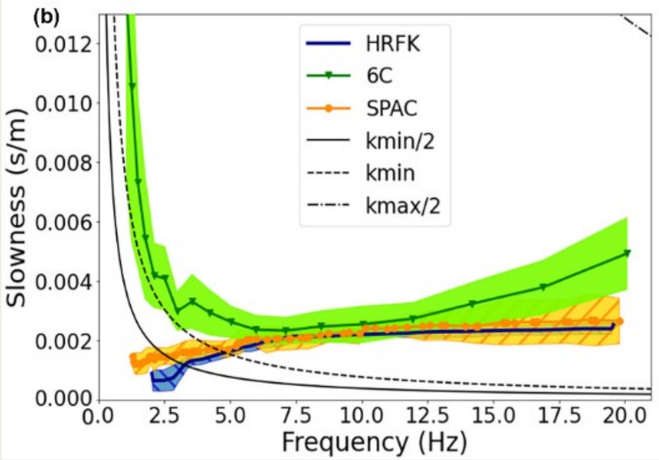
The **frequency dependent amplitude ratio between rotation and translation** can be used to **determine a dispersion curve** from a point measurement. The resulting curve can be inverted for local near-surface structure. Source information is not needed.

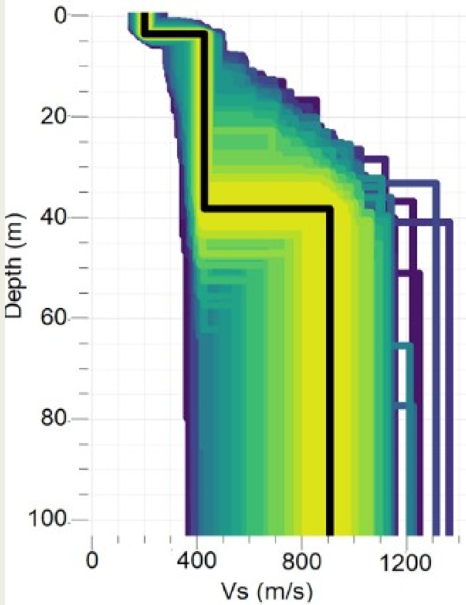
In addition, the joint processing of translations and rotations opens up **new possibilities for tomographic studies**.

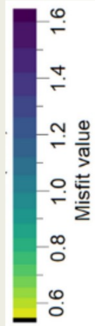
Mw 7.4 Kuriles earthquake on Jan. 15, 2009 recorded at Wettzell, Germany



Kurrle et al. 2010

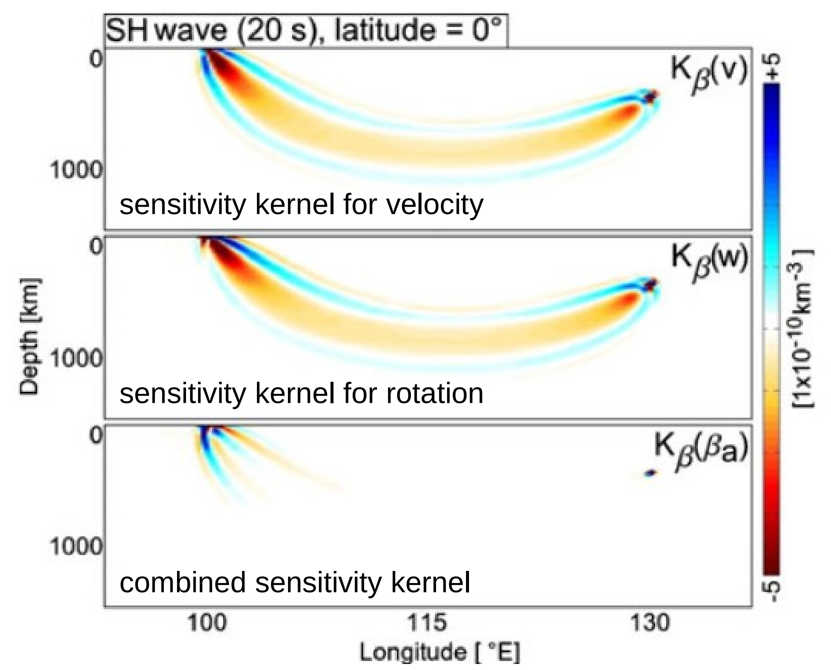




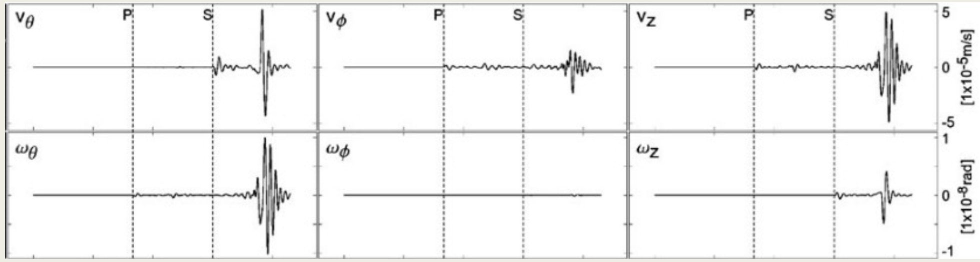


Keil et al. 2022

singel 6C site characterisation close to Munich, Germany



synthetic tomographic study



Bernauer et al. 2012

BGR Federal Institute for Geosciences and Natural Resources

Benefits of Rotational Ground Motion Measurements for On-Site Inspection (OSI) Activities

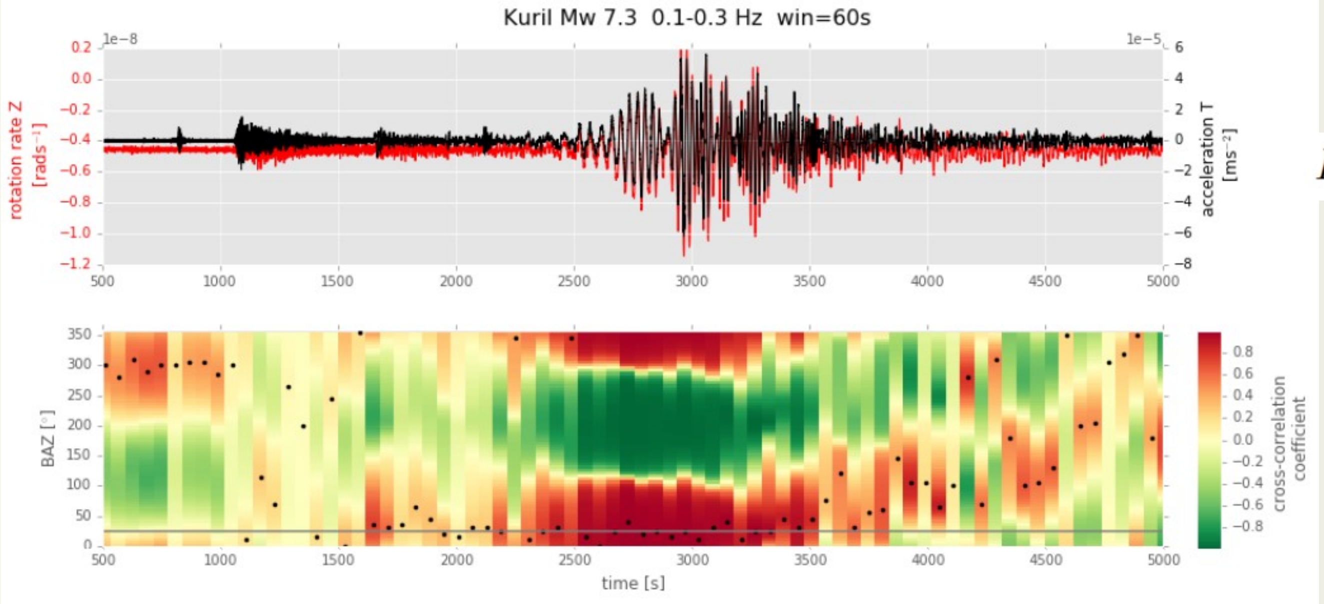
S. Donner, P. Gaebler, J. Lehr, M. Hobiger, and N. Gestermann

Single station direction finding and earthquake location

In principal, it is possible to locate the epicenter and origin time of an event from 3-components of translation only. However, this method comes with large uncertainties. **Adding just one component of rotation (vertical), the results improve enormously** and additionally provide a depth estimate. Location from a single 6C recording are reliable and, hence, can **reduce logisitic efforts** drastically. Detailed knowledge on the velocity model is not needed.

- determine backazimuth (BAz) from cross-correlating translation **u** with rotation **ω** or polarisation analysis of rotations only (result improve when wavefield separation is applied first)
- distance Δ and origin time from P- and S-wave arrival time difference using the Wadati method → latitude, longitude
- depth estimate from definition of incident angle via phase velocity and ray-path

Example: Mw 7.3 Kuriles earthquake on January 15, 2009 recorded at Wettzell, Germany, (ringlaser and broadband seismometer).



$$\frac{\ddot{u}_T}{\dot{\omega}_Z} = -2c$$

$$BAz = -arctan(\dot{\omega}_N/\dot{\omega}_E)$$

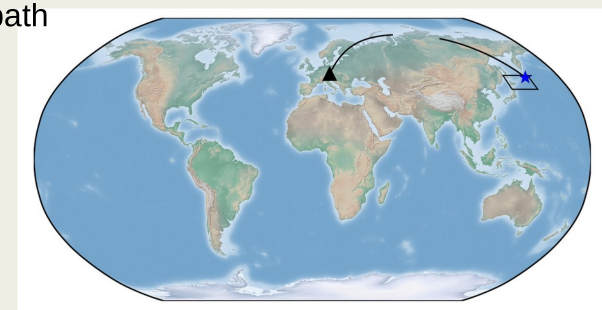
Wassermann et al. 2016

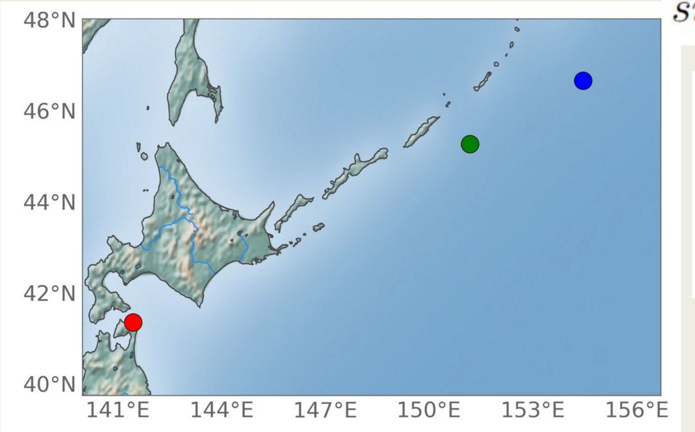
Yuan et al. 2020

$$t_P = t_0 + \Delta/v_P$$

$$\Delta = (t_S - t_P)\,\frac{v_P v_S}{v_P - v_S}$$

$$sin\ i = \frac{v_S}{c} = \frac{180}{\pi} \cdot \frac{v_P}{radius_E - h} \cdot p(\Delta, h)$$





Kuril	46.97° N	155.16° E	Mw 7.3
	EMSC	3C	4C
source time	17:49:38	17:48:08	17:48:08
distance [km]	8755	8772	8772
BAZ [°]	25	32-41	15-40
depth [km]	40		< 35

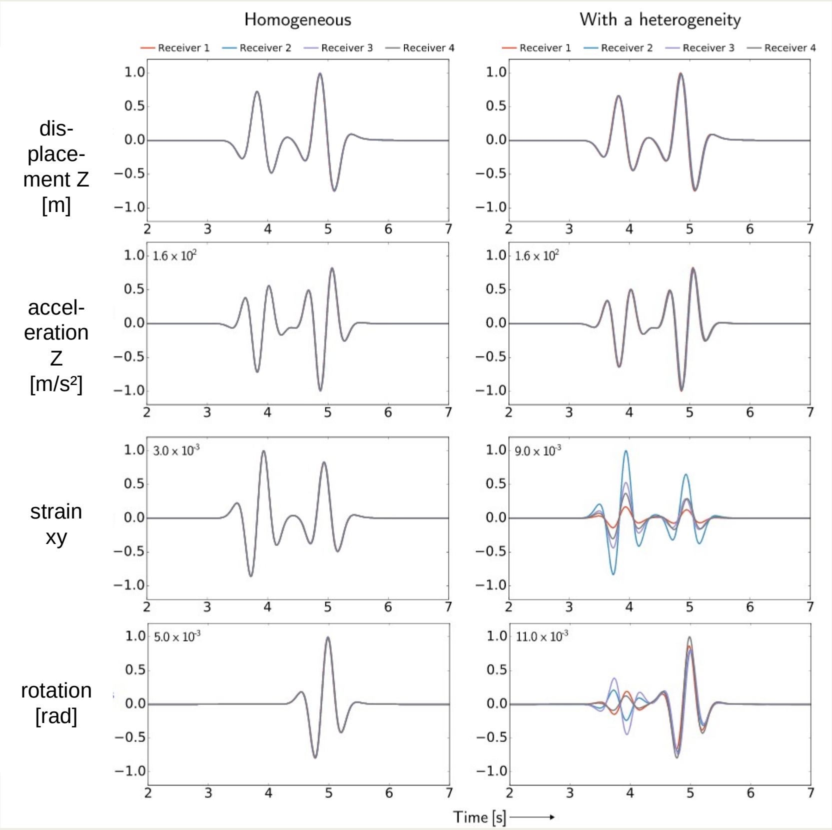
Benefits of Rotational Ground Motion Measurements for On-Site Inspection (OSI) Activities

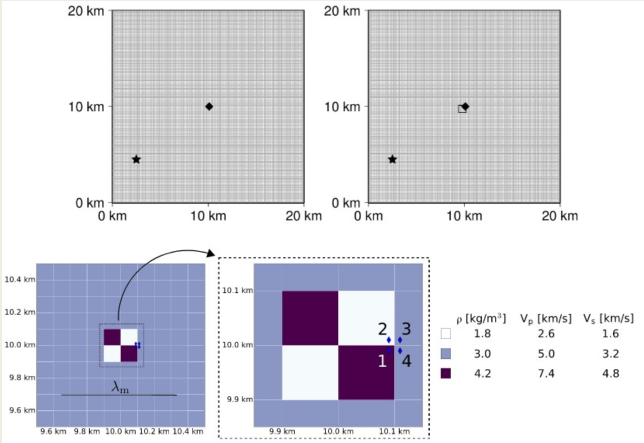
S. Donner, P. Gaebler, J. Lehr, M. Hobiger, and N. Gestermann

P3.1-353

Influence of local heterogeneities and anisotropy on rotational ground motions

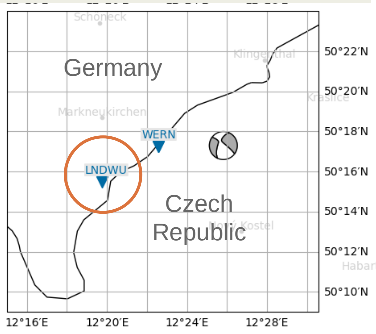
Rotational ground motions are **strongly influenced by local heterogeneities and structural anisotropy**. This fact may provide an **opportunity to detect underground caverns** from explosions during On-Site Inspections.



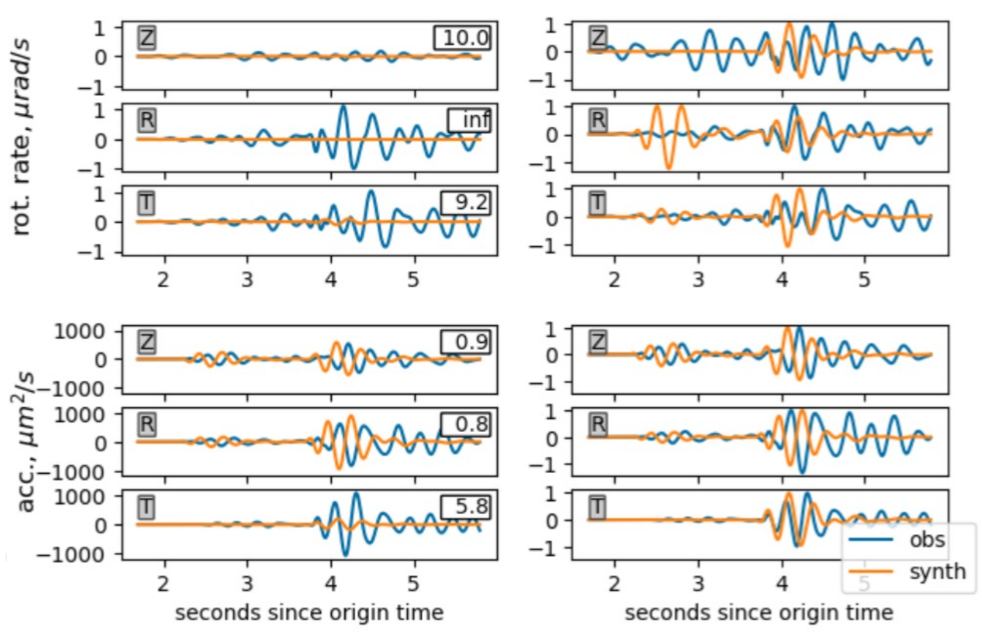


2D structure to calculate synthetic waveforms with and without heterogeneity at the station location (top left and right). Star marks the source. Bottom line shows details of the heterogeneity.

Singh et al. 2020



Comparison of observed and synthetic 6C waveforms from a ML 2.9 earthquake on Nov. 11, 2023 at station LNDWU in the Vogtland region (border region between Germany and the Czech Republic). Filter: Butterworth 2-4 Hz. Top: rotation rate; bottom: acceleration. Left: true amplitudes with factor in a box; right: normalised amplitudes.
Station LNDWU shows strong signs of aniyotropy, especially for the SH-wave field. This feature could be used for structural studies.



Lehr, Donner et al. in preparation

BGR Federal Institute for Geosciences and Natural Resources

Benefits of Rotational Ground Motion Measurements for On-Site Inspection (OSI) Activities

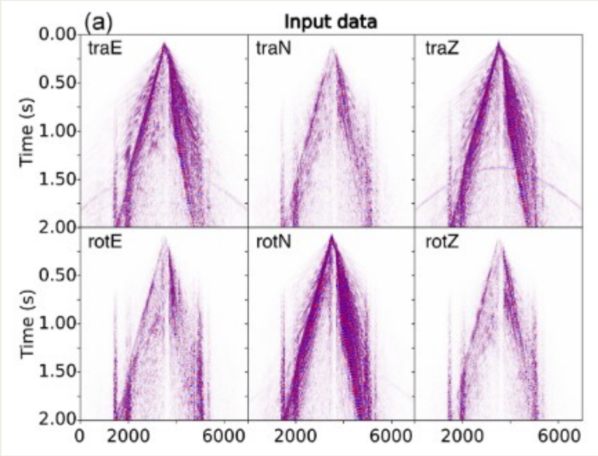
S. Donner, P. Gaebler, J. Lehr, M. Hobiger, and N. Gestermann

P3.1-353

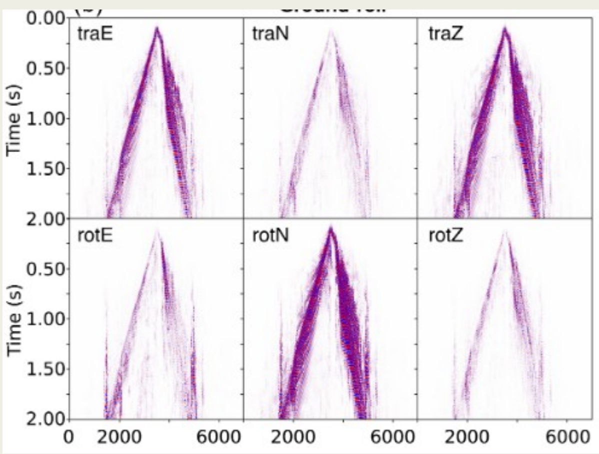
Single station ground-roll suppression and wave field separation

Rotational ground motion help to **overcome typical problems in seismic exploration**, such as the requirement of dense spatial sampling to avoid spatial aliasing of surface waves and ground roll suppression.

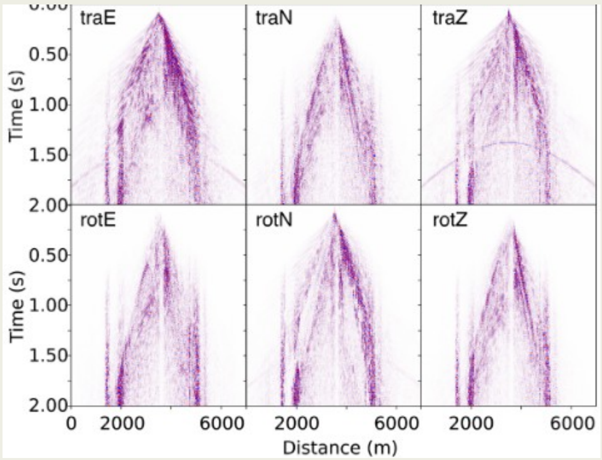
To distinguish ground-roll from body waves not only ellipticity but also local propagation velocity is used.



ground roll

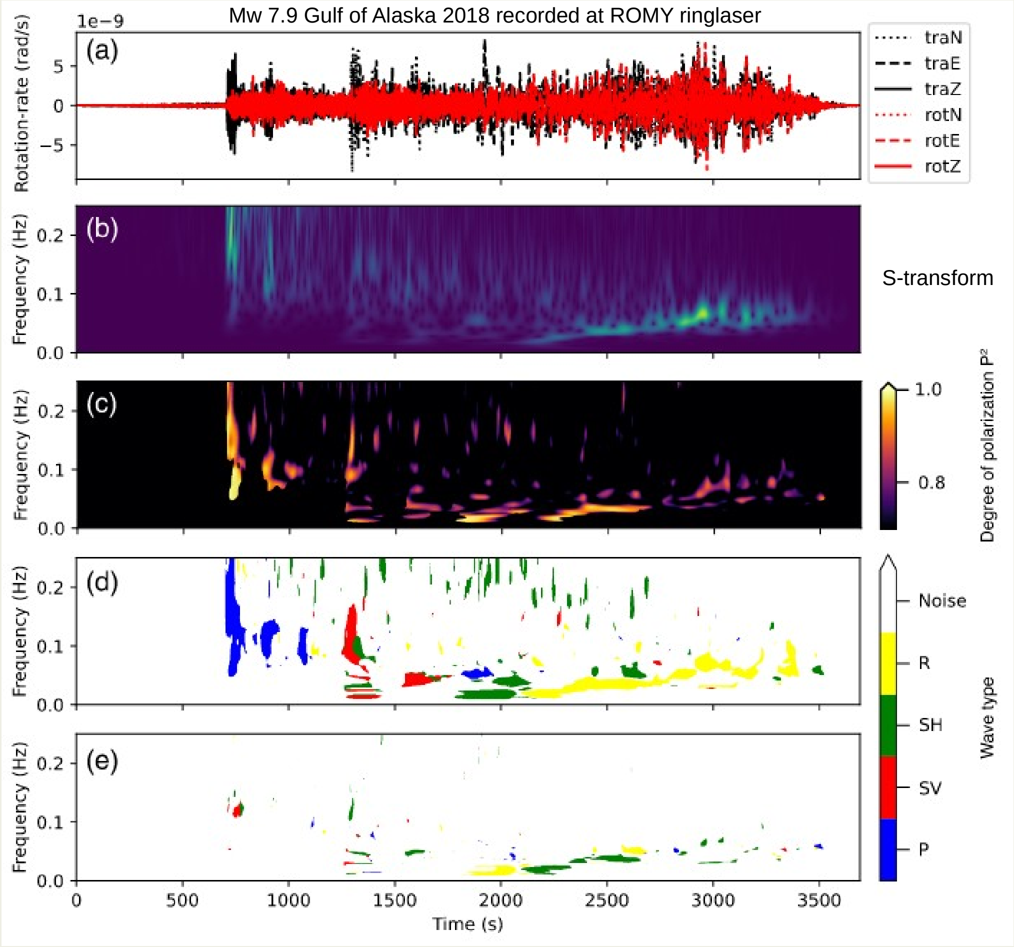


remaining wave feld



Sollberger et al. 2023

Each wave type leaves a unique 6C ‚fingerprint'. It can be extracted by an eigenanalysis of the data covariance matrix (similar to conventional polarisation analysis).



TwistPy (https://twistpy.org)
Toolbox for Wavefield Inertial Sensing Techniques

BGR Federal Institute for Geosciences and Natural Resources

Benefits of Rotational Ground Motion Measurements for On-Site Inspection (OSI) Activities

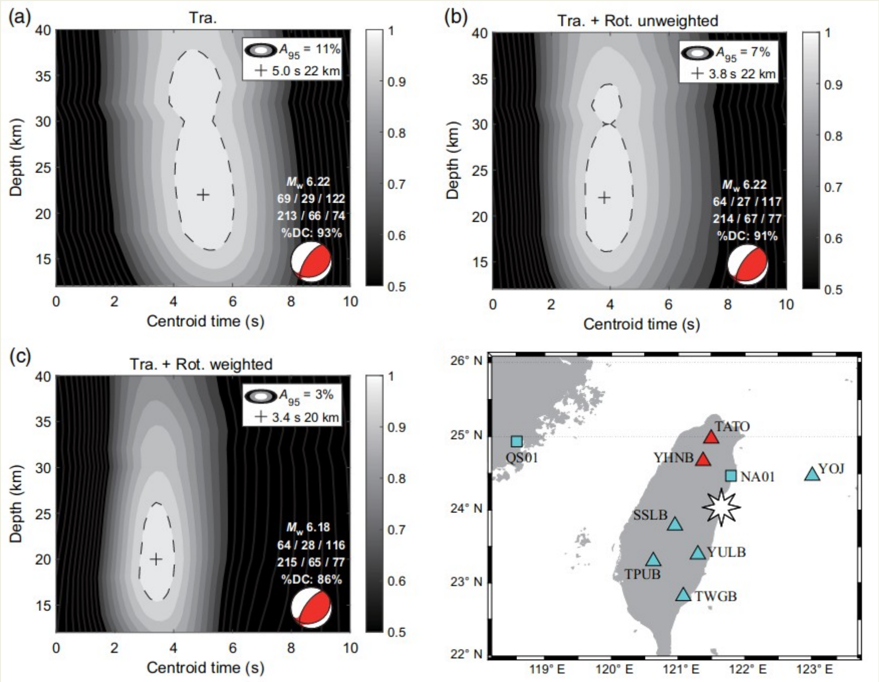
S. Donner, P. Gaebler, J. Lehr, M. Hobiger, and N. Gestermann

Waveform inversion for the seismic moment tensor

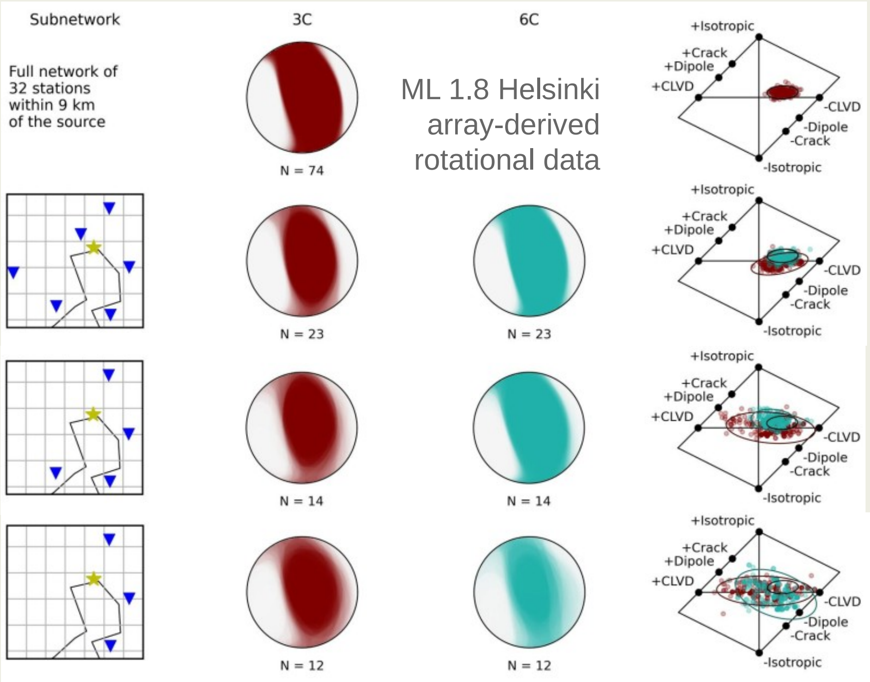
Based on synthetic waveforms it was shown that 6C (translations + rotations) waveform inversion for the seismic moment tensor compared to 3C (translations only) inversion results in:

- **improved resolution of moment tensor components and isotropic source part**
- **improved resolution of centroid depth**
- **reliable results from only 3-4 station locations (depending on geometry)**

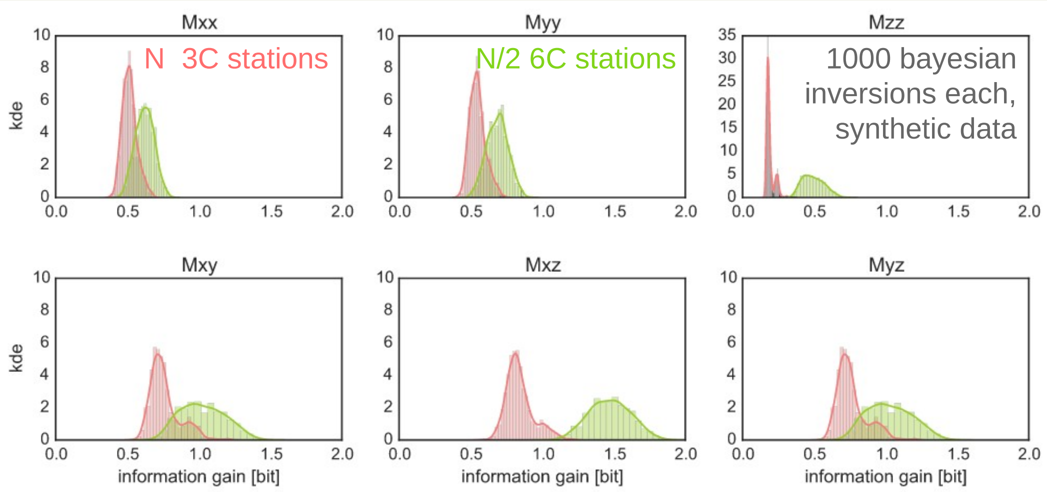
Studies based on real observations, body and surface waves, confirm the synthetic results.



Xu et al. 2016



Donner et al. 2016



Rintamäki et al. in prep.

BGR Federal Institute for Geosciences and Natural Resources

SnT 2025 CTBT: SCIENCE AND TECHNOLOGY CONFERENCE
8 SEPTEMBER ONLINE DAY
9 TO 12 SEPTEMBER AT HOFBURG PALACE, VIENNA & ONLINE

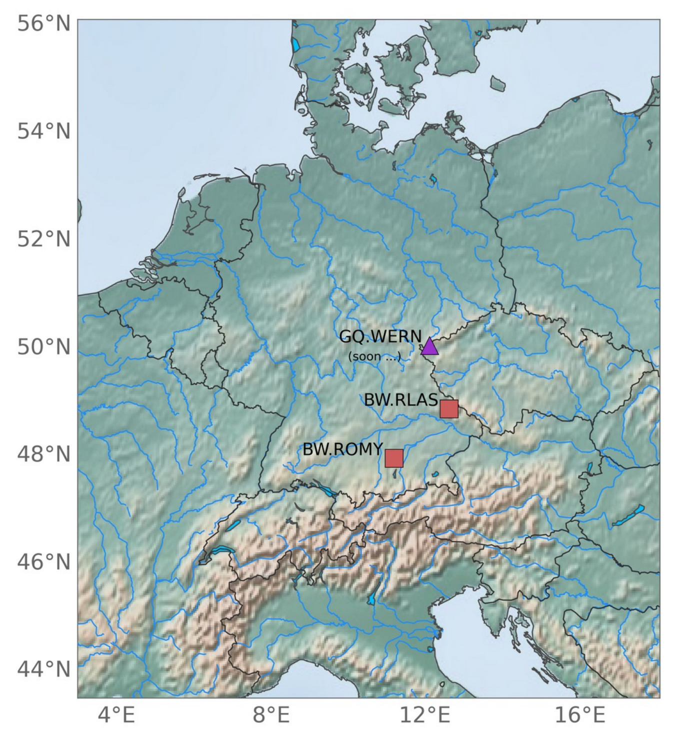
Benefits of Rotational Ground Motion Measurements for On-Site Inspection (OSI) Activities

S. Donner, P. Gaebler, J. Lehr, M. Hobiger, and N. Gestermann

P3.1-353

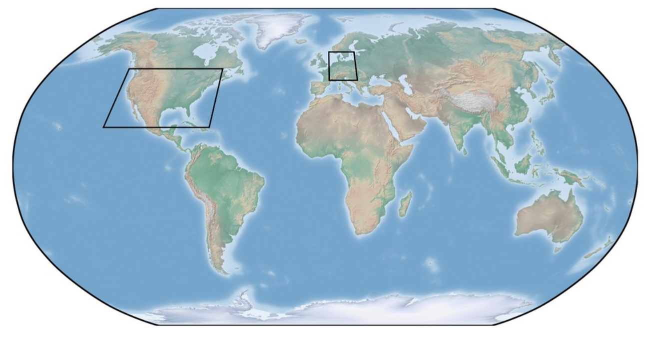
Availability of Rotational Ground Motion Measurements

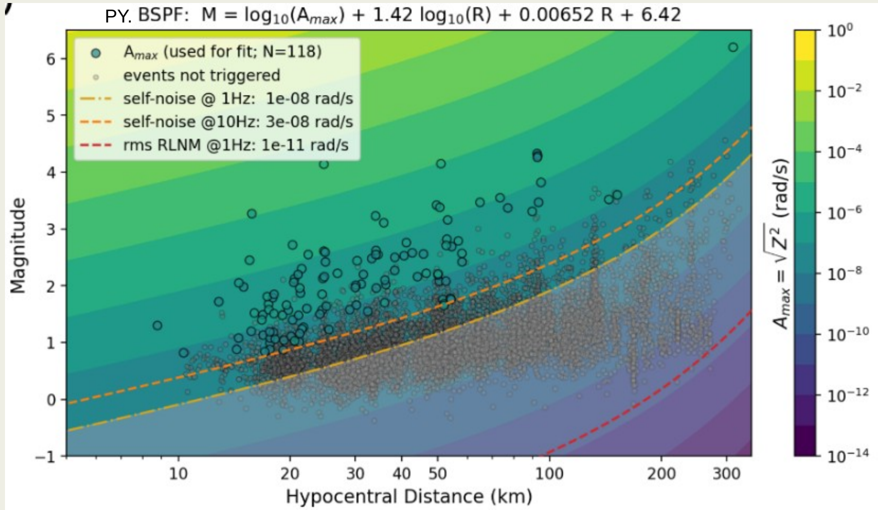
There are **data from four locations permanently available** via the International Federation of Digital Seismograph Networks (FDSN, https://www.fdsn.org/): two **ringlasers** (BW.RLAS, BW.ROMY) and one location equipped with a **BlueSeis-3A** (PY.BSPF). Another location equipped with a BlueSeis-3A sensor will be available from 2026 on (GQ.WERN).



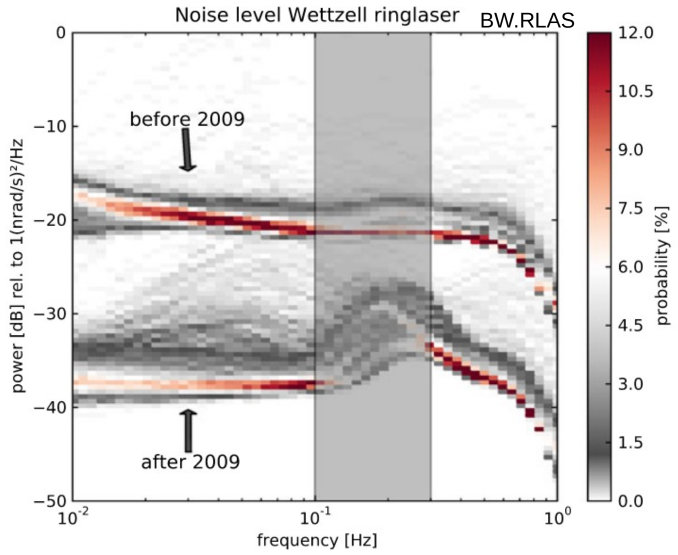
See also the Rotational Seismology Event Database for waveform download and exemplary Python code for analysis:

https://rotations-database.geophysik.uni-muenchen.de/





Brotzer et al. 2025



sensititvity levels of BlueSeis-3A sensors (top) and ringlaser RLAS (left).

Hadziioannou et al. 2012

BGR Federal Institute for Geosciences and Natural Resources

Benefits of Rotational Ground Motion Measurements for On-Site Inspection (OSI) Activities

S. Donner, P. Gaebler, J. Lehr, M. Hobiger, and N. Gestermann

References

- Aki and Richards 2002. Quantitative Seismology. University Science Book.
- Bernauer et al. 2012. Measurements of translation, rotation and strain: new approaches to seismic processing and inversion. Journal of Seismology, 16, 669-681, doi 10.1007/s10950-012-9298-3.
- Brotzer et al. 2025. On single-station, six degree-of-freedom observations of local to regional seismicity at the Piñon Flat Observatory in Southern California. Seismica, 4/1, doi 10.26443/seismica.v4i1.1416.
- Cochard et al. 2006. Rotational motions in seismology: theory, observation, simulation. In: Teisseyre, Majewski, Takeo (eds.) Earthquake Source Asymmetry, Structural Media and Rotation Effects. Springer. doi 10.1007/3-540-31337-0_30.
- Donner et al. 2016. Inversion for seismic moment tensors combining translation and rotational ground motions. GJI, 207, 562-570, doi 10.1093/gji/ggw298.
- Hadziioannou et al. 2012. Examining ambient noise using colocated measurements of rotational and translational motion. Journal of Seismology, 16/4, 787-796, doi 10.1007/s10950-012-9288-5.
- Keil et al. 2022. Comparing single-station 6C measurements and array measurements for seismic microzonation in Munich, Germany. GJI, 231/3, 1634-1652, doi 10.1093/gji/ggac273.
- Kurrle et al. 2010. Can we estimate local Love wave dispersion properties from collocated amplitude measurements of translations and rotations? Geophys. Res. Lett., 37/4, L04307, doi 10.1029/2009GL042215.
- Rintamäki et al., in preparation. Six-component full waveform inversion for moment tensor analysis of a Mw 1.9 induced earthquake using translational observations and array-derived rotational estimates.
- Schmelzbach et al. 2018. Advances in 6C seismology: Applications of combined translational and rotational motion measurements in global and exploration seismology. Geophysics, 83/3, doi 10.1190/geo2017-0492.1.
- Singh et al. 2020. Suryanto 2006. Rotational Motion in Seismology, Theory and Application. Dissertation thesis, LMU Munich, Germany. GJI, 220, 996-1011, doi 10.1093/gji/ggz479.
- Sollberger et al. 2023. Efficient wave type fingerprinting and filtering by six-component polarization analysis.
- Suryanto 2006. Rotational Motion in Seismology, Theory and Application. Dissertation thesis, LMU Munich, Germany.
- Wassermann et al. 2016. Toward a Single Station Approach for Microzonation: Using Vertical Rotation Rate to Estimate Love Wave Dispersion Curves and Direction Finding. BSSA, 106/3, 1316-1330, doi 10.1785/0120150250.
- Xu et al. 2025. Incorporating Directly Observed Rotational Seismic Data into Moment Tensor Inversion for the 2019 Mw 6.2 Hualien Earthquake. Seismol. Res. Lett., xx, 1-13, doi 10.1785/0220240470.
- Yuan et al. 2020. Six Degree-of-Freedom Broadband Ground-Motion Observations with Portable Sensors: Validation, Local Earthquakes, and Signal Processing. BSSA, 110/3, 953-969, doi 10.1785/0120190277.
- **and many more …**

BGR Federal Institute for Geosciences and Natural Resources