An Event Database for Rotational Seismology

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Abstract

We introduce a new event database for rotational seismology. On the corresponding website (http:www.rotational-seismology.org) the user can access 17000+ processed global earthquake events starting in 2007. For each event, we provide waveform and processing plots for the seismometer station at Wettzell and its vertical component ring laser (G-Ring), as well as further characteristics (e.g., peak amplitudes, S/N ratios). Tutorials and illustrated processing guidelines are available and ready to be applied to other data sets. The aim is to promote the use of joint rotational and translational ground motion data demonstrating their potential for characterizing seismic wavefields and solving inverse problems.

Introduction

Since the beginning of the 20th century, seismology has been dominated by one type of observation: translational ground motions (usually measured as three orthogonal components: N-S, E-W, vertical). In the past two decades, due to the emerging ring laser technology and its evolution towards higher ad higher sensitivities (Stedman, 1997; Schreiber and Wells, 2013) for geodetic applications, rotational ground motions have become available as a new observable in seismology. Aki and Richards (1980) pointed out that - to reconstruct complete ground motions - rotational motions should also be observed.
In this regard, McLeod et al. (1998); Pancha et al. (2000) have shown that vertical rotation rate and transverse acceleration are in phase and Igel et al. (2005, 2007) and Kurrle et al. (2010) found that from amplitude ratios of these measurements at a single point, it is possible to estimate dispersion curves of Love waves generated by (teleseismic) earthquakes.
Until then, the determination of the event source direction, was difficult without seismic array measurements (e.g. beam-forming). Igel et al. (2007) presented a straight-forward approach to infer the source direction (=backazimuth) from collocated broadband seismometer and ring laser recordings using a cross-correlation grid search.

The initiation of the presented event database has two main intentions: The first main goal is to make rotation data publicly available in order to promote its usage and significance for seismological applications. The database contains event plots and separate meta-data files including valuable wavefield parameters.
The second goal is to show how rotational waveforms (e.g. vertical component rotation rates from the Wettzell **G-Ring**) can be accessed and processed. For this purpose, we provide interactive tutorials in the form of open source Jupyter Notebooks (Pérez and Granger, 2007)

which graphically document the basic processing - as used for the database entries - while providing helpful background information. The python-based notebooks use routines from the well-known **ObsPy** library (Megies et al., 2011; Krischer et al., 2015).

Currently, we process data provided by a single station, the Wettzell Geodetic Observatory in S-E Germany. The 4 x 4 m G-Ring ring laser, located there, measures the Sagnac frequency at very high resolution. This yields a self-noise level around the vertical axis of $\approx 60 \cdot 10^{-14} \frac{rad}{s} Hz^{-\frac{1}{2}}$ before 05/2009 and $12 \cdot 10^{-14} \frac{rad}{s} Hz^{-\frac{1}{2}}$ since 05/2009 (Schreiber and Wells, 2013). That is high enough to record even smaller (magnitude<6) teleseismic events at reasonable signal-to-noise ratio as well as Earth's free oscillations (Igel et al., 2011) and ocean-generated noise (Hadziioannou et al., 2012). Translational ground motions are measured with a collocated (distance $\approx 250m$) Streckeisen STS-2 broadband seismometer, the station WET of the German regional seismic network (GRSN). So far, since 2007 more than 17000 events have been processed (see figure 1) using this station's data. As soon as continuous rotational motion recordings of other ring lasers are available, we will include them in our database allowing inter-station comparison. The database is accessible via the website of the International Working Group on Rotational Seismology (http://www.rotational-seismology.org).

Web Interface

The website provides the visitor with a graphical user interface of the database as well as additional information and links to topic-related projects (see figure 2).

Upon defining query parameters (time period, magnitude, depth, latitude/longitude, waveform correlation, peak rotation rate and signal-to-noise ratio), the user can choose between a downloadable QuakeML-catalog and a map representation of the specified available event catalog. On the zoomable world map, the earthquake event markers are sized and colored according to the earthquake's moment magnitude and source depth, respectively. This is intended to help find the desired event more quickly. By clicking on the event markers, a popup menu opens yielding a short description of the event by means of source time, magnitude and depth. The menu also contains links to a couple of plots for the automatically processed waveform data of rotational and translational ground motions. These plots display:

1. Event background information (location, time, etc.)

2. Waveform comparison (4 different time windows)

3. Parameter estimation (Love wave phase velocity [figure 3], backazimuth [figure 4])

4. P-coda analysis

Finally, the menu links to a metadata parameter file in the JSON* format (*JavaScript Object Notation). This file contains all event and data fetching information and most importantly, the calculated parameters such as peak values (displacement, acceleration, rotation rate, correlation), signal-to-noise ratios, mean phase velocities (+ standard deviations), estimated and theoretical backazimuth. These parameters are also part of the QuakeML catalog. In order to make the processing and the produced plots reproducible, we include a downloadable processing guide and example code snippets. Additionally, **Jupyter notebooks** interactively explain the processing steps from data download over instrument correction to phase velocity and backazimuth estimation.

Processing

In the following sections we illustrate joint processing steps carried out on the collocated translational and rotational ground motions for each seismic event in the catalogue.

Pre-processing

The event database is automatically updated on a daily basis. Scripts are fed by quick CMT solutions provided by the Global Centroid Moment Tensor (GCMT) catalog (Dziewonski et al., 1981; Ekström et al., 2012) and updated to the proper solutions once they are available. This catalog contains global earthquake events featuring moment magnitudes $M_w > 4.5$. After fetching the event information (origin time, epicenter, depth, etc.), ring laser and collocated seismometer waveforms are downloaded from the GRSN data center. The pre-processing of the downloaded seismic data streams is determined by the epicentral distance (cf. table 1).

The procedure starts with the removal of the seismometer's impulse response, to convert to ground acceleration $\mathbf{nm/s^2}$ for the translational measurements and the scaling of the ring laser's rotation rate measurements to $\mathbf{nrad/s}$. The traces are low-pass filtered to decrease the impact of high frequency body waves and the ambient cultural noise. Furthermore, for teleseismic events, a bandstop-filter (5-12s) is applied to reduce the effect of the secondary microseism ($\approx$ 7s period) which is more prominent than the primary microseism (Hadziioannou et al., 2012) and can cause shifts in our backazimuth estimation especially for Mid- to South-Atlantic events for the case of the Wettzell station location.

To determine the theoretical arrival times for the P- and S-wave windows we run the ObsPy-**TauP** (Crotwell et al., 1999) routine with IASP91 travel time tables (Kennett and Engdahl, 1991). The surface wave arrivals are based on interpolated IASP91 surface wave travel times. The processing leading to the subplots of image 3 is described in the subsections about phase velocity and backazimuth estimation. It is notable, that for the P-coda analysis (image 4), shorter time windows (local: 2s; teleseismic: 5s) are used for the cross-correlation analysis to show that there is a (weak) signal of P- or SV-converted S_H waves in the high-frequency P-coda and thus before the theoretical S-wave arrival (Pham et al., 2009).

Love wave phase velocity estimation

In order to derive Love wave phase velocities, the observed and pre-processed signals are compared analogous to Igel et al. (2005). Under the assumption of a transversely polarized plane wave, the vertical rotation rate $\dot{\Omega}_z$ and transverse acceleration a_t are in phase and the amplitudes are related by:

$$\frac{a_t}{\dot{\Omega}_z} = -2c \tag{1}$$

where c is the (apparent) horizontal phase velocity. In a first step, we therefore rotate (by the theoretical BAz) the horizontal acceleration components (North-East) in the source-receiver plane to radial-transverse to obtain a phase-match with the vertical rotation rate. The transverse acceleration and vertical rotation rate traces are then divided into sliding windows of equal size depending on the epicentral distance of the event (see table 1). For each of these windows, a zero-lag normalized cross-correlation analysis is applied to a_t and $\dot{\Omega}_z$ to check the coherence between the two waveforms (figure 3 [top]). The resulting cross-correlation coefficient (CC) is used as a quality criterion for the determination of the phase velocities. For windows with CC $>$ 0.75, the horizontal phase velocity c is estimated by inserting peak values of a_t and $\dot{\Omega}_z$ into equation 1 (figure 3 [bottom]). For broadband traces and high waveform coherence (=high quality signal) we obtain an impression of the dispersive behaviour of fundamental mode Love waves immediately by looking appreciating the temporal evolution of the phase velocity: the dominant frequency of Love waves increases with time while phase velocities decrease.

Backazimuth Estimation

Similar to the phase velocity estimation and analogous to Igel et al. (2007), we investigate sliding windows throughout the signal to determine the evolution of the signal source direction. The traces are split into windows according to table 1. For each window, we estimate the direction of the signal in two pre-processed traces (vertical rotation rate & transverse acceleration) employing a grid search optimization algorithm.

The loops through all possible backazimuth directions (0° to 360°) in 1°- steps rotates the horizontal component acceleration (N-E) by the specified BAz-angle and then cross-correlates it with the vertical rotation rate. The process is illustrated in figure 4 [a] where a color range is assigned to different BAz rotation angles. The CCs are maximal for a rotation from N-E to radial-transverse which is equivalent to rotating in the direction of the strongest signal source (note: transv. acc. (black) and vert. rot. rate (red) are in phase).
In practice, only windows reaching 90% correlation after rotation are considered in the estimation of the final BAz value, which is the average of the associated (CC>0.9) BAz results (solid line in figure 4 [c]). Larger discrepancies between the theoretical and estimated BAz in combination with higher CCs on the estimated BAz side may indicate deviations of the Love wave path in the source-receiver plane. Thus, it might suggest heterogeneities/scatterers of similar size as the dominant wavelength along the direct great-circle wave path.

Conclusions

In the light of the rapidly improving rotation sensor technology and prospects of portable broadband rotation sensors for seismology (Bernauer et al. (2016), www.blueseis.com), we intend to promote the processing and use of rotational motion recordings by providing waveform plots and parameters as well as illustrated real data processing examples using ObsPy. Event parameters and waveform plots of more than 17000 earthquakes since 2007 can be downloaded and used for statistical analysis. This allows investigating the peak rotational ground motions as a function of magnitude and distance and the analysis of azimuthal effects on the wave field.

In the future, we plan on including recordings of additional ring lasers, such as the ones located at the observatories of Piñon Flat (USA, GEOsensor, Schreiber et al. (2003a)), Gran Sasso (IT, GINGERino, Ortolan et al. (2016), Christchurch (NZ, Schreiber et al. (2003b)) and the 4-component ring laser in Fuerstenfeldbruck (DE, ROMY = Rotational Motions in Seismology) to be installed in 2016. We also plan to integrate measurements of array derived rotations and portable rotation sensors as soon as sophisticated measurements are available.

Acknowledgments

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Data and Resources

The Global Centroid Moment Tensor Project database was searched using www.globalcmt.org (last accessed 5 August 2015)

The facilities of IRIS Data Services, and specifically the IRIS Data Management Center, were used for event metadata. IRIS Data Services are funded through the Seismological Facilities for the Advancement of Geoscience and EarthScope (SAGE) Proposal of the National Science Foundation under Cooperative Agreement EAR-1261681.

Tables

Table 1: Pre-processing parameters

	distance range	**lowpass cutoff**	**resampling decimation factor**	**cross-correlation window length**	**microseism bandstop**
close	$0° \leq d \leq 3°$	4 Hz	2	3 s	-
local	$3° \leq d \leq 10°$	2 Hz	2	5 s	-
tele	$d > 10°$	1 Hz	4	120 s	5 s - 12 s

Figures

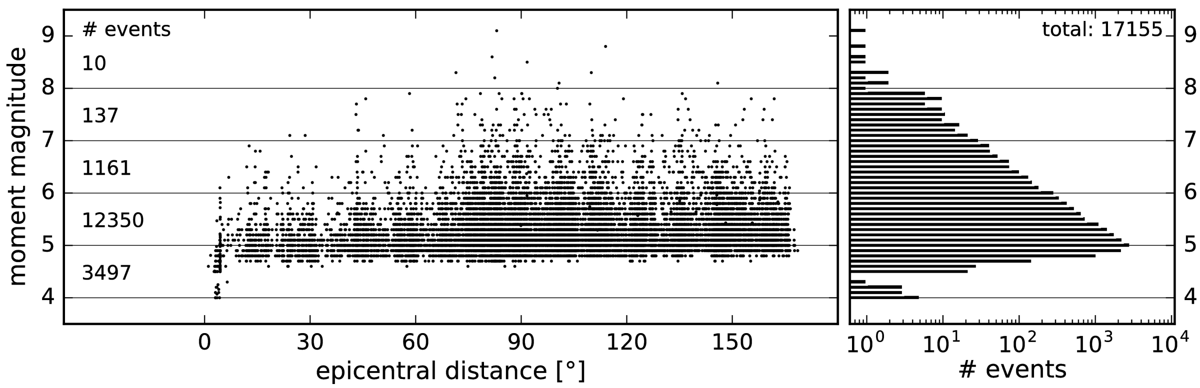

Figure 1: Distribution of the processed events from July 2007 to July 2016 by distance and magnitude [left] and number of events per magnitude in 0.1-steps [right]. Events provided by the Global Centroid Moment Tensor (GCMT) catalog.

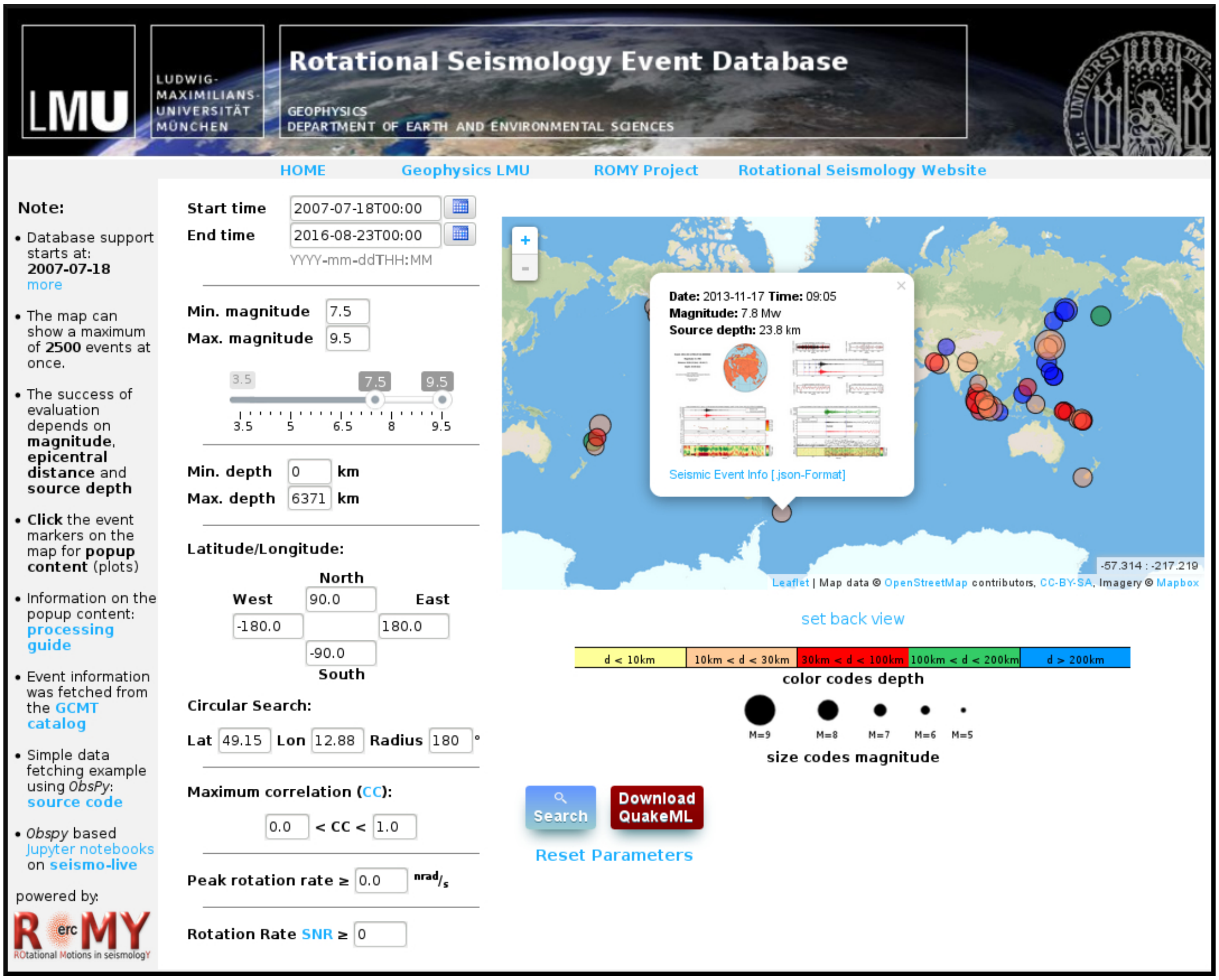

Figure 2: Web view of the event database for rotational seismology.

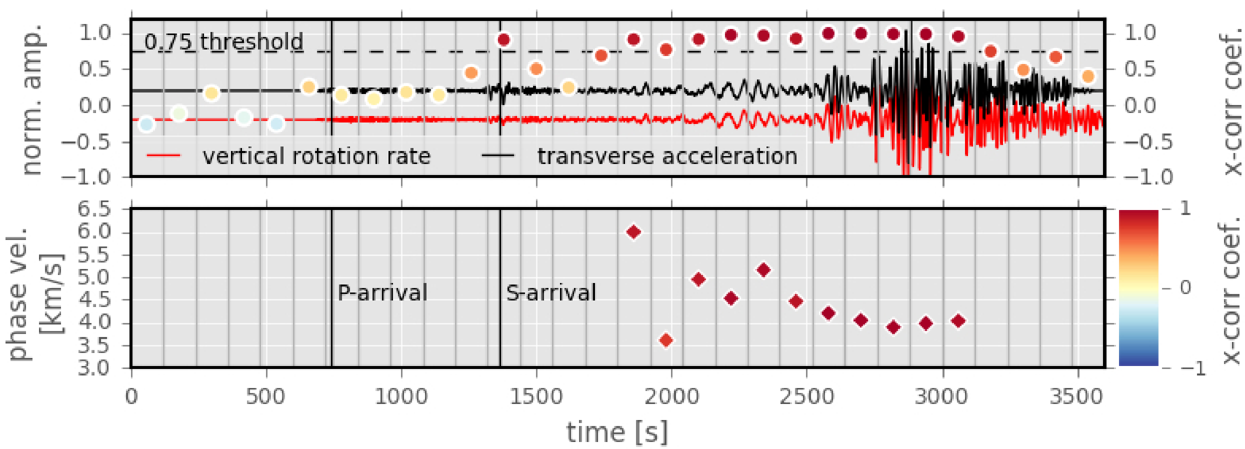

Figure 3: Visualization of the sliding window phase velocity estimation for the M9.0 *Tōhoku* earthquake 03/11/2011. For each of the time windows, a cross-correlation is performed between vertical rotation rate and transverse acceleration [top]. We estimate phase velocities for windows associated with correlation coefficients (**CC**) larger than 0.75 and later than S-waves [bottom].

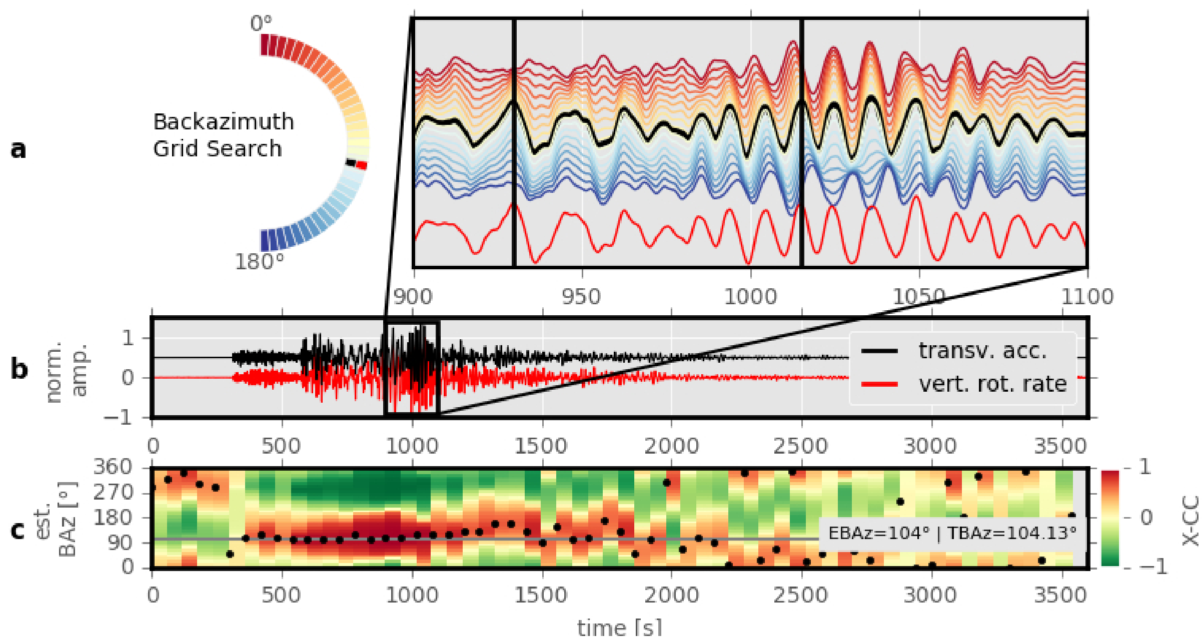

Figure 4: Illustration of the backazimuth estimation workflow at the example of the M7.1 Turkey quake 10/23/2011. (a) The grid search algorithm loops through all possible source directions (red to blue) in 1°-steps, cross-correlating the two traces of a_t and $\dot{\Omega}_z$, shown in (b). In (c) for each time window, the BAz-value related to maximum correlation is displayed as a black dot. Here, red color displays correlation, while green is anti-correlation of the traces for the specific BAz angle. Estimated (EBAz) and theoretical backazimuth (TBAz) are indicated by the gray solid line.

Figure Captions

Figure 1:

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Figure 2:

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