# 6th International Working Group on Rotational Seismology Meeting 2022

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## — Abstracts —




*by Andreas Brotzer (LMU)*

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# Longterm stable inertial rotation sensing: the detection of the variations in the ‘Length of Day’

Ulrich Schreiber (1), Jan Kodet (1) and Urs Hugentobler (1)

Large ring laser gyroscopes have continuously improved in stability and sensitivity over the last 25 years, when they have been taken back to the laboratory in order to be applied to measurement problems in space geodesy. The desired detection of the variation in the “Length of the Day” signal required an enhancement in sensitivity of 6 orders of magnitude over the early square-meter size cavities and a more than 5 orders of magnitude improvement in sensor stability. After following a rather bumpy road of important and continuous progress, we have come to the point where this challenging goal has become a reality. This talk outlines what our sensors can now do and what the next challenges on this road ahead are like.

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# Field testing the QRS rotational seismometer for geohazards and scientific monitoring

Paul Bodin, Krishna Venkateswara, William Wilcock, Harold Tobin, Jerome Paros

Accurate and precise observation of the rotational components of vibration of the ground and of structures is challenging and remains at the advancing forefront of seismological monitoring. In the context of geohazards monitoring several objectives fuel continued research and development of both instrumentation and theory. For example, a long-standing objective of rotational seismology is to directly identify the rotational elements of the seismic wavefield to obtain more accurate S-phase arrivals from earthquakes. Another objective is to identify rotational interference and “crosstalk” that may afflict co-located translational seismic data channels and ameliorate artifacts they cause. Observations of rotations have also been recently shown to have potential value in volcano monitoring. Rotational modes of motion of built infrastructure components are important for recognizing and reducing the risk of structural damage and failure. We present a description and initial test results from a new Quartz Rotation Sensor, QRS, developed by Quartz Seismic Sensors and Paroscientific. The portable QRS combines a mechanical angular accelerometer sensing rotational torque with a load-sensitive resonant quartz crystal to provide inherently digital broadband observations of rotation. The combination provides superior isolation of rotations from translational motions and a lower noise floor than other similar-sized designs currently employed. We deployed a QRS system alongside a broadband seismic station in a quiet vault in Washington state for a 3-month-long test. During the experiment we observed rotational and translational motions from several small (M<3) local and regional earthquakes as well as longer-period waves from large teleseisms. The noise floor was measured to be ~45 pico-radian/Hz-1/2 at 1 Hz and ~23 pico-radians/Hz-1/2 at 0.1 Hz, the sensor’s resonant frequency. Among other similar-sized, broadband rotation sensors, this represents more than two orders of magnitude improvement in noise floor. Further lowering the noise floor and isolation from translational motions are key objectives for advancing the usefulness of rotations in geohazard monitoring.

# Fiber optical sensors applications in geoscience

Sunjay (1)

Distributed Fibre Sensing (DFS) includes Distributed Acoustic Sensing (DAS) Distributed Vibration Sensing (DVS) seismometer , distributed stain sensor DSS and Distributed Temperature Sensing (DTS). DFS using fibre-optic cables, in the wellbore , DAS for the measurement of ground motion in a land surface seismic environment using trenched horizontal fibre-optic cables . The use of DFS in the downhole environment is an established technology particularly for VSPs Vertical seismic profiling and temperature measurements. The sensing probe of the fiber Bragg grating geophone is made up of Fiber Bragg Gating (FBG). The information which it collects is embodied in wavelength. The modulation-demodulation is accomplished by FBG geophone directly. Compared with traditional geophone, there are many advantages, such as higher resolution, wider bandwidth, higher accuracy and better immunity to electromagnetic interference, which meet the new needs in the seism probing field.The coupled mode equations are built by means of expanding perfect wave-guide modes, the relationships between the reflective spectrum characteristics of fiber Bragg gratings and their structural parameters(grating length, coupled coefficient)are obtained. The temperature, strain and pressure sensing mechanisms of fiber Bragg gratings are studied systematically.A high sensitive Fiber Bragg Grating(FBG) geophone/optical sensor is employed for seismic exploration and hydrocarbon production. Real Time Fiber Optic Casing Imager (RTCI) provides a three- dimensional image of the casing or sand control screens as they are stressed during production by shifting formations such as salt or unconsolidated sandstones. Distributed optical fiber temperature sensors adopting optical fiber scattering theory can overcome the shortcomings of traditional point electronic sensors that cannot work in environments of high temperature, high pressure, corrosion, strong geomagnetic disturbances, etc. Monitoring temperature data obtained by the distributed optical fiber temperature sensing monitoring system is inevitably adulterated with noise, thus affecting the accuracy of monitoring data.DTS signal is so weak that the signal is very difficult to be detected. The noise level in the acquired signal is very high, and the temperature error is not little. A wavelet transform is employed to decrease the temperature error by signal denoising.A high sensitive Fiber Bragg Grating(FBG) geophone/optical sensor is employed for seismic exploration and hydrocarbon production.Fiber Bragg Grating Peak Wavelength Detection is done by Wavelet Analysis, discrete wavelet transform (DWT) for the demodulation, demultiplexing and denoising of sensor data, as well as in the detection, extraction and interpretation of measurand-induced change from an acquired sensor signal. Singular value decomposition is used for FOS data analysis. Large data set terabyte data analysis is done by machine learning, deep learning ,statistical learning. FOS data full waveform inversion of seismic data , curvelet seismic wavefield for lithosphere subsurface imaging.

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# 3D transversely isotropic shear-wave velocity structure of India and Tibet from joint modeling of Rayleigh and Love waves group velocity dispersion.

Siddharth Dey, Monumoy Ghosh, Rupak Banerjee, Shubham Sharma, Supriyo Mitra, SN Bhattacharya

We use regional Rayleigh and Love wave data, from 4750 earthquakes (M >= 4.0) recorded at 726 stations across India and Tibet, to compute fundamental mode group velocity dispersion between 10 s and 120 s, using the Multiple Filter Technique (MFA). These result in the dense coverage of 14,706 and 14,898 ray-paths for Rayleigh and Love waves, respectively. The dispersion data at discrete periods have been combined through a ray-theory based tomographic formulation to obtain 2D maps of lateral variation in group velocities, where the best resolution is up to 2.5° and 4° for Rayleigh and Love waves tomographic maps, respectively. The Peninsular Shield, the Himalayan foreland basin, the Himalayan collision-zone and the Tibetan Plateau, have been sampled at unprecedented detail. Rayleigh and Love wave dispersion curves, at each node point of the tomography, have been inverted for 1D isotropic shear-wave velocity structure of Vsv and Vsh, respectively, which are combined to obtain 3D Vsv and Vsh structures across India and Tibet. We jointly invert the two datasets at each node to obtain an isotropic 1D velocity structure. The isotropic inversion fits the two datasets reasonably well, however, the misfit in the dispersion dataset both at high and low periods is high. For this, we incorporate radial anisotropy in the velocity structure and parameterize the crust with three layers and upper mantle with two layers. Assuming this radially anisotropic earth structure, we use Genetic Algorithms (GA) to explore the model space extensively. The synthetic dispersion curves are computed using Thomson-Haskell method with reduced delta matrix. The free parameters used in the inversion are VPH and VSH, layer thickness (h) and Vs anisotropy represented by Xi (ξ=VSH/VSV)2. The non-linear inversion technique converges to a best-fitting model by iteratively minimizing the misfit between the observed and the data. The 2D group velocity dispersion heterogeneities, the 3D structures of Vsv and Vsh (both isotropic and transversely isotropic) will be presented with a focus to characterize a) the structure of the Indian plate and it's extent of underthrusting beneath Tibet, and b) to quantify the low-velocity zone at the base of the Himalayan wedge, across the basal decollement, which ruptures in megathrust earthquakes.

## Application of rotation rate measurements for model updating of damaged reinforced concrete beams

Bońkowski Piotr Adam, Bobra Piotr, Zembaty Zbigniew

The model updating is a group of techniques used for determination of parameters of finite element models based on the static or dynamic response of a real structure. With this technique, stiffness and mass distribution can be obtained for the analyzed structure. By analyzing the change in the stiffness distribution during the lifetime of the object, one is able to localize and quantify damages in the structure, which is the main task of structural health monitoring. The structural health monitoring systems of civil engineering structures consist of many types of sensors such as MEMS accelerometers or fiber Bragg grating strain sensors. Despite extensive research, structural health monitoring still struggles with precise damage detection of complex, nonlinear structures like reinforced concrete structures. In reinforced concrete structures, the applied load produces cracks and reduces structural stiffness, which hinders the detection of damage. Here, we propose the application of novel rotation rate sensors for the reconstruction of the stiffness distribution of reinforced concrete elements with the model updating technique. The rotation rate measurements provide information on the first spatial derivative of natural modes, which can be easily compared with the numerical model. In the presentation, experimental results of progressively damaged reinforced concrete beams are presented. Rotation rate measurements are shown to enhance the stiffness reconstruction of damaged reinforced concrete elements.

## Single-point dispersion measurement of surface waves combing translation and rotation or strain in weakly anisotropic media: theory

Le Tang, Heiner Igel and Jean-Paul Montagner

A new approach is proposed for measuring the single-point dispersion relation of surface waves in weakly anisotropic media using a single station, which consists of translation and rotation or strain. The azimuth-dependent surface wave dispersion curve can be directly obtained only by using the translation to rotation or strain ratio, which can characterize the azimuthal anisotropy of subsurface media. The amplitude ratio method gives the localized azimuth-dependent dispersion relations of the formation right beneath a receiver without requiring knowing any of the source or model information, which will not be affected by the heterogeneity or anisotropic regions in the propagation path. The theory shows that the generated coupled waves between quasi-Rayleigh (qR) wave and quasi-Love (qL) wave will result in rotational motions to become elliptical polarization in anisotropic media instead of linear polarization in isotropic media, whose polarization plane remains perpendicular to the direction of propagation of the phase velocity indicating the applicability of calculating azimuths of the direction of propagation utilizing horizontal rotational components. Our numerical results demonstrate the correctness and applicability of derived equations for measuring the azimuth-dependent dispersion curves and azimuths, which will support higher lateral spatial resolution for anisotropic study.

## Analysis of volcano-seismicity on Etna using rotational sensor data

E. P.S. Eibl, M. Rosskopf, M. Sciotto, G. Di Grazia, G. Currenti, P. Jousset, F. Krüger, and M. Weber

Etna volcano in Italy is one of the most active volcanoes in Europe. We recorded the volcanic activity including degassing and vigorous strombolian activity using a seismometer and a rotational sensor in August to September 2019. We test the newly developed rotational sensor in the field in comparison to the broadband seismometer and seismic-network-based locations using the INGV network. We demonstrate that a single rotational sensor co-located with a seismometer can be used to identify specific seismic wave types, to estimate the back azimuth of wave arrivals and the local seismic phase velocities.

Using the rotational sensor, we easily detected the dominant SH-type waves composing volcanic tremor during weak volcanic activity and the recorded VLP/ LP events. Changes in the composition of the tremor wavefield caused by the onset of vigorous volcanic activity are obvious and can be detected in near real-time if data is streamed. We discuss the changes in the wavefield composition from SH-type waves to a mixed wavefield in the context of the volcanic activity, the back azimuth of the signals and associated phase velocities. Our findings are consistent with observations by INGV and hence the rotational sensor reliably enlarges our sensor portfolio in volcanic environments.

# A small-aperture seismic array for dynamic deformations northwest of the Guerrero seismic gap, Mexico

Miguel Angel Santoyo, Raul Daniel Corona-Fernandez, Oscar Castro Artola

Recent studies have shown that several devastating earthquakes in Mexico are strongly related to the occurrence of Slow Slip Events along the Mexican Subduction Zone (MSZ), describing a succesive development of events interacting with each other on a regional scale, produced among others by dynamic perturbations from passing seismic waves across the states of Guerrero and Oaxaca south Mexico. In this frame, it becomes essential to study in detail, the dynamic deformations including strains and rotations, as also the dynamic stresses at depth, produced by subduction and intraslab earthquakes close to the seismic sources.

The analysis of dynamic deformations derived from seismic ground motion observations at surface allows to estimate the underground strains, rotations and stresses at depth, by means of, for example, the surface waves eigenfunctions at the interest sites. During March 2018, it was installed a temporal seismological network, consisting of three triaxial broadband (T=120s) seismic stations configured as a small-aperture array, that together with a permanent seismological station operated by the National Seismological Service SSN of Mexico, allows to compute from recorded data, the surface displacement gradients and the dynamic deformations including strain and rotation time histories. This array was installed in the close vicinity of the ZIIG-SSN station, in the Ixtapa-Zihuatanejo International Airport area.

In this array the relative distance between stations was set $\Delta r < 150$m, allowing to estimate relatively high frequency time histories for deformations and rotations, as $\Delta r < \frac{1}{4} \lambda$, where $\lambda$ is the minimum wavelength of interest. For the deformation computations, we first corrected for the possible minor sensor orientation deviations relative to North, that occasionally occurs during the station installation. Here, we computed the dynamic strains and rotations for different recorded earthquakes with magnitudes $4.0<M<5.2$, occurring in the vicinity of the array along the Mexican Subduction Zone between April 2018 and October 2019.
Our first results show that this network allows well to identify the surface dynamic deformations in this specific site on the MSZ. The orientation deviations of sensors observed here were found all smaller than 4º which were adequately corrected. The dynamic strains and rotations using the seismo-geodetic and single station method shows good agreements, allowing the dynamic rotations obtained here to be included as new constraints for source inversion. Additional result shows also that the dynamic rotations obtained may be also included as new constraints for hypocentral locations of the local seismicity.

## Deep earth rotational seismology

Rafael Abreu, Stephanie Durand, Sebastian Rost and Christine Thomas

Rotational seismology opens a new avenue to study the deep interior of the Earth. Using data from the Wettzell Observatory, Germany, where a ring laser gyroscope and a 3-component translational broadband seismometer are co-located, we report the presence of clear ScS and SdS signals on both rotational and translational seismograms. Using these deep Earth sampling arrivals we propose a new methodology to extract information on velocity changes in the lower mantle directly. We show that combining rotational and translational signals is powerful and can directly provide lower bound velocity estimates without the need of inversion techniques. We validate the methodology using sensitivity kernels and synthetic tests. The estimated velocity perturbations derived from the Wetzell dataset show similarities with recent models of the study region.

## Comparing single-station 6C measurements and array measurements for seismic microzonation in Munich, Germany

Sabrina Keil, Alexander Wilczek, Joachim Wassermann, Simon Kremers

The essential goal of seismic microzonation is the estimation of the shallow velocity structure in order to characterize the local earthquake shaking characteristics. This is of special importance in densely inhabited areas with unfavorable soil conditions. The common approach is the analysis of ambient noise array data using frequency-wavenumber (FK) or spatial autocorrelation (SPAC) techniques. However, the installation of arrays is difficult, especially within urban environments, making single-station approaches more desirable. In this study, we directly compare the recently developed approach of velocity estimation using single-station six-component (6C) measurements, combining three translational and three rotational motions, with the established methods of FK and SPAC analysis. We conduct measurements in Munich's inner city using a geophone array and an iXblue blueSeis-3A rotational motion sensor together with a Nanometrics Trillium Compact Seismometer, respectively. From the array data, as well as from the 6C data, Love and Rayleigh dispersion curves are estimated and further inverted for 1D P- and S-wave velocity profiles. We find that all methods give similar results, indicating the potential of the novel 6C approach.

## Machine learning applied to 6C polarization analysis

David Sollberger

We present a technique to automatically classify the wave type of seismic phases that are recorded on a single six-component recording station (measuring both three components of linear motion and rotational ground motion) at the Earth's surface. We make use of the fact that each wave type leaves a unique 'fingerprint' in the motion of the six component sensor. This fingerprint can be extracted by performing an eigenanalysis of the data covariance matrix, similar to conventional three-component polarization analysis. To assign a wave type to the fingerprint extracted from the data, we compare it to analytically derived six-component polarization models that are valid for pure-state plane wave arrivals. For efficient classification, we make use of the supervised machine learning method of support vector machines that is trained using the data-independent, analytically-derived six-component polarization models. This enables the rapid classification of seismic phases in a fully automated fashion, even for large data volumes, such as found in land-seismic exploration or ambient noise seismology.

We illustrate the benefits of our approach for applications such as automated phase picking, ground-roll suppression in land-seismic exploration, and the rapid extraction of surface wave dispersion curves from single-station recordings of ambient noise. Additionally, we argue that an initial step of wave type classification is necessary in order to successfully apply the common technique of extracting phase velocities from combined measurements of rotational and translational motion.

# Wave field prediction for denoising of gravitational wave measurements using an autoencoder network

Jana Klinge (1), Dirk Gajewski (1), Celine Hadziioannou (1), Jan Walda (1)

The composition of the ambient seismic noise wave field – in absence of any earthquakes – is particularly relevant for the construction of the Einstein Telescope (ET). As the proposed underground infrastructure to host a gravitational-wave observatory of third generation, ET aims to achieve a significantly enhanced sensitivity in comparison to preceding generations. However, different seismic noise sources affect the measurements of the ET detector and are thus a major concern regarding the entire data analysis pipeline. The adoption of machine learning in different sectors demonstrates by now a huge potential of multiple techniques applicable also to learn specific features of a dataset. We make use of deep learning to predict the wave field development and will use this information in future steps to remove random noise post-measurement. Our work follows a two-fold strategy and targets, on the one hand, the measurement of seismic noise using rotational seismometers as well as its characterization with data correlation as the backbone of seismic interferometry. On the other hand, we make use of an autoencoder network in a self-supervised fashion. While aiming to reconstruct its input, a customized setup enables to investigate suitable configurations essential to automatically learn a representation of the wave field and predict its spatial development.

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# Accounting for sub-wavelength heterogeneities in full waveform inversion based on wavefield gradient measurements

Kota Mukumoto (1), Sneha Singh (2) , Yann Capdeville (2), Takeshi Tsuji (3)

Seismic full waveform inversion uses mostly translational motions including displacement, velocity, and acceleration both for numerical tests and real applications. Translational motions are insensitive to sub-wavelength structures. Recent advances in seismic sensors enable us to observe new types of data including strain, spatial gradient, and rotation. As opposed to translational motions, such new types of data have sensitivity to localized sub-wavelength structures. Nevertheless, this subwavelength sensitivity is limited to the vicinity of the receivers. In this work, we study if this different nature of wavefields could make difference in the resolution, accuracy, and inversion strategy of full waveform inversion. We show that the local sensitivity of spatial gradient measurment measurement is more a difficulty in full waveform inversion rather than improving the spatial resolution. We find that full waveform inversion using a spatial gradient could estimate incorrect tomographic images due to the effects of sub-wavelength structures, even when accurate images can be obtained using displacement data. This finding suggests a new strategy for full waveform inversion using a spatial gradient is necessary.
We propose a new inversion method to mitigate the effects of sub-wavelength structures based on the two-scale homogenization theory which has been recently introduced to seismology. Here, a two-step inversion is adopted. One is the inversion of correctors that need for modeling the effects of sub-wavelength structures and adding correctors to simulated data. The second step is the inversion of model parameters. We show that this two-step inversion using spatial gradient data can successfully mitigate the small-scale effects. In addition, we conducted a statistical analysis of inverted model parameters for the evaluation of our two-step inversion and found that the full waveform inversion using spatial gradient has a similar resolution compared to one using displacement if the inversion is performed with correctors.

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## Recording of the rotational events in Poland – Time horizon & fascinating future of fiber-optic seismograph

A.T. Kurzych, L. R. Jaroszewicz, M. Dudek, Jerzy K. Kowalski, T. Widomski

Geological and engineering aspects of rotational seismology are ones of the most developing interests among seismological and civil engineering societies. Recently, the ultimate goal is to achieve full six degree-of-freedom ground-motion data which is a key point to better understand the origin of earthquakes and in particular to relate them to the geological context. The paper presents a huge Fiber-Optic Seismograph (FOS5-04) with its rotational motion recordings induced by natural factors as well as mining activities including its historical perspective. FOS5-04 utilizes the Sagnac effect based on a minimum optical configuration and all digital closed-loop processing designed for a fibrer-optic gyroscope with a special attention to angular motion detection. The experimental results indicated that FOS5-04 is characterized by a wide measuring range, it detects signals with amplitudes ranging from several dozen nrad/s up to even few rad/s and frequencies from 0.01 Hz to 100 Hz. We present the recordings of rotational events generated by the exploitation of the copper ore deposit as well as long-term measurements, showing results confirming positive detection of small differences in Earth's rotation rate. Moreover, the future three-axes Fiber-Optic Seismograph (FOS6) system is presented which gives a broad view of its potential application in the area of rotational seismology including seismic monitoring in observatories, buildings, mines, chimneys and even on glaciers and in their vicinity.

## Validation of back azimuth estimates using 8 BlueSeis-3A rotational sensors in an active source experiment

Gizem Izgi, Eva P.S. Eibl, Frank Krüger and Felix Bernauer

To assess the performance of the rotational sensors blueSeis-3A in seismology a two stage experiment including five explosions was performed in Fürstenfeldbruck, Germany in November 2019. In this study, we used eight blueSeis-3A rotational sensors and conventional seismometers to locate the artificial explosions from varying locations. In the first stage, all rotational sensors were located inside a bunker with a Streckeisen STS2.5 seismometer and two explosions were performed. Whereas in the second stage, we formed two arrays each including four rotational sensor and recorded three explosions at varying distances with 1500 g of explosives. We used two methods to estimate the back azimuths. We compare our back azimuth estimates from using vertical rotation rate/transverse acceleration with back azimuth using only horizontal rotational components. We investigated the signal to noise ratios of each sensor to assess the reasons for the discrepancy of the estimated back azimuth angles. We point out that the source distance, amount of explosives, buried objects causing scattering, tree roots and any electrical source such as power lines has an impact on the signal to noise ratio. Back azimuths calculated using only horizontal rotational components give more accurate results which is consistent with the priori that explosions create predominantly SV type of waves. We also observe SH type of waves due to source scattering. Thus, using the vertical rotation rate and transverse acceleration is also a successful option if the rotational sensor is accurately co-located with a seismometer. Although the SNR accordingly varies with aforementioned features, rotational sensors can be used to reliably estimate the back azimuth of explosion using both methods.

## Effect of shallow heterogeneities on wavefield gradients measurements

Michel Campillo, Helle Pedersen, Romain Brossier, Ludovic Margerin

In the last years the use of rotational sensors and DAS became a topic of raising interest within the seismological community, due to their increasing sensitivity and affordability. Many works show the high sensitivity of rotational measurements to shallow velocity perturbations in the medium. In the context of seismic monitoring, we investigate the sensitivity of several observables to shallow localized velocity changes in a homogeneous media. We performed many numerical simulations, using an appropriately modified 3D seismic spectral element simulation code to observe, in addition to the displacement, the rotation and the strain as a direct output.

Seismic monitoring aims at studying waveform changes through the time, and to relate them with velocity or structural changes in the medium. Due to the presence of noise, the amplitude of a signal is generally difficult to measure very precisely. For this reason common ways to study velocity changes in the medium take advantage of the phase shift recorded through the time considering couples of receivers.

Keeping this in mind, in this study we studied two cases, the first where the velocity change is 10%, the second where it is 70%. For completeness of discussion we investigate the phase shift and the change in amplitude.

In all the simulations discussed in this study we considered seismic arrays deployed above a region where the velocity is changed between two realizations. We considered shallow sources described by moment tensors.
We then compared the phase-shift and the change of amplitude of the displacement wavefield, its time derivative and its gradients in the form of normal deformation and rotation to represent the new observables.

## On the subsurface monitoring capabilities of wavefield gradients: a case study from Mt. Zugspitze (German/Austrian Alps)

Fabian Lindner, Shihao Yuan, Krystyna Smolinski, Joachim Wassermann

Recent studies show that wavefield gradients, i.e. rotation and strain, provide novel insights into wave propagation. While rotational motions provide significant additional information on polarization properties, dynamic strain observations from distributed acoustic sensing (DAS) allow unprecedented spatial resolution. In addition, both rotation and strain observations exhibit increased sensitivity to near-receiver heterogeneities compared to the classical translational measurements. Incorporation of wavefield gradients is thus expected to advance the monitoring of subsurface changes towards a detailed spatio-temporal approach. Here, we present the first findings of an ongoing project dedicated to permafrost monitoring on Mt. Zugspitze (German/Austrian Alps). In summer/fall 2021, we installed three small seismic arrays (aperture ~40 m) designed for array-derived rotation/strain and ambient noise monitoring along the ridge of Mt. Zugspitze. In addition, we deployed a roughly 2 km long fiber-optic cable for DAS beneath the ridge in tunnel facilities, which we periodically interrogate (about once per quarter year for roughly ten days). Furthermore, we temporarily installed two blueSeis rotation sensors in summer 2022, hence, both array-derived rotations and strains can be compared to direct measurements.
We investigate the fidelity of direct and array-derived gradient observations with various recorded signals including artificial avalanche triggering explosions. We also use these signals to determine the wave’s propagation direction and velocity from six-component measurements (co-located rotations and translations). Finally, we calculate cross-correlations with wavefield gradients and find evidence for velocity changes similar to those from translational motions, which we attribute to seasonal freeze-thaw processes.

# Estimating the site effect parameters from rotational and translational signals produced by anthropogenic seismicity

Dariusz Nawrocki (1)

The seismic observation of the rotational and translational motion was carried out by two stations located in the central part of the Upper Silesian Coal Basin. The seismicity was caused by the exploitation of the hard coal by surrounding mines, and as a consequence, 110 events were registered by a translational accelerometer and a rotational seismometer. The Horizontal to Vertical Spectral Ratio (HVSR) method was used to estimate site effect parameters, i.e., resonance frequency and amplification value from translational motion. Estimating the rotational site effect parameters was performed using the modified HVSR technique, known as the Torsion to Rocking Spectral Ratio (TRSR). In general, a comparison of the obtained results between rotational and translation motion showed that rotations were characterized by a higher resonance frequency and lower amplification values than translations.

Nevertheless, the stations were situated in different geological conditions, i.e., depth level of the sediments and hard solid rock structures, which caused different amplification curves of the translational motions. Similar observations were noticed for the rotational motion. For the first station, the resonance frequency was equaled: 1.6 Hz and 1.8 Hz, respectively, for translations and rotations. While in the case of the second station, the resonance frequency was equaled 4.2 Hz and 5.6 Hz, respectively, for translations and rotations. The resonance frequency f0 can be approximated by the following equation:f0 = Vs /4H, where Vs and H denotes shear wave velocity and thickness, respectively.Considering the dependence of rotational resonance frequency on the shear velocity and thickness in a similar way as for the translational motion, it seems that the same geological layers generated the local site effect of the rotation and translation at a similar depth level for the first station. On the other hand, the resonance frequency of the rotations for the second station was significantly higher than for the translations, which suggested that shallower layers were responsible for producing the rotational site effect. Based on the geological profile for the second station, it seems that the difference between translational and rotational amplification may be related to the occurrence of the strong fracturing as well as the presence of the watertable, which did not occur in the case of the first seismic station.

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## Uncertainty assessment of the array derived rotation measurements

Roxanne Rusch (1,*), Olivier Sèbe (1), Stéphane Gaffet (2), Jean-Baptiste Decitre (2), Daniel Boyer (2), Alain Cavaillou (2), François Schindelé (1)

Analyzing the rotational motions of the seismic wavefield is useful for a multitude of applications ranging from the wavefield decomposition to geological structure estimation or source inversion (Igel et al. 2015, Sollberger et al. 2020). Despite the recent progress in performance (Bernauer et al. 2018), portable rotation sensors are not yet able to measure the seismic background noise in quiet environment. Parallel to the construction of high performance observatory sensors (Igel et al. 2021), several experimentations have shown that seismic rotation motions can be derived from the recordings of classical three translational component (3C) seismometers when arranged in a dense seismic array (Spudich et al. 1995, Suryanto et al. 2006) . Even if these Array Derived Rotation (ADR) measurements can theoretically estimate the seismic rotation background noise, the accuracy of this kind of indirect measurements can be strongly affected by the quality and the variability in the sensors response or installation conditions across the seismic array (Donner et al. 2017).
This work proposes to quantify, as a function of the array aperture and wavefield properties (frequency and wavelength), the uncertainty of the ADR measurements due to uncertainty or lack of detailed knowledge in the precise locations of sensors, orientations and instrumental response, along with the effects of some incoherent disturbing noises across the seismic sensor array. This approach has been applied to the ADR measurements performed with the (3C) dense seismic array deployed at the Low Noise Inter-Disciplinary Underground Science & Technology laboratory (LSBB), Rustrel, France. This analysis shows that a particular attention has to be paid, beyond the standard practices accepted for most seismic arrays, concerning the sensors' setting up in order to reach uncertainty lower than 10% on the derived rotation measurements.

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# Finite-fault simulations for rotations and strains in the near-fault subjected to layered reduced micropolar half-space

Mohammad Atif, S. T. G. Raghukanth, S R Manam

The unmatched seismic theoretical rotations to the experimental data leads the researchers to developed the reduced micropolar theory in seismology. The study here mainly focus to the finite-fault simulations for rotations and strains in the near-fault region for a causative strike-slip fault of Mw 6.5 event. Firstly, the parametric investigation is performed on additional material parameter viz. micropolar couple modulus and micro inertia density to the rotations and strains. Secondly, the seismic source parameters such as rupture velocity, slip velocity, burial fault depth, earthquake magnitude, hypocenter location and slip amplitude are varied to see the effect of these parameters on rotations and strains seismograms. The results in different scenarios are compared to the classical elastic medium and reduced micropolar medium. The rotations obtained using reduced micropolar theory are comparatively high to the rotations of classical elastic theory. Although, the obtained displacement in both the theories are almost the same. The normal strains in both theories are equivalent, while the shear strains differ as the shear strains in reduced micropolar theory are asymmetric and rotation dependent. The increment in the value of micro inertia density increases the rotations, however the converse is true in the case of micropolar couple modulus. The parametric analysis results demonstrate that near-fault ground rotations and strains are highly sensitive to changes in the seismic source parameters. For instance, modeling the medium homogeneous decreases the amplitude and duration of seismograms sharply compared to layered media. Finally, peak ground contours of displacements, rotations and strains are presented for different hypocenter locations using grid point simulation, and it is found that change of hypocenter location alters the spatial distribution of peak values of these quantities in the near-fault region of surface plane. Nevertheless, the maximum limit of peak values over the entire ground surface is near equal for the different hypocentral locations.

## Can we use only one 6C-station to perform deep characterisation of a building?

Yara Rossi, Konstantinos Tatsis, John Clinton, Eleni Chatzi, Markus Rothacher

We demonstrate that a detailed characterisation of the dynamic response of an engineered structure can be obtained from measurements at just a single position, if rotation is recorded in combination with translation measuring 6 components (6C). A detailed characterization goes beyond simply identifying natural frequencies by also including information on modeshapes. Such a 6C-station approach can save significant time, effort and cost when compared with traditional structural characterization using accelerometer arrays. In our contribution we will focus on the monitoring of a high-rise building by tracking its dynamic properties and their variation, e.g., natural frequencies and mode shapes, over 1 year. We present the system identification for the concrete frame Prime Tower in Zurich – the third highest building in Switzerland with a height of 126 m, using both arrays and the multi-sensor 6C-station.
The building has been continuously monitored by an accelerometer (EpiSensor), a co-located rotational sensor (BlueSeis) and a weather station located near the building center on the roof. Roof and vertical seismic arrays were deployed for short periods. The first 6 modes within the frequency band from 0.3 to 4 Hz are characterized using the stochastic subspace identification (SSI) method that is well known in the structural monitoring community. We compare the quality of the estimated frequencies and mode shapes of the 6C-station to array solutions and find that the 6C-station solution is of high quality and reliable. The daily and yearly frequency variations are tracked equally well as with the array solution. However, only the 6C-station solution allows to distinguish between torsional and bending modes clearly and easily, from using only 1-2 h of data. The analyzed frequency band is of key interest for earthquake excitation, making an investigation and knowledge thereof essential.

# Using rotational motions to understand material damage in civil engineering structures

Anjali C. Dhabu (1), Felix Bernauer (2), Chun-Man Liao (3), Celine Hadziioannou (1), Ernst Niederleithinger (3), Heiner Igel (2),

The increasing evidence of rotational motions due to earthquakes is now motivating civil engineers to investigate the effects of rotational ground motions on structures. With the advancement in instrumentation techniques, rotational sensors have been developed in the past few years, which can measure three components of rotational waves in addition to the translational waves. Conventionally, buildings are designed to withstand horizontal and vertical translational ground motions to minimize the damage to human life and financial losses during an earthquake. Damage to the structure is identified at two levels; (i) structural and (ii) material. The structural damage in reinforced concrete buildings is visible in the form of cracks and spalling concrete, which reduces the overall load-carrying capacity of the building. The damage at the material level is not visible to the human eye. This damage can be identified using coda wave interferometry techniques. In this method, a high cross-correlation between the coda of two waves passing a point on different days of experiment indicates a negligible change in the shear wave velocity of the material. In comparison, a lower cross-correlation signifies considerable change in the material properties.

In order to understand how rotational motions affect reinforced concrete structures and how these can be simulated, the present work makes a novel attempt to use the newly developed rotation measuring sensors, BlueSeis 3A and IMU50, to understand the damage in a model concrete bridge structure (BLEIB). We employ advanced sensors in addition to conventional broadband and ultrasonic sensors on the 24m long two-span continuous reinforced concrete bridge equipped with various non-destructive sensing techniques and subjected to a variable pre-tension force of up to 450kN and various static loads. As an initial analysis, we first identify the bridge's first three fundamental frequencies and mode shapes from both recorded translational and rotational data. The analysis shows that the same fundamental frequencies are obtained from the recorded translational and rotational data. However, we expect to see a difference in the mode shapes. Theoretically, rotations are maximum at the bridge support and minimum at the centre of the bridge span. This behaviour is the reverse of what we observe from translational motions, where maximum translations are observed at the centre of the span while minimum at the supports. As the study plans to simulate rotational motions for reinforced concrete structures, a finite element model of the prototype bridge is also developed, and the fundamental frequencies and mode shapes of the model are validated with those obtained from the recorded data. This work shall be extended to applying coda wave interferometry to the rotational data recorded on the bridge to understanding the change observed in material properties when the bridge is subjected to active and passive forces.

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## Reduced micropolar theory: an alternative to model the earth medium and simulate earthquake ground motions?

Anjali C. Dhabu (1), Raghukanth S. T. G. (2)

Ground motions due to earthquakes cause heavy losses to human habitation and the economy. To reduce the damage from earthquakes, ground motions are often simulated to estimate the forces a building will be subjected to when an earthquake strikes. Conventionally, the buildings are designed to withstand horizontal and vertical translational ground motions. However, with the improved earthquake recording instruments and growing evidence of rotational ground motions due to earthquakes, there is a need to obtain reliable estimates of rotational ground motions synthetically. The characteristics of the simulated ground motions depend upon the medium of wave propagation, the seismic source, and the boundary conditions. Traditionally, the medium of wave propagation is modeled using classical elastic theory. Researchers have recently attempted to explore micropolar theory to represent the Earth medium. In this context, Schwartz et al. (1984) proposed the Reduced micropolar theory to model wave propagation in a granular media. In this theory, there are two basic equations of motion and displacement and rotation are coupled. In addition to the density ρ and Lame's constants, λ and μ, the theory requires two additional constants, κ and j, to describe the motion. As the top layers of the Earth medium can be considered granular media, it will be interesting to model the Earth medium using this theory and estimate ground motions. As the theory is still in a developing stage, the analytical solutions of the medium subjected to different forces are not yet available. Therefore, as an initial attempt, we modeled the Earth medium as a homogeneous reduced micropolar half-space to determine its response to a given force. For a given applied force, the obtained mathematical solutions can be used to determine the response of the homogeneous reduced micropolar half-space. Specific solutions for translations and rotations for the homogeneous half-space subjected to uniformly distributed load, impulse and earthquake forces are also determined in this study. Parametric analysis is carried out to determine the effect of the additional material parameters on the ground motions simulated for an earthquake force. It is found that the translational motions show negligible change for different values of κ and j. However, a significant change is observed in the simulated rotational ground motion for different values of the additional material properties. To further understand this effect of additional material properties, an attempt is made to model the Earth as a layered reduced micropolar medium. Analytical solutions are determined for the layered reduced micropolar half-space subjected to an earthquake, modeled as a point source. Translational and rotational ground motions are simulated for the 5.9 Mw Wutai earthquake by modeling the wave propagation medium as reduced micropolar half-space and classical elastic half-space. It is observed that the rotational ground motions for reduced micropolar half-space are considerably higher as compared to those obtained from a classical elastic medium. Also, the peak rotational ground motion about the vertical direction obtained from reduced micropolar half-space matches well with the peak rotational ground motion reported in the literature for this earthquake. The analysis shows that reduced micropolar theory can be further explored in the context of its applications in seismology.

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## Core-mantle boundary heterogeneities inferred from 6-DoF single-station observations

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The core-mantle boundary is highly heterogeneous containing multiple poorly understood seismic features across various scales. The smallest but strongest heterogeneities yet observed are 'Ultra-Low Velocity Zones' (ULVZ), some of which have been interpreted as the base of mantle plumes. Seismic diffracted waves (Sdiff) along the core-mantle boundary might shed some light on those mysterious structures. In a recent study, a rare core-diffracted signal refracted by the ULVZ at the base of the Hawaiian mantle plume is observed and shows remarkably longer time delays, indicating exceedingly reduced shear-wave velocity, up to 40%, within the Hawaiian ULVZ (Li et al, 2022). Such velocity perturbations may cause evident multipath effect and strongly distort the arrival-angles of the diffracted waves. Traditional studies may use beamforming techniques based on seismic array measurements to study the directions of incoming phase and its associated post-cursors. However, the resolution of beamforming might be limited by the aperture and distribution of seismic arrays.

Alternatively, the 6-degree-of-freedom (6-DoF) measurement, which combines translational and rotational observations at a single station, can deliver similar information compared to an array of triaxial seismometers. The ring laser gyroscopes (ROMY and G-ring) and the collocated seismometers at the LMU and Wettzell geophysical observatory provide a fascinating opportunity to record broadband 6-DoF ground motions with possibly unprecedented accuracy for teleseismic events.

In this study, we measure the arrival-angle anomalies of core-diffracted shear waves using the 6-DoF point measurement. We find the lateral refraction may be more common than previously expected. By exploiting the 6-DoF synthetics, we also demonstrate that the observed Sdiff lateral refraction is difficult to be explained by the heterogeneity elsewhere, even under some enhanced tomography models. These lateral refractions are more likely to be attributed to the lower mantle structure. We are working towards a robust, quantitative, and panoramic assessment of the multipath effect caused by the lower mantle heterogeneities.

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## Rotational signals and noise on ocean bottom seismometers

Wayne C. Crawford and Felix Bernauer

Ocean bottom seismometers (OBSs) can greatly expand the spatial coverage of rotational seismology networks and offer unique applications for rotational measurements, including the rotational motion of the seafloor under ocean wave forcing (rotational compliance). Unfortunately, the horizontal channels for most low frequency OBS measurements are dominated by rotation of the sensor by seafloor currents. OBSs can be buried in seafloor sediments to reduce this noise, but at great cost. I will present the major opportunities and challenges of seafloor rotational seismology. A rotational seismometer in a seafloor instrument should allow a reduction of horizontal noise levels down to those of a buried instrument, while a rotational seismometer in a buried instrument should allow useful compliance and “classical” measurements. A new broadband ocean bottom seismometer under construction, using two single-axis fiber optic rotational seismometers, will be used to ground-truth seafloor measurements and applications.

## Characterizing the seismic background noise level for rotational ground motions on Earth

Andreas Brotzer (1), Felix Bernauer (1), Eleonore Stutzmann (2), Joachim Wassermann (1), Urich Schreiber (3) and Heiner Igel (1)

The development of high-sensitive ground motion instrumentation for Earth and planetary exploration is governed by so-called low-noise models which characterize the minimum level of physical ground motions observed across a broad frequency range. For decades, broad-band instruments for seismic translational ground motion sensing allowed for observations at the Earth's low noise model. This resulted, in particular, to the highly successful use of ambient seismic noise to image subsurface and time-dependent internal structures of Earth. Such a low noise model currently does not exist for rotational ground motions. In the absence of a substantial observational data base, we propose a preliminary rotational low noise model (RLNM) based on certain wavefield assumptions and subsurface structures. This RLNM can be used as guidance for the development of high-performance rotation instrumentation that measure the complete seismic wavefield.

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## 6C sensing applied to structural health monitoring

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Observing motion within a building in six degrees of freedom (three components of translational motion plus three components of rotational motion, instead of the classical three components of translation, only) opens completely new approaches to structural health monitoring. Inspired by inertial navigation, we can monitor the absolute motion of a building or parts of it without the need for an external reference. With directly recorded rotational motions, we can also correct translational acceleration recordings for dynamic tilt. In addition, rotational motion sensors can directly measure harmful torsional modes of a building, which has always been challenging and prone to errors with translation sensors, only. Currently we are developing methodologies to include rotational motion observations to coda-wave interferometry which in theory helps to better detect, locate and characterize structural damage. Within the framework of the GIOTTO project (funded by the German Federal Ministry for Education and Research, BMBF) we explore these approaches.
Here, we introduce a newly developed 6C sensor network for structural health monitoring. It consists of 14 inertial measurement units (IMU50 from iXblue, France) that were adapted to the needs of seismology and structural health monitoring. We performed experiments at the BLEIB test structure of the Bundesanstalt für Materialforschung und -prüfung (BAM), a 24 m long concrete beam serving as a large scale bridge model. We present results on instrument performance tests, as well as on detecting changes in the frequencies of the normal modes of the beam with varying pre-stress and load, as derived from translation, rotation and dynamic distributed fiber optic strain (DAS) measurements. We could detect seismic velocity changes within the concrete by means of coda wave interferometry with measurements of rotational motions and present first steps for a novel approach to detect seismic velocity changes in civil engineering structures by comparing amplitudes of translational to rotational motions at a single measurement point.

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## Wavefield gradient measurements and small scale heterogeneities

Yann Capdeville, Sneha Singh, Kota Mukumoto and Heiner Igel

The objective of this presentation is to show and explain the different nature of the seismic displacement field from the gradient of the displacement field concerning sub-wavelength heterogeneities. Through examples, we first show that the displacement field (or velocity or acceleration) is more or less insensitive to heterogeneity scales much smaller than the minimum wavelength and that this is not the case for any wavefield gradient measurement such as its rotational. We then explain these observations thanks to the homogenization theory. This special sensitivity to small-scale heterogeneities can be seen as, depending on the situation, an advantage or a serious issue. For most traditional applications such as tomography, this is a problem and we show how to correct it. We also show how it could be used as an advantage in some situations.

## FOSREM - from sky across ground up to underground

T. Widomski, J.K. Kowalski, A.T. Kurzych, M. Dudek, L.R. Jaroszewicz

The sensor operates as a result of the measurement of a difference between two interfering light beams propagating around a closed (very long) optical path, in opposite directions,

- Unique high-accuracy technology, so far available from 2 countries only;
- Sagnac effect, independent of Earth Gravity, for which the only frame of reference is Einstein's space time;

The Sensor produces high-resolution Big Data output for the next step of profile computing. When synchronized in the time domain, the sensors provide unique new 3D information not available from a single sensor. In addition, Rubidium's high-frequency option improves the resolution of frequency domain operations, providing so far undiscovered data. The main business profiles are Microseismic sensing (gas & oil, thermal water, mining industry), military, autonomous vehicles (autonomous cargo ships/drones/plains/robots), industry asset management.

## 3D P-phase reconstruction from a few days continuous recorded seismic ambient noise above the Chémery gas filed

Ali Riahi

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