OPOLE UNIVERSITY OF TECHNOLOGY

OPOLE 7 IWGoRS

Book of abstracts

7th Meeting of the *International Working Group on Rotational Seismology*

June 23rd – 26th, 2025

Faculty of Civil Engineering and Architecture

***Opole University of Technology*, Opole, Poland**

Introduction

This booklet contains set of 44 abstracts from the 7th Meeting of The International Working Group on Rotational Seismology (IWGoRS, https://www.rotational-seismology.org/) held at the *Faculty of Civil Engineering and Architecture*, *Opole University of Technology* (Opole, Poland) between June 23rd and June 26th 2025 (https://iwgors7.po.edu.pl/).

As the previous workshops, initiated in 2007 in Menlo Park (USA), and continued every three years worldwide, the lectures of the *7th IWGoRS Meeting* primarily deal with investigations covering all degrees of freedom of the seismic wave field, by extending conventional translational ground motion recordings along X, *Y*, *Z* axes with ground rotations about these axes: ψ_X, ψ_Y, ψ_Z. This extended set of recordings constitutes six component measurements (denoted in short 6C or 6-dof). Additional subjects discussed during the Workshop concern rotational metrology, measuring rotations in seismic and structural engineering, soil-structure-interaction, structural health monitoring (SHM), satellite geodesy, and last but not least, gravitational wave measurements.

The present workshop takes place almost a year after a successful, special, „rotational" session held during the *18th World Conference on Earthquake Engineering* in Milan: https://www.wcee2024.it/

https://program.wcee2024.it/?mode=session&id=GRM1

The subject of rotational seismology and rotational seismic engineering was described in the two keynote lectures by Igel et al., as well as by Bońkowski and Zembaty, which are now available online:

Igel H., Bernauer F., Wassermann J., Lindner F., Keil S., Tang L., Brotzer, A., Rotational Motions In Seismology and Engineering, *Proceedings of 18th WCEE*, Milan, June 30th – July 5th, 2024 https://proceedings-wcee.org/view.html?id=23167&conference=18WCEE

Bońkowski P.A., Zembaty Z., Rocking Ground Motion Effects on Towers and Tall Buildings, *Proceedings of 18th WCEE*, Milan, June 30th – July 5th, 2024 https://proceedings-wcee.org/view.html?id=23154&conference=18WCEE

The above two papers present a good introduction to the subject of both that special session of the 18th WCEE, as well as of the present Workshop in June 2025, in Opole, Poland.

Heiner IGEL and Zbigniew ZEMBATY

Program of 7th International Working Group on Rotational Seismology Meeting

Faculty of Civil Engineering & Architecture, Opole University of Technology, June, 23rd- 26th, 2025
(presenting author's names are underlined).

Monday, June 23rd, 2025

17.00 --- 21.00 Registration and icebreaker party

Aula of the Faculty of Civil Engineering & Architecture, Opole, Katowicka 48 street.

Tuesday, June 24th, 2025

8.00 --- 9.00 Registration

Hall of the New Wing of the Faculty of Civil Engineering & Architecture, Opole, Katowicka 48 street

9.00 --- 9.30 Welcoming addresses and introductory presentations,

9.30 --- 10.20 Session #1. (Chair: Yara Rossi & Varun Singla)

9:30-9:25 **keynote: SCHREIBER Ulrich K.** ***High Resolution Inertial Earth Sensing with Large Sagnac Interferometers***
9:55-10:00 Discussion
10:00-10:15 BROTZER Andreas, WIDMER-SCHNIDRIG Rudolf, IGEL Heiner, *On the influence of ambient atmospheric pressure on rotational ground motion at ROMY*
10:15-10:20 Discussion
10:20-10:35 BOŃKOWSKI Piotr, ZEMBATY Zbigniew, *Bounds for estimations of rocking ground motion effects on slender towers and buildings*

10.40 --- 11.40 Posters and coffee – part 1

11.40 --- 12.40 Session #2. (Chair: Toshiro Tanimoto & Piotr Bońkowski)

11:40-11:55 KURZYCH Anna, PAWEL Marc, DUDEK Michal, STASIEWICZ Karol, ZINOWKO Pawel, KONARSKI Karol, ZEMBALA Lukasz, SAKOWICZ Bartosz, JAROSZEWICZ Leszek, *Identifying and localizing the source of mechanical disturbance through the deployment of an appropriate array of FOS6 class fiber-optic rotational seismometers,*
11:55-12:00 Discussion
12:00-12:15 QIN Linpeng, GUO Zhen, WANG Yun*, Torsional and translational resonance amplification in a high-rise building*
12:15-12:20 Discussion
12:20-12:35 **commercial presentation by Güralp Stratis:** HILL Phil, MALETRAS Francois, WATKINS Neil, RESTELII Federica, LINDSEY James, MOHR Sally, *A Commercial 6 Degree of Freedom Seismometer for Academic and Research Applications,*
12:35-12:40 Discussion

12.40 --- 13.40 Lunch.

13.40 --- 15.10 Session #3. (Chair: Eva Eibl & Zbigniew Zembaty)

13:40-14:05 **keynote: KAUSEL Eduardo** ***On ground displacements, their spatial derivatives, and instrument rotations from SSI***
14:05-14:10 Discussion
14:10-14:25 SINGLA Varun Kumar, *On Computation of Rocking Response Spectra at Short Periods,*
14:25-14:30 Discussion
14:30-14:45 BOŃKOWSKI Piotr, *Sensor fusion in the modal identification of civil engineering structures,*
14:45-14:50 Discussion
14:50-15:05 TANIMOTO Toshiro, *Shallow Earth Structure from the Analysis of Lamb Waves in the Coupled Earth*,
15:05-15:10 Discussion

15.10 --- 15.40 Coffee break

15.40 --- 16.50 Session #4. (Chair: Kui Liu & Piotr Bońkowski)

15:40-16:05 **keynote: LAI Carlo** ***Damping Measurement in Soils by Inversion of Dispersion Functions of P and S waves***
16:05-16:10 Discussion
16:10-16:25 LU Hongbin, WANG Yibo, SHAO Jie, XUE Qingfeng*, High-Precision Wavefield Separation Method Using Single-Station Six-Component Seismic Observations*
16:25-16:30 Discussion
16:30-16:45 **commercial presentation: Modern test hardware and software offered by EC TEST Systems**
16:45-16:50 Discussion

18.00 --- 19.15 Guided Tour about the downtown

19:15 – 19:45 Organ Concert at St. Sebastian Church

Wednesday, June 25th, 2025

9.00 --- 10.30 Session #5. (Chair: Heiner Igel & Tomasz Maleska)

9:00-9:25 **keynote: ERRICO Luciano, *High precision tiltmetry above 10 mHz for gravitational physics experiments, ARCHIMEDES project***
9:25-9:30 Discussion
9:30-9:45 GUATTARI Frédéric, DUPONT Hippolyte, ROBERT Olivier, HAJAALI Hugo, Arnaud GAILLOT, PONCEAU Damien, POTTIE Paul-Eric, LEFÈVRE Hervé, ARDITTY Hervé, *MAÅGM, write a new chapter in rotational seismology instrumentation*
9:45-9:50 Discussion
9:50-10:05 Wentao ZHANG, Wenzhu HUANG, Yanjun CHEN, Zhengbin LI, Li LI, *Fiber optic 6-C seismometer*
10:05-10:10 Discussion
10:10-10:25 BERNAUER F., KÖBER D., BUTENWEG C., MONGABURE P., MICCOLI L., HESSE M., NOMIKOU, M. KALOIDAS V. DUMITRESCU M., *6DoF sensors for structural health monitoring: Show cases from the ECORE shake table experiments*
10:25-10:30 Discussion

10.30 --- 11.10 Posters and coffee – part 2

11.10 --- 12.40 Session #6. (Chair: Luciano Errico & Damian Bęben)

11:10-11:35 **keynote: ROSSI Yara, GUEGUEN Philippe, BERNAUER Felix, CHEN Kate Huihsuan, LIN Chin-Jen, KU Chin-Sang, CHEN Yaochieh, *Enhancing structural monitoring through 6C measurement techniques*,**
11:35-11:40 Discussion
11:40-11:55 Di VIRGILIO Angela, *GINGER Scientific objectives*
11:55-12:00 Discussion
12:00-12:15 LIU Kui, CHEN Yuxuan, ZHONG Yuhong, LIU Yawen, CAI Yangsheng, LIU Zhanhao, CHEN Fan, HU Ningxiang, TU Liangcheng, SCHREIBER Ulrich Karl, LU Zehuang, ZHANG Jie, *Recent Progress of Large Green Laser Gyroscopes in China*,
12:15-12:20 Discussion
12:20-12:35 De LUCA Gaetano, Di VIRGILIO Angela D. V., BASTI Andrea, CARELLI Giorgio, DI SOMMA Giuseppe, MACCIONI Enrico, MARSILI Paolo, BARBERIO Marino Domenico, FAMIANI Daniela, PIZZINO Luca, GOVONI Aladino, BRAUN Thomas Di CARLO Giuseppe, PREVITALI Ezio, BEVERINI Nicolò, FUSO Francesco, PETITTA Marco, TALLINI Marco, *Multi-parametric observations of the large bang of August 14th, 2023 in the Gran Sasso aquifer, Central Italy*
12:35-12:40 Discussion

12.40 --- 13.40 Lunch.

13.40 --- 15.30 Session #7. (Chair: Anna Kurzych & Piotr Bońkowski)

13:40-14:05 **keynote: XU Weiwei, Optical Fiber Sensing in the CSES Project: Opportunities and Challenges**
14:05-14:10 Discussion
14:10-14:25 IGEL Heiner, BROTZER Andreas, BERNAUER Felix, WASSERMANN Joachim, SCHREIBER Ulrich, *Challenges with ring laser observations in seismology*,
14:25-14:30 Discussion
14:30-14:45 WASSERMANN Joachim, BRAUN Thomas, KEIL Sabrina, IGEL Heiner, *About the Use of 6C Measurements on Active Volcanoes*
14:45-14:50 Discussion
14:50-15:05 EIBL Eva P. S., YASAROGLU Harun, HEIMANN Sebastian, HERSIR, Gylfi Páll, *Investigating the subsurface structure at Strokkur geyser, Iceland, using 6 DoF measurements*,
15:05-15:10 Discussion
15:10-15:25 NAWROCKI Dariusz, RUDZINSKI Łukasz, *Directional amplification effect observation across quaternary faults: comparison on rotational and translational H/V spectra*,
15:25-15:30 Discussion
15:30-15:55 **keynote: KATUNIN Andrzej, *Evaluation of modal rotation fields using shearography for structural damage identification***
15:55-16:00 Discussion

19.00 --- 22.00 Conference Dinner.

Thursday, June 26th, 2025

9.00 --- 10.20 Session #8. (Chair: Manon Morin & Zbigniew Zembaty)

9:00-9:15 DĘBSKI Wojciech *Rotational Waves in solid amorphic media - Discrete Element Method simulations*,
9:15-9:20 Discussion
9:20-9:35 **keynote: TODOROVSKA Maria, CRUZ Lichiel, KISOMI Hossein Bazeghi, TRIFUNAC Mihailo D, LIN Guoliang & CUI Jianwen, *Rotations in the seismic response of a tall building on piles***
9:35-9:40 Discussion
9:40-9:55 CHEN Yanjun, ZHU Lanxin, WANG Wenbo, HUANG Huimin, ZHOU Ziqui, SHI Fangshuo, CAO Xinyu, LI Zhengbin, *Fiber-optic rotational seismometer with enhanced temperature adaptability,*
9:55-10:00 Discussion
10:00-10:15 CHANG Chen, WANG Yun, *Rotational Motions Observations in Deep Underground Laboratories*,
10:15-10:20 Discussion

10.20 -- 10.50 Coffee break

10:50---12.10 Session #9 (Chair: Felix Bernauer & Wojciech Dębski)

10:50-11:05 THIBAUT Brieux, LAKKIS Muhamad Haidar, AMOROSI Anthony, GUATTARI Frederic, COLLETTE Christophe, *Coupling mitigation in low frequency active vibration isolation systems based on optical gyroscopes*,
11:05-11:10 Discussion
11:10-11:25 MORIN Manon, SEBE Olivier, BEUCLER Eric, CAPDEVILLE Yann, BOYER Daniel, DECITRE Jean-Baptiste, GILLES Micolau, *Assessment of the variability of seismic waves back azimuth estimates based on array-derived 6C analysis*,
11:25-11:30 Discussion
11:30-11:45 IZGI Gizem, *Exploring Seismic Attenuation with Rotational Ground Motion*
11:45-11:50 Discussion
11:50-12:05 CAPEZZUTO Marialuisa, D'APICEL Ferdinando, ZAHOOR Rizwan, De NATALE Paolo, GAGLIARDI Gianluca, GALLUZZO Danilo, AMATO Luigi Santamaria, AVINO Saverio, *Monitoring of seismic induced ground rotations at the Campi Flegrei volcanic area with a fiber-optic gyroscope: preliminary results*,
12:05-12:10 Discussion

12.10 --- 13.00 Final Discussion and closure of the Meeting. (Chair: Heiner Igel & Zbigniew Zembaty)

13.00 -- 14.00 Lunch.

Friday, June 27th, 2025

Excursion to Cracow (optional)

List of posters (size of the poster area: 100cm vertical and 70cm – horizontal):

1. BEVERINI Nicolo, CARELLI Giorgio, De LUCA Gaetano, DI SOMMA Giuseppe, Di VIRGILIO Angella, FUSO Francesco, GOVONI Aladino, MACCIONI Enrico, MARSILI Paolo, *First-Time Use of AI in GINGERINO Data Analysis for Fast Frequency Reconstruction and Seismic Event Recognition*
2. ROSSI Yara, APPLE Shoshana, BODIN Paul, ROSS Michel, GUNDLACH Jens, *Data curation and quality assessment of novel ground rotation sensor data at LIGO sites in the USA*
3. TANG Le, IGEL Heiner, MONTAGNER Jean-Paul, VEMON Frank, *Seismic anisotropy from 6C ground motions of ambient seismic noise*,
4. BOŃKOWSKI Piotr, KURZYCH Anna, JAROSZEWICZ Leszek, *The usefulness of the different rotational sensors for structural health monitoring*,
5. NAWROCKI Dariusz, LESNODORSKA Anna, MTUPA-NDIAYE Agnieszka, *The EPOS TCS AH EPISODES platform as a tool for the seismic scientific analysis and a source of the rotational motion data*.
6. JAWORSKI Marcin, BOŃKOWSKI Piotr, ZEMBATY Zbigniew *Rotation measurements for plastic hinge detection as an early warning of seismic damage of moment-resisting frames*
7. CARELLI G., *Ginger Status report*
8. ZENNER Jannik, GEREONS Thomas, SCHREIBER Karl Ulrich & STELLMER Simon, *Technical advancements of active and passive ring laser gyroscopes for seismological application*
9. MALEK Jiří, BROKESOVA Johana, *Seismogram noise reduction using non-linear stacking: application to six-degree-of-freedom Rotaphone data*
10. BROTZER A., BERNAUER, Felix. Guattari F., JAROSZEWICZ Leszek, KURZYCH Anna, GARRIDO C. L. Alzar, LANDRAGIN A., PIOT D., De RAUCOURT S., *Ultra-High Performance Gyroscopes for future X-Ray interferometer missions*

Session #1, Tuesday

High Resolution Inertial Earth Sensing with large Sagnac Interferometers

K. Ulrich SCHREIBER

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Ring lasers are now resolving the rate of rotation of the Earth with 8 significant digits. Technically they constitute a Sagnac interferometer, where a traveling wave resonator, circumscribing an arbitrary contour, defines the optical frequency of two counter-propagating resonant laser beams. Subtle non-reciprocal effects on the laser beam however, cause a variable bias, which reduces the long-term stability [1]. Over the last two years, we have improved the performance of the G ring laser to the point, that we obtain long-term stable conditions over more than a year. Advances in the modeling of the non-linear behavior of the laser excitation process as well as some small but significant improvements in the operation of the laser gyroscope are taking us now right to the point, where the periodic part of the Length of Day variation of the Earth rotation can be recovered [2]. Furthermore, we have now managed to recover the precession and nutation motion of the earth itself as well. This corresponds to a rotation signal of 50 seconds of arc per year. It is the first time that this has been achieved by an inertial sensing technique [3]. This talk outlines the current state of the art of inertial rotation sensing in the geosciences and its remaining challenges. Furthermore, we discuss promising ways for a further enhanced sensor stability. At this point in time there is no apparent fundamental limit for this technique in sight.

References

[1] Schreiber, K. U. & Wells, J.-P. R. Invited Review Article: Large ring lasers for rotation sensing. *Review of Scientific Instruments* **84**, 041101-041101–26 (2013).
[2] Schreiber, K. U., Kodet, J., Hugentobler, U., Klügel, T. & Wells, J.-P. R. Variations in the Earth's rotation rate measured with a ring laser interferometer. *Nat. Photonics* 1–5 (2023) doi:10.1038/s41566-023-01286-x.
[3] Schreiber, K. U. *et al.* Gyroscope Measurements of the Precession and Nutation of the Earth Axis. *Science Advances* (2025) (under review).

On the influence of ambient atmospheric pressure on rotational ground motion at ROMY

Andreas Brotzer[1], Rudolf Widmer-Schnidrig, Heiner Igel[1]

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For long period observations of seismic acceleration (below 20 mHz), tilt-coupled accelerations introduced due to atmospheric pressure deformation dominate the signal. This mechanism and contribution is not yet entirely understood. Removing tilt contributions to acceleration recordings would improve observations at long periods (e.g., for the study of the Earth‘s free oscillations).

A high-sensitive, large-scale ring laser gyroscope provides access to direct observations of local rotational ground motions. A tetrahedral configuration of ring laser gyroscopes, such as ROMY (ROtational Motions in seismologY), located in a Geophysical Observatory near Munich, Germany, provides all three components of ground rotations. Co-located, six degrees-of-freedom observations of a translation and rotation sensor can be used for dynamic tilt correction of horizontal components of acceleration. Moreover, knowing and understanding the background noise levels for vertical and horizontal rotational ground motions at long periods dominated by atmospheric pressure loading is essential for instrument development.

We use several months of multi-component data of vertical and horizontal rotational ground motion by ROMY and a co-located barometer to derive the pressure compliance for rotational motions at this site. Focusing on frequencies below 20 mHz, we find that time windows with energetic weather patterns consistently lead to high coherence of atmospheric pressure and horizontal rotations, but only little coherence between the atmospheric pressure and vertical rotation. We consider this as a first indication that atmospheric pressure induced ground tilts are detected by the ROMY horizontal components. Different effects of ambient atmospheric pressure changes on the optical gyroscope itself, such as cavity deformation, are discussed.

Modelling of the tilt caused by a local and travelling pressure wave model is applied to the data to infer linear model coefficients. These coefficients seem to converge for a statistical analysis and result in a high variance reduction (>70%) for pronounced transient signals. A barometer array of six stations around ROMY provides first direct observations of the pressure gradient field towards an enhanced model.

Bounds for estimations of rocking ground motion effects on slender towers and buildings

Piotr Adam BOŃKOWSKI, Zbigniew ZEMBATY

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It was probably Rosenblueth who was the first to suggest that rotational seismic ground motions could represent a possible source of additional substantial seismic effects on the slender tall structures & buildings [1]. Due to a lack of credible, strong ground motion recordings, respective rotations were derived indirectly from seismic wave interactions at the ground surface, starting from the paper by Trifunac [2]. Later, various papers explored this indirect research track to conclude about the contribution of potential strong ground rotations in the seismic response of buildings (e.g. [3,4]). From among three rotations about the three cartesian axes *x, y, z* on the ground surface, the rotations y_x and y_y about two horizontal axes *x* & *y* may result in non-conservative seismic structural responses. This is why their effects are of particular concern. Yet, only when the first strong ground motion recordings were acquired [5] did the credible rocking seismic effects on slender, tall structures become available and applied in seismic computations (e.g. [6,7]).

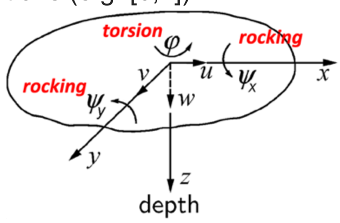

Fig 1 Three strong motion rotations on the ground surface

The purpose of the proposed presentation for the 7th IWGoRS is to make a critical analysis of the estimations of the maximum rocking ground motion contributions in seismic building responses depending on seismic intensity, as reported by various authors (including e.g. [3-4], [6-7] and many more), and draw conclusions about a potential to include rocking ground motion in practical computations of seismic response using design codes as was e.g. the case in [8]

References

[1] Rosenblueth, E., Tall Buildings under Five Component Earthquakes. *J. Struct. Div. ASCE* 102, 1976, p.455

[2] Trifunac, M. D. A note on rotational components of earthquake motions on ground surface for incident body waves. *Int. J. Soil Dyn. Earthq. Eng*., 1, 1982, p.11

[3] Falamarz-Sheikhabadi MR. Simplified relations for the application of rotational components to seismic design codes. *Eng Struct* 2014;59:141–52. https://doi.org/10.1016/j.engstruct.2013.10.035.

[4] Guidotti R, Castellani A, Stupazzini M Near-field earthquake strong ground motion rotations and their relevance on tall buildingsnear-field earthquake strong ground motion rotations and their relevance on tall buildings. *Bull Seismol Soc Am,* http://dx.doi.org/10.1785/0120170140

[5] Sbaa S, Hollender F, Perron V, Imtiaz A, Bard P-Y, Mariscal A, et al. Analysis of rotation sensor data from the SINAPS@ Kefalonia (Greece) post-seismic experiment— link to surface geology and wavefield characteristics. *Earth Planets Space* 2017;69:124, https://doi.org/10.1186/s40623-017-0711-6

[6] Bonkowski P.A., Zembaty Z., Minch Y.M., Engineering analysis of strong ground rocking and its effect on tall structures, Soil Dyn. Earthq. Eng., 2019, vol. 116, p.358

[7] Vicencio F., Alexander N.A., Seismic Structure-Soil-Structure Interaction between a pair of buildings with consideration of rotational ground motions effects, *Soil Dynamics and Earthquake Engineering*, vol. 163, December 2022, 107494, DOI: 10.1016/j.soildyn.2022.107494

[8] Zembaty, Z., Rossi, A., Spagnoli, A. (2016). Estimation of Rotational Ground Motion Effects on the Bell Tower of Parma Cathedral. In: Zembaty, Z., De Stefano, M. (eds*) Seismic Behaviour and Design of Irregular and Complex Civil Structures II*. Geotechnical, Geological and Earthquake Engineering, vol 40. Springer, Cham. https://doi.org/10.1007/978-3-319-14246-3_4

Session #2, Tuesday

Identifying and localizing the source of mechanical disturbance through the deployment of an appropriate array of FOS6 class fiber-optic rotational seismometers

Anna KURZYCH[1,2], Paweł ZINÓWKO[2], Karol KONARSKI[2], Bartosz SAKOWICZ[3], Grzegorz LIZUREK[4], Paweł MARĆ[1,2], Michał DUDEK[1,2], Karol STASIEWICZ[1,2], Łukasz ZEMBALA[2], Leszek R. JAROSZEWICZ[1,2]

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4 – Institute of Geophysics Polish Academy of Sciences, 64 Księcia Janusza Street, 01-452 Warsaw, Poland

Since the Sagnac-Von Laue effect is definitively relativistic, devices utilizing this phenomenon, such as fiber-optic rotational seismometers (FOS), can detect rotational movement without requiring a reference frame. [1]. Such devices are practically used in the field for recording the rotational events connected with natural and artificial events connected with earthquakes and ground detonations [2,3]. However, up to now, no data have been associated with them for the localization and identification of the sources of disturbances. In this work, we present the initial results recorded by FOS6 systems for the abovementioned objectives. FOS is a rotational seismometer with a resolution below 40 nrad/Sqrt(s), maximum rotation rate detection of about 10 rad/s, bias instability below 10 nrad/s, and detection bandpass 0.01-100 Hz [4].

We present field experiment results directed at the localization of the source of disturbance based on a suitable matrix of FOS6es, where high mutual correlation and applied time synchronization in the range of 10 ns is the key solution (Patent Appl. to the Polish Patent Office P.450532). This solution exploits the dependence of the different recording times of the same disturbance by an array of four FOS6es with their mutual spatial arrangement. Additionally, regarding the Patent Application to the Polish Patent Office P.450531, a system matrix is used for automatic recognition of the type of source of disturbance (natural, artificial, detonations, etc.), where the essential element is to perform spectral analysis of the recorded signals and compare them with the available standards with the application of AI.

The Polish Agency for Enterprise Development has financed this work as project FENG.01.01-IP.02-1714/23 “FOM-MEM – Fibre-Optic Matrix for Mechanical Events Monitoring.”

References

[1] Schreiber U., Wells J. P., *Rotational Sensing with Large Ring Lasers*, Cambridge Univ. Press, 2023
[2] Bernauer F. *et al*., Rotation, strain and translation sensors performance tests with active seismic sources”, *Sensors* 21, 264, (2021) https://doi.org/10.3390/s21010264
[3] Kurzych A. T. *et al.* Rotational motion investigation in seismology – remote sensing by an optical fiber seismograph, *Adv. Opt. Technol.* 13, 1494705, (2024) https://doi.org/10.3389/aot.2024.1494705
[4] Zając P. et al., Self-noise reduction in a FOG-based rotational seismometer confirmed by Allan variance analysis, *Opto-Electron. Rev*. 32(4), (2024) https://doi.org/10.24425/opelre.2024.152766

Torsional and translational resonance amplification in a high-rise building

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This study focuses on a high-rise building with a square cylindrical shape (total height: 192 m) [1-2]. The response of its fundamental translational and torsional resonance modes to external excitations are analyzed using Power Spectral Density (PSD), Horizontal-to-Vertical Spectral Ratio (HVSR) and Rotational Vertical-to-Horizontal Spectral Ratio (RVHSR) [1] methods, including vibration amplitude and dominant vibration direction. In the experiment, three-component translational seismometers are installed starting from the second floor, with one seismometer placed every two floors. Additionally, seismometers are placed on the first floor and underground floors B1, B3, and B5. Rotational seismometers are installed on the top floor, bottom floor, refuge floor, and every tenth floor in between. The results show that in the absence of external excitations (such as earthquakes or typhoons), the peak PSD values of the fundamental translational and torsional modes observed on floors above the fourth floor exhibit a strong correlation with wind speed variations, indicating that wind speed affects the resonance intensity of the high-rise building. The peak accelerations induced by both translational and torsional resonance modes increase linearly with floor. The refuge floor effectively suppresses the amplification of the translational mode, manifesting as a reduction in the amplitude on the evacuation floor and a decrease in the amplification factor for the floors above. Under earthquake excitation, the peak accelerations caused by both translational and torsional resonance modes show an enhanced nonlinear increase with floor. The refuge floor similarly suppresses the amplification of the translational resonance mode. However, for the torsional resonance mode, both amplitude and amplification factor increase before and after the refuge floor, suggesting that the refuge floor has a limited effect in mitigating the torsional resonance mode under earthquake excitation.

References

[1] Qin L., Wang Y., Chen C., Wei Y., Liao C., Zhang Y., Wang C., Wan W., Shao Q., Resonance Analysis in a High-Rise Building: Combined Translational and Rotational Measurements, Journal of Earth Science, 35(3), 1069–1074 (2024).

[2] Qin L., Wang Y., Guo Z., Zhang Y., Liao C., Chen C., Zhang B., Structural Health Monitoring of a High-Rise Building Using Ambient Noise Recordings and a Regional Earthquake Record, Seismological Research Letters, 96(1), 260–269 (2024).

Güralp Stratis - a Commercial 6 Degree of Freedom Seismometer for Academic and Research Applications

Phil Hill, Francois Maletras, Neil Watkiss, Federica Restelli, James Lindsey, Sally Mohr

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Traditional research grade 3-component seismic sensors by their very design are sensitive to both translational ground movement as well as rotational (or tilt) motion. This is most prevalent in the horizontal components of sensors which are most sensitive to tilt of the ground. The outputs of traditional seismometers represent a sum of rotation and displacement information. Most applications processing the data make the assumption that the outputs are proportional to purely displacement although this is not strictly the case in commercial devices.

New technologies are now allowing for accurate and precise discrimination between the two components which make up the vast majority of seismic records.

Stratis is the world's first integrated seismic sensor offering simultaneous output of both rotational and displacement data in all 3 axis. Stratis offers six concurrent outputs providing Z, N, and E ground displacement channels proportional to velocity (meters/second) and rotation channels in the Z, N, and E planes proportional to velocity in rotation (Radians/Second). The provision of the measurement of the six degrees of freedom now permits derivation of the Elasticity Tensor from a single sensor.

The Stratis displacement output removes these rotation effects and gives a 'pure' displacement measurement. This is unique in the seismic sensor marketplace, providing true displacement data that is uncontaminated by rotational signals. This will therefore allow for higher fidelity seismic measurements, improving our analysis and understanding of earthquake processes.

These six parameters are measured at a single point in the geometric center of the sensor. Use of multiple separated sensors to derive rotation can only approximate true rotation at the same point as displacement. By integrating these measurements into a single instrument, the installation process is also greatly simplified thereby enabling wider access to rotational seismic data. Naturally, the separation of rotational information from the displacement outputs also gives a pure displacement sensor – something unique for the seismological community.

Session #3, Tuesday

On ground displacements, their spatial derivatives, and instrument rotations from SSI

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Summary: In the context of wave motion described by linear elasticity, it is well known that the rotations of ground particles are negligible compared to translations, and are thus not taken into account when deriving the wave equations. Still, when seismic instruments or sensors are placed on —or within— the ground, they are seen to experience both translations and rotations. This is so because the sensors are not point-like particles but have finite physical dimensions. In addition, they are rigid bodies that cannot deform and so they cannot accommodate ground strains. Hence, they can't readily follow ground deformations exhibiting spatial variability between contact points of the sensors with the ground, and this causes the sensors to rotate. In the theory of Soil-Structure Interaction, this phenomenon is referred to as *Kinematic Interaction* or *Wave Passage*. In essence, the sensors respond to spatially varying ground motions, that is, to strains. This is then the topic considered in this technical note.

Objective: Provide explicit expressions for the rotations of sensors of three-dimensional geometry when placed on or within a homogeneous elastic half-space that is being "illuminated" or "insonified" by plane waves propagating within. In the context of signal processing theory, it is also shown that by measuring simultaneously translations and rotations, one can achieve more accurate descriptions of the seismic environment in the vicinity of the sensors. That is, measurement of the rotations helps unravelling the wave content.

Methodology: An approximate yet highly accurate theory due to Iguchi is first presented for the estimation of the translations and rotations of sensors of arbitrary shape, especially for waves whose wave lengths are larger than the sensor dimensions [1]. These expressions are then demonstrated by means of applications to sensors of cylindrical shape. At the same time, a rigorous methodology is presented to enhance the resolution of seismic motion recorders by simultaneously measuring the spatial derivatives of the motion field [2].

Results: Although no experimental or numerical results are presented, the theory demonstrated is readily applicable to rotational seismology.

Conclusions: Although the *rotations* in rotational seismology do not actually refer to particle rotations, but instead to the rotations of finite size rigid bodies such as seismic sensors or of the buildings where these may be installed, it is true that by measuring the rotations, a much better resolution is achieved in the displacement field obtained with sensors during an actual earthquake.

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On Computation of Rocking Response Spectra at Short Periods

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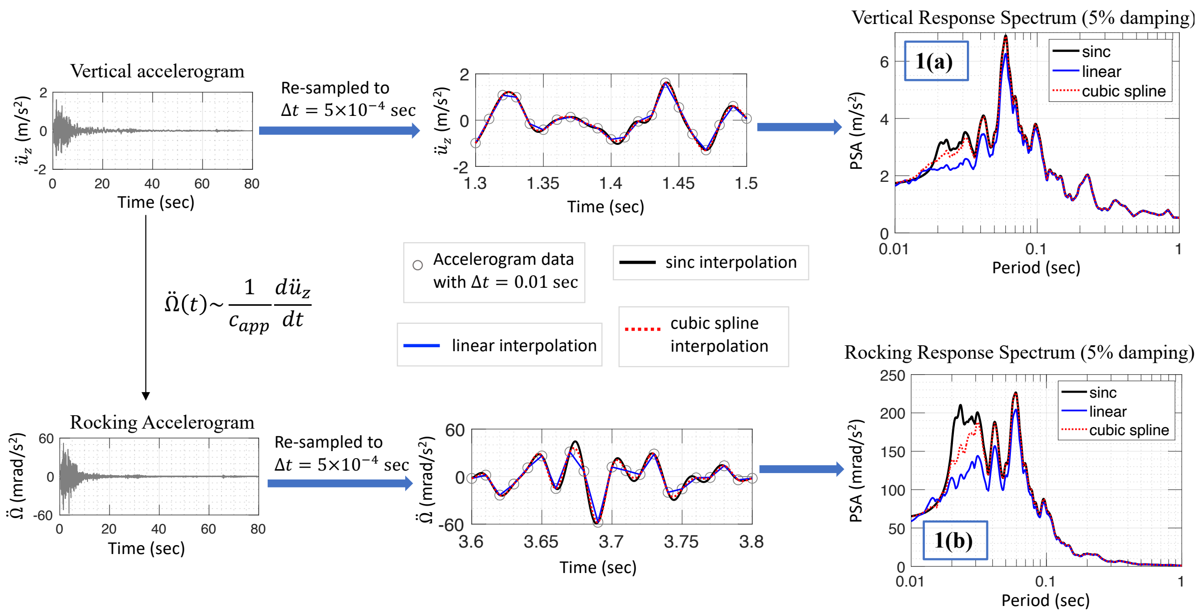
Objective: To correctly compute the rocking response of simple structures at short periods

Methodology

This study is concerned with the accurate computation of the response of linear single-degree-of-freedom (SDOF) systems subjected to the rocking (tilt) component of strong ground motion. To this end, the vertical accelerograms of a few major earthquakes are considered and the corresponding rocking accelerograms are synthesized by assuming these to result from a horizontally travelling (non-dispersive) plane-wave [1]. The rocking accelerograms are then re-sampled to a time-step 20 times smaller than the shortest considered period of the structure by using three interpolation schemes: (i) 'sinc', (ii) linear, and (iii) cubic spline. Here, 'sinc' interpolation refers to the technique wherein the frequency content of the original time series is perfectly preserved in the re-sampled series [2]. The re-sampled accelerograms are finally used to obtain the (dynamic) structural responses using a standard time-stepping method [3].

Results and Conclusions

Comparisons of the rocking response spectra of the re-sampled accelerograms show that both the linear and cubic spline interpolation schemes can underestimate the peak responses at short periods, with the former scheme performing much worse than the latter. The figures below illustrate these findings in the case of a vertical accelerogram record of Mw 6.61 San Fernando (1971) earthquake whose original time-step of 0.01 sec was further reduced to 0.0005 sec. It is also observed that the rocking response spectra (at short periods) are more sensitive to the re-sampling method than the corresponding vertical response spectra (compare figures 1(a) and 1(b).



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Sensor fusion in the modal identification of civil engineering structures

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In the field of structural health monitoring (SHM) of civil engineering structures, an accurate identification of structural parameters, such as stiffness and mass distribution, is an essential part of damage detection. The civil engineering comprises a wide range of structural types, e.g. beam or wall-type structures, and materials, e.g. steel, masonry, or reinforced concrete (r/c). The latter ones are especially interesting due to the damage in the form of numerous cracks along the length of the elements. Therefore, it is not surprising that numerous identification methods are being developed. In recent years, scientists have focused on sensor fusion strategies that combine data from multiple sensor types. In this way, structural parameters can be estimated more accurately [1].

The aim of this presentation is to demonstrate sensor fusion techniques utilising novel MEMS rotation rate sensors with traditional translational accelerometers for modal identification of structural elements. The rotations can be considered as spatial derivatives of structural deformations. As such, they more closely follow structural modifications due to stiffness changes. The addition of directly measured rotations to the established measurement techniques proves to increase monitoring accuracy. Such sensor fusion can be based on model-updating strategies such as in recently published stiffness [2] and mass [3] identification papers. In the presentation, it will be shown that response-based techniques can also be applied. This approach is much less computationally intensive than FEM-based and can be very efficient in damage localisation [4].

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Shallow Earth Structure from the Analysis of Lamb Waves in the Coupled Earth

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The compliance method is based on the analysis of data from co-located pressure and seismic sensors. It has been shown to provide constraints on shallow elastic structure. The method was applied to observations on the ocean floor (e.g., Crawford et al., 1991) and on land (e.g., Tanimoto and Wang, 2019). These studies analyzed ambient seismic noise at lower frequency (< 0.1 Hz), where the coherence between surface pressure changes and ground motions was high. Selecting highly coherent frequency intervals ensured that we could identify both the cause of deformation (surface pressure) and its outcome (ground deformation).

In this paper, we demonstrate that a similar compliance approach can be used when large atmospheric pressure waves, excited by a volcanic eruption, propagate around the Earth. Specifically, we examine the case of the eruption of Hunga Tonga-Hunga Ha'apai (hereafter referred to as Hunga-Tonga) on January 15, 2022. This eruption has been widely reported to have generated atmospheric pressure waves (Lamb waves) that traveled around the globe (e.g., Matoza et al., 2022). These pressure waves were associated with ground deformations on the Earth's surface, an integral part of Lamb waves in the coupled Earth system. In our method, we compute Lamb waves within a coupled Earth model by extending the approaches of Pekeris (1948), Press and Harkrider (1962), and Harkrider (1964) to include the elastic, solid Earth.

As a compliance method, our approach analyzes the ratio between vertical displacement and surface pressure observed when the Lamb wave passes a co-located station. We first compute the eigenfunctions of a Lamb wave mode and obtain the depth sensitivity kernels for the compliance ratio through numerical differentiation. These kernels exhibit primary sensitivity to the near-surface shear modulus, with additional sensitivity to the shallow bulk modulus at hard rock sites. Given the Lamb wave phase speed of approximately 310 m/s and the high-coherence range limit of around 0.01 Hz, the depth range of reliable resolution is constrained to the upper crust (approximately the uppermost 15 km).

We point out two useful products based on the analysis of compliance ratios. The first product is a method to constrain shallow elastic structures. However, the applicable highly-coherent frequency range is narrow, typically between 0.01 Hz and 0.05 Hz. The second product leverages these data to test shallow structures in existing seismic velocity models. The compliance data can refine the shallow structural parts in these models, which is critical for accurate ground motion predictions in seismically active regions worldwide.

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Session #4, Tuesday

Damping Measurement in Soils by Inversion of Dispersion Functions of P and S waves

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Modeling the mechanical response of geomaterials to dynamic excitations and experimentally measuring the corresponding material parameters is a topic of considerable importance in computational seismology, soil dynamics and earthquake engineering. In fact, the formidable advances in theoretical seismology, numerical analysis and computer technology occurred in recent years have made achievable 3D physics-based simulations of ground shaking scenarios in large-scale, urbanized areas from the fault rupture to the ground surface taking into account topographic irregularities and even the presence of civil infrastructures. Although these high-performance computational platforms are the cutting-edge products of contemporary research, they require the input of a consistent set of material parameters which need to be experimentally measured or properly back-calculated. Failure to do so may yield undesirable effects like violation of causality, loss of stability and convergence of the algorithms or just simply inaccurate results. Yet, current methods to measure soil stiffness and damping ratio at low strain suffer from a number of flaws and inconsistencies. Even their very same definition is imprecise and in a way contradictory. Curiously enough this occurs both in seismology and in soil/rock dynamics albeit in different ways. For instance, in seismology damping is assumed hysteretic over the seismic band while in soil dynamics violation of physical causality is disregarded and low-strain stiffness and damping are treated as if they were independent parameters.

This talk presents an alternative and more rigorous approach to determine the low-strain constitutive parameters of soil dynamic behaviour which is based on exploiting the solution of the Kramers-Kronig (K-K) equation of linear viscoelasticity. This is a singular Fredholm integral equation of the second kind with Cauchy kernel which has been explicitly solved by Meza and Lai (2007) using the theory of singular integral equations thereby allowing damping ratio (or quality factor) spectra to be calculated from the inversion of the dispersion functions of P and S waves. With this approach, the interdependence of V_P, VS and their corresponding damping ratios DP, DS is automatically taken into account jointly with their rate-dependence. Despite the technical difficulties associated with the experimental implementation of the method, the preliminary results are encouraging. They are shown through a non-conventional interpretation of the borehole seismic cross-hole test applied to S waves and the *causal* analytical solution of the classical Lamb problem

High-Precision Wavefield Separation Method Using Single-Station Six-Component Seismic Observations

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Six-component (6C) seismic observations, integrating rotational and translational measurements, enable a more comprehensive wavefield characterization than traditional three-component methods. However, existing separation techniques rely on dense arrays, which are costly and impractical. This study proposes a novel single-station 6C polarization-based wavefield separation framework capable of identifying and separating P-, SV-, SH-, Rayleigh, and Love waves, overcoming the limitations of traditional dense array deployments by relying on a single 6C station.

The method constructs a weighted linear combination of wave models, optimizing factors via the Broyden-Fletcher-Goldfarb-Shanno (BFGS) algorithm for high-precision separation. A refined polarization-based masking strategy, incorporating likelihood estimation, degree of polarization, and energy distribution ratios, enhances robustness, particularly in low signal-to-noise conditions. To mitigate energy leakage, time-frequency domain processing employs the Short-Time Fourier Transform (STFT) and inverse STFT (iSTFT), addressing the loss issues.

Validated with synthetic and real teleseismic data, the method effectively reconstructs the original waveform with high fidelity. Sensitivity analyses confirm robustness under varying noise levels. The ability to reconstruct the original waveform by linearly superimposing the separated wavefields further ensures accuracy and reliability. This framework provides a powerful tool for seismic phase identification, surface wave suppression, dispersion analysis, and multi-phase joint inversion, contributing to seismic exploration, earthquake monitoring, and planetary seismology.

Session #5, Wednesday

High precision Tiltmetry above 10 mHz for gravitational physics experiments

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In the last seven years the Napoli Gravitational Physics group developed high precision opto-mechanical suspended beams for the ARCHIMEDES experiment and for Virgo/Einstein Telescope scientific collaborations. In these experiments such instruments have been designed for several scopes: to monitor ground tilt and Newtonian noise for gravitational waves detectors, to measure extremely small weight variations due to quantum energy fluctuations or for the search of ultralight dark matter. Even if it was not the initial aim, this work allowed us to develop tiltmeters with world-record sensitivity in a very wide range of frequency, from 10 mHz to 10 Hz [1]. Such tiltmeters have been tested in various sites in Italy, particularly in Sos Enattos in Sardinia, one of the site candidates to host the Einstein Telescope. In such environment our tiltmeter was the first to measure directly the ground tilt spectrum between 100 mHz and 10 Hz without being limited by technical or fundamental noises, and the quiet of the site showed that the tiltmeter reached the thermal noise between 20 and 50 mHz [2]. In Virgo site (Cascina, Pisa) the AKINETOS tiltmeter was installed in 2023 and is taking ground tilt data since then, with a duty cycle greater than 80%. The resonance frequency of AKINETOS is 7.7 mHz, the lowest reached in our experience, which significantly decouples the tilt signal of AKINETOS from the ground translations. Such decoupling is very important to analyze seismic noise and separate the tilt contribution from the shift, and it could be used to better filter seismic noise from the suspended mirrors in gravitational waves detectors. In the next years the commissioning on the mentioned tiltmeters will continue and it’s expected to improve the sensitivity below 100 mHz; moreover, a new compact version of AKINETOS tiltmeter will be developed and its use as “field instrumentation” will be explored.

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MAÅGM, write a new chapter in rotational seismology instrumentation

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MAÅGM was established to build upon the groundbreaking work of blueSeis, addressing the increasing demand for high-performance rotational seismology instruments. While blueSeis demonstrated the
potential of fiber-optic gyroscopes (FOGs) for seismic applications, MAÅGM aims to advance this technology further, focusing on enhanced sensitivity while maintaining field deployability. Our mission is to deliver an industrial instrument capable of achieving a sensitivity of 10^{-10} rad/s/√Hz, unlocking the full potential of rotational seismology.
MAÅGM brings together a team of experts in optics, mechanics, and precision instrumentation, all sharing the goal of translating laboratory-grade performance into rugged, portable, and scalable field instruments. The company was structured to facilitate innovation at the intersection of academic research and industrial development, ensuring that the next generation of rotational seismometers is informed by cutting-edge scientific insights and driven by the expertise of skilled geoscience professionals.
This presentation will outline MAÅGM's ongoing efforts to develop a commercially viable, portable rotational seismometer for the scientific community. The primary challenges are:

- Achieving state-of-the-art sensitivity while ensuring long-term stability in field conditions.
- Optimizing system usability for seamless integration into seismic networks.

To mitigate risks associated with these ambitious goals, MAÅGM is developing two candidate technologies, each with unique advantages but both targeting the 10^{-10} rad/s/√Hz performance threshold at
0.1 Hz. The talk will detail our development strategy, validation steps, and roadmap towards delivering the first deployable instrument that meets these specifications.
Beyond performance, ease of deployment and remote operation are crucial for widespread adoption. Therefore, MAÅGM is also developing:

- The NJORD product line, offering True North station orientation solutions, including Laser Line Kits, optical gyrocompasses from Exail, and Dual Antenna True North systems.
- The LOKI technology, enabling remote (>10km) and real-time optical readout of electronic-less sensors with moving parts at their core.

By addressing both sensor performance and field usability, MAÅGM aims to bridge the gap between experimental prototypes and widespread field deployment.

Fiber optic 6-C seismometer

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Six component seismic wave measurement has various implications for many fields, such as earthquake engineering, geodesy, strong-motion seismology, tectonics, etc. Fiber optic seismograph has shown potential applications in deep-well or deep-sea seismic monitoring. In this manuscript we report a six- component optical fiber seismometer for the simultaneous detection of translational and rotational aspects of wide-band seismic waves. The translational component is based on fiber optic Michelson interferometer and inverted pendulum structure. Zero-pole compensation is used to extend the lower frequency bandwidth to 120 s while maintaining a high sensitivity of 35,000 rad/g within this bandwidth. A demodulation technique that combines Kalman filtering with elliptical fitting [1] has effectively mitigated phase noise, resulting in a noise level of 10 ng/√Hz at 1 Hz [2]. Combining the high-sensitivity inertial structure design and low-noise fiber phase demodulation, the translation fiber seismograph has achieved international recognition for its measurement frequency band (DC-1kHz) and noise level (4.87×10^{-13}m/√Hz@1Hz, 7.9×10^{-12}m/√Hz@0.01Hz). The rotational component is based on a fiber optic Sagnac interferometer. By optimizing the rotational seismograph system, the parasitic interference noise and thermal phase noise are suppressed, the tilt coupling effect is compensated. These developments lead to a high sensitivity (9×10^{-10}rad/s/√Hz) of the three rotational component with a wide band (1mHz-125Hz). The calibration tests of the fiber optic 6-C seismometer are carried out, seismic observation experiments are performed. We have also developed the signal co-processing methods for the six-component fiber optic seismometers. We believe that the new equipment is a support for the study of slow earthquakes, including their identification, mechanisms, and incubation processes in the field of Earth sciences.

6DoF sensors for structural health monitoring: Show cases from the ECORE shake table experiments

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Observing six degrees of freedom (6DoF) of motion within a building (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. Directly recorded 6DoF motions enable to correct translational acceleration recordings for dynamic tilt and for mis-orientetion during strong shaking (attitude correction). 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.

The ERIES transnational access opportunity acknowledged the ECORE project for funding during the first call. The ECORE experiments were conducted at the AZALEE facility at CEA Paris Saclay that hosts a 6DoF shaking table facility. We installed a network consisting of 14 6DoF sensors in a lightweight concrete test specimen with a square plan layout of about 4 × 4 m and two levels.

In this contribution we present the test specimen along with the installed instrumentation and the test procedure. We present first results that demonstrate the ability of the new 6DoF approach to significantly improve inter-story drift observations derived from double integration of accelerometer recordings.

This work is part of the transnational access project "ERIES – ECORE", supported by the Engineering Research Infrastructures for European Synergies (ERIES) project (www.eries.eu), which has received funding from the European Union's Horizon Europe Framework Programme under Grant Agreement No. 101058684.

Session #6, Wednesday

Enhancing structural monitoring through 6C measurement techniques

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The characterization of existing civil engineering structures, is critical for understanding their behavior and structural condition. In particular, rotational components provide additional information that can enhance the translation-based characterization of structural response. Among the parameters of interest, the values of modal frequencies, mode shapes and damping provide insights into dynamic behavior such as shear versus bending. The advantages of including rotation motion in structural monitoring is shown using a 6-component (6C) data set from TAIPEI 101, Taiwan, consisting of an Eentec-R1 rotation sensor collocated with an EpiSensor accelerometer.

By quantifying the relationship between translational and rotational components, it is possible to extract structural vibration features, on par with classic acceleration sensor arrays. The minimization of the sensor footprint from an array to a 6C station without loss of information opens up new observation possibilities. The relationship between angle and deflection enables us to distinguish between shear and bending behavior using only a single location with 6C observations. It is even possible to track the variation of the point of rotation in the torsional modes and the correlation to external factors such as damping, temperature and other environmental parameters. Specifically for TAIPEI101 there is a correlation between the activation of the tuned mass damper in the 90th floor and a change of the center of torsion. The findings demonstrate a significant contribution of rotational component to understanding specific structural behaviors, thereby promoting the adoption of 6C sensors (three translational and three rotational) for enhanced structural characterization.

GINGER, Scientific objectives

Angela D. V. DI Virgilio,

for the GINGER collaboration

GINGER, Gyroscopes IN GEneral Relativity, is an array of ring lasers gyroscopes (RLG), at present two RLG are under construction inside the underground INFN international laboratory of Gran Sasso (LNGS), in a second time the GINGERINO apparatus will be upgraded in order to become the thrird component of the GINGER array. The experimental layout, and the development envisaged for the GINGER project will be outlines. The project brings together different scientific disciplines aiming at building an array of Ring Laser Gyroscopes (RLGs), exploiting the Sagnac effect, to measure continuously, with sensitivity better than pico-rad/s, large bandwidth (larger than 100Hz), and high dynamic range, the absolute angular rotation rate of the Earth. The feasibility of the apparatus with respect to the ambitious specifications above, as well as prove how such an apparatus, which will be able to detect strong Earthquakes, very weak geodetic signals, as well as general relativity effects like Lense-Thirring and de Sitter, will help scientific advancements in Theoretical Physics, Geophysics, and Geodesy, among other scientific fields. In order to fit inside the available space in the cave, the side of the optical cavities of the GINGER RLGs has been scaled down to 3m, this will limit the expected shot noise limit, but we hope to go below the pico-rad/s sensitivity in any case. When GINGER will be operational, it will be possible to combine the data of the two european arrays, providing an unique opportunity to distinguish local from global signals, insights on the calibration issue, and by in using the coincidence between the two arrays will be in principle possible to improve the identification of rare transient signals.

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Recent Progress of Large Green Laser Gyroscopes in China

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Large-scale laser gyroscopes, renowned for their wide bandwidth and high sensitivity, are indispensable inertial sensors for precisely measuring Earth's rotation. Widely used in the research of seismology, geodesy, and fundamental physics, these instruments often necessitate deployment in multiple orientations to capture comprehensive rotational vector data and ensure measurement consistency. The integration of multi-station, grid-connected observations using these advanced gyroscopes is therefore of great scientific significance. In response to this need, we have initiated research on high-sensitivity large-scale laser gyroscopes at our facilities in Wuhan and Zhuhai. At our Wuhan laboratory, we have developed a passive laser gyroscope that enhances performance by increasing laser power, enlarging the cavity size, and reducing the operational wavelength. This approach has yielded an improved scale factor and a lower shot noise limit, enabling closed-loop operation with a 532 nm solid-state green laser, frequency-locked to an 8 m×8 m ring cavity, exhibiting a quality factor exceeding 6×10^{12}. The system achieves a rotational sensitivity of 7×10^{-11} rad/s/√Hz and a resolution of 4×10^{-11} rad/s at an integration time of 2000 seconds, with seismic wave detection performance comparable to that of the commercial seismometers. Additionally, we are constructing a 10 m×10 m twin laser gyroscope in Zhuhai to facilitate future joint measurements with our Wuhan facility. Together, these initiatives aim to advance precision rotational measurement capabilities and contribute to deeper insights in Earth science research.

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Multi-parametric observations of the large *bang* of August 14th, 2023 in the Gran Sasso aquifer, Central Italy

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A novel approach in monitoring the inner dynamics of mountains, massifs, and of the Earth crust in general, involves hydrogeological measurements, as well as new generation multi-component seismic stations. This is particularly important when the instrumentation used have high sensitivity and are able to access frequencies below 1 mHz, opening the possibility to observe very slow signal of local origin. Since several years, the ring laser gyroscope GINGERINO is operative inside the underground Gran Sasso Laboratory (INFN-LNGS), and monitors the local Earth angular velocity in the horizontal plane. GINGERINO is a ring laser gyroscope, with square optical cavity with 3.6 m side, oriented such to record the local rotation around the vertical axis. It is one of the first eterolithic ring laser able to operate continuously since about 10 years in the Gran Sasso area, a well known seismically active area. Together with the co-located IV.GIGS broad-band seismometer (seismic stations of national network of INGV), it constitutes a 4C seismic station; the 4 degrees of freedom put together give an insight of the Gran Sasso massif inner movements, that find correspondence in measurements conducted on the water of the aquifer. In particular, the hydrogeological interpretation of the slow dynamics of the period going from May to August 2023, and of the powerful mountain bang of August 14th, 2023, is consistent with data from GINGERINO. Unfortunately GINGERINO was not operating in the optimal conditions, we remind that GINGERINO is mainly limited by instrumental disturbances, because the optical cavity is not tight enough, it has been the prototype for the GINGER apparatus, and was built to learn the ring laser technique. Nevertheless it was possible to find evidence of the special events induced by the aquifer, mainly evident at lower frequency where the standard seismometers are blind. The data analysis will be reported in details, the paper about this special event is in progres.

Session #7, Wednesday

Optical Fiber Sensing in the CSES Project: Opportunities and Challenges

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The China Seismic Experimental Site (CSES), a major national scientific i_n_f_r_a_s_t_r_u_c_t_u_r_e_ _u_n_d_e_r_ _C_h_i_n_a_'s_ _1_4_t_h_ _F_i_v_e_-Year Plan, aims to advance earthquake science and risk mitigation by deploying 1,769 multi-disciplinary observation stations (seismic, geochemical, deformation, gravity, and others) in seismically active regions such as Sichuan and Yunnan. This initiative focuses on unraveling the mechanisms of continental strong earthquakes and improving earthquake monitoring and hazard assessment technologies.

In this talk, I will highlight the integration of cutting-edge optical fiber sensing (OFS) technologies into the CSES framework. Specifically, we introduce three observational approaches: (1) distributed fiber optic sensing for high-resolution strain and temperature monitoring along fault zones, (2) fiber optic rotational sensing to capture subtle ground rotations during seismic events, and (3) long-baseline strain observations for detecting crustal deformation dynamics. Preliminary studies demonstrate the potential of OFS in enhancing spatial-temporal resolution and operational efficiency compared to traditional methods. We also address technical challenges, including managing massive data volumes, data interpretation complexity, and large-scale deployment logistics. By sharing our progress and insights, we aim to foster collaboration with interested institutions and individuals to further develop and integrate this technology into seismic research and disaster mitigation efforts.

Challenges with ring laser observations in seismology

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Twenty years ago, the first extensive data study with G-ring observations of the vertical component of rotation and a collocated broadband sensor revealed the potential of joint rotation and translation observations [1]. These initial results triggered the developments in portable rotation sensing but – as of today – there still is no portable sensor that matches the sensitivity of large ring lasers. Therefore, ring lasers – in particular the multi-component ROMY ring laser installed in the Geophysical Observatory in Munich in 2016 – can serve today as the test bed for any future portable high-sensitivity 6 DoF setups. In this talk the various "first-of-its-kind" observations with ring laser data will be reviewed. This includes surface wave dispersion, Earth's free oscillations, ocean generated noise and Love-to-Rayleigh amplitude ratios, seismic source tracking. We discuss in detail the difficulties in having long-term stability with a heterolithic ring laser (ROMY) [2]. Heterolithic ring lasers are much cheaper to construct compared to monolithic ring lasers that are mounted on thermally stable material (G ring). This implies that temperature and pressure and potentially internal vibrations alter the scale factor leading to loss of lasing and erroneous observations. Recently, a rotational low noise model for our planet was proposed based on the connection between rotational and translational amplitudes under the assumption of fundamental mode surface wave propagation. Both G and ROMY ring lasers are characterized by flat power spectral densities below 0.1 Hz which was considered as the noise floor of the instrument itself. New results indicate that there is a strong correlation between atmospheric pressure and rotation-rate observations in this frequency band. While further studies are necessary, this may well indicate that in this range the atmosphere dominates the rotational ground motion, hiding smaller seismic wave induced rotational motions. We will discuss the potential of ring lasers for highly precise ground motion observations around gravitational wave detectors (e.g. Einstein Telescope).

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About the Use of 6C Measurements on Active Volcanoes

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Near field recordings of volcano-induced events often suffer from unaccounted effects of local tilt and unknown shallow velocity structure. Most of the time the station number is limited and thus source locations, source tracking or moment tensor inversions are very often unconstrained. Possible obvious advantages of gradient measurements in these fields, however, come also with a price: the wavefield gradient is very sensitive to local site conditions/heterogeneity. To investigate the advantages and problems of the combined recording of translational and rotational motion measurements (6C) in more detail, we designed several experiments using blueSeis-3A rotational motion sensors together with traditional seismometers at Stromboli volcano, Italy in 2018 and 2022, as well as Kilauea, Hawaii. To estimate the differences in site responses as well as to evaluate the performance of 6C recordings for location and moment tensor inversion, the stations were distributed along at different height levels and distances to the center of volcanic activity. In order to examine the influence of different site effects we extensively used the spectral element code SALVUS to simulate various structural contributions. Finally we try to correct local site effects by estimating the response of the site using cross-correlation of translational and rotational motions, respectively. This might be seen as a first attempt to solve the problem of very local heterogeneity and strain tilt coupling which often degrades the usability of 6C recordings.

Investigating the subsurface structure at Strokkur geyser, Iceland, using 6 DoF measurements

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A geyser is a multiphase geothermal feature that exhibits frequent, jetting eruptions of hot water and non-condensable gases such as CO2. Their eruptions can be either driven by gas accumulating in a bubble trap or by a thermal instability leading to flash boiling of water. First evidence exists that Strokkur geyser in Iceland is fed from a bubble trap [1]. In 2020 we installed two 6 DoF stations at 8 different locations at less than 30 m from the presumed bubble trap. The 6DoF station consists of a Trillium Compact 120s sensor collocated with a BlueSeis 3A rotational sensor. We assess the wavefield, derive back azimuths using SH-type of waves and SV-type of waves and finally back project the recorded seismic signals. We identify a complex hydrothermal tremor wavefield generated by bubble migration and bursting in the subsurface. We confirm a bubble reservoir and discuss its dimension in 3D.

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Directional amplification effect observation across quaternary faults: comparison on rotational and translational H/V spectra.

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The directional amplification effect (DA) refers to amplifying the signal along site-specific azimuth in the horizontal plane, which is observable on both earthquake wavefield and ambient noise measurements [1]. The origin of such an effect is connected with the anisotropy of local subsoil geological structures. Various geological conditions can be a source of the directional amplification effect occurrence, which can be distinguished: fractured rock slopes and landslides, volcanic zones and also fault zones. Regardless of the geological framework, the azimuth of the DA tended to be in the orthogonal direction to the primary orientation of the predominant fractured field in the fault damage zones [2]. The Horizontal-to-Vertical Spectral Ratio method (HVSR) is a known way of determining local site effect parameters. However, following some research [3], the HVSR can be applied in the DA effect determination. The calculation methodology is based on the rotation of the registered time history of the horizontal components by an angle in the first step and the estimation of the HVSR spectrum for each case of the rotation in the next step. Determination of the HVSR can be performed by using the Fourier Spectra Analysis (FSA) and also from the Response Spectrum Analysis (RSA), however using the spectrum methods interchangeably may lead to inaccuracies in resonant frequency determination [4]. The RSA approach should be used in the HVSR determination in cases where the amplification spectrum calculated from the FSA approach shows more than one peak, which fulfils the criteria of the amplification peak reliability according to the SESAME criteria. It cannot be ignored that the HVSR is obtained from the translational motion records. However, the rewritten equation of the HVSR allows to determination of the rotational site effect parameters [4] and is called Torsion-to-Rocking Spectral Ratio (TRSR).

Considering the presented research, determining the directional amplification effect of rotational and translational motions as an effect of the closest proximity to Quaternary faults was a subject of the analysis. Therefore, rotational and translational records of the induced seismic events at two sites located in the Upper Silesian Coal Basin (USCB) were the source of the HVSR and TRSR estimations, which were derived from the FSA and the RSA approach for each case of the rotated components, with a 5-degree step. The obtained results for the rotational and translational motions presented a perpendicular orientation of the DA azimuth compared to the direction closest to the station faults. Comparing the FSA and RSA approaches of the translational motion presented a high level of similarity. However, in the case of the rotational motions, the method comparisons show differences. The reason was connected with the impact of the sensor settings on the pedestal on the RSA estimations.

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Evaluation of modal rotation fields using shearography for structural damage identification

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Shearography is the interferometric measurement technique, which uses light intensity related to the phase, and resulting in phase maps that contain a pattern of interferometric fringes. Due to its full-field and non-contact measurement properties as well as high sensitivity to local damage, shearography gained attention in numerous fields of study, and found numerous applications, primarily as the non-destructive testing technique, approved e.g. by the Federal Aviation Administration for inspection of aircraft structures.

The resulting phase maps from shearographic measurements are characterized by the high level of noise and presence of discontinuities, therefore, their filtering and processing is required for further analysis. In commercial devices for shearographic inspection, these procedures end with obtaining the displacement fields and these fields are used for detection and identification of structural damage. However, by taking the first derivative of displacement fields, one obtains rotation fields, which have higher sensitivity to damage, as confirmed in experiments [1,2]. The idea of identification of structural damage using shearography is based on localization of spots resulting from local stiffness decrease caused by the presence of damage in a specific location. The acquired rotation fields acquired can be further processed using spatial transforms to improve sensitivity to the smallest damage, which is not identifiable from the raw shearographic measurements. For this purpose, a variety of wavelet transforms [1-3] as well as other integral non-parametric transforms [4] can be applied. In this way, the rotation fields acquired e.g. from modal analysis using shearography technique are filtered to localize disturbances resulting from local decrease of stiffness, and identify damage. This approach makes it possible to identify damage at the level of ca. 3-5% of stiffness decrease with providing its location and spatial dimensions. It can be useful especially in the cases of internal damage, which does not reveal any detectable signatures on the surface of a tested structure.

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Session #8, Thursday

Rotational Waves in solid amorphous media - Discrete Element Method simulations

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Rotational waves in solid media have been an intriguing issue for physicists for years. Within the classical linear theory of elasticity such waves - transient propagation in time and space of rotational energy do not exist. The reason for this is that the (classical) theory of elasticity completely ignores an internal micro-structure of solid media by assuming that particles building the medium : a) have no intrinsic orientation in space b) an interaction between particles building the medium is short-range what supports an idea that any interaction

of two (real or virtual) elements of the medium goes through the traction forces acting over an element of a surface shared by elements. In consequence, there is no way to deal with rotational energy and its transport.

In case of seismology a quest of an existence of rotational seismic waves was not undertaken for a long time. One of the reason of this was that an application of the linear theory of elasticity in seismology to compute seismic waves propagation has been proved to be very successful. For variety of seismic waves propagation issues and its particular applications including seismic imaging or seismic tomography this theory is absolutely sufficient. However, accumulating evidence of rotational displacement caused by shallow earthquakes has raised an interest about rotational waves as a possible cause of such effects.

In this talk I will present results of numerical simulations of generation and development of rotational waves in an amorphic medium with a stochastic microstructure. We approach the problem with the best suited to the task numerical method, namely the Discrete

Element Method (DEM) which particular feature is representation the body under studies as an ensemble of bounded particles. Thus it inherently includes the fact of an existence of microstructure of the medium. An initial goal of presented analysis was a numerical verification of an existence of rotational waves in amorphic media. The answer is positive, however, ongoing progress of simulations and gaining knowledge about the problem

has raised new questions among which the quest of dependency of properties of visible rotational waves on a micro-structure and generation of rotational energy by particulate sources are discussed here.

Rotations in the seismic response of a tall building on piles

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The rotational motions observed at the base of structures during earthquakes are due to the incident waves as well as the inertia forces and moments with which the vibrating structure acts onto the soil (soil-structure interaction). The former are larger near the earthquake source, while the latter depend on the properties of the structure and soil and on the amplitudes of the response. Directly recorded rotations in structures during earthquakes are rare due to the added cost. Tongde Plaza Yue Center (TPYC), a densely instrumented 50-story skyscraper in Kunming, Yunnan Province of China, is a rare example of a building located in a seismic area that has been permanently instrumented with rotational seismometers (R2, one in the basement and the other one under the roof). Records of 49 earthquakes have been retrieved from the continuous streams of data during its four and a half years of operation, with $2.1 \le M_S \le 7.7$ and at epicentral distances $10 \le R \le 1{,}600$ km, including the recent $M_W 7.7$ Mandalay, Myanmar (Burma) earthquake of March 28, 2025 ($R = 773$ km) and Tingri, Tibet earthquake of January 7, 2025 ($R = 1{,}600$ km). A detailed finite element model was developed of the structure, its 4-level basement and pile foundation, which reaches 50 m depth, and the surrounding soil (shear wave velocity $V_S \approx 220$ m/s at least up to 100 m depth). We used the model to study the effective input motion and the structural response to plane waves, incident vertically [1,2] and at an angle, for site specific soil and different modeling assumptions [1], and for variable soil, with V_S between 50 and 800 m/s. The excitation is a 3-component motion applied as a combination of incident P-, SV- and SH-waves. The motions are such that the model free-field motion for vertically incident waves matches the recorded motion at the surface near the building. Then, the same P-, SV- and SH-waves are applied incident at an angle (not yet published). We present a simple analysis of the recorded rotations and results of simulated responses to three earthquakes, with emphasis on the effective input motion to the structure, i.e., the translations and rotations near the center of the 4th basement, where 6DOF motion was recorded. The amplitudes of the recorded and simulated rotations in the basement are ~10^{-5} rad and their Fourier spectra have peaks at the natural frequencies of the building. As V_S of the model increases, the effective input motion translations increase, approaching those of the fixed-base model, while the effective input motion rotations decrease, approaching zero. The model rotations for the vertically incident waves and site specific V_S have similar amplitudes to the recorded ones. We conclude that, for the three earthquakes considered (R between 116 and 506 km), the recorded rotations in the basement of the building are caused mostly by the soil-structure interaction. Animations of recorded response during selected earthquakes can be viewed on the Youtube @TPYC-seismic channel [3].

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Fiber-optic rotational seismometer with enhanced temperature adaptability

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Objective

As a kind of high-sensitivity and portable rotational motion sensor, fiber-optic gyroscope has become a powerful tool for rotational motion measurement. However, the sensitivity of optical fibers to the change of temperature field reduces the environmental adaptability of fiber-optic rotational seismometers (FORS), thereby degrading their performance in applications. We will introduce two strategies to improve the temperature adaptability of FORS.

Methodology and Results

FORS detects rotational motion by the Sagnac phase difference between two light beams transmitted clockwise and counterclockwise. When two light beams pass through the same region at different times, they are affected by different time-varying temperatures, resulting in a non-reciprocal phase shift of light, known as the Shupe effect [1]. This phase shift is superimposed on the rotational signal and can hardly be distinguished. We propose a dual-channel differential-mode configuration [2]. By combining two coils with dual-quadrupolar winding pattern [3], the light in both channels of the configuration is affected by the temperature field in almost the same space at the same time, resulting in the Shupe effect being almost identical. Therefore, the phase shift caused by Shupe effect is suppressed through the differential-mode configuration. In a time-varying temperature experiment, the output of the dual-channel differential-mode configuration, compared with that of the conventional FORS, becomes more stable.

In the high-sensitivity Sagnac interferometer, when the Shupe effect is basically suppressed, the thermal phase noise becomes the dominant temperature effect [4]. Therefore, we propose a high-order frequency modulation method. By high-order frequency modulation, the operating point of FORS is upconverted to the frequency band with low thermal phase noise. In a time-varying temperature experiment, compared with the conventional method, the performance of FORS is more stable, and the temperature sensitivity is suppressed by 32 times.

We have integrated these technologies into the newly developed FORS, the performance of which will be presented at the meeting.

Conclusions

The experimental results show that the dual-channel differential-mode configuration and high-order frequency modulation method can effectively improve the temperature adaptability of FORS, and provide a more powerful tool for practical application.

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Rotational Motions Observations in Deep Underground Laboratories

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. Deep underground laboratories are characterized by low environmental noise, making them suitable for high-precision gradient field observations of multi-physical fields such as gravity, geomagnetism, electromagnetism, and earthquake (Wang et al., 2023). Previous studies have shown that the thick sedimentary layers above deep underground laboratories effectively shield high-frequency noise originating from the surface, significantly reducing vibration noise in the underground. This enhances the Signal-to-Noise Ratio and epicentral distance of observable seismic events (Simonelli et al., 2016; Wan et al., 2024). Moreover, the favorable temperature and pressure conditions within deep underground laboratories improve the stability of temperature- sensitive optical sensors, making them suitable for long-term stable observations using fiber-optical rotational seismometers. Since 2020, we have conducted rotational observations and numerical simulations in multiple deep underground laboratories. The results show that: (1) A portable rotational seismometer installed at the Huainan deep underground laboratory at 870 meters depth successfully recorded far-field seismic signals from an epicentral distance exceeding 1000 km. By combining translational and rotational observations, epicentral location can be determined through intersection (Igel et al., 2007). (2) Compared to location determination using only three translational components, the additional rotational components reduces azimuthal estimation errors and avoids 180º ambiguity, thus improving the accuracy of epicentral location in sparse seismic networks (Chen et al., 2023). (3) The rotational components exhibit distinct site.

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Session #9, Thursday

Coupling mitigation in low frequency active vibration isolation systems based on optical gyroscopes

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The science case to extend observation windows at low frequency is very high for gravitational wave astronomy. This would render possible the observation of a large number of previously invisible phenomena, as well as the development of multi-messenger astronomy by enabling early detection of gravitational waves. This is the goal of the future Einstein Telescope (ET) to be built in the following decade [1]. Extending the observation bandwidth at low frequency means also to be capable of extending the seismic isolation at very low frequency as well. Currently, the main limitation for low-frequency isolation comes from the sensitivity of inertial sensors to translation and rotation. Indeed, this feature makes it difficult to analyse seismic motion and perform seismic isolation in the frequency band in which both translation and rotation contribute, typically below 1 Hz [2].

In this paper, we present the basis of a novel approach which consists of using optical gyroscopes alongside classical inertial sensors for controlling a platform. The ultimate advantage is that these types of gyroscopes, relying on the Sagnac effect, are inherently insensitive to translation. This allows to mitigate the coupling between translational and rotational motion by two orders of magnitude down to 10 mHz, leading the system to achieve greater isolation in the sub-Hz frequencies. The concept is illustrated on a simplified model and tested experimentally on a large platform.

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Assessment of the variability of seismic waves back azimuth estimates based on array-derived 6C analysis

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Several publications show interest in having a co-localized measurement of the displacements and spatial gradient of the seismic wavefield for the characterization of its source, in terms of position or focal mechanism. Since 2015, a 3C broadband seismometer antenna has been deployed on the surface and in the galleries of the Low Noise Underground Laboratory (LSBB) in France. Using dense-antenna seismic approaches, recent studies have demonstrated that this antenna enables indirect measurement of the seismic spatial gradient, which can resolve the microseismic background noise.
A database of Array Derived Rotation (ADR) measurements, including signals from regional and global earthquakes as well as microseismic background noise, is compiled from the LSBB recordings. A systematic 6C analysis is performed on this database, of co-located observations of translation and rotation, to estimate the local propagation direction and apparent phase velocity of the shear waves (body and surface). This database allows us to study the ability of local 6C data to detect and locate far field seismic events. Nevertheless, the recovered back azimuth reveals a large variability in the agreement with known propagation direction, depending on the selected subset of stations: surface, gallery or the whole antenna. In order to identify the origin of these discrepancies and for increasing the robustness of the local rotational motion calculation, a sensitivity study is carried out sequentially on the role of instrumental conditions (antenna geometry, station quality) and processing parameters (signal duration, filtering). Furthermore, the impacts of source mechanism or nature of the waves, and local conditions due to the geological and topographical heterogeneities, on the sensitivity of back azimuth estimates are also investigated. For validation purposes, numerical full waveform simulations are carried out in parallel. This work leads to several preliminary statements regarding the estimation and use of array-derived 6C data to characterize seismic waves and their sources.

Exploring Seismic Attenuation with Rotational Ground Motion

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Understanding seismic attenuation is essential for characterizing Earth's subsurface properties, including thermal structure, fluid content, and scattering heterogeneities. While conventional attenuation models rely on translational ground motion, rotational seismology provides an additional perspective by capturing angular velocities and strain. This study explores the potential of radiative transfer theory (RTT) to model seismic energy loss using rotational ground motion, aiming to extend existing methodologies to 6C (six-component) seismology.

We develop numerical simulations to investigate how incorporating rotational measurements affects the estimation of intrinsic and scattering attenuation. Our approach adapts the theoretical framework of RTT to rotational energy density, allowing for a more detailed analysis of seismic wave propagation in complex media. By simulating wavefields across heterogeneous structures, we aim to evaluate whether rotational data can provide new insights into azimuthal variations and energy partitioning.

This research is a work in progress, focusing on refining the computational model and validating its assumptions. Future steps include comparing synthetic results with observational data to assess the practical implications of rotational measurements for attenuation studies. By integrating rotational ground motion with RTT, this study seeks to advance our ability to model and interpret seismic energy loss in diverse geological settings.

Monitoring of seismic induced ground rotations at the Campi Flegrei volcanic area with a fiber-optic gyroscope: preliminary results

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For nearly a century, gyroscopes have been widely used, alone or included in more complex systems, as inertial sensor able to measure angular rates without any external reference. They are the basis of many applications and can be found, for example, in smartphone, sea and air navigation, automatic and robotic system [1,2].

We describe a fiber-optic gyroscope (FOG) with a sensitivity in the range of $10^{-6} - 10^{-8}\, rad/s/\sqrt{Hz}$ over the frequency bandwidth 5 mHz – 50 Hz. The core of the system is an interferometer realized through a 2 Km long polarization maintaining optical fiber wound around a spool with a diameter of 25 cm.

The general principle of a FOG is based on the Sagnac effect [3]. A beam of light is split in two beams (50% ratio) that circulate along the same optical path but in opposite directions. A rotation induces a change of the time of flight of photons travelling inside the interferometer which translates in a phase difference between the counter-propagating light beams. The Sagnac phase shift at the interferometer output is proportional to the effective area which is the area of a single turn multiplied by the number of turns [4]. The interrogation system is based on a broadband incoherent source centered at 1550 nm and a serrodyne modulation/demodulation technique [5].

To characterize our systems, the FOG has been employed for real-time monitoring of the Earth crust rotational motion generated by earthquakes. In particular, it has been combined with standard seismic sensors (seismometers, accelerometers, tiltmeters) provided by the Osservatorio Vesuviano, Istituto Nazionale di Geofisica e Vulcanologia (OV-INGV) in order to measure nine motional components. The nine- component of system was placed in a laboratory of the CNR-INO located in the middle of the Campi Flegrei (Pozzuoli), an active seismic and volcanic area. We continuously acquired data for five months, during which we have recorded tens of local earthquakes.

The system performance have been carefully characterized [6], while the seismological data are currently undergoing a deeper analysis. Now, we are working on the improvement and optimization of the system.

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Posters

First-Time Use of AI in GINGERINO Data Analysis for Fast Frequency Reconstruction and Seismic Event Recognition

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Ring lasers, based on the Sagnac effect, measure absolute angular rotation rate, for this reason they are also called ring laser gyroscopes (RLG). RLGs with large area have demonstrated top sensitivity. GINGERINO is a RLG, based on a square cavity with 3.6m side, currently taking data inside the underground INFN international laboratory of Gran Sasso. It has been built in order to validate the Gran Sasso laboratory for the installation of the GINGER experiment, based on an array of RLG, which is currently under construction. Large frame RLGs sensitivity enables the detection of geophysical signals, including polar motion, tides, and seismic events, and allow fundamental physics tests. Our analysis addresses systematic corrections, focusing on backscattering, and null-shift corrections caused by non linear laser dynamic. In general the signal reconstruction requires several seconds, for this reason we use the new advanced AI tools to speed up to 10msec the time necessary to reconstruct the angular rotation from the interference signal between the two counter-propagating beams in the cavity. Using AI we have created the mask to classify the different physical phenomena affecting the RLG, for example laser disturbances or seismic events. We developed a novel data acquisition system capable of surpassing traditional Fast Fourier Trasformation (FFT) based methods. The new system reduces delay times to just one-hundredth of a second while achieving twice the precision of FFT algorithms on this delay. By exploiting the interplay between laser gyroscope physics and fringe contrast monitoring, the reconstructed signal is effectively classified, allowing for robust characterization of physical phenomena. Moreover, this approach integrates a specialized neural network for seismic event recognition, which has demonstrated exceptional accuracy rates between 99% and 100% on available test datasets. This advancement makes first step for AI-driven data analysis in future GINGER experiment.

Data curation and quality assessment of novel ground rotation sensor data at LIGO sites in the USA.

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We present a newly discovered ground rotation data set of several ground rotation sensors which has been nearly continuous from 2016 to the present. The sensors are inertial mechanical sensors consisting of a beam balance [1,2] that are sensitive to pure rotations about horizontal axes. The 1 component Beam Rotation Sensor (BRS), which has low sensor self-noise of 0.3e-9 rad/sqrt(Hz) above 0.1 Hz, is part of the active seismic isolation system for the LIGO gravitational wave interferometers at Hanford, Washington and at Livingston, Louisiana. The BRSs are collocated with seismometer sensors. The BRS data provide important benchmarks for the next generation of truly portable low-noise ground rotation sensors, which enable the development of 6-degree-of-freedom field acquisition systems.

We present preliminary performance and quality assessments of the expansive data set comprised of combined co-located 3C translations and 1C rotations by analysing the recordings from large tele-seismic earthquakes (Mw 6.9 - 7.4) and also small local events (Ml< 3). The existence of six rotation sensors with a noise level low enough to measure the ocean microseism is a game-changer for rotational seismology in the US. Even though the BRS sensor itself is not portable and only contains a single component, its successors, currently in production, allows the observation of global seismic rotation signals which so far was only possible with ring laser technology. A key component is that the sensors are reliable in the frequency range of interest for seismology. We present a preliminary quality assessment using correlation and coherence analysis on the rotation data. An important aspect is the amplitude and phase comparison of the six BRS sensors. Additionally, we explore the relationship between rotation and translation by cross-comparing the BRS to the collocated six 3C translational seismometers.

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Seismic anisotropy from 6C ground motions of ambient seismic noise

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Since the emergence of ambient noise techniques, the cross-correlation functions have been successfully applied to extract the average phase velocity of the surface wave between two stations based on the travel time or phase difference. However, it has been an open scientific challenge whether rotational observations of ambient seismic noise can provide additional constraints for the Earth's interior. Here, we propose a new approach to measuring local seismic anisotropy from 6C (three-component translation and three-component rotation) amplitude observations of ambient seismic noise data. Our recent theory demonstrates that the amplitude ratio of 6C cross-correlation functions (CCFs) enables retrieving the local phase velocity. This differs from conventional velocity extraction methods based on travel time. Its local sensitivity kernel beneath the 6C seismometer allows us to study anisotropy from azimuth- dependent CCFs, avoiding path effects. Such point measurements have great potential in planetary exploration, ocean bottom observations, or volcanology. We apply this approach to a small seismic array at Pinon Flat Observatory (PFO) in southern California, array-deriving retrieves rotational ground motions from microseismic noise data. The stress-induced anisotropy is well resolved and compatible with other tomography results, providing constraints on the origin of depth-dependent seismic anisotropy.

The usefulness of the different rotational sensors for structural health monitoring

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Structural health monitoring (SHM) seems to be the most important in providing security for any engineering structure during normal exploitation and probing its damage. Since 2009, rotational seismology (RS) in engineering applications has been treated as a new scientific area of interest regarding SHM [1]. The main reason for this is that three-dimensional rotational vibrations are observed in engineering structures, which are the research subject for RS. Unfortunately, rotational seismometers meeting the technical requirements for SHM applications [2] are currently available in limited numbers.

This paper reviews the application of point-based rotation measurements in experimental studies in SHM. The primary focus is on dynamic measurements using rotation rate sensors and rotation acceleration. However, selected studies utilizing static inclinometers are also presented. Full-field rotation measurements using the shearography technique [3] are also possible. However, in the authors' opinion, they mainly focus on measurements of small-scale elements in opposition to a fibre-optic gyroscope (FOG), the base for constructing a fibre-optic rotational seismometer (FORS). Therefore, this technique is not reviewed here. The study is primarily based on the review of the rotation sensors application in the recent habilitation thesis [4] as well as the review paper [5], which, to the author's knowledge, is the only comprehensive review in this area. The current review is updated with new studies, and the possible application of FORS is commented on.

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The EPOS TCS AH EPISODES platform as a tool for the seismic scientific analysis and a source of the rotational motion data

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The EPISODES platform (episodesplatform.eu), is the core of the Integrated Research Infrastructure of EPOS Thematic Core Service Anthropogenic Hazards, connected to international data storage nodes, which offers open access to multidisciplinary datasets and applications [1;2]. Datasets available within the EPISODES Platform ore organised in “episodes”. Episode is a set of time-correlated seismic, technological, and other relevant geo-data that relate comprehensively anthropogenic seismic processes to their industrial causes. Episodes contain data on seismicity cases induced by industrial activities such as: underground mining, reservoir impoundment, geothermal energy production, conventional and unconventional hydrocarbon extraction, underground gas storage and wastewater or fluid injection . The platform offers as well access to a large set of embedded applications for processing, analysis, and visualization of the data. The applications can be used to relate seismicity and technological factors for hazard assessment and other scientific purposes. The platform offers a personal workspace where individual data processing and analysis can be carried out using data and software available on the platform or user’s own scripts utilizing access to HPC facilities. The workspace provides the user with a framework to organize data and applications into integrated scientific projects. Access to the EPISODES Platform facilitates collaborative and interdisciplinary scientific research, public understanding of science, knowledge dissemination and offers educational resources on anthropogenic hazards related to geo-resource exploration and exploitation. Access to the EPISODES Platform is free for all registered users. EPISODES Platform gives wide possibilities of processing data. The most worth to highlight to the IWGoRS community is (1) source mechanism and its spectral properties estimations, (2) seismic moment tensor decomposition and stress inversion, (3) parameters of the attenuation law and Gutenberg-Richter relation determination. The Platform provides also the statistical approach of the mentioned analysis verification. Apart from known translational motion records of the induced seismic events, the EPISODES platform, as a set of the Upper Silesian Geophysical Observation System (USGOS) [3], contains the datasets of the recorded rotational motions. The data coming from the ongoing seismic observations of the rotational are registered by three different seismic stations located in the Upper Silesian Coal Basin (USCB). EPISODES Platform offers also the historical rotational data within the MUSE1 episode.

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Rotation measurements for plastic hinge detection as an early warning of seismic damage of moment-resisting frames

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Moment-resisting frames represent a popular class of civil engineering structural systems designed to withstand strong seismic ground motion. Their predominant failure mode is caused by plastic hinge formations between columns and spandrels. With better and cheaper rotation rate sensor inventory of SHM (*Structural Health Monitoring*) – see, e.g. [1] – there is a possibility to instrument the moment resisting frames using rotation rate sensors to detect the rotations in the frame connections caused by the damage. The purpose of the presentation proposed for the 7th IWGoRS is to report recent progress in *the Finite Element Method*, detailed simulations aimed at finding proper rotation rate sensor localisations and minimum levels of excitations for credible warnings of damage initiations.
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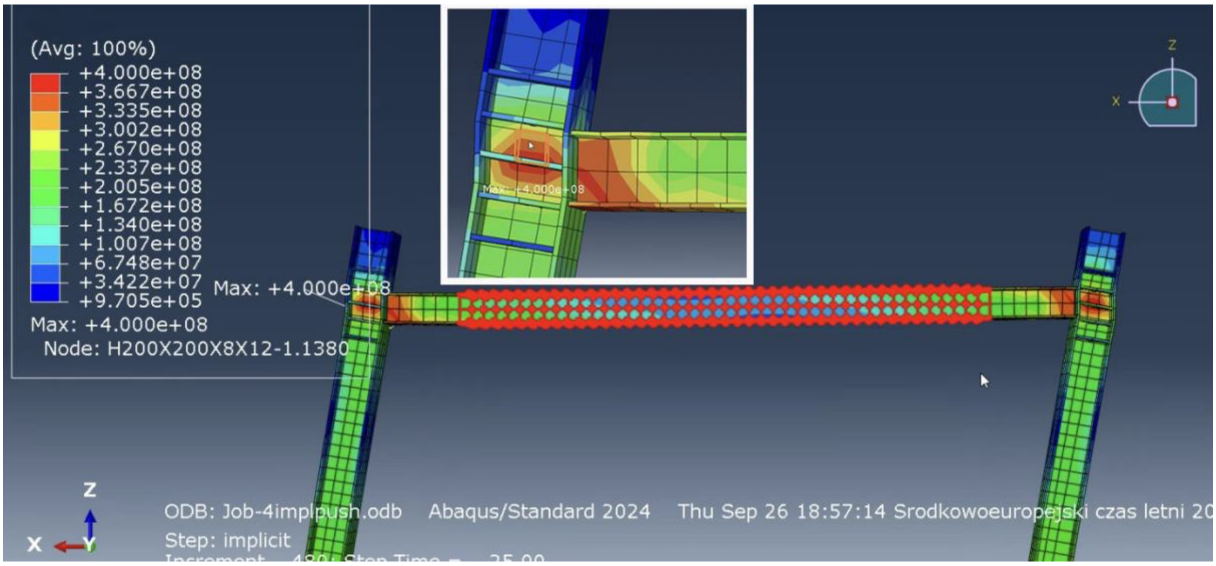

Fig. 1 *Abaqus* FEM model of a steel moment resisting frame under damaging seismic excitations and respective stress maps

In Fig. 1. an example detail of the FEM mesh of moment resisting frame is shown to illustrate angle variations between column and spandrel when the frame is under damaging seismic excitations. During the 7th IWGoRS, parametric analyses of the plastic hinge formation will be presented in detail.

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Ginger Status report

G. CARELLI

For Ginger collaboration

A progress report on the construction of Ginger, an array of ring laser gyroscopes (RLGs), will be presented. The Ginger project aims to build an array of RLGs to continuously measure the absolute angular rotation rate of the Earth. A set of independent and co-located RLGs will be built to reconstruct the full vector. The experimental setup will consist of three RLGs built inside the INFN-LNGS underground facility. Gingerino, a single ring prototype, was used to validate the site. It has been in operation, almost unattended since 2021 and we have used it to resolve the details of remote control and data acquisition. By studying its shortcomings, we have also executed a new design for the mechanical control of the RLGs. The collaboration has already identified the tunnel in which the experiment will be built, and LNGS will shortly provide basic site preparation.

The long-term stability of the setup depends on the material used for the RLG structures. Two materials have been selected: granite and silicon carbide. Granite has already been tested for our purposes on older prototypes. In the proposed design structure for Ginger, each ring has a granite core and SIC spacers to achieve the lateral length. The rings will be oriented horizontally (RLH), at the maximum signal (RLX), and outside the meridian plane (RLO), respectively. RLX and RLO will be about 3m on each side, the maximum allowed space in the tunnel. They will be placed on equal granite structures, but one aligned with the

Earth's axis and the other rotated about 35 degrees. The granite base is divided into two parts, so we can independently fix it to the rock and carefully control the ring orientation. The optical cavity will be enclosed in a vacuum tank system, and we have already tested a new control system in Pisa. Once the two structures are built, Gingerino will be upgraded with the new mechanical components, and it will become RLH. The collaboration released the executive project last year. The granite components will be delivered soon, and the tender for the vacuum part has already been published.

Technical advancements of active and passive ring laser gyroscopes for seismological application

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In recent years, large ring laser gyroscopes have undergone continuous advancements, enabling highly precise measurements of earth's rotation. These improvements facilitate the detection of subtle variations in earth's rotation, driven by various geophysical processes, as well as the study of signals produced by seismic events. However, to achieve best precision, the perimeter of the ring laser must be maintained at or below the parts-per-billion level. We present two approaches that enable stabilization of the ring laser perimeter to a few nanometers, corresponding to a relative instability in the 10^{-10} range, bringing our heterolithic setup on par to monolithic designs. For our setup, consisting of a square ring laser with a side length of 3.5 m, we implement either an absolute frequency lock using a wavelength meter or a free spectral range phase lock. The best performance is achieved with the free spectral range phase lock, providing a relative perimeter stabilization accuracy of $4.1 \cdot 10^{-10}$, which equates to a standard deviation of the perimeter of 5.8 nm. Additionally, when performing long-term measurements of the Sagnac frequency, discontinuous jumps due to variations in the laser dynamics were successfully suppressed by both stabilization techniques. With a sensitivity of $5 \cdot 10^{-9}$ rad/s/√Hz, the minimum of the Allan deviation of the recorded Sagnac signal reaches $5 \cdot 10^{-6}\ \Omega_E$ using the FSR phase lock, where Ω_E represents the earth's rotation rate. Further improvements could be achieved by positioning the gain medium outside the optical resonator and therefore overcoming laser power limitations to potentially improve the sensitivity by orders of magnitude. Furthermore, the passive configuration removes systematic limitations by completely evacuating the vacuum chamber. We will present the current status of this unique setup, in which active, passive and hybrid operation is possible, comparing and characterizing the different operating modes.

Seismogram noise reduction using non-linear stacking: application to six-degree-of- freedom Rotaphone data

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A novel method of non-linear seismogram stacking is used for detection of very weak phases in seismograms. It is based on the GAS method (Málek et al., 2007) which has proven to be very effective. Its advantage over other methods is that it suppresses noise while causing little distortion of the input signal. It was developed to improve signal-to-noise ratio of coherent signals in seismograms from seismic arrays. With a great advantage the method can be performed on 6DOF Rotaphone data in which all the six components are available in several realizations that can be stacked. Especially suitable for this purpose are the records from Rotaphone-D, the latest Rotaphone model design recently tested and calibrated in the U.S.A. (USGS Albuquerque Seismological Laboratory and several field measuring campaigns). These records provide 8 realizations of vertical translational component, 3 realizations of each of the horizontal translations, the same for the two tilts (horizontal-axis rotation rate) and 4 realizations of torsion (vertical-axis rotation rate) – all of them from the same instrument. The application to the Rotaphone data eliminates the problems of unequal instrumental characteristics of the individual instruments in the array, their relatively large distance and the associated potential differences in local conditions.

The method is demonstrated in two examples. First example is a record from Vrancea (Romania) where the measuring campaign started on July 6, 2024. The locality is characterized by the occurrence of deep earthquakes (110 to 160 km). The presented record is from the earthquake of magnitude 5.2 at the depth of 132 km, almost directly below the Rotaphone-D site, which leads to strong vertical rotational component compared to horizontal ones. The specific features of this 6DOF record are therefore weak tilts and relatively strong torsion. The second example are records from Long Valley Caldera (California, USA). The caldera, formed 760,000 years ago as a result of very large volcanic eruption, is characterized by geothermal activity and pronounced unrest in the last five decades, including recurring earthquake swarms. The measuring campaign there lasted 2 years (2022-2024) during which we collected thousands of high-quality records of local microearthquakes with magnitudes above 1. The measurement setup included two Rotaphone- D instruments about 200 m apart. This allows to compare denoised coherent signals from both instruments in the respective frequency range given by the instrument configuration and their frequency characteristics.

The Rotaphone-D proved to be a suitable instrument for registering weak local earthquakes. By utilizing rotation-to-translation relations it can identify much weaker earthquakes than conventional three-component seismographs.

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References

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Ultra-High Performance Gyroscopes for future X-Ray interferometer mission

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X-ray interferometry bears the possibility to image astronomical objects in microarcsecond (μas) resolution, where 1 μas corresponds to 4.8 prad. This target resolution sets extreme requirements for the precision of the measurement of the orientation of the spacecraft carrying the X-ray interferometer. Usually, spacecraft orientation is measured using three single-axis gyroscopes that measure the Euler angles (yaw, pitch and roll) in a spacecraft fixed coordinate frame. These measurements can be complemented by a star tracker. Gyroscopes that are capable of determining the orientation with the required accuracy and stability need to outperform the current highest-performance navigation-grade gyroscopes by several orders of magnitude.

High-accuracy rotation angle and rotation rate measurements become increasingly important in many scientific fields: (1) Seismologists want to observe the local rotation from elastic and non-elastic deformation caused by earthquakes to fully observe the seismic wavefield. (2) The next generation of gravitational wave detectors needs high-precision rotation measurements for active seismic noise isolation and Newtonian noise mitigation. (3) Geodesists want to measure the Earth's rotation rate and its variations with Earth fixed instruments. All these applications require gyroscopes with sensitivity in the range of 1 prad/s/√Hz to 1 nrad/s/√Hz, covering a frequency range from below 0.01 Hz to up to 100 Hz.

This contribution presents a road map study towards the development of gyroscopes that can reach the required sensitivity. We investigate several technological approaches as well as combinations of them. We focus on fiber-optic gyroscopes, ring-laser gyroscopes, cold atom gyroscopes and mechanical gyroscopes.

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