MILITARY UNIVERSITY OF TECHNOLOGY

A highly sensitive instrument for direct and long-term observations of seismic and natural-mode rotational movements

Leszek Jaroszewicz, **Anna Kurzych** and Michał Dudek
Institute of Technical Physics, Military University of Technology., 2 gen. S. Kaliskiego Str., Warsaw, Poland PL-00-908
Elproma Electronics Ltd., 2A Dunska Str., Czosnow, Poland PL-05-152

EGU General Assembly 2022

Rotational seismology

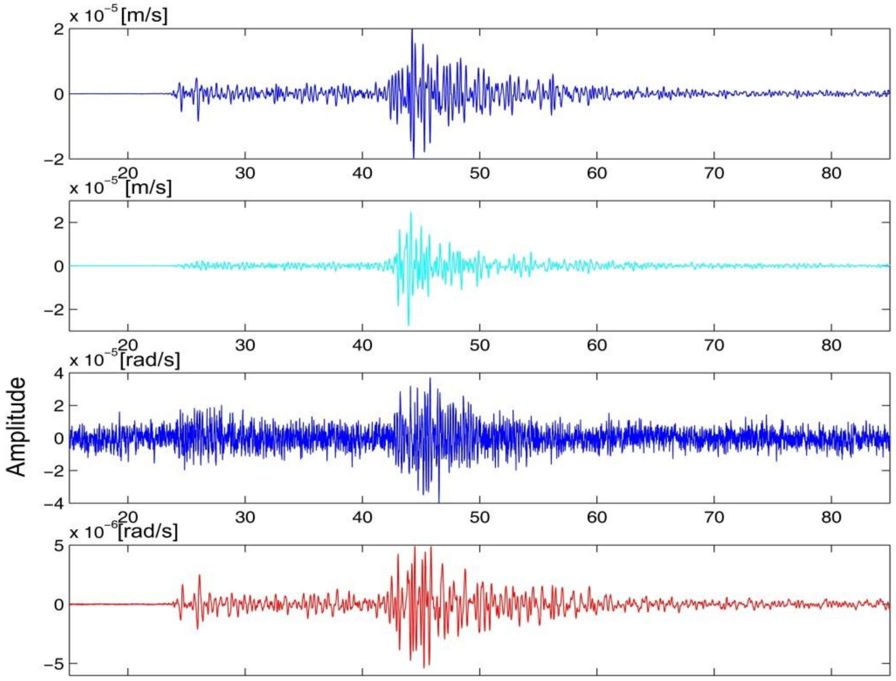
Rotational Seismology [Lee et al. *BSSA*, **2009**, *99*, 945-957] a new, emerging field for the study of all aspects of rotational ground motion induced by earthquakes, explosions, and ambient vibrations

Seismological application:

- broadband seismology [Igel et al., *Geophys. J. Int*., **168(1)**, (2006), 182–197],
- strong-motion seismology [Anderson, 2003, Chap. 57, 937-965],
- earthquake physics [Teisseyre et al. Springer, 2006; Teisseyre et al., Springer, 2008],
- seismic hazards [McGuire, *Earthq. Eng. Struct. D.*, **37**, (2008), 329–338],
- seismotectonics [www.geophysik.uni-muenchen.de/ ~igel/Lectures /Sedi/sedi_tectonics.ppt],
- geodesy [Carey, *Expanding Earth Symposium*, (1983), 365-372],
- physicists using Earth-based observatories for detecting gravitational waves [Ju et al., *Rep. Prog. Phys.*, **63**, (2000), 1317–1427; Lantz et al., *BSSA*, **99**, (2009), 980-989]

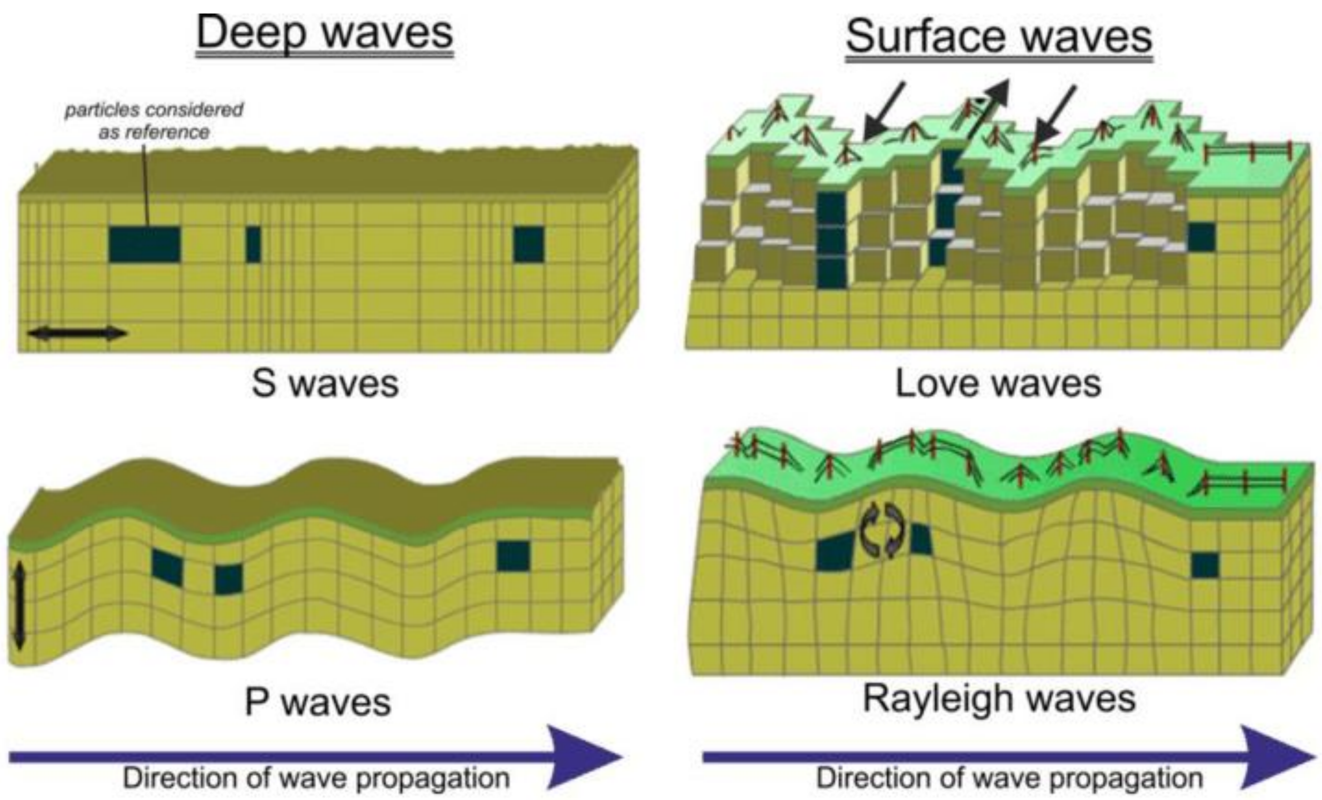
Engineering application:

seismic behaviour of irregular and complex civil structures [Trifunac, *BSSA*, **99**, (2009), 968-97; Mustafa, InTech, 2015]



[Kurzych et al., IntechOpen; (2015), DOI: 10.5772/59595]

Rotational seismology - Seismological application



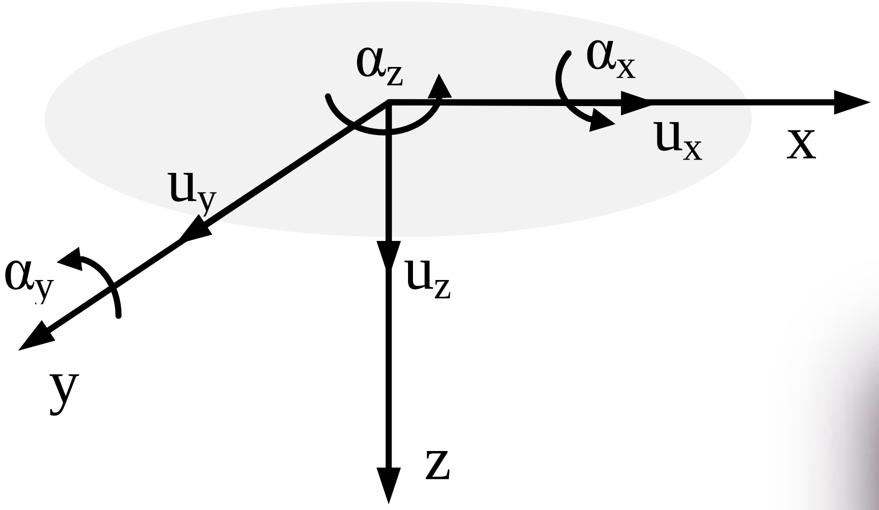
[Martínez-Moreno F., Ph.D. Thesis (2015)]

[Hinzen, J. Seisml., 16(4), (2012), 797–814]

Tombstone in Kushiro Cemetery after the Tokachi-Oki Earthquake 2003

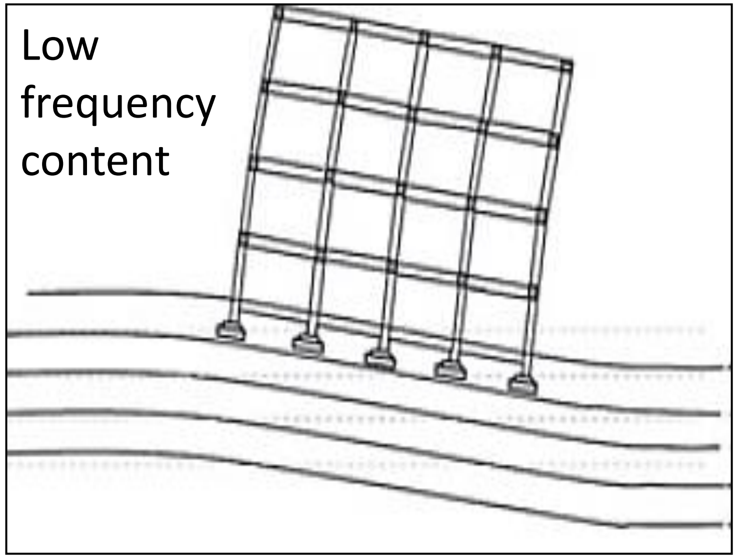
Rotational seismology – 6 degree of freedom

Application domains of 6-DOF (3 translations + 3 rotations) ground motion observations:

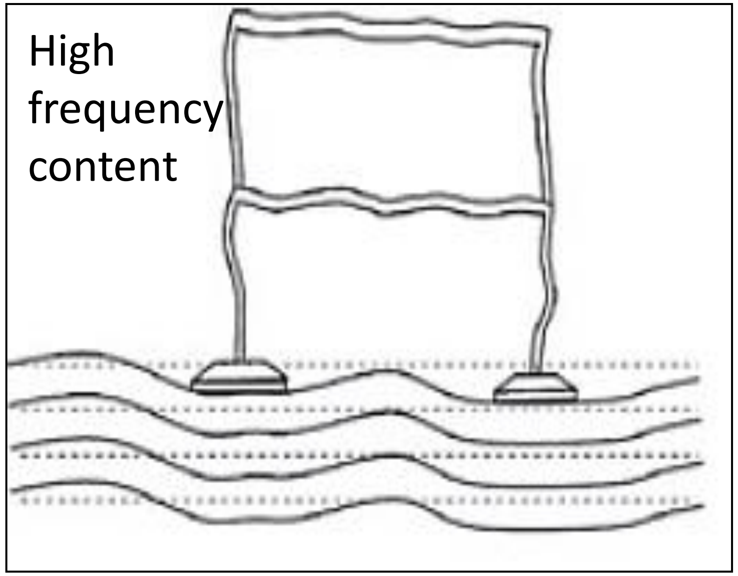


- Earthquake sources,
- Tilt correction,
- Wavefield separation,
- Wave direction,
- Wave dispersion,
- Scattering properties,
- Seismic imaging.

Rotational seismology - Engineering application



- Higher stress in structural element
- **Overturning moment**
- Horizontal displacement of the center of mass



- **Local vibration of beams and columns**
- Meaningless motion of the building center of mass

[Castellani, Guidotti, 2nd Workshop of IWGoRS Masaryk 's College Prague, (2010)]

921 Earthquake Museum of Taiwan, Teichung. Effects of Chi-Chi earthquake, 1999 [private photo]

Rotational seismology - requirements

Seismological application	Engineering application
Insensitivity to linear motion, or at any time opportunity to detect linear and rotational motions independently	
Mobility, stability with respect to environmental conditions, including changes of temperature	
Independent power supply	
ROTATIONAL SEISMOGRAPH network of seismometers + precise time source + recording device + network	
Measuring range: signal amplitude: from 10^{-8} rad/s, frequency: 0.01 Hz – 0.1 Hz	Measuring range: signal amplitude: up to 10 rad/s, frequency: 0.01 Hz – 100 Hz

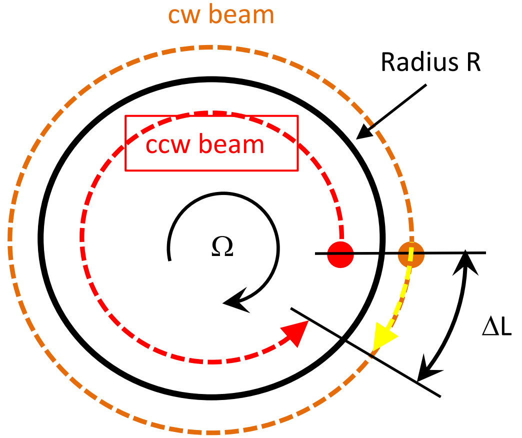
[Jarozsewicz et al., Sensors, 16, 2161 (2016)]
[Bernauer et al., J. Seismol., 16, (2012)]

Dynamic range	Frequency band	Power consumption	Thermal stability
10^{-8} - 10 rad/s	10^{-3} - 200 Hz	5 - 8 W	<0,1% / ^{o}C

Fibre optic seismograph – theory background

Sagnac-Von Laue effect

Light beams propagating in oposite directions in a rotating frame experience a different optical path length



At rest, the time of flight through the loop is

$$T_0 = \frac{Circumference}{Speed\ of\ light} = \frac{2\,\pi\,R}{c}$$

When rotated at rate Ω

-Cw beam travels father to catch up with the moving beam spliter, and its time of flight becomes:

$$T_{cw} = \frac{2\pi R + \Delta L}{c} = \frac{2\pi R + R\Omega T_0}{c}$$

- Ccw beam travels a shorter distance:

$$T_{ccw} = \frac{2\pi R - \Delta L}{c} = \frac{2\pi R - R\Omega T_0}{c}$$

- **Difference in times of flight:**

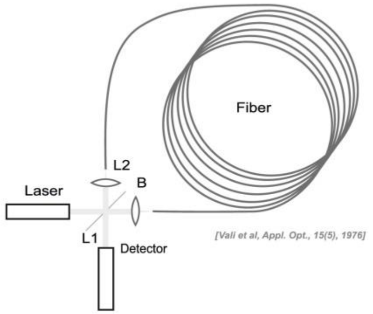
$$\delta T = |T_{cw} - T_{ccw}| = 2\frac{R\Omega T_0}{c}$$

- **Phase difference (Sagnac-Von Laue phase shift):**

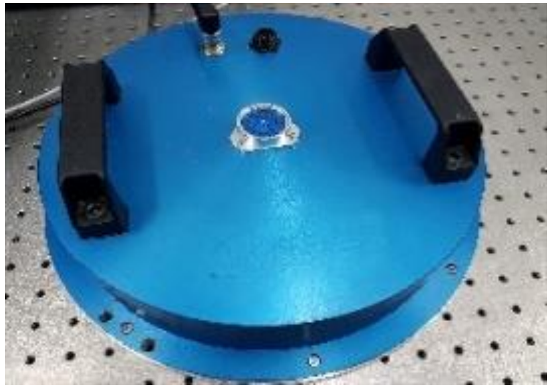
$$\varphi_s = 2\frac{R\Omega T_0}{c} = \frac{8\pi^2 R^2 \Omega}{c\lambda} = Scale\ factor\ x\ \Omega$$

The two beams experience a Sagnac phase shift proportional to the rotation rate and the coil area

$$\varphi_s = \frac{4\pi RL}{c\lambda}\Omega = \frac{1}{S_o}\ x\ \Omega$$

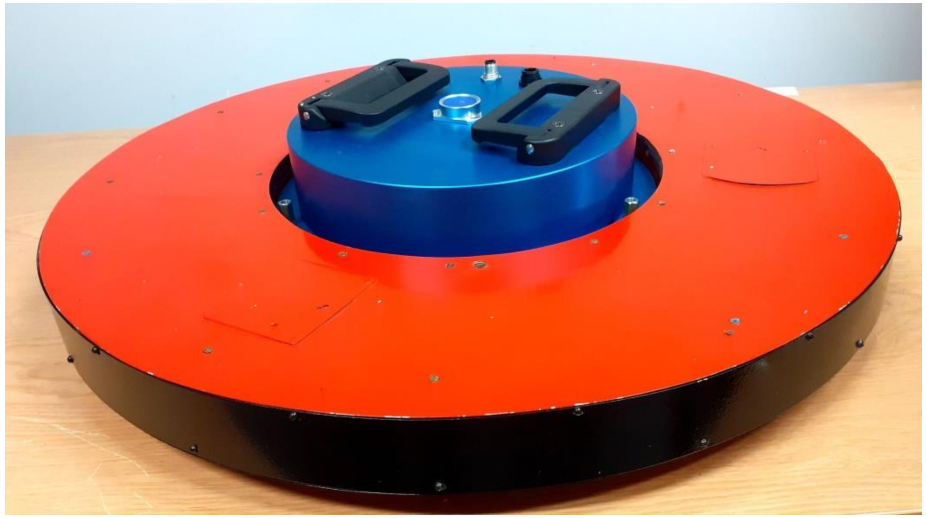


Fibre optic seismograph - construction



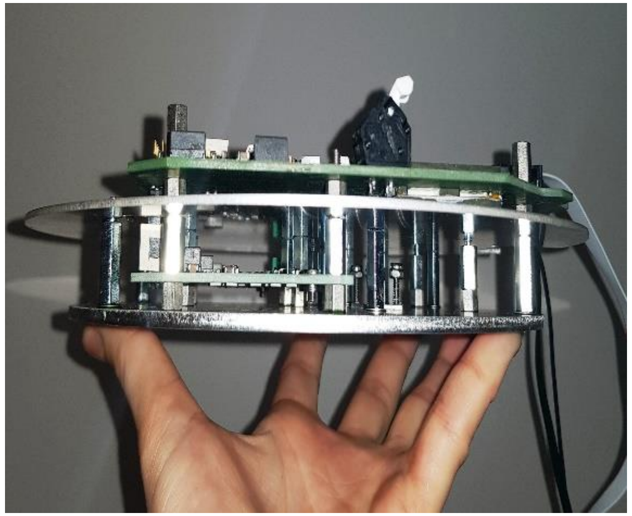
FOS5-01, -02, -03:
- 5 km long SMF
- 0.25 m diameter

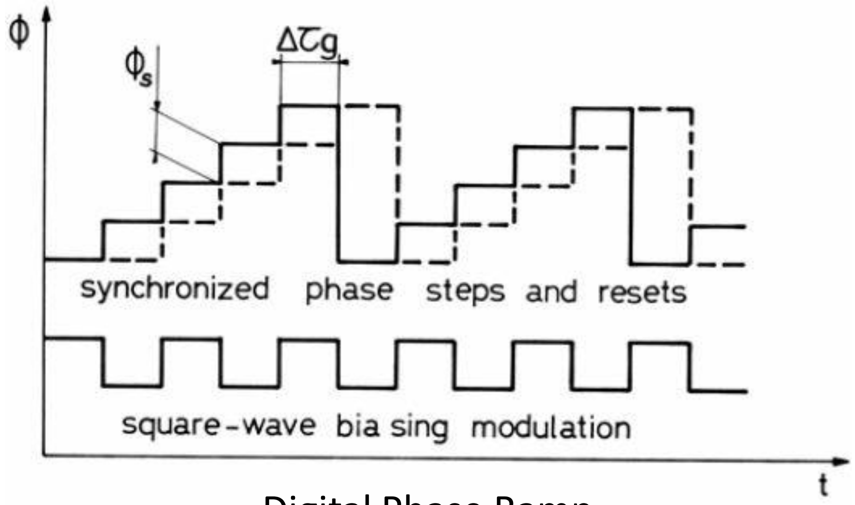
theoretical sensitivity:
$3.41 \cdot 10^{-8}$ rad/(s√Hz)



FOS5-04:
- 15 km long SMF
- 0.60 m diameter

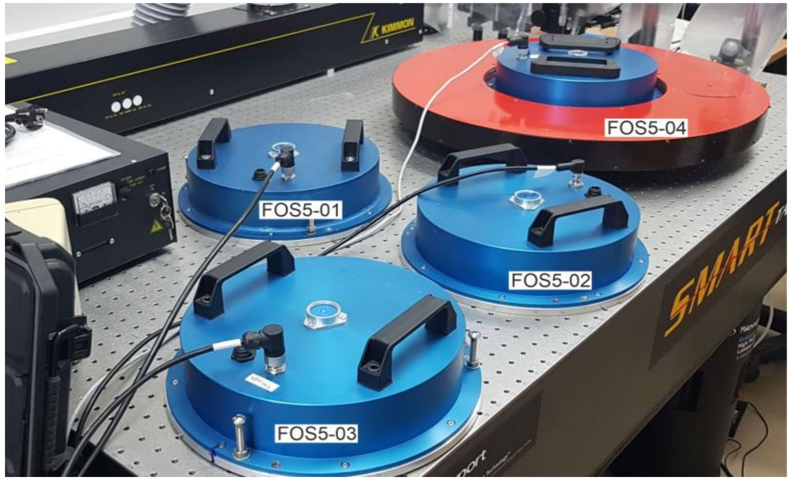
theoretical sensitivity:
$5.67 \cdot 10^{-9}$ rad/(s√Hz)



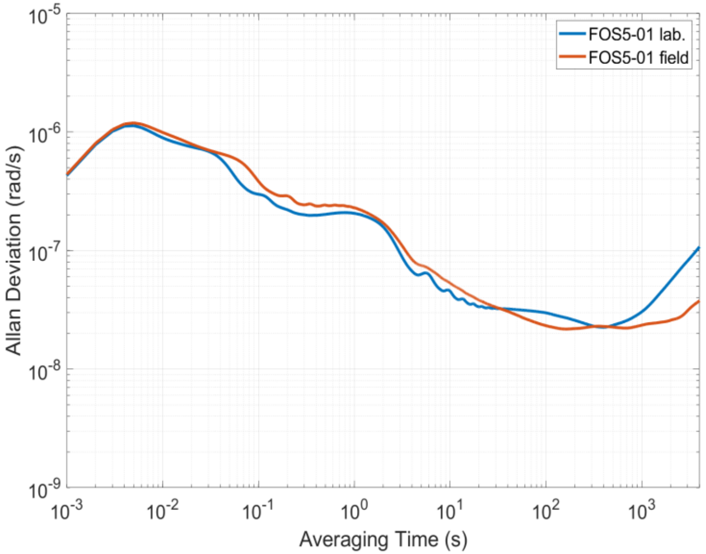


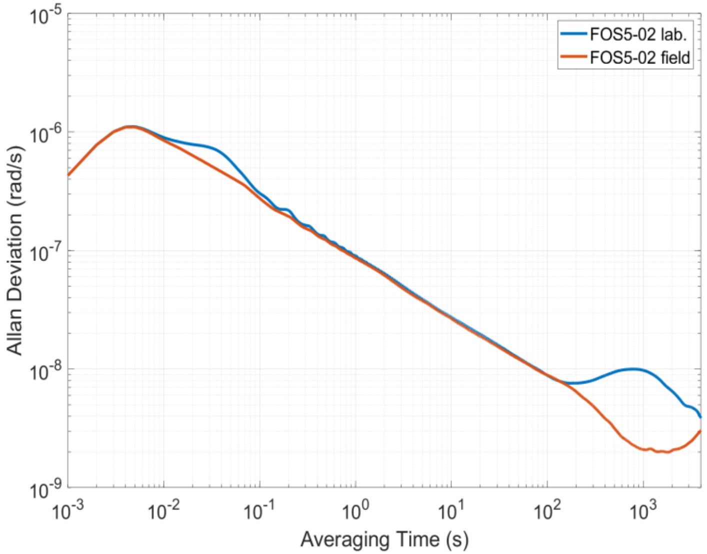
Digital Phase Ramp

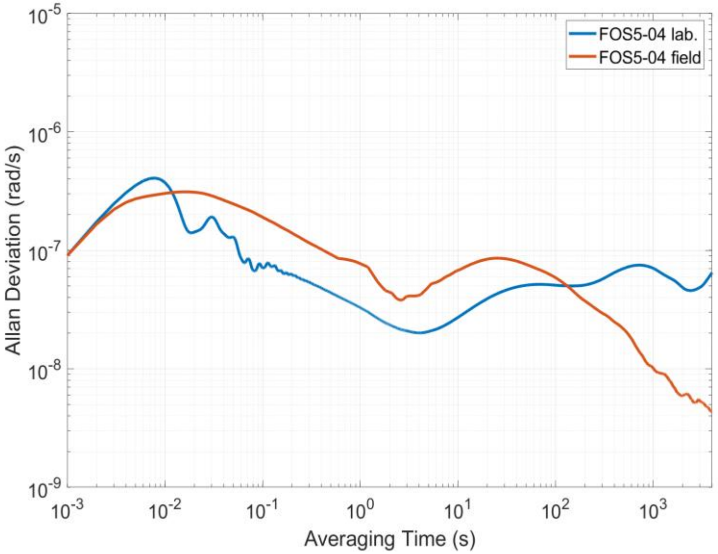
[Lefevre. The Fiber-Optic Gyroscope, 2nd Ed., Artech House, 2014]



Fibre optic seismograph – Allan variance analysis







Position	FOS5-01		FOS5-02		FOS5-04	
	ARW [rad/√s]	BI [rad/s]	ARW [rad/√s]	BI [rad/s]	ARW [rad/√s]	BI [rad/s]
Lab.	$2{\cdot}10^{-7}$	$2{\cdot}10^{-8}$	$9{\cdot}10^{-8}$	$2{\cdot}10^{-9}$	$3{\cdot}10^{-8}$	$2{\cdot}10^{-8}$
Field	$2{\cdot}10^{-7}$	$2{\cdot}10^{-8}$	$9{\cdot}10^{-8}$	$1{\cdot}10^{-8}$	$8{\cdot}10^{-7}$	$4{\cdot}10^{-8}$

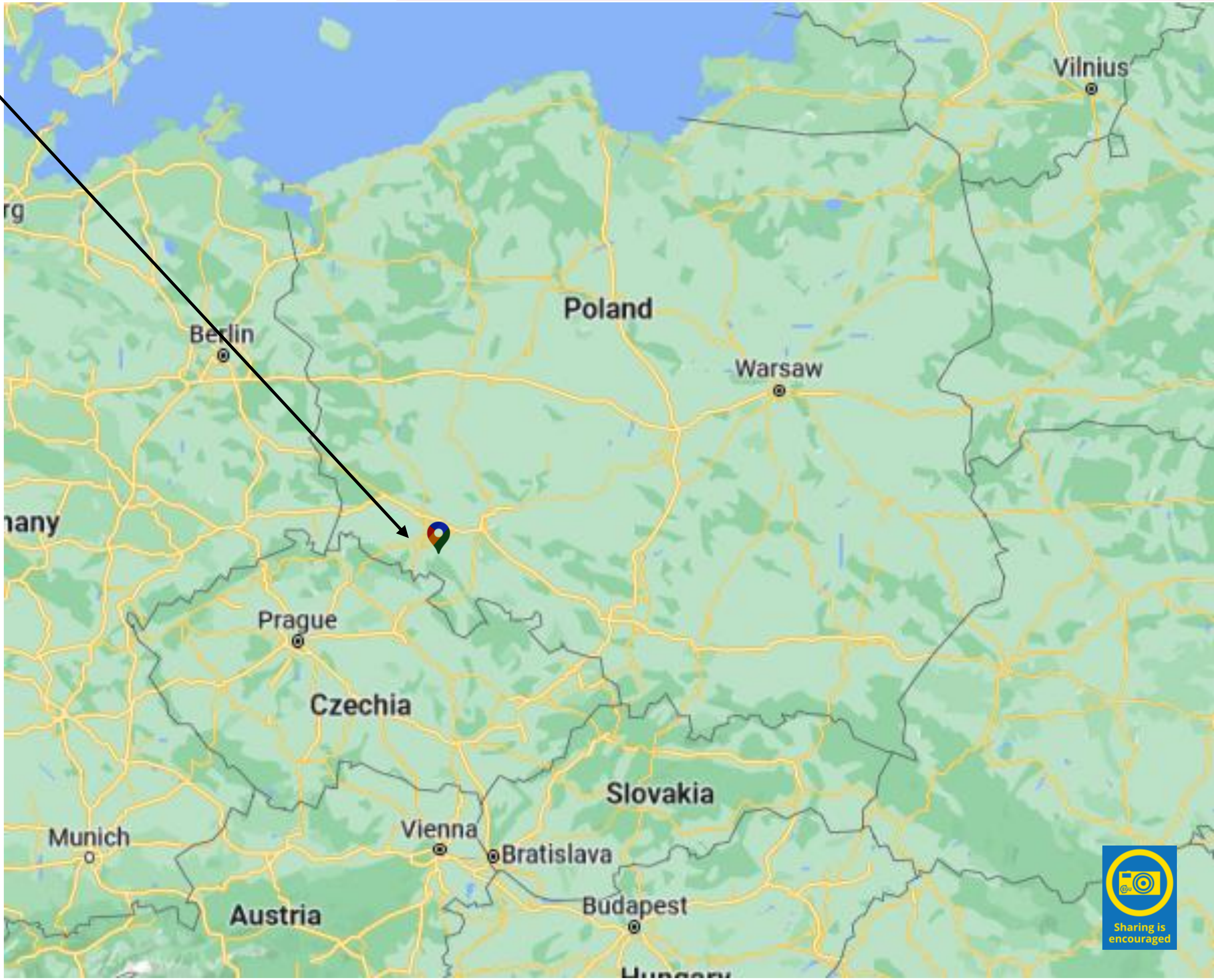
ARW (Angle Random Walk) represents device's sensitivity (data obtained for 1 s averaging time)
BI (Bias instability) - the graph minimum in device frequency range

Fibre optic seismograph – field application

Seismological observatory in the basements of Książ Castle in Wałbrzych, Poland 50°50'34"N 16°17'35"E

FOS5-04 is located in one of the chambers at a depth of approximately 49 m under the main castle courtyard

- *The observatory is located about 60 km away from the city of Legnica, which is the largest center of the Legnica-Głogów Copper District (LGCD)*
- *Mining tremors in this region are generated by the mining of copper ore*
- *this region is considered as the most seismically active mining area in Poland*
- *The phenomenon of mining tremors is most often associated with rock fracture, as well as its breakdown or displacement along fault planes, which makes it a source of shock waves*
- *The exploitation depth in the range of 600-1100 m*



Fibre optic seismograph – field application

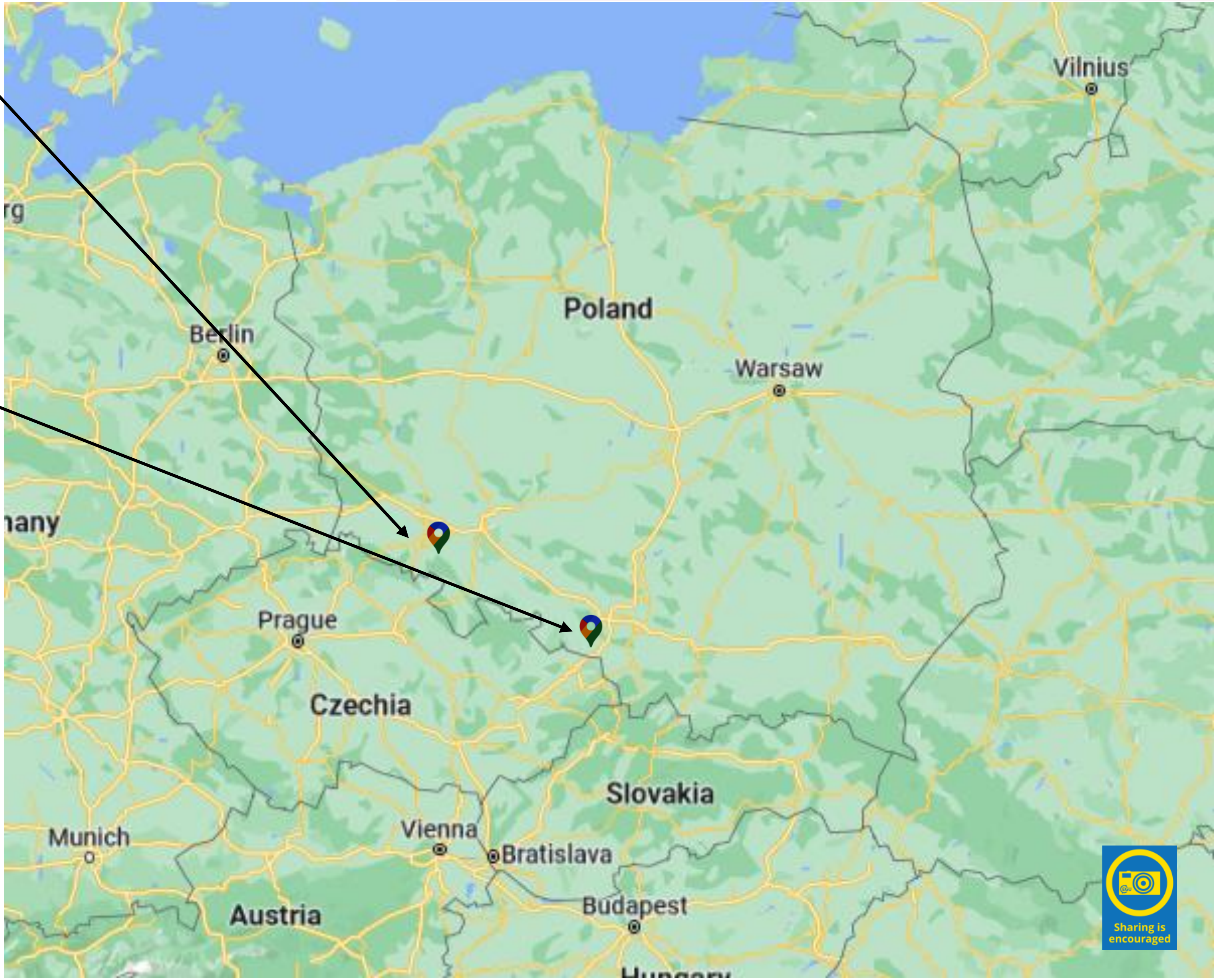
Seismological observatory in the basements of Książ Castle in Wałbrzych, Poland 50°50'34"N 16°17'35"E

FOS5-04 is located in one of the chambers at a depth of approximately 49 m under the main castle courtyard

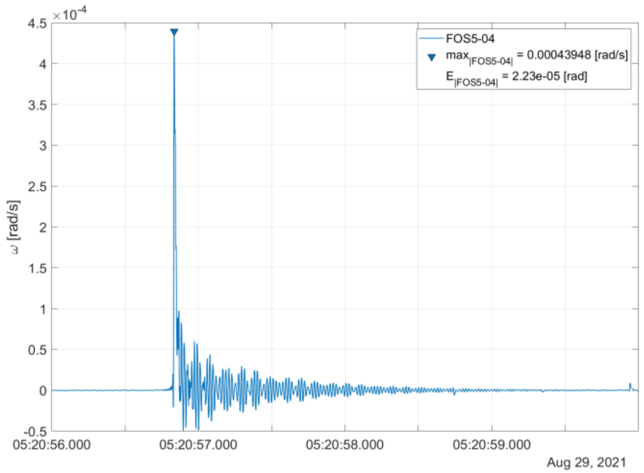
Historic Mine Ignatius, Rybnik, Poland 50°03’44,6”N 18°28’00,7”E

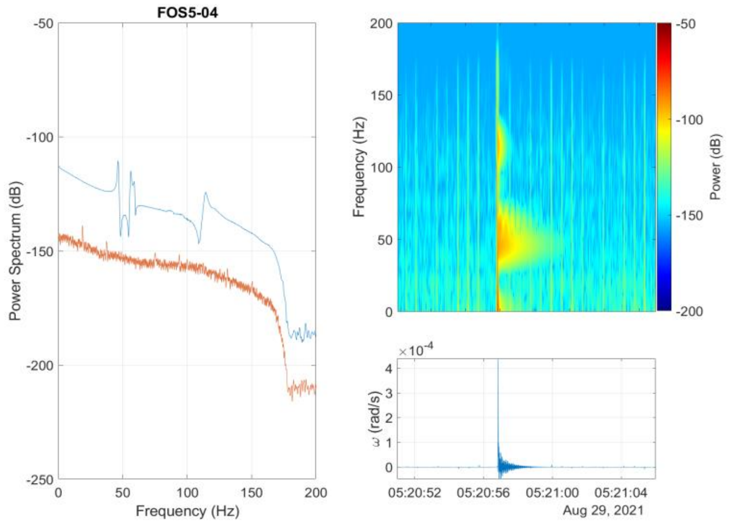
FOS5-01, -02 installed on a concrete pedestal seismically isolated from the surrounding building in order to monitor seismic activity in the lower Silesian coal basin caused by coal mines

- *Seismic activity is not uniform*
- *The variability of the geological structure of the area, including the lithological formation of the rocks in the vertical and horizontal profile, results in a varied number and intensity of rock bursts*



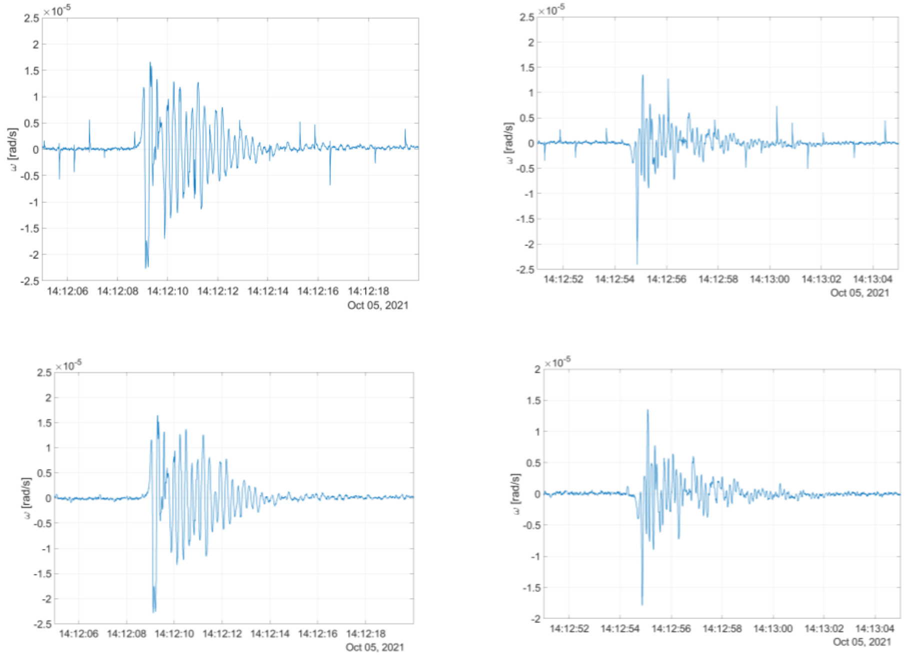
FOS5-04 – field application



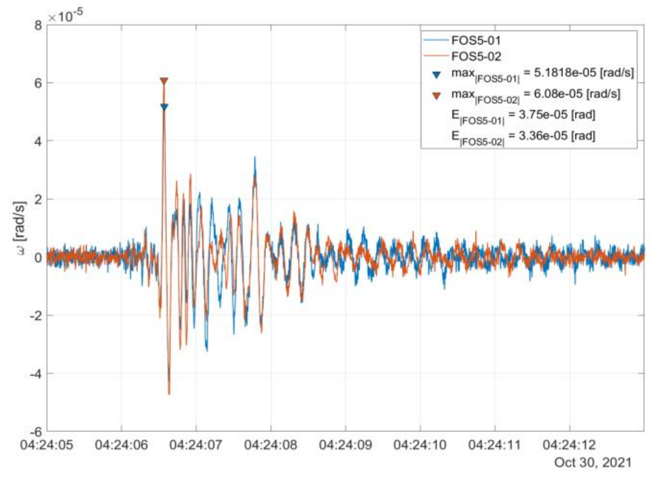


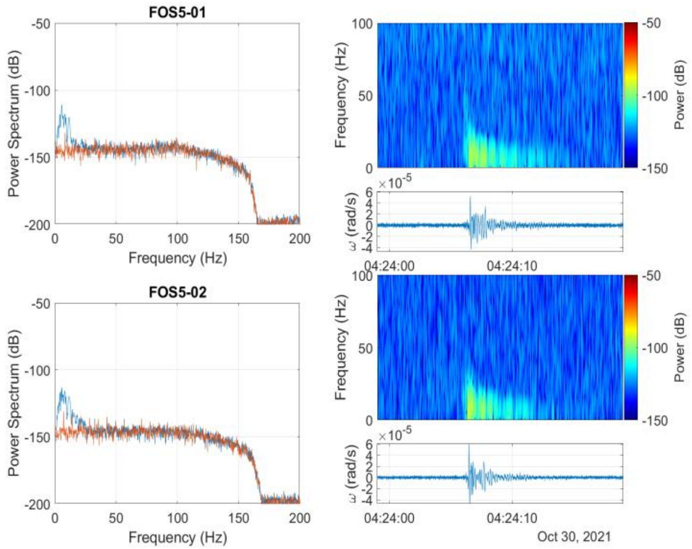
[Jaroszewicz et al., Opto-Electronics Review, 29, 4 (2021)]

- A strong initial amplitude of about 0.44 mrad/s and signal duration of about 6 s
- As the FOS5 series had the low-pass filter implemented with stopband frequency at about 170 Hz, the power spectrum and spectrogram are limited to 200 Hz even though the sampling rate of these devices was equal to 1 kHz
- Some low-amplitude perturbations repeating with a period of about 0.6 s are present in the signal



FOS5-04 – field application

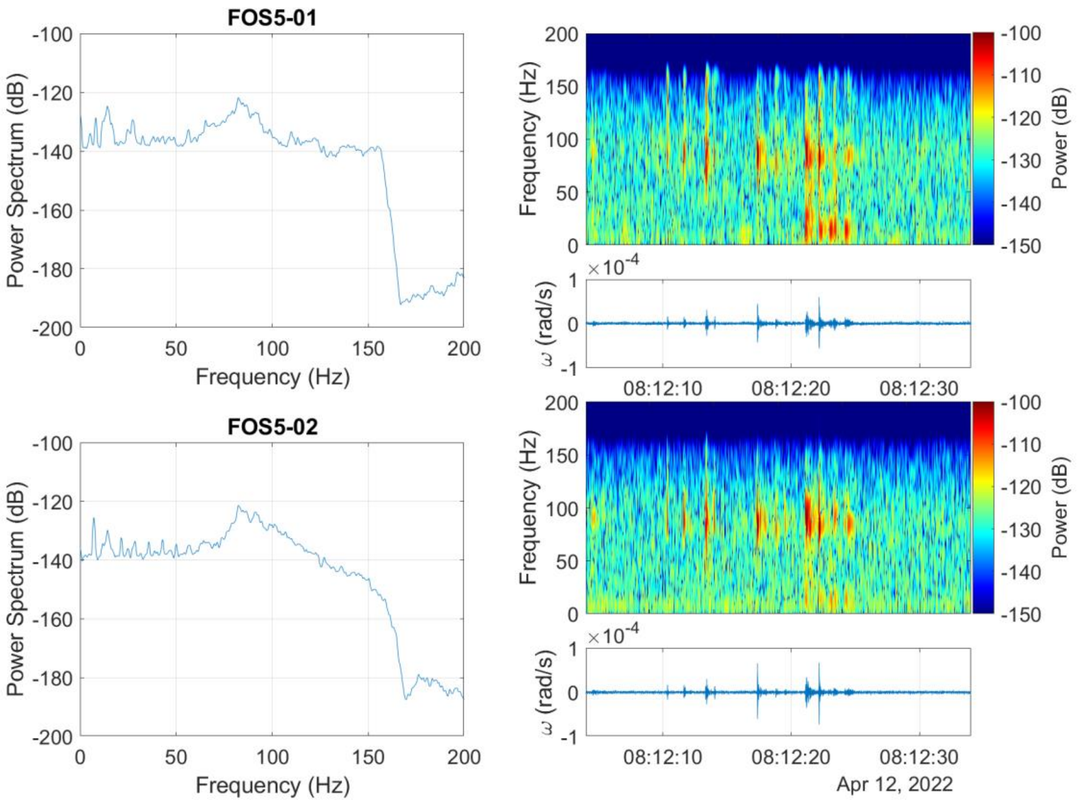


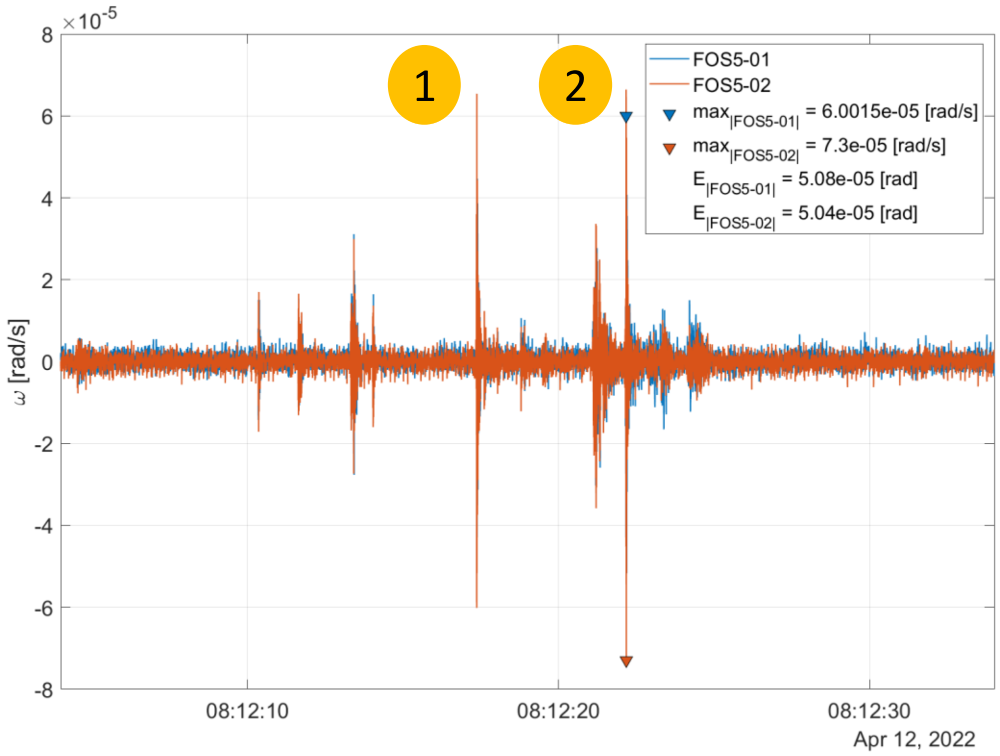


- maximum amplitude of the recorded signal was about 0.06 mrad/s
- most of the signal's spectral components were below 20 Hz
- Pearson's correlation coefficient equal to 0.80

[Jaroszewicz et al., Opto-Electronics Review, 29, 4 (2021)]

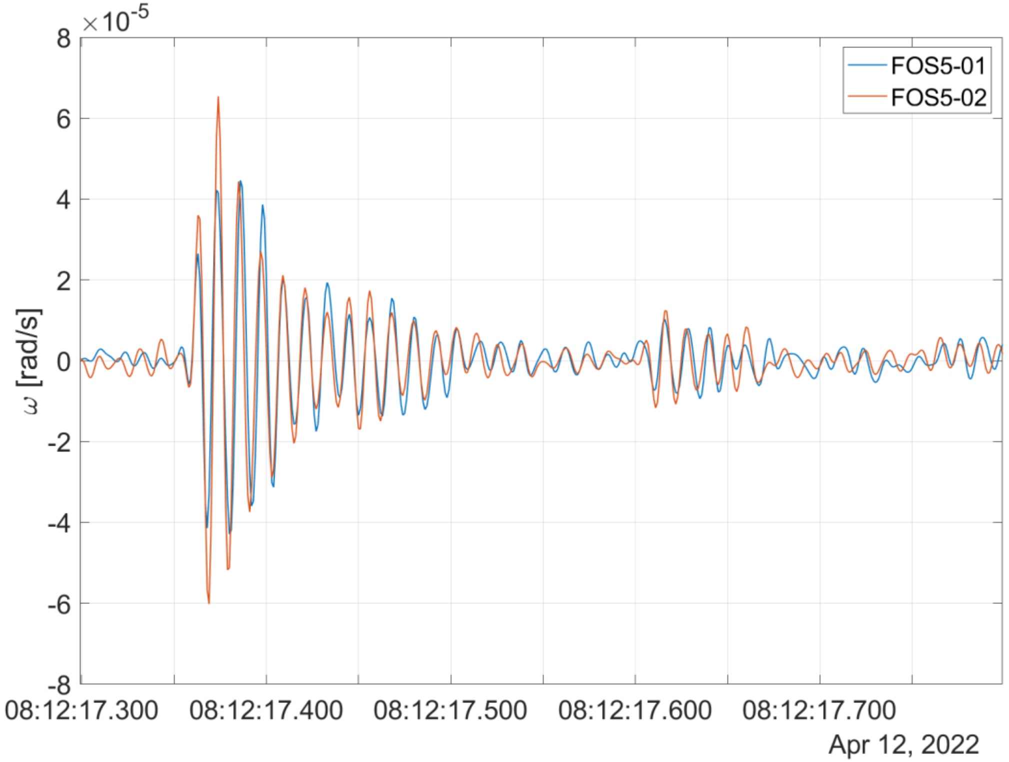
FOS5-01 and -02 field application



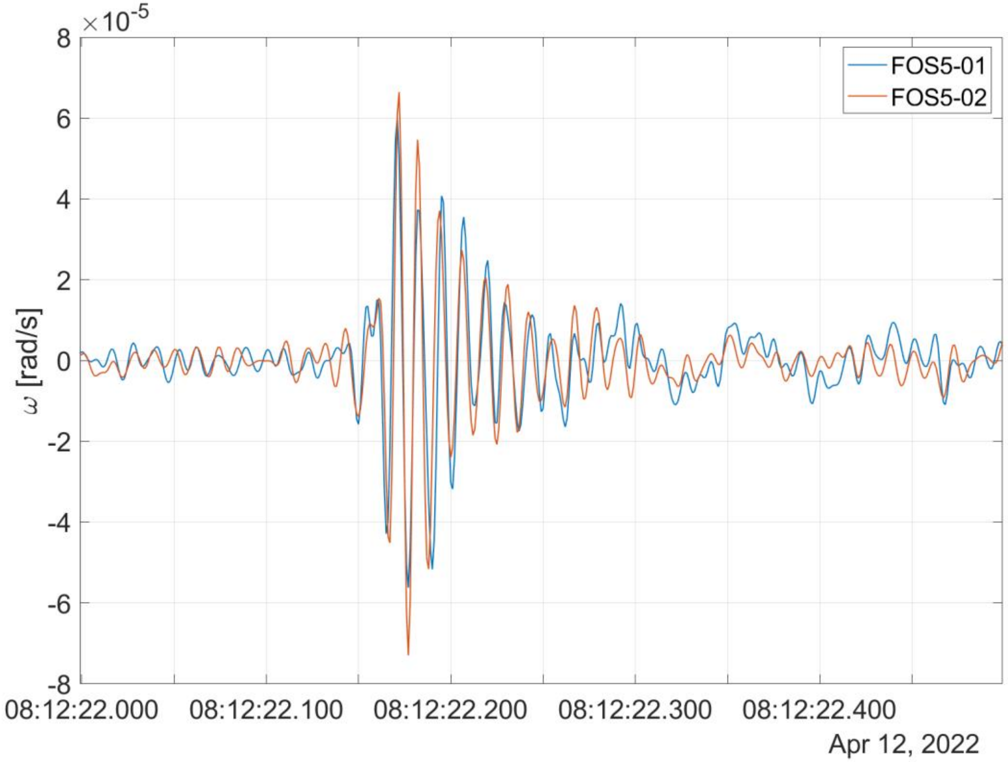


- maximum amplitude of the recorded signal was about 0.07 mrad/s

FOS5-01 and -02 field application



1 Pearson’s correlation coefficient equal to 0.86

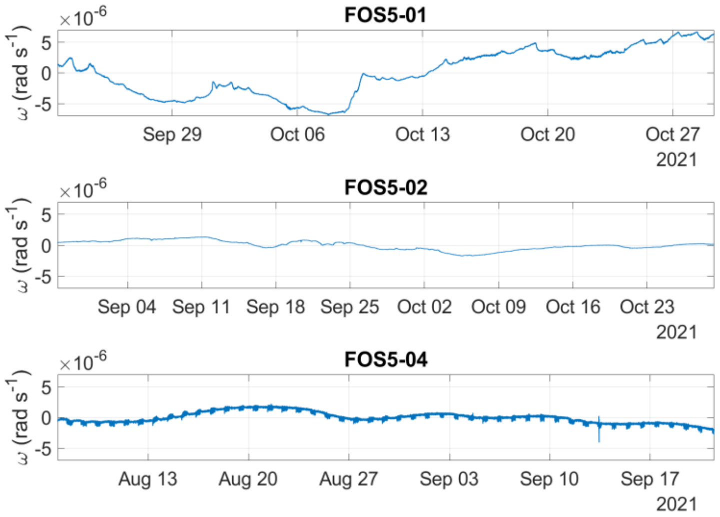


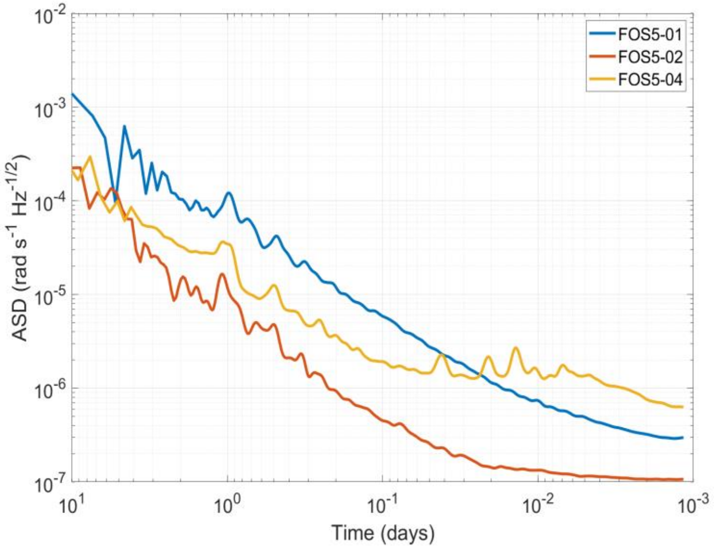
2 Pearson’s correlation coefficient equal to 0.81

Military University of Technology

ELPROMA ELECTRONICS

FOS5s – field application





- Long – term registration: data collected in the year 2021 between September and October
- averaged rotation signals are shown with 50 s time window
- FOS5-04 is a repeating pattern of high and low averaged amplitudes, which comes from touristic activities during the day and calm nights, respectively.
- For FOS5-04 we mainly observed additional peaks for 60 min, 30 min, 20 min, 15 min and 10 min, which are directly connected with touristic activity in the Książ Castle basements between 10:00 AM and 6:00 PM. However, some insights into physical phenomena can be given based on the ASD features repeating in all three of the instruments. The highest similarity is visible for the period equal to about one-day and half-day, where peaks are evident in all three ASD characteristics. Most probably it is connected with small disturbances of the earth rotation rate caused by natural factors – diurnal polar motion, as well as diurnal and semidiurnal tides.

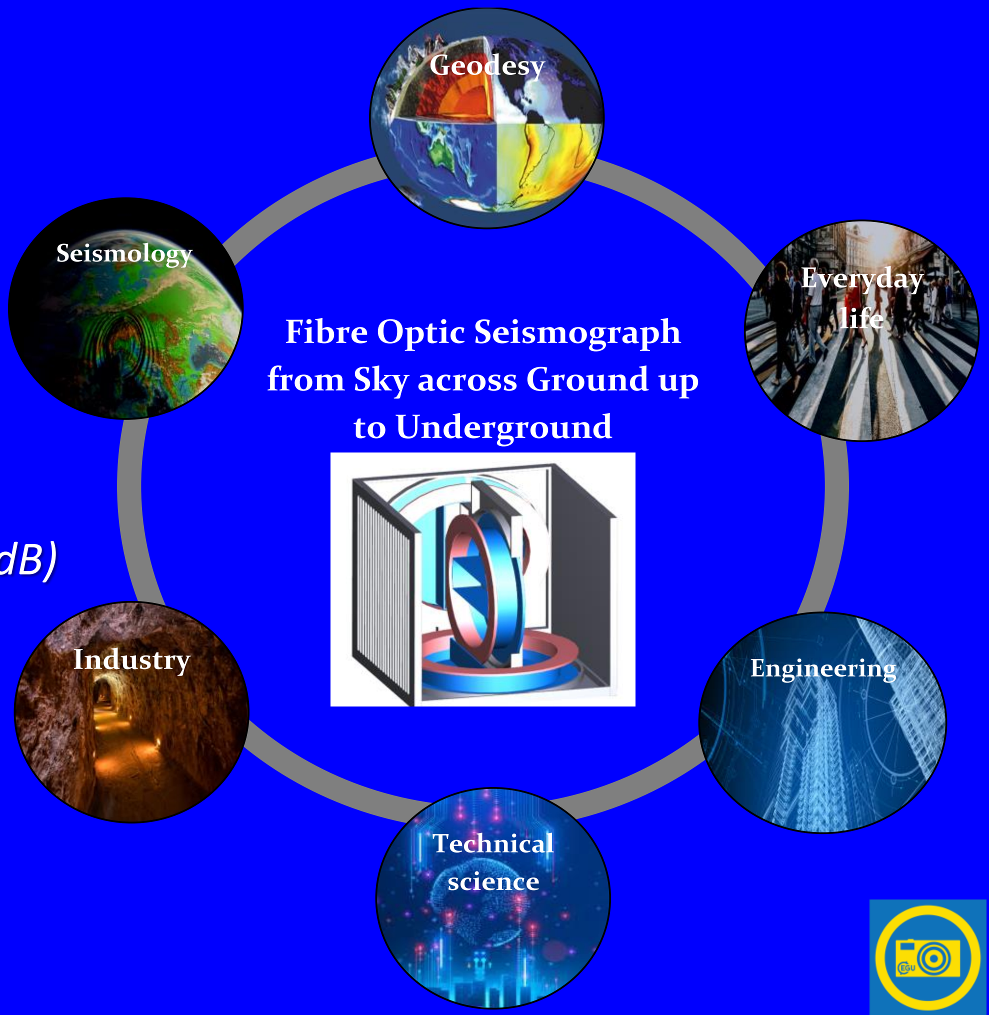
[Jaroszewicz et al., Opto-Electronics Review, 29, 4 (2021)]

Conclusions

- *The information available in the literature illustrates that the rotational seismology undergoes a rapid development*

- *To further expand the functionalities of the presented fiber-optic seismograph, we plan to construct the next generation of FOS with three perpendicular axes. The ultimate goal is to achieve full six degree-of-freedom ground-motion data, which will require connecting the FOS with translational seismometers*

FOSREM-3D



FOSREM-3D (FOS6) main parameters:

- *Three axes*
- *Measuring range from several dozen nrad/s to 10 rad/s (dynamics of 180 dB)*
- *Frequency detection bandpass: from DC to 200 Hz*
- *Built-in time scale synchronization system (accuracy 10 μs)*
- *Weight: less than 10 kg*
- *Web-Based Management Interface*
- *Possibility of mobile, autonomous operation*
- *Equipped with photo-solar cells, battery or wind generator*

Military University of Technology
ELPROMA ELECTRONICS

FOSREM®

A highly sensitive instrument for direct and long-term observations of seismic and natural-mode rotational movements

Thank you for your attention

anna.kurzych@wat.edu.pl
leszek.jaroszewicz@wat.edu.pl
michal.dudek@wat.edu.pl

This research was financially supported by the Ministry of the National Defense of the Republic of Poland, project GBMON/13-995/2018/WAT as well as the National Centre for Research and Development, Poland project – POIR.01.01.01-00-1553/20-00

Sharing is encouraged