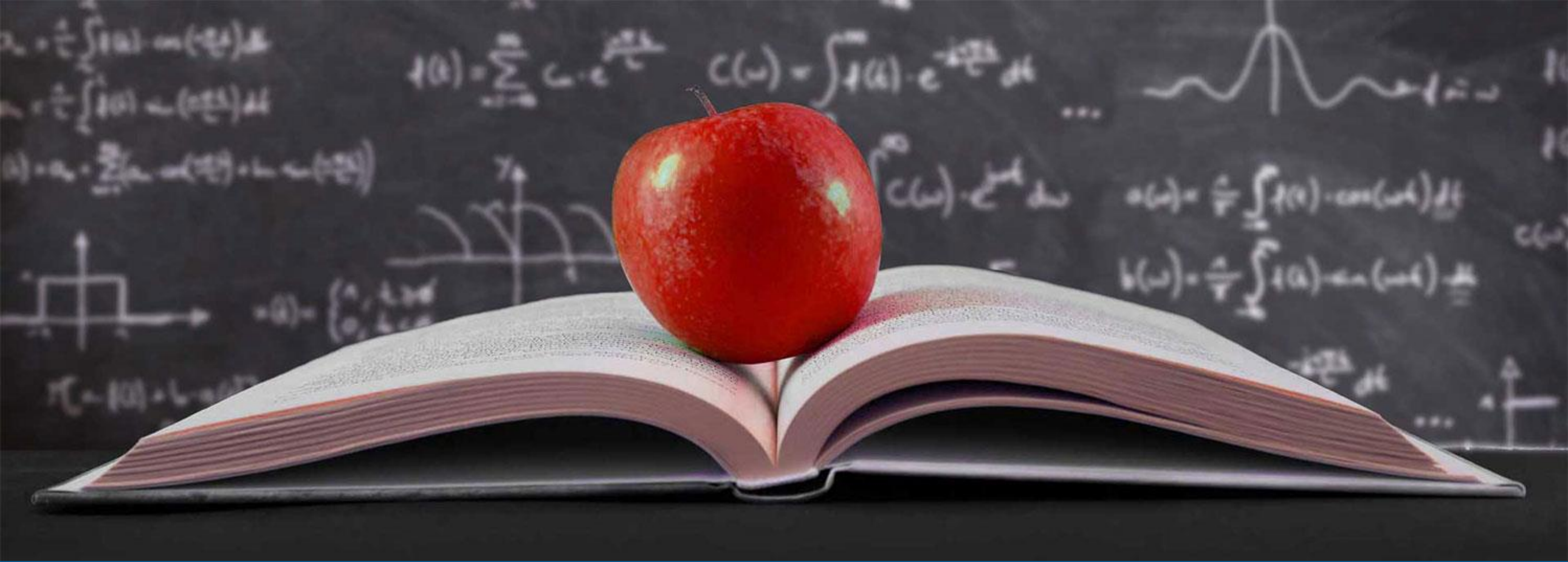


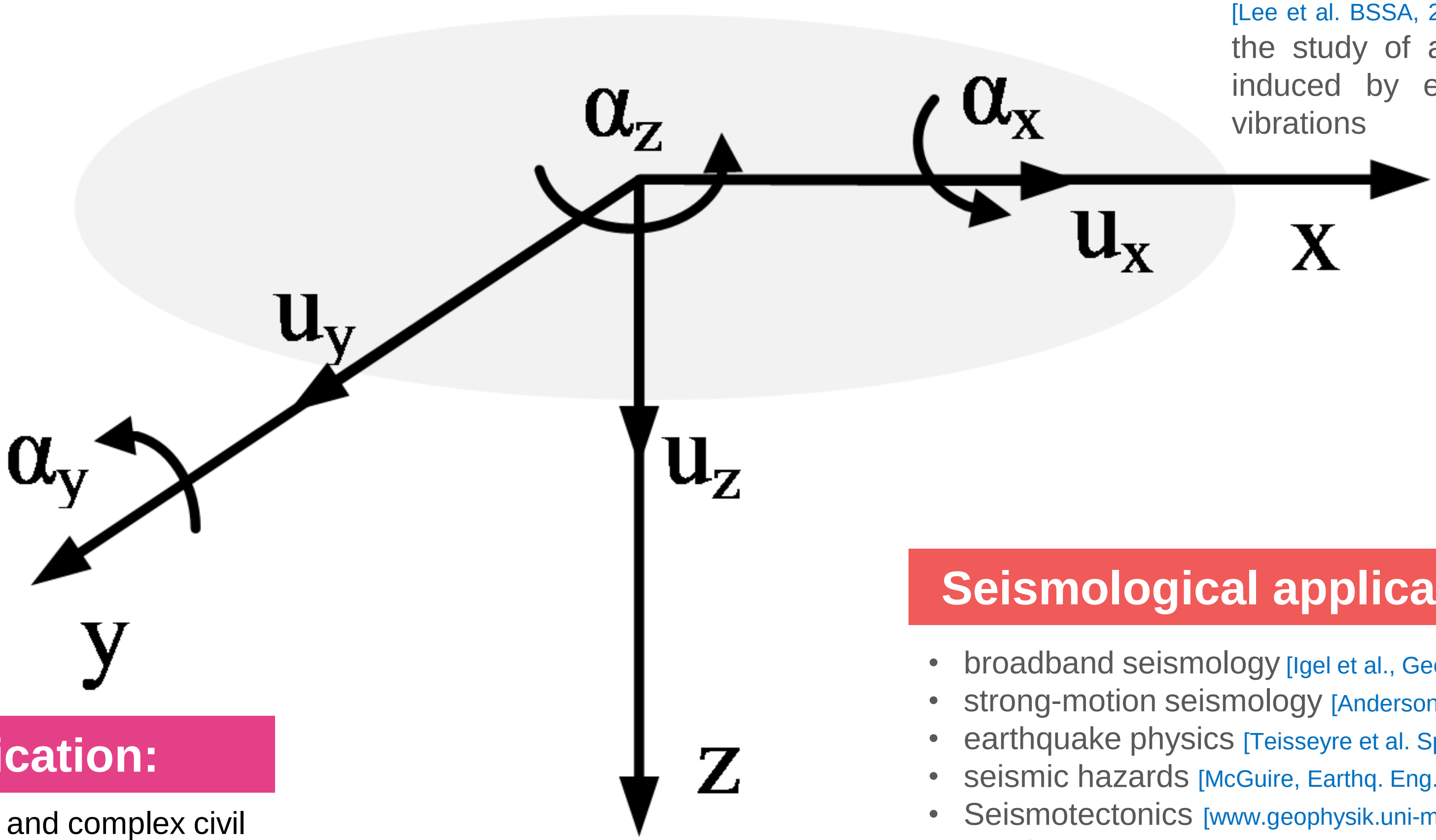
Large Fiber-Optic Seismograph detecting the rotation rate caused by natural factors as well as mining activities

Anna Kurzych[1,2], Michał Dudek[1,2], Leszek R. Jaroszewicz[1,2]
[1]*Institute of Technical Physics, Military University of Technology., 2 gen. S. Kaliskiego Str., Warsaw, Poland*
[2]*Elproma Elektronika Ltd.,2A Duńska Str.,Czosnów*
anna.kurzych@wat.edu.pl

Motivation

6-DOF

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



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

.

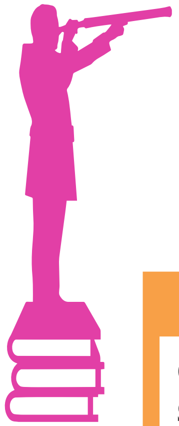
Engineering application:

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

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]

Fibre-Optic Seismograph historical brief

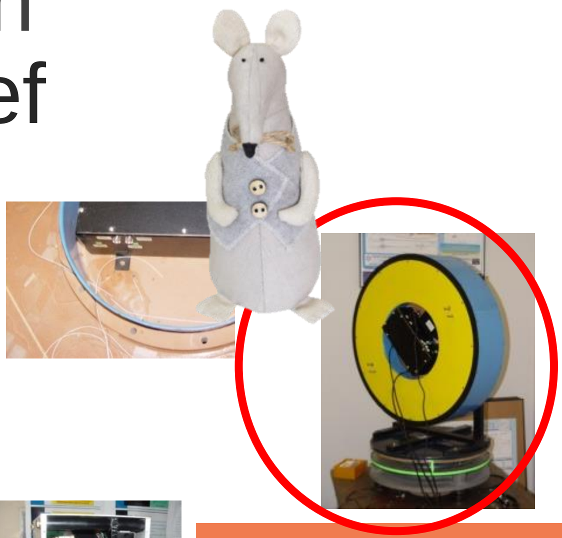


1998

GS-13P
Ω_{min}: $3.49 \cdot 10^{-3}$ rad/s
SL: 380 m PANDA
Radius: 0.1 m

2001

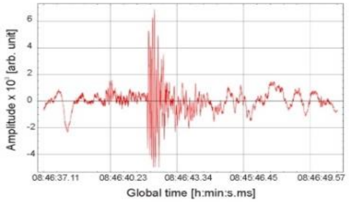
FORS-I
Ω_{min}: $2.2 \cdot 10^{-6}$ rad/s
Ω_{max}: $4.8 \cdot 10^{-4}$ rad/s
SL: 400 m PANDA
Radius: 0.1 m

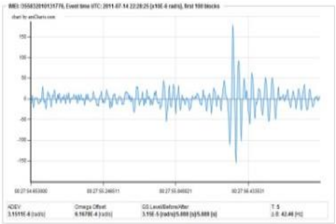


2004, 2010

FORS-II, FOS1
Ω_{min}: $4.2 \cdot 10^{-8}$ rad/s
Ω_{max}: $4.8 \cdot 10^{-4}$ rad/s;
SL: 11 000 m SMF
Radius: 0.34 m

FOS2
Ω_{min}: $4 \cdot 10^{-9}$ rad/s,
Ω_{max}: $6.4 \cdot 10^{-3}$ rad/s
SL: 15 000 m SMF
Radius: 0.34 m



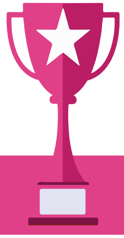


2015

FOSREM – FOS3 & FOS4
Ω_{min}: $2 \cdot 10^{-8}$ rad/s,
Ω_{max}: few rad/s
SL: 5 000 m SMF
Radius: 0.125 m

2018

FOS5
Ω_{min}: $7 \cdot 10^{-8}$ rad/s,
Ω_{max}: 10 rad/s
SL: 5 000 m SMF,
Radius: 0.125 m

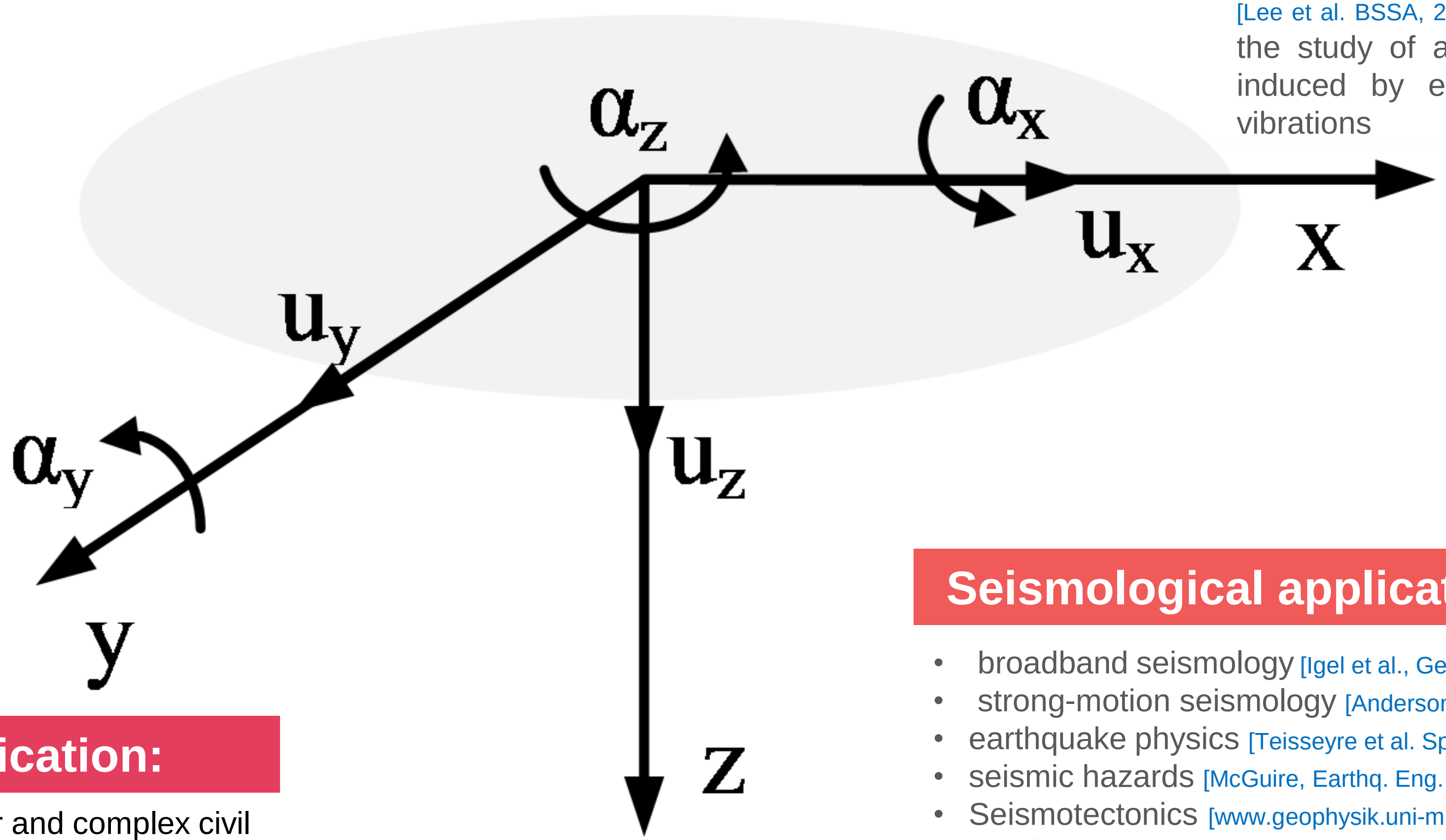


Fibre-Optic Seismograph FOS6
3- Axis with 10 μs time synchronization
Ω_{min}: several dozen nrad/s
Ω_{max}: 10 rad/s
SL: 6 000 m SMF
Radius: 0.125 m
Weight: 10 kg

Motivation

6-DOF

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



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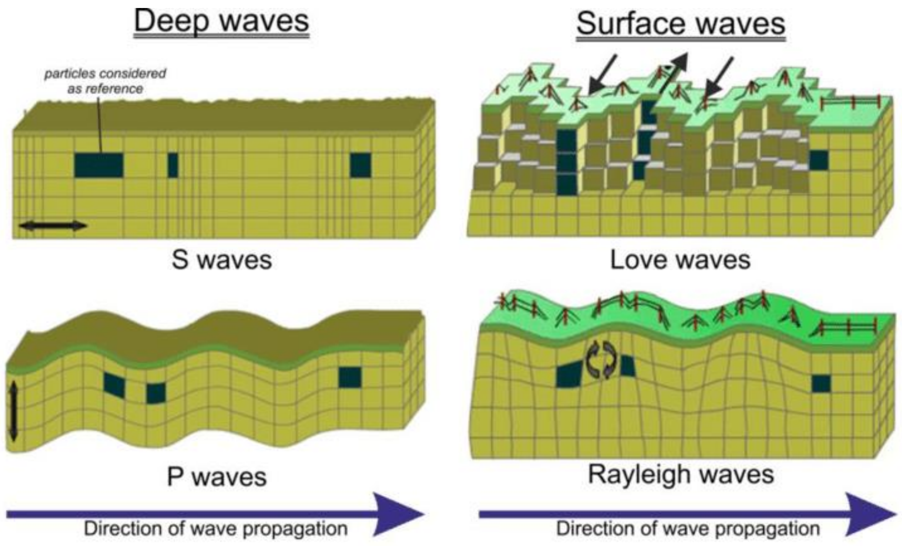
Rotational seismology



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

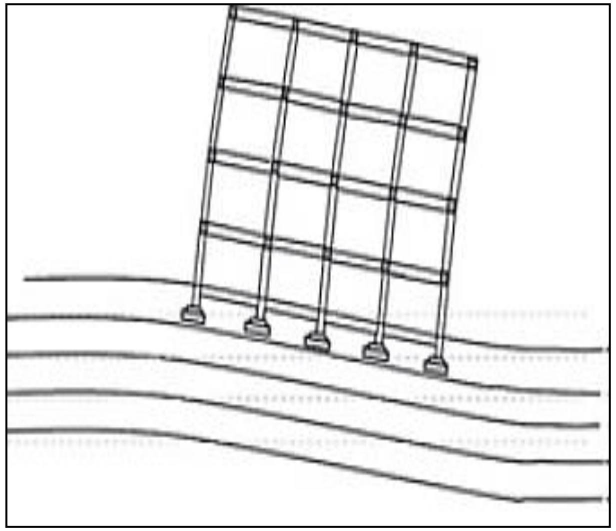
[Hinzen, J. Seismol., 16(4), (2012), 797–814]
Tombstone in Kushiro Cemetery after the Tokachi-Oki Earthquake 2003

Seismological application

Rotational seismology

Low frequency content

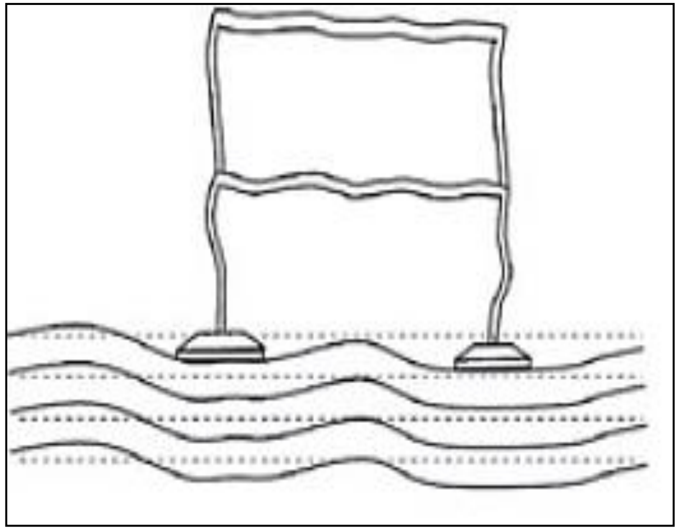
- Higher stress in structural element
- **Overturning moment**
- Horizontal displacement of the center of mass



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

High frequency content

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



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

Engineering application

Requirements

COMMON

ROTATIONAL SEISMOGRAPH
network of seismometers + precise time source + recording device + network

Seismological application

Measuring range

signal amplitude:
from 10^{-8} rad/s,
frequency:
0.01 Hz – 0.1 Hz

Common

- 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
- Dynamic range 10^{-8} - 10 rad/s
- Frequency band 0.01 - 100 Hz
- Power consumption 5 – 8 W
- Thermal stability <0,1% / ^{o}C

Engineering application

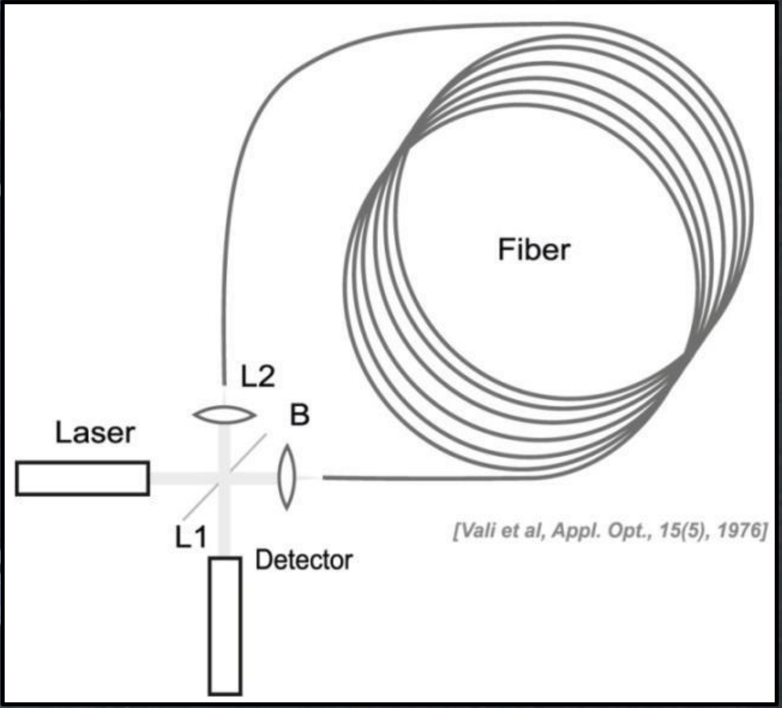
Measuring range

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)]

BACKGROUND

The diect utilization of the Sagnac effect

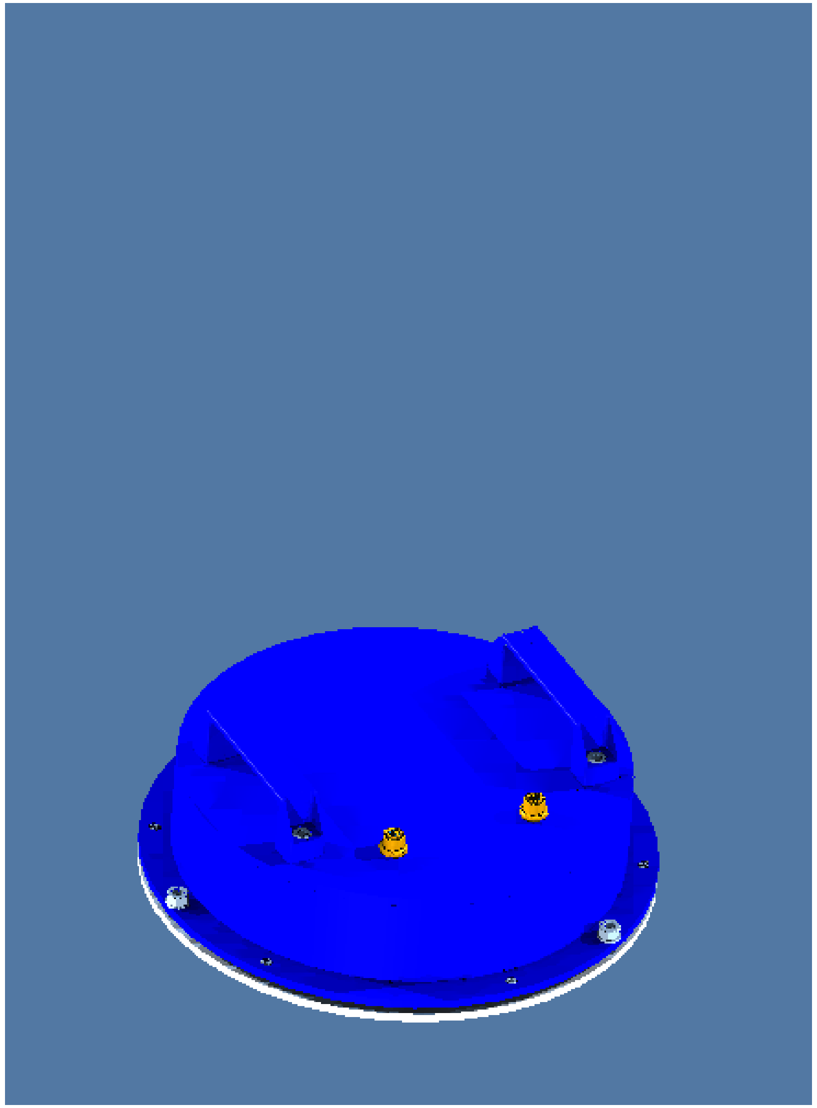


Sagnac effect shows the difference between phase of two beams propagating around closed optical path, in opposite direction when this path is rotating with rotational rate Ω. In a fiber-optic implementation the rotation rate Ω is expressed by induced phase shift Δφ as:

$$\Omega = S_o \cdot \Delta\varphi = \frac{\lambda c}{4\pi RL} \cdot \Delta\varphi$$

L – length of the fiber in the sensor loop, R – sensor loop radius, λ – wavelength of used source, c – velocity of the light in vacuum, S_0 – the optical constant of interferometer

Fiber Optic Seismograph

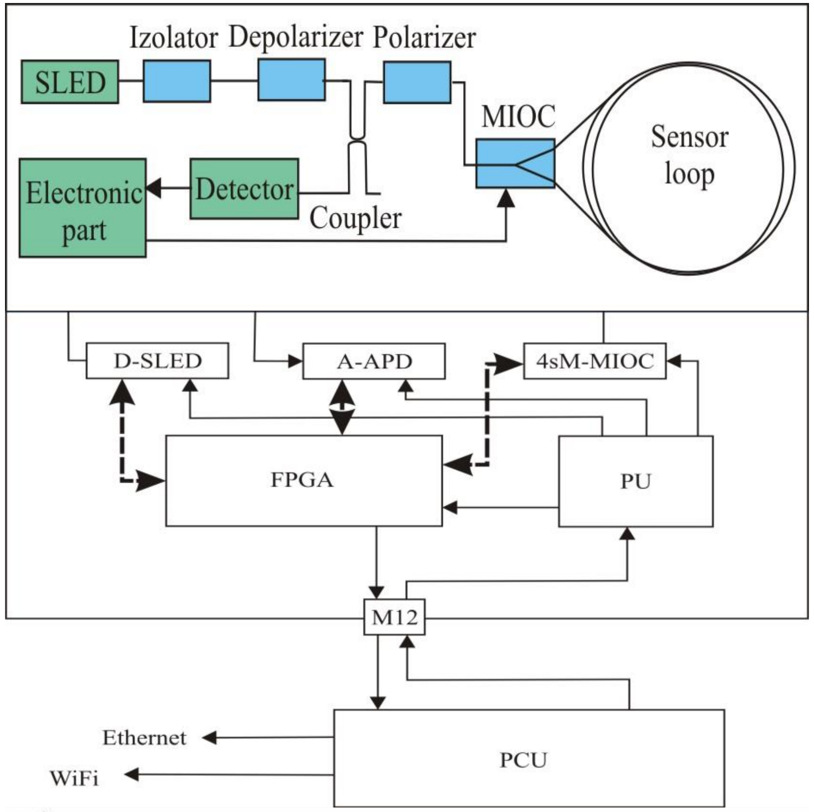


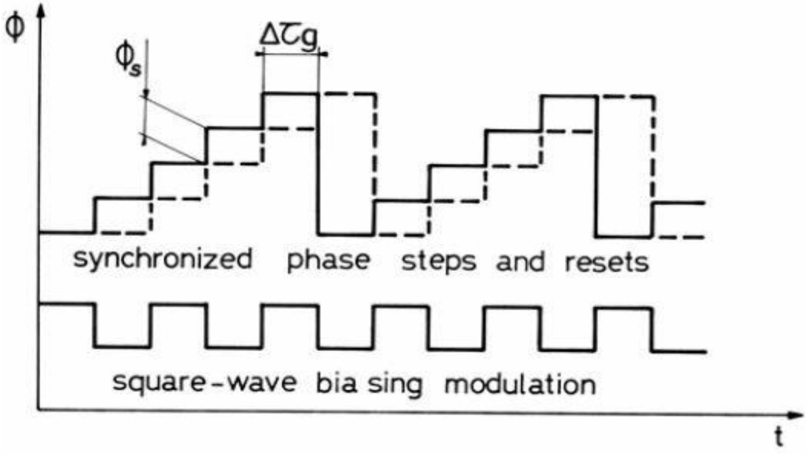
01 OPTICAL PART

generates the phase shift Δφ proportional to the measured rotation rate Ω which is perpendicular to the sensor loop plane

02 ELECTRONIC PART

enables to calculate and record information about rotational motions via digital closed-loop signal processing

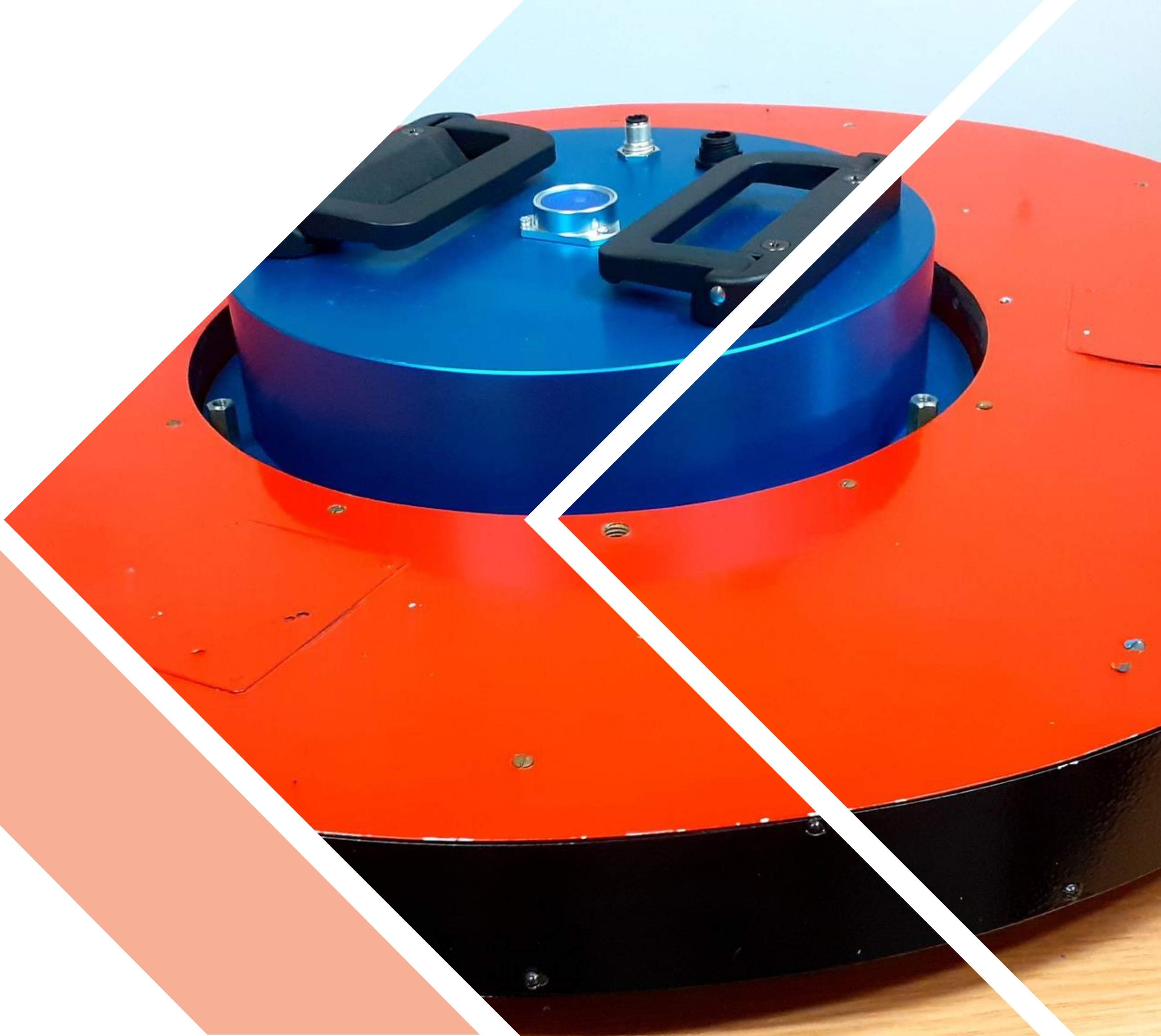




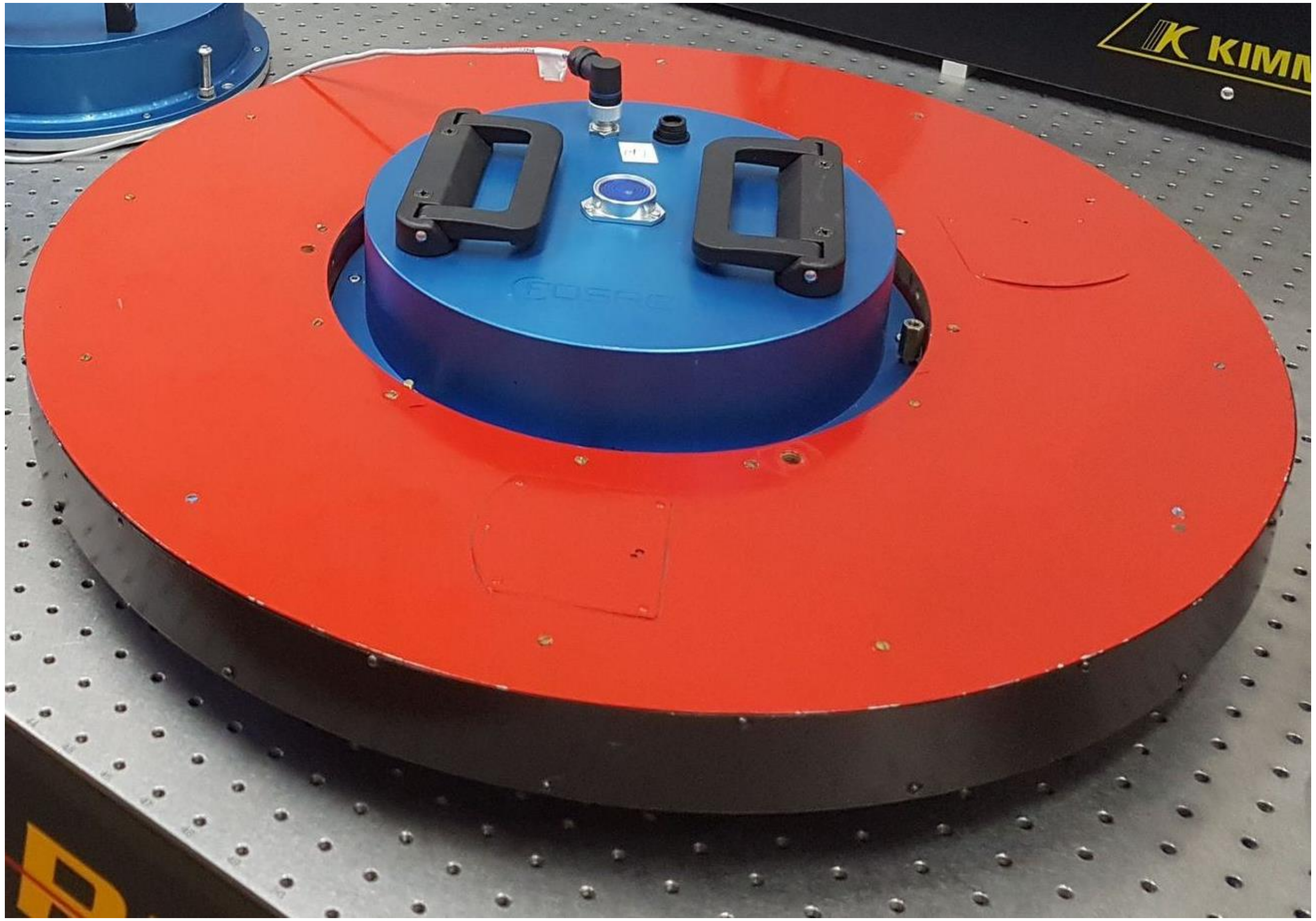
Large Fiber-Optic Seismograph

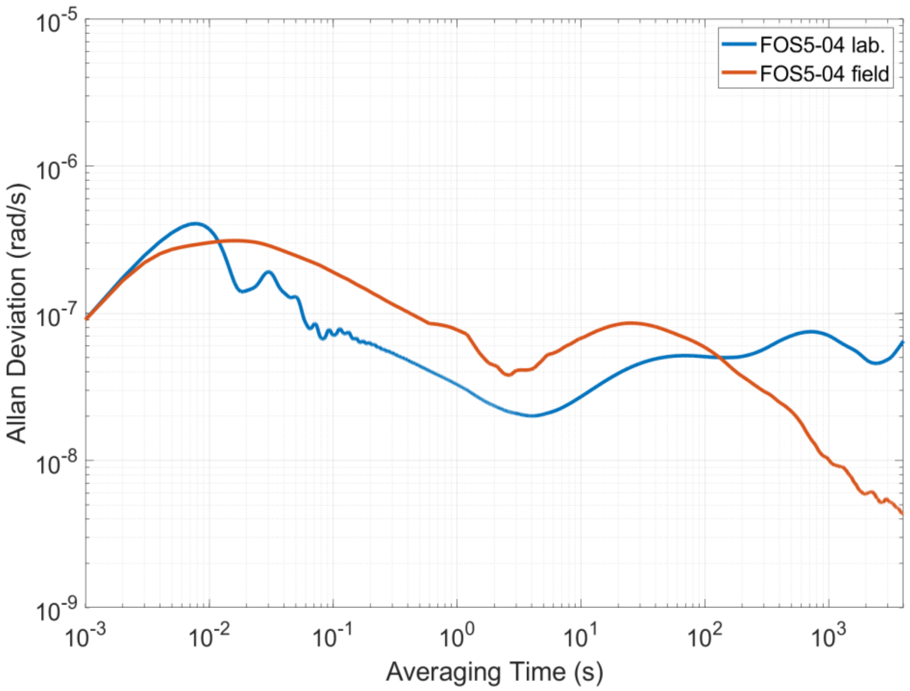
THEORETICAL SENSITIVITY
$1.14 \cdot 10^{-8}$ rad/(s√Hz)

FOS5-04 uses a 15 km long fiber wound in loop of 0.61 m in diameter.
Transmission optical losses equal to 17.41 dB



Fibre optic seismograph – Allan variance analysis

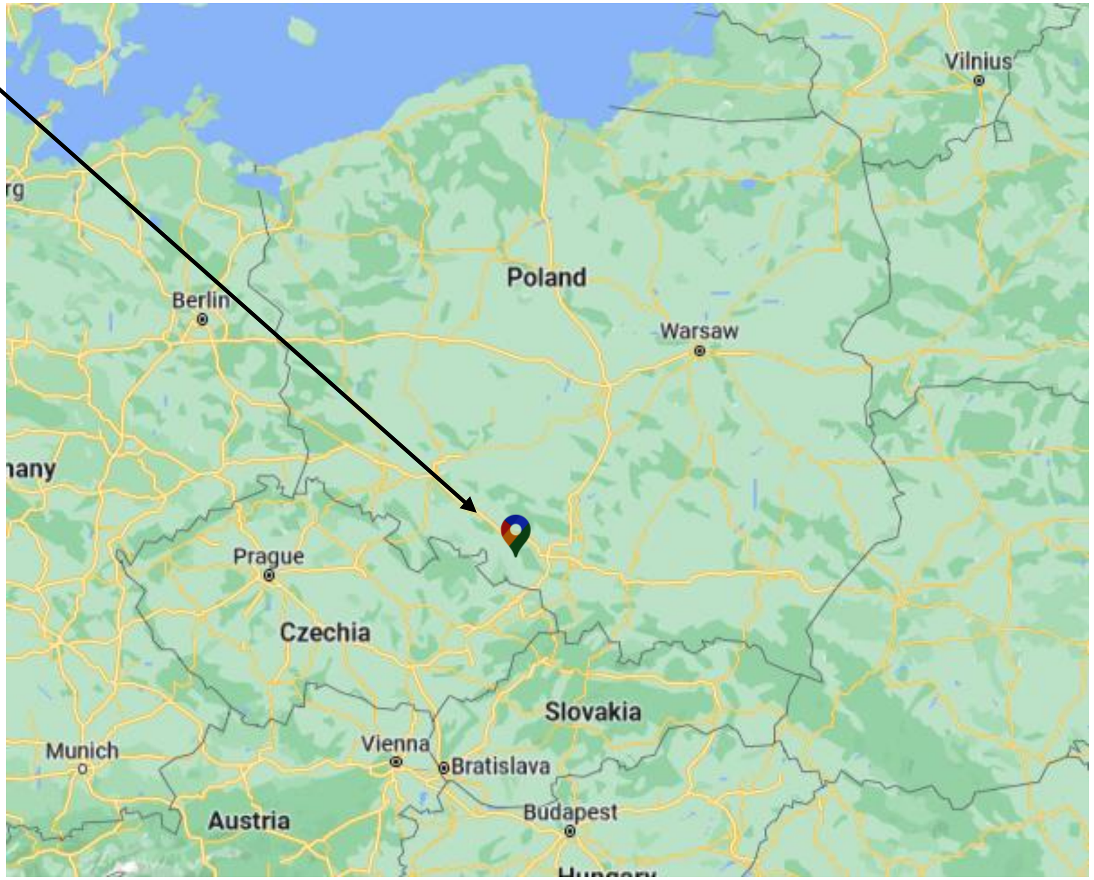




Position	Angle Random Walk [rad/√s]	Bias instability [rad/s]
Lab.	$3 \cdot 10^{-8}$	$2 \cdot 10^{-8}$
Field	$8 \cdot 10^{-7}$	$4 \cdot 10^{-8}$

Fibre optic seismograph – field application

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

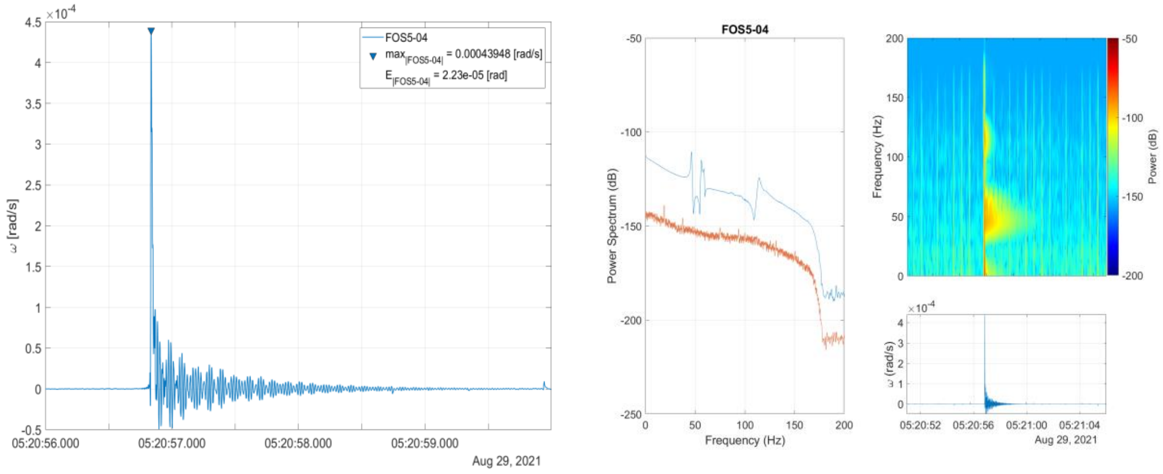


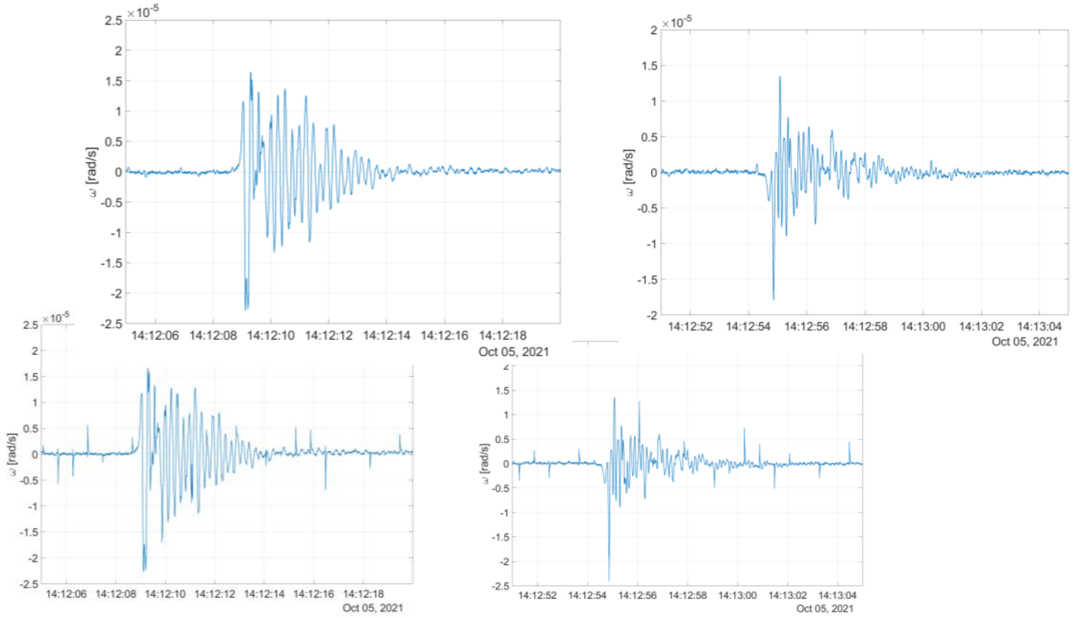
The observatory is located about 60 km away from the city of Legnica, which is the largest center of the Legnica-Głogów Copper District (LGCD)

Fibre optic seismograph – recordings

Analysis

- 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
- Two examples of rotational events recorded on 5th October, 2021
- The maximum amplitudes of the recorded signals are equal to $1.62 \cdot 10^{-5}$ rad/s and $1.35 \cdot 10^{-5}$ rad/s
- Some parasitic peaks are present connected with the location of the device
- A dedicated algorithm was implemented in post-processing





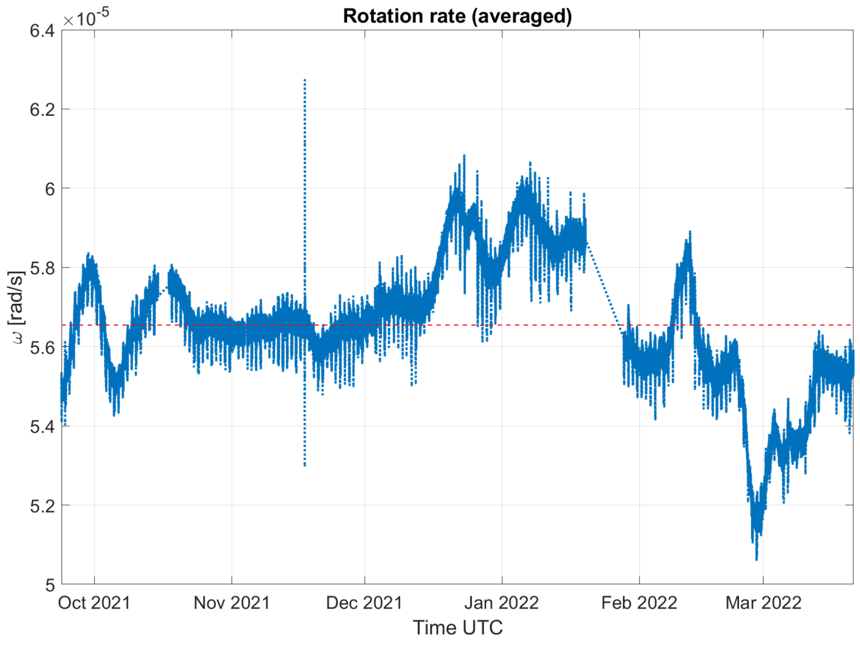
[Jaroszewicz et al., Opto-Electronics Review, 29, 4 (2021)]

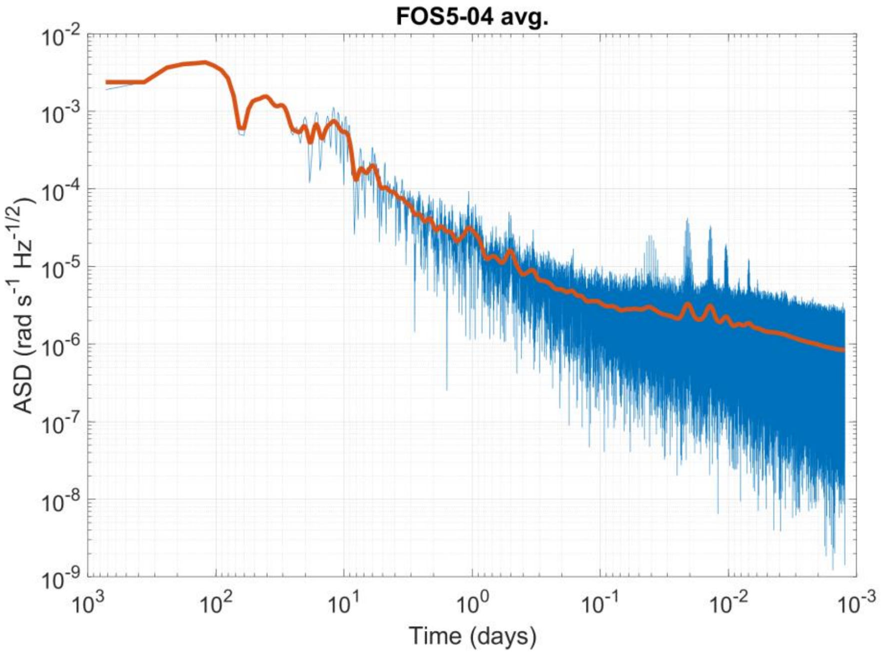
Fibre optic seismograph – recordings

“

Analysis

- A long-term recording of averaged signal (50 s window) in the period from October 2021 to March 2022 together with the theoretical value of rotation rate calculated for this location (50°50'34"N 16°17'35"E)
- The observed peaks for 60 min, 30 min, 20 min, 15 min and 10 min are directly connected with touristic activity in the Książ Castle basements between 10:00 AM and 6:00 PM
- Increases of the amplitude at the periods of approximately one day and half a day can be directly connected with changes of Earth’s rotation rate due to diurnal polar motions, as well as diurnal and semidiurnal tides.

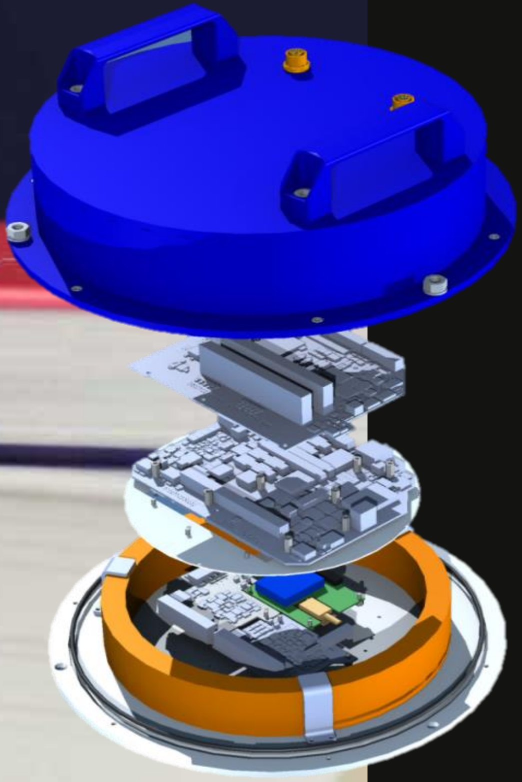


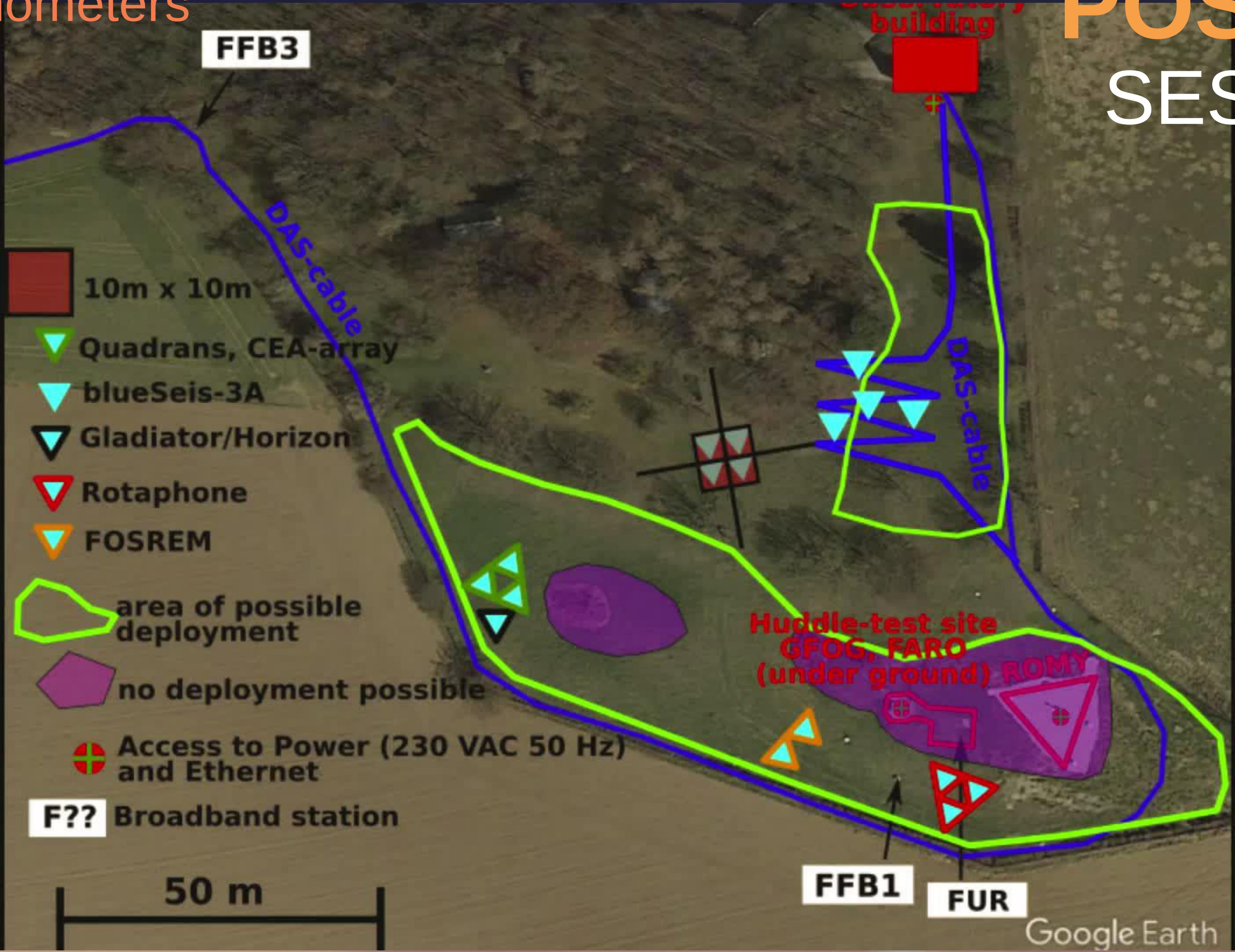


Towards Uniformity of Rotational Events Recording – Common Test Engaging More Than 40 Sensors Including a Wide Number of Fiber-Optic Rotational Seismometers

ID-3386916

POSTER SESSION





Conclusions

1. **Rotational seismology** undergoes a rapid development
2. Future plans - next generation of FOS6 with three perpendicular axes

FOS 6
FROM SKY ACROSS GROUND
UP TO UNDERGROUND

THREE AXES

- Measuring range from several dozen nrad/s to 10 rad/s (dynamics of 180 dB)
- Frequency detection bandpass: from 0.01 to 100 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

Meet Our Team

Financial support:
National Centre for Research and Development, Poland
project – POIR.01.01.01-00-1553/20-00

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27th International Conference on Optical Fiber Sensors
OFS 2022
August 29–September 2, 2022 | The Westin Alexandria | Alexandria, Virginia, USA

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