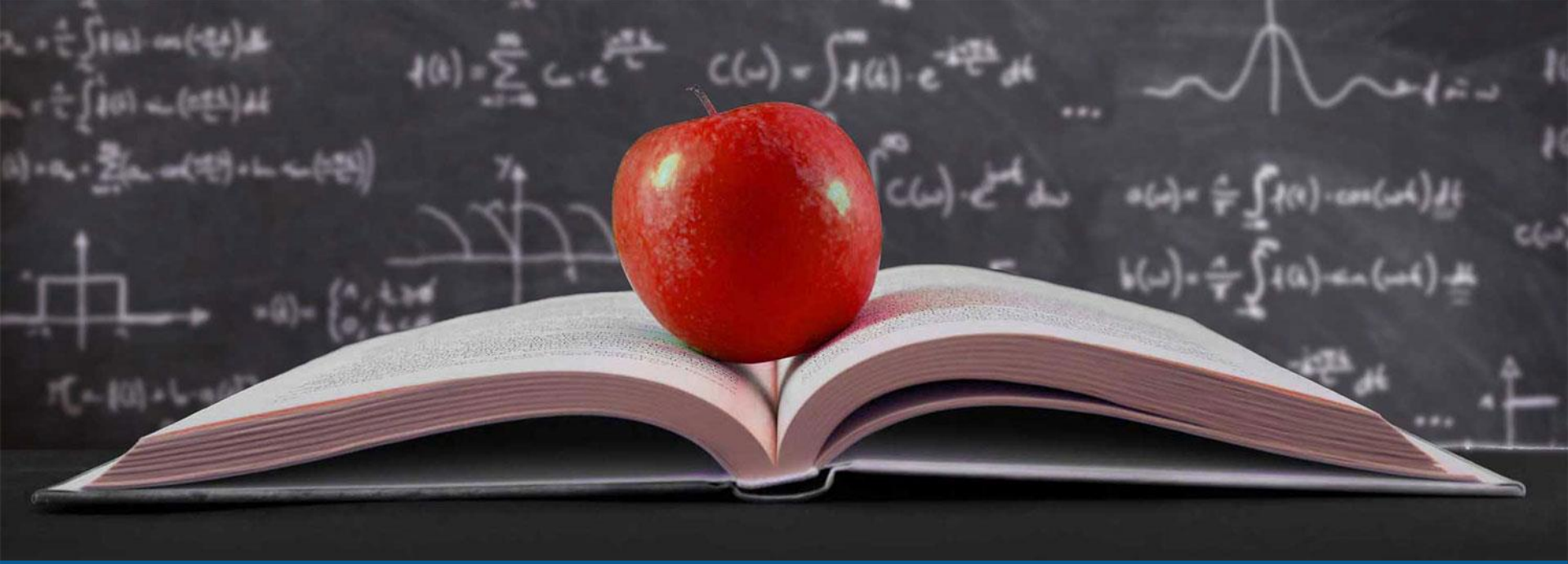

Filed investigation of the FOS5-04 the gain fiber-optic seismograph operates in closed-loop configuration

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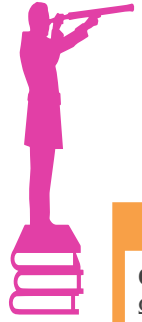
Fiber-Optic Seismograph historical brief



1998

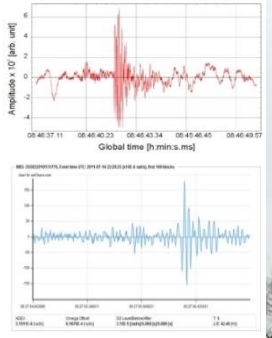
GS-13P
Ω_{min}: $3.49 \cdot 10^{-5}$rad/s
SL: 380 m PANDA
Diameter: 0.2 m

2001

FORS-I
Ω_{min}: $2.2 \cdot 10^{-6}$ rad/s
Ω_{max}: $4.8 \cdot 10^{-4}$ rad/s
SL: 380 m PANDA
Diameter: 0.2 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
Diameter: 0.68 m
FOS2
Ω_{min}: $4 \cdot 10^{-9}$ rad/s,
Ω_{max}: $6.4 \cdot 10^{-3}$ rad/s
SL: 15 000 m SMF
Diameter: 0.68 m



2015

FOSREM – FOS3 & FOS4
Ω_{min}: $2 \cdot 10^{-8}$ rad/s,
Ω_{max}: few rad/s
SL: 5 000 m SMF
Diameter: 0.25 m

2019

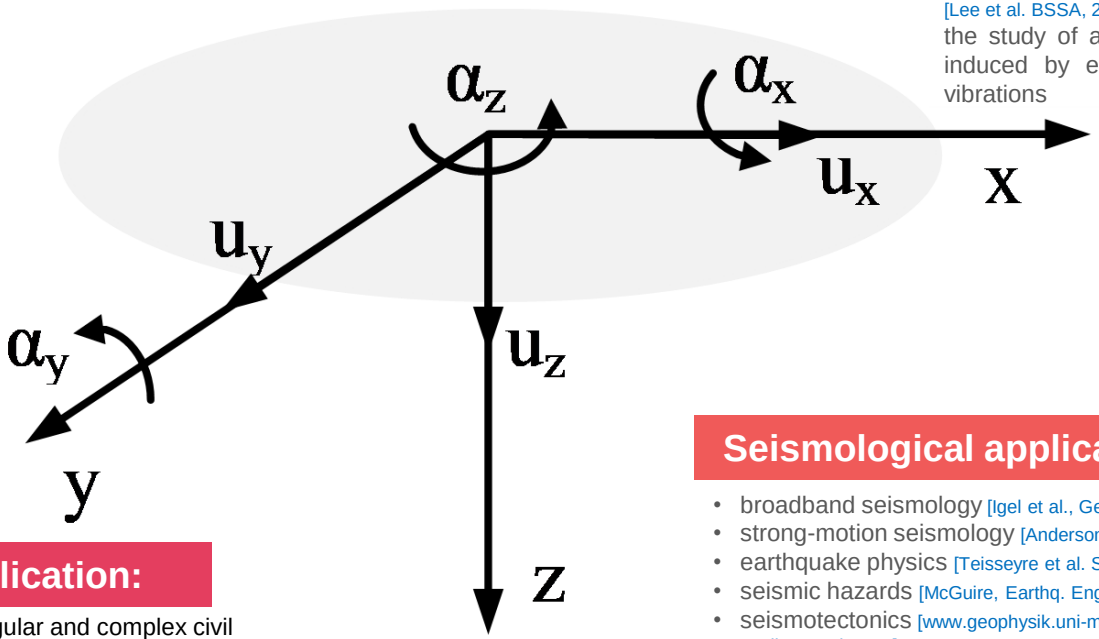
FOS5-0# (#=1, 2, 3)
Ω_{min}: $7 \cdot 10^{-8}$ rad/s,
SL: 5 000 m SMF,
Diameter: 0.25 m
FOS5-04
Ω_{min}: $1.14 \cdot 10^{-9}$ rad/s,
SL: 14 400 m SMF,
Diameter: 0.61 m
Ω_{max}: 10 rad/s

FOS6
3-Axis with
10 μs time synchronization
Ω_{min}: several dozen nrad/s
Ω_{max}: 10 rad/s
SL: 6 000 m SMF
Diameter: 0.25 m
Weight: 10 kg

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

.

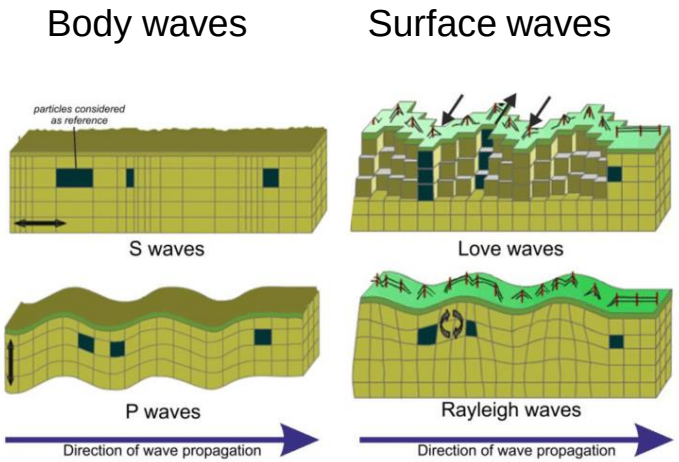
Engineering application:

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

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]

Seismological application



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

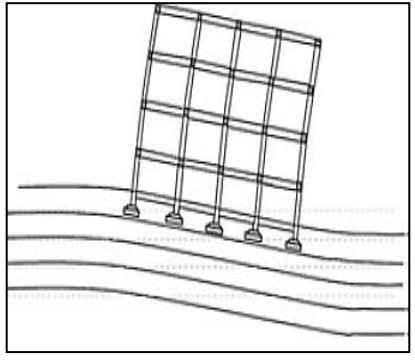
[Hinzen, J. Seisml., 16(4), (2012), 797–814]
Tombstone in Kushiro Cemetery after the Tokachi-Oki Earthquake 2003

Rotational events realy exist in Earth structure and event as rotational waves

Engineering application

Low frequency content

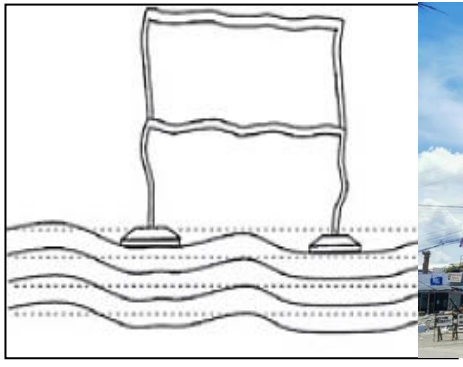
- Higher stress in structural element
- **Overturning moment**
- Horizontal displacement of the center of mass



[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]

[https://www.britannica.com/list/7-women-warriors]

[https://www.businessinsider.com/earthquake-taiwan-east-coast-2018-2?IR=T]

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

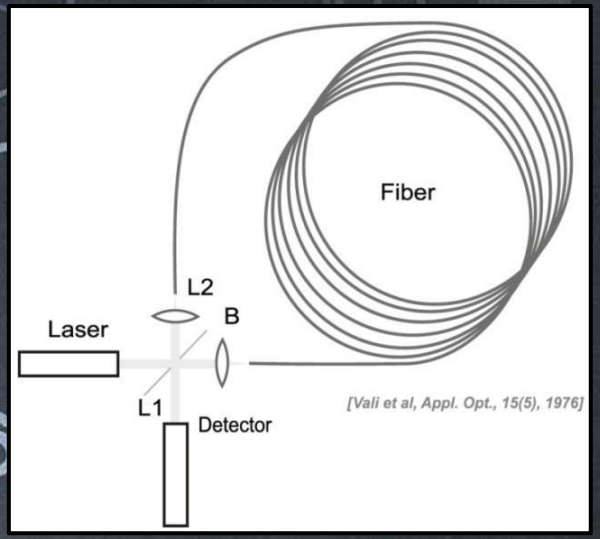
Measuring range

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 direct utilization of the Sagnac effect



Sagnac effect (1913) 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 $\Delta\phi$ as:

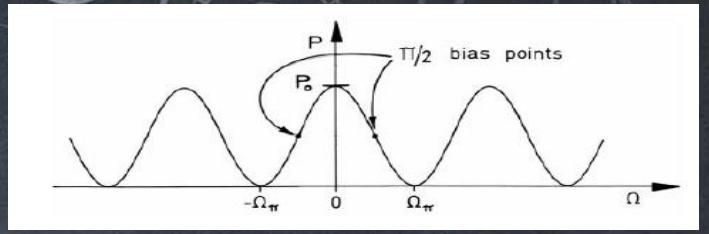
$$\Omega = S_o \cdot \Delta\phi = \frac{\lambda c}{2\pi DL} \cdot \Delta\phi$$

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

$$\Delta\phi = \frac{2\pi LD}{\lambda c}\Omega = \frac{2\pi * 1000[m] * 0.2[m]}{1310[nm] * 300000000[m/s]} 1[\frac{deg}{h}] = 0.15[mrad]$$

$$P(\Delta\phi) = \frac{P_o}{2}[1 + cos\Delta\phi]$$

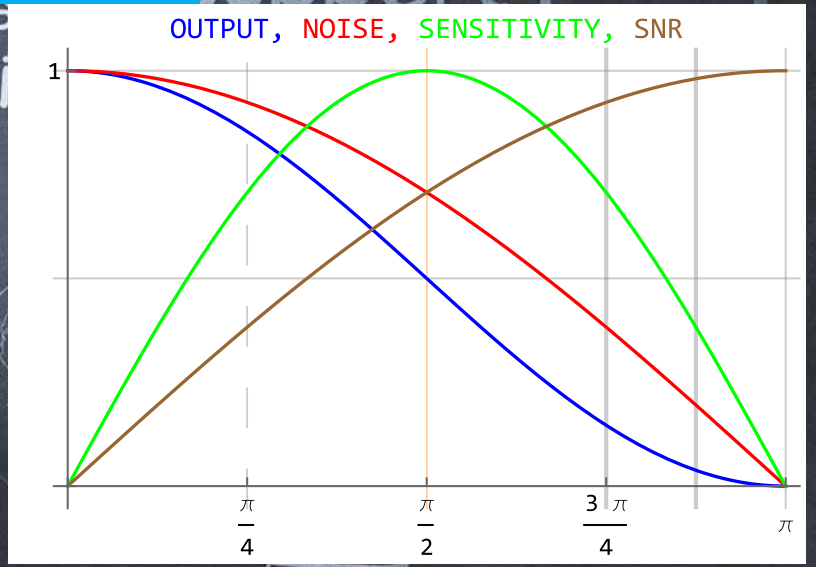
$$\Omega_\pi = \frac{\lambda c}{2LD} \rightarrow \begin{cases} L = 5\,000m, D = 0.25\,m, \lambda = 1310\,nm => 0.16\,rad/s \\ L = 14\,400m, D = 0.61\,m, \lambda = 1310\,nm => 0.02\,rad/s \end{cases}$$



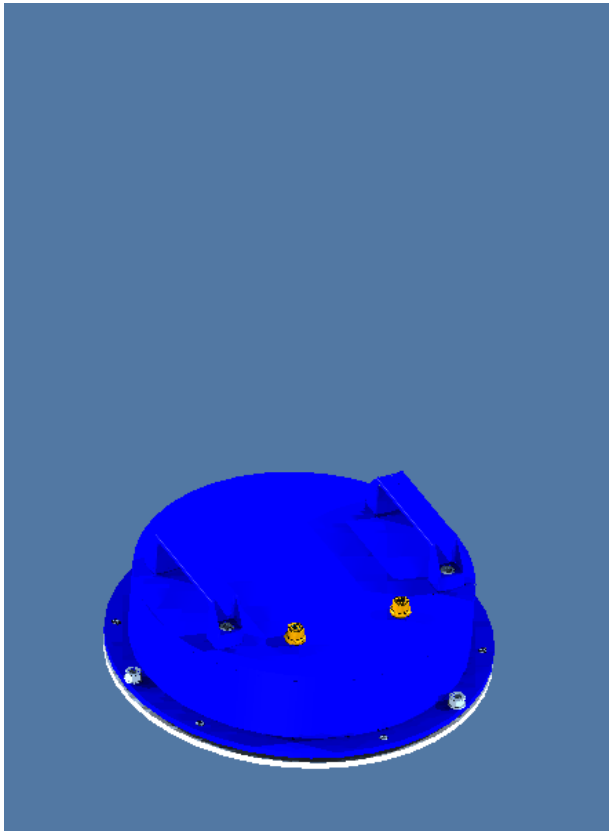
$$\Omega_\mu = \frac{\Omega_\pi}{\pi 10^6} \rightarrow \begin{cases} L = 5\,000m, D = 0.25\,m, \lambda = 1310\,nm => 5.1\,10^{-8}\,rad/s \\ L = 14\,000m, D = 0.61\,m, \lambda = 1310\,nm => 6.4\,10^{-9} rad/s \end{cases}$$

BACKGROUND

- Reduction other than Sagnac nonreciprocal effects
- Losses minimalisation to operate in shot noise level
- Stable bias to proper operate point
- Possibility to extend measurement range



Fiber Optic Seismograph

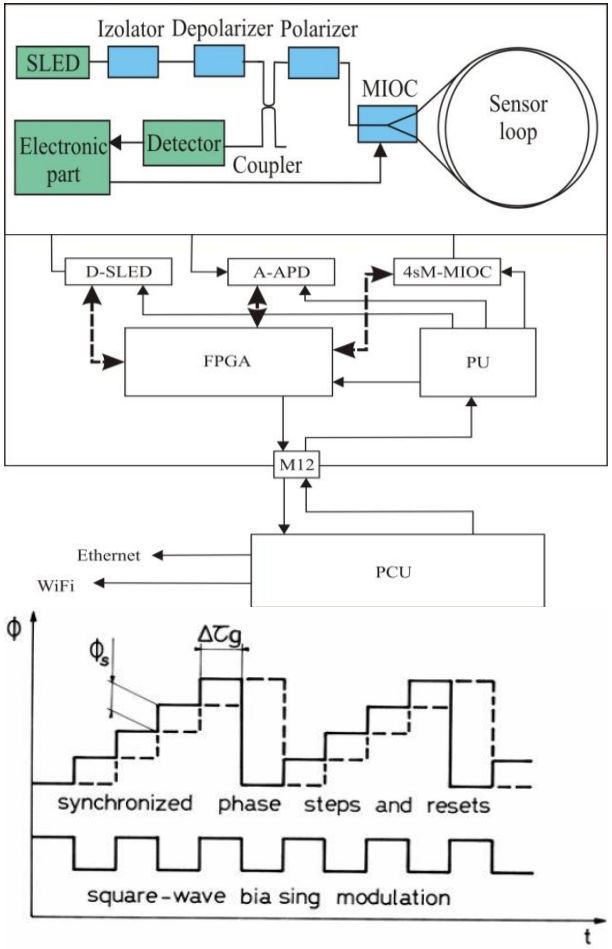


01 OPTICAL PART

generates the phase shift $\Delta\phi$ proportional to the measured rotation rate Ω which is perpendicular to the sensor loop plane in so-called minimum configurarion

02 ELECTRONIC PART

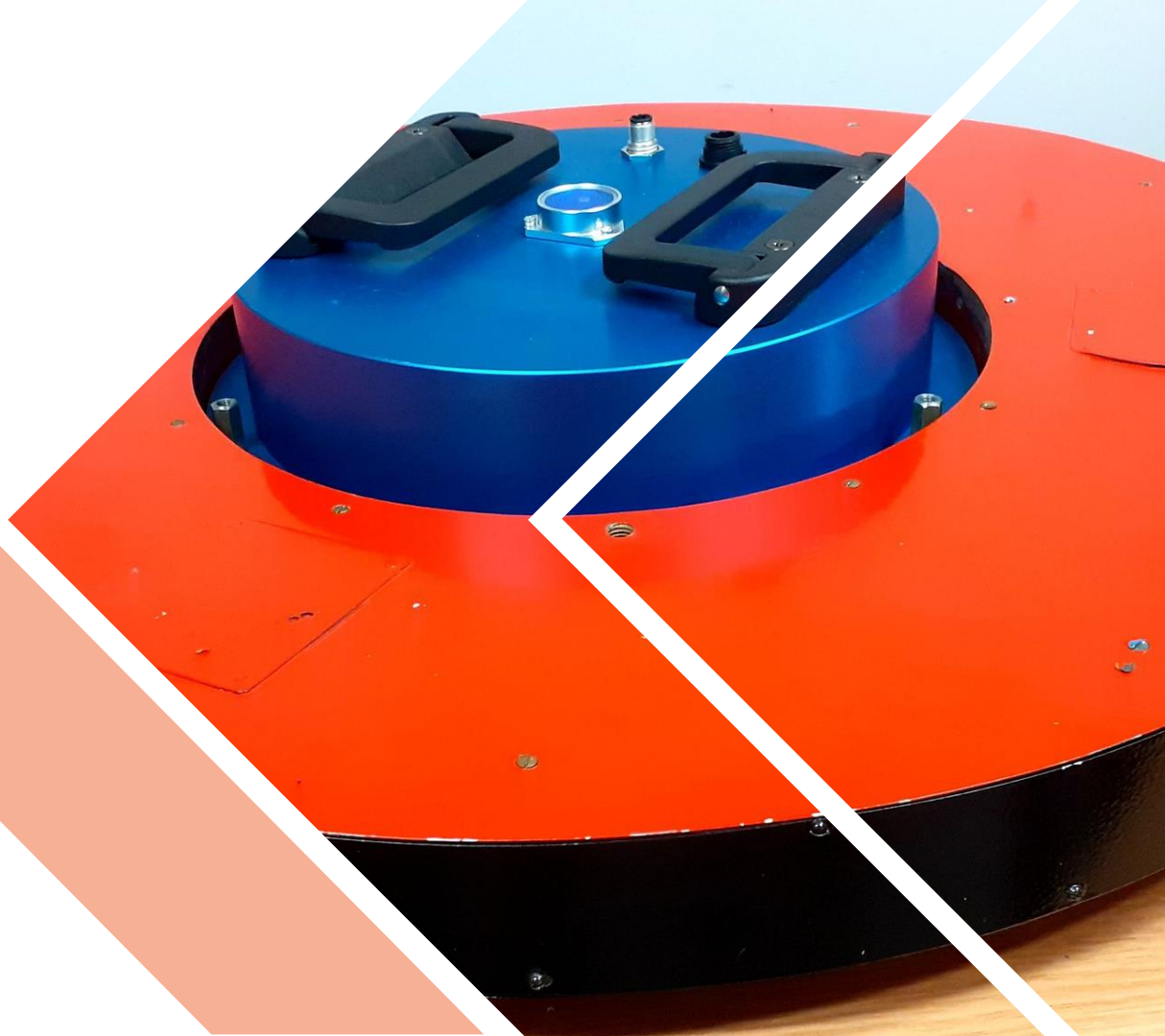
enables to calculate and record information about rotational motions via digital closed-loop signal processing



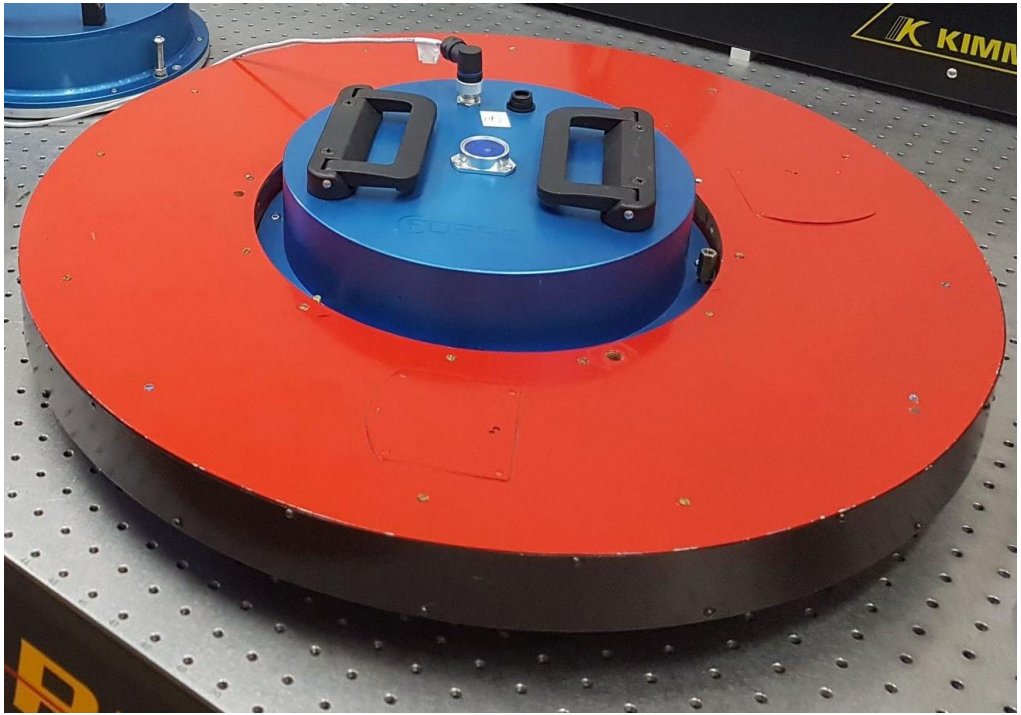
Huge Fiber-Optic Seismograph

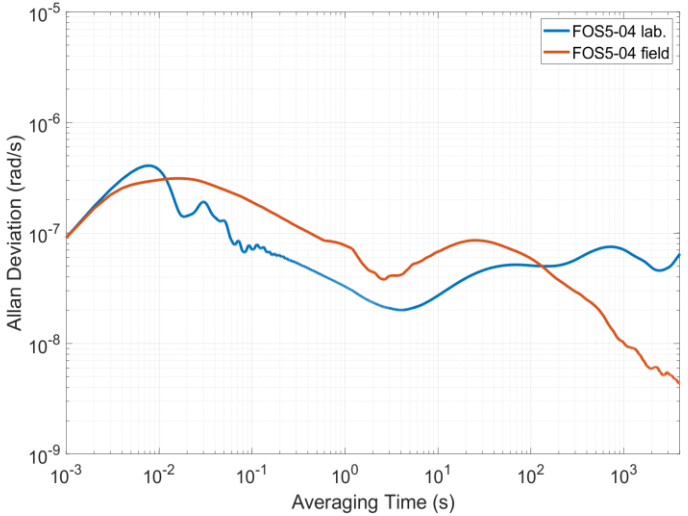
THEORETICAL SENSITIVITY
$1.14 \cdot 10^{-9}$ rad/(s√Hz)

FOS5-04 uses a 14.4 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

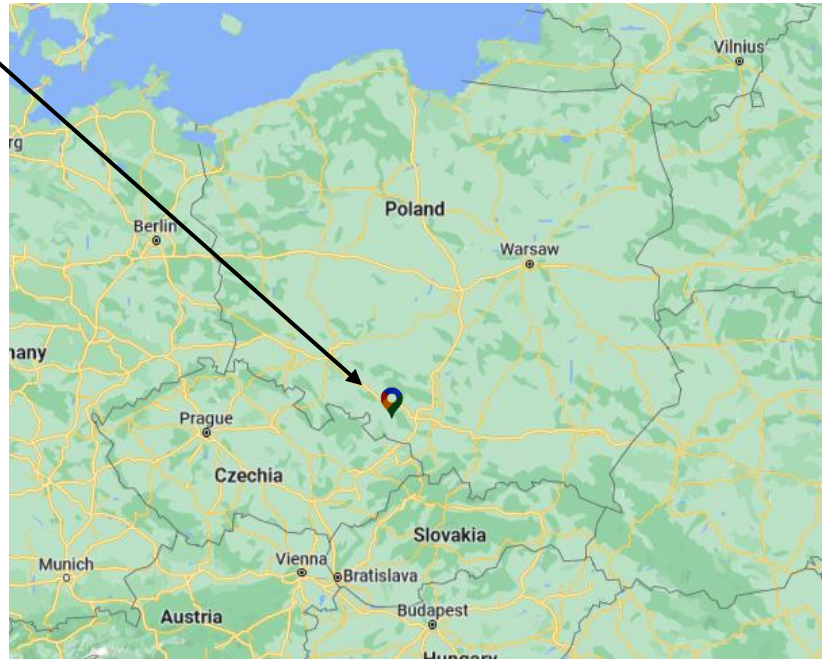




Position	Angle Random Walk [rad/√s]	Bias instability [rad/s]
Lab.	$3 \cdot 10^{-8}$	$2 \cdot 10^{-8}$
Field	$8 \cdot 10^{-7}$	$4 \cdot 10^{-8}$

Fibre optic seismograph – field application

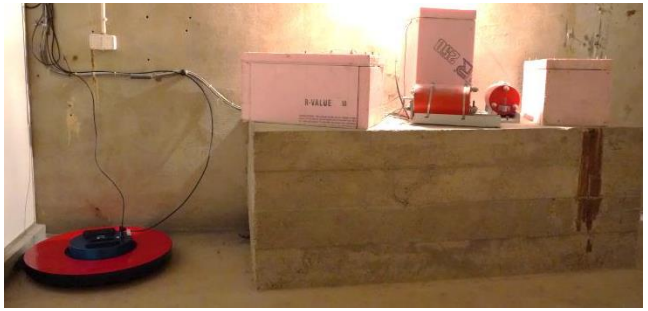
Seismological observatory in the basements of Książ Castle in Wałbrzych, Poland 50°50'34"N 16°17'35"E



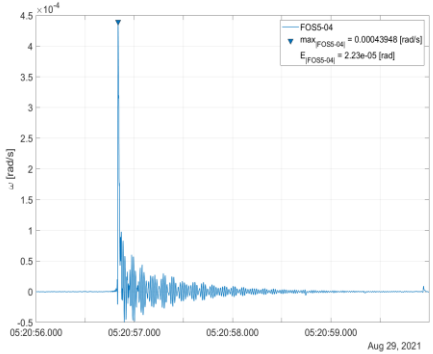
The observatory is located about 60 km away from the city of Legnica, which is the largest center of the Legnica-Głogów Copper District (LGCD)

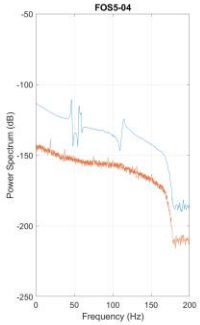
Fibre optic seismograph – recordings

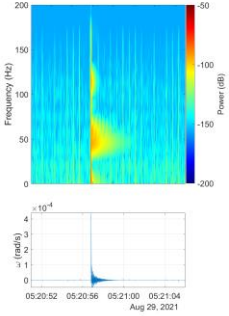
Analysis

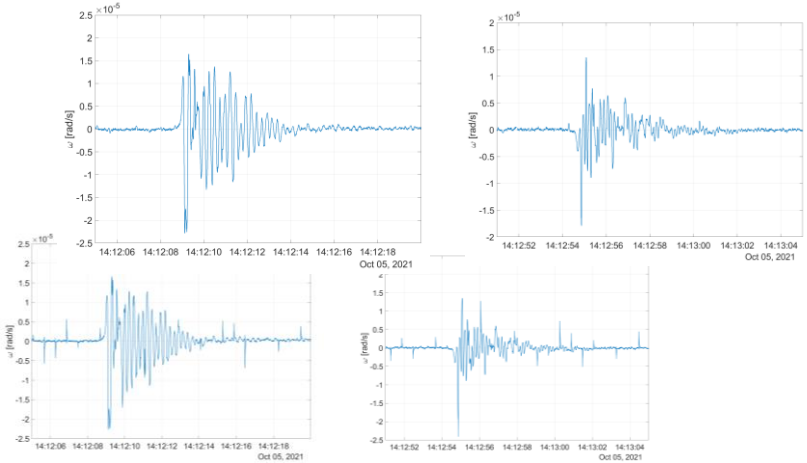


- Initial amplitude of about 0.44 mrad/s and signal duration of about 6 s
- Some low-amplitude perturbations repeating with a period of about 0.6 s
- Two examples of rotational events recorded on 5th October, 2021
- The maximum amplitudes of the recorded signals are equal to $1.62 \cdot 10^{-5}$ rad/s and $1.35 \cdot 10^{-5}$ rad/s
- A dedicated algorithm was implemented in post-processing







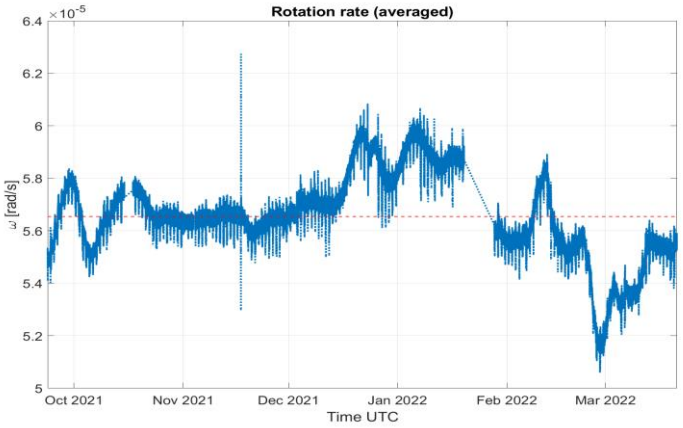


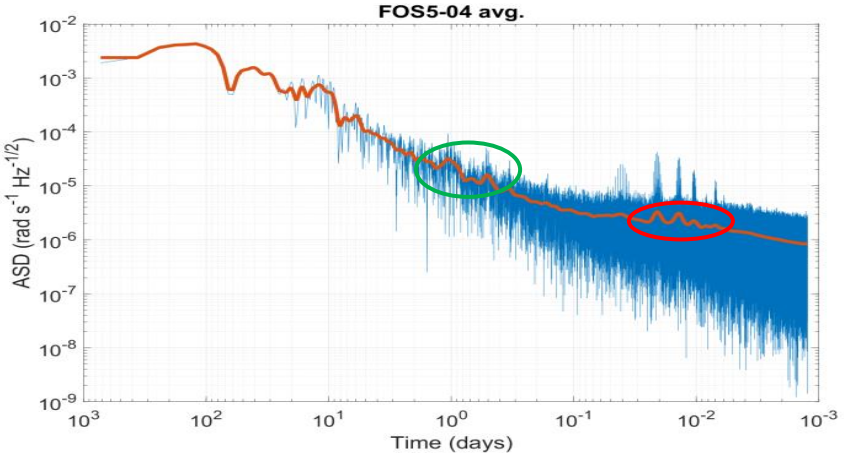
[Jaroszewicz et al., Opto-Electronics Review, 29, 4 (2021)]

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.





Conclusions

1 **Rotational seismology** undergoes a rapid development. FOS5-04 is capable to detect changes in Earth's rotation rate.

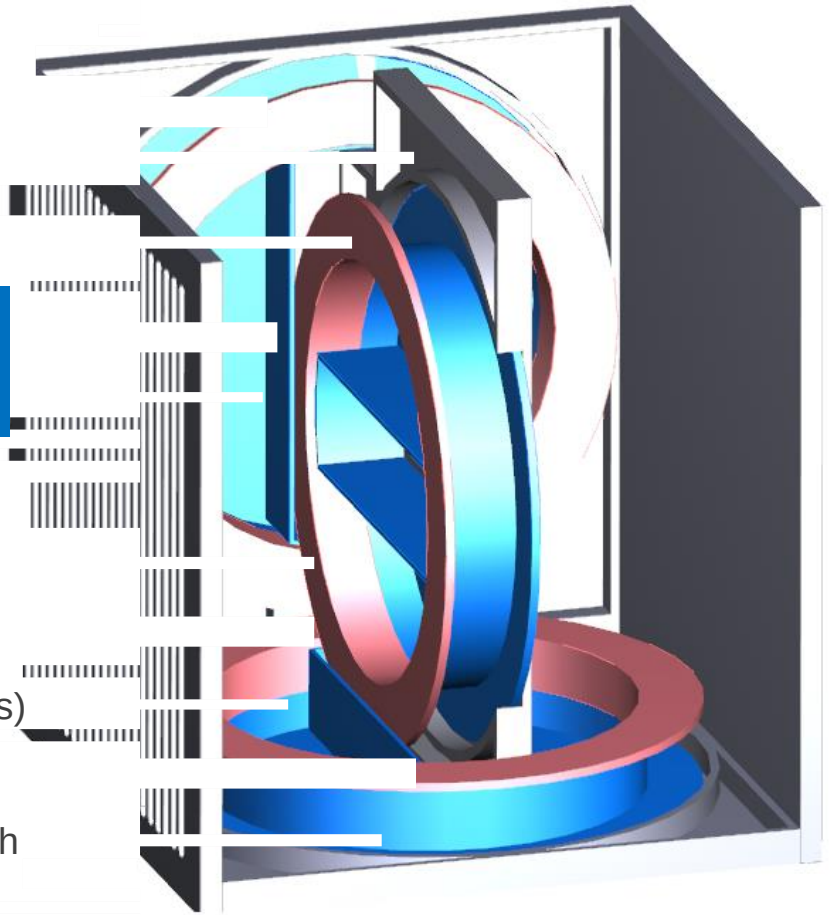
2 Current work - next generation of FOS6 with 3-perpendicular axes

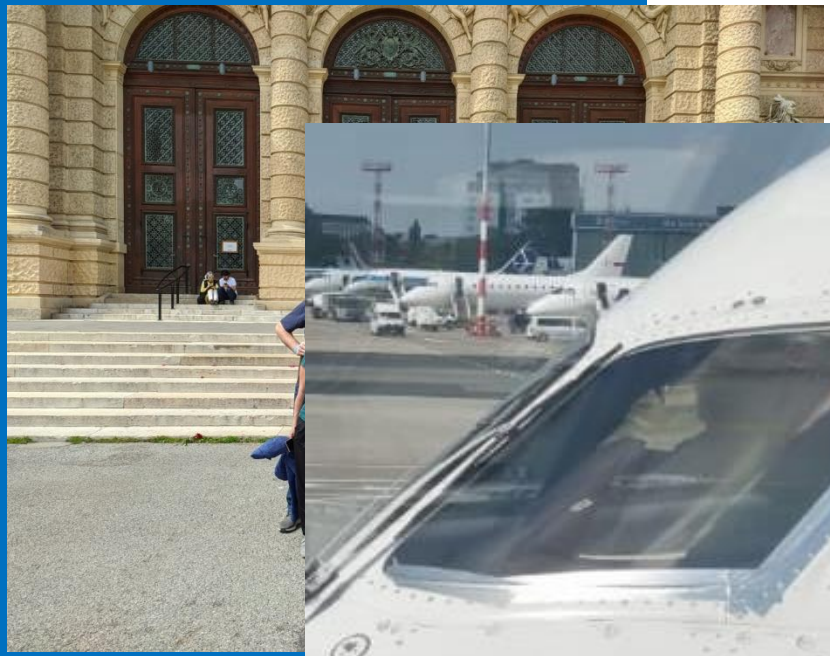
FOS 6
FROM SKY ACROSS GROUND UP TO UNDERGROUND

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

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

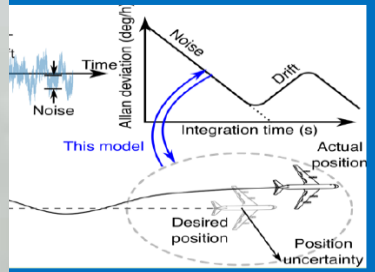




Meet Our Team

Additional Remark:

Scientific Work *versus* Practical Uses



er, IEEE Sen., 22(5), (2022), 4207]

Presention based on two works presented at