# Fiber-Optic Rotational Seismograph as adequate device for recording rotational components caused by artificial events

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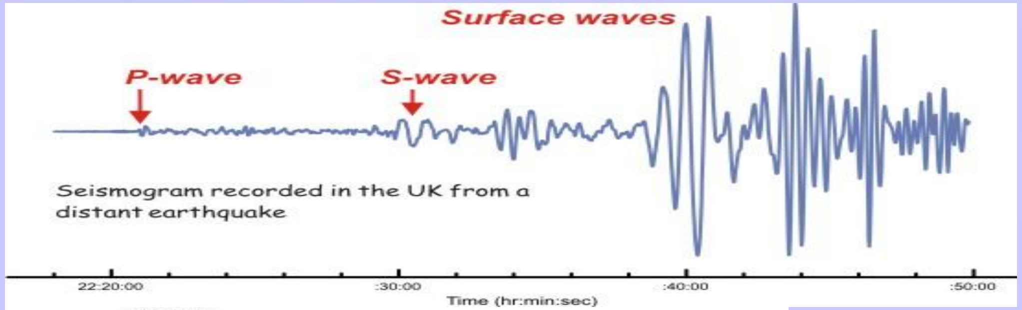
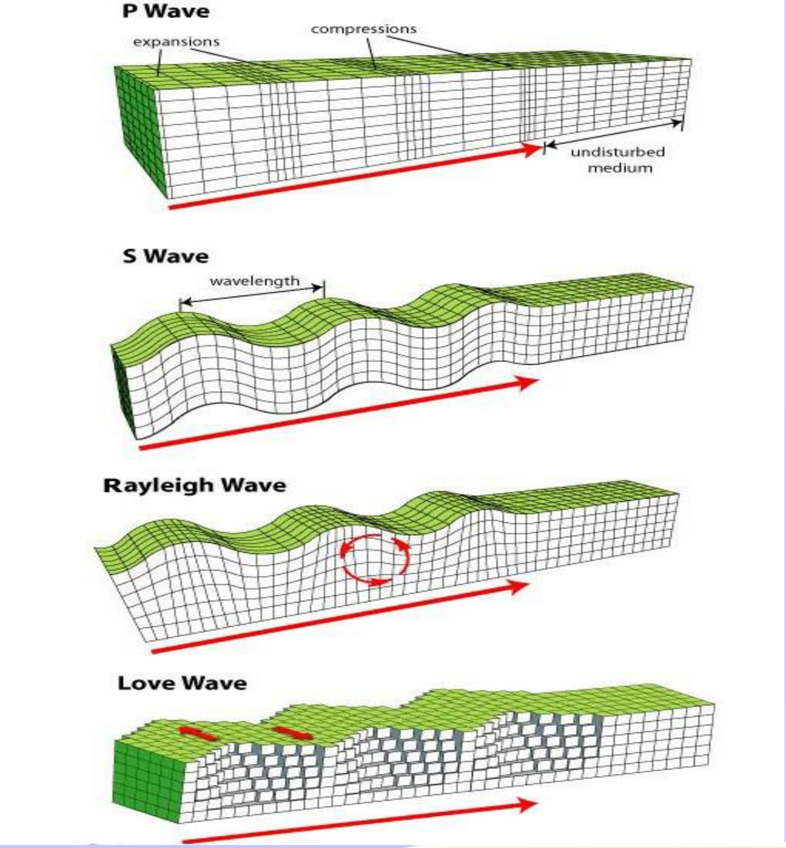
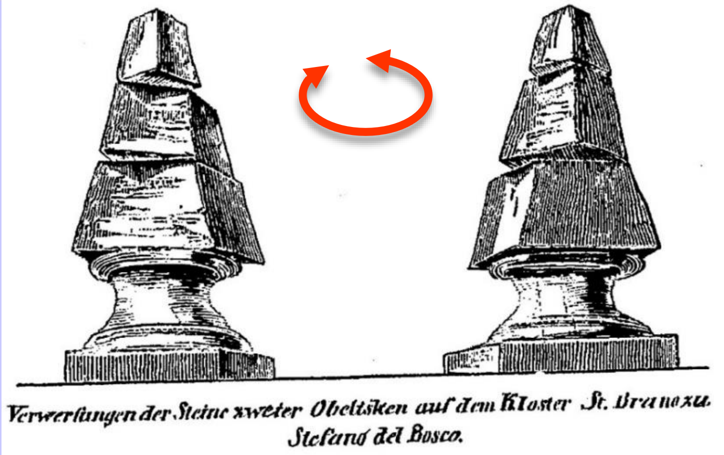
# AGENDA

- Seismological investigation of rotational effects
- Rotational instrumentations
- Sagnac/(von Laue) effect – theoretical background
- Fiber-Optic Rotational Seismograph – innovative idea
- FORS types of FOS5 and FOS6
- FOS5 field test
- FOS6 field test

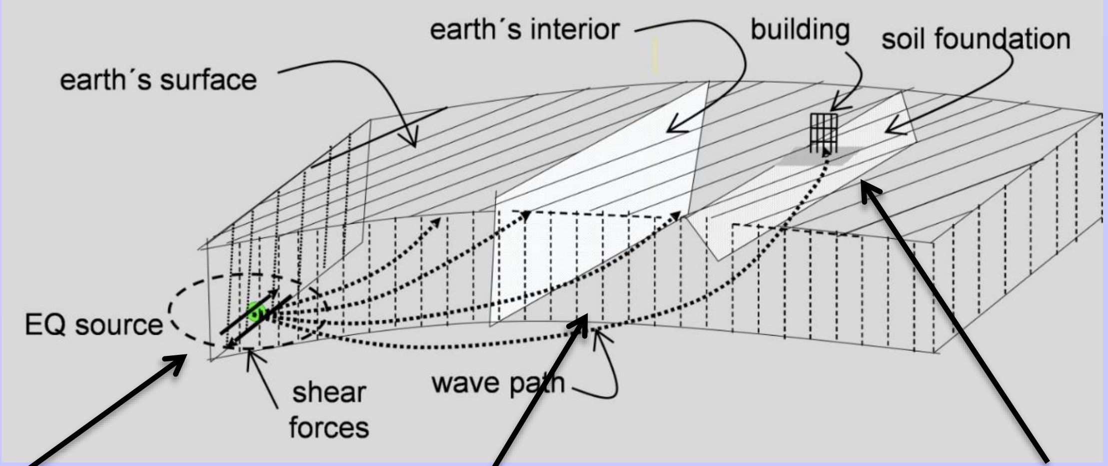



CALABRIA, 05.02.1783

[Gordon et al., *BSSA*, ***60***, 953-971, 1970]




Finite size
as near field effects

(hypothetic) rotational wave
(Teisseyre Roman) "anti-Richter"

reflection & interference
„rotation of geological blocks"

[prof. Z. Zembaty lecture, *SMOiO KM PAS* 14.10.2016]

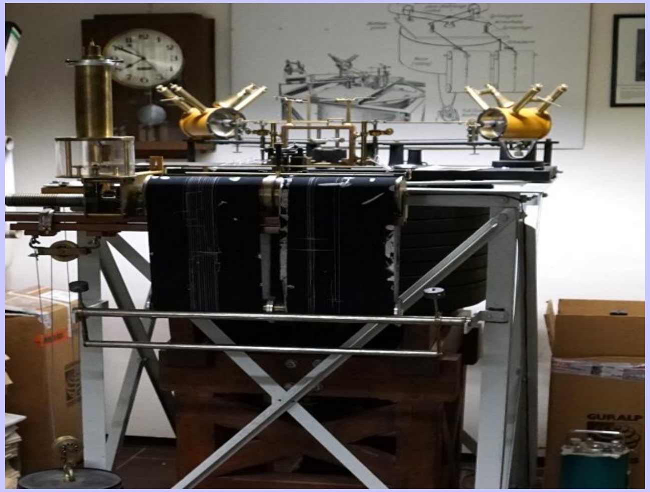
**Rotational Seismology** [Lee et al. *BSSA*, **99**, (2009), 945-957] a new, emerging field for the study of all aspects of rotational ground motion induced by earthquakes, explosions, and ambient vibrations

**Seismological application:**

- broadband seismology [Igel et al., *Geophys. J. Int.*, **168(1)**, (2006), 182–197],
- strong-motion seismology [Anderson, *The Intern. Handbook of Earthquake and Engineering Seismology*, 2003, Chap. 57, 937-965],
- earthquake physics [Teisseyre et al., Springer, 2006; Teisseyre et all, 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]

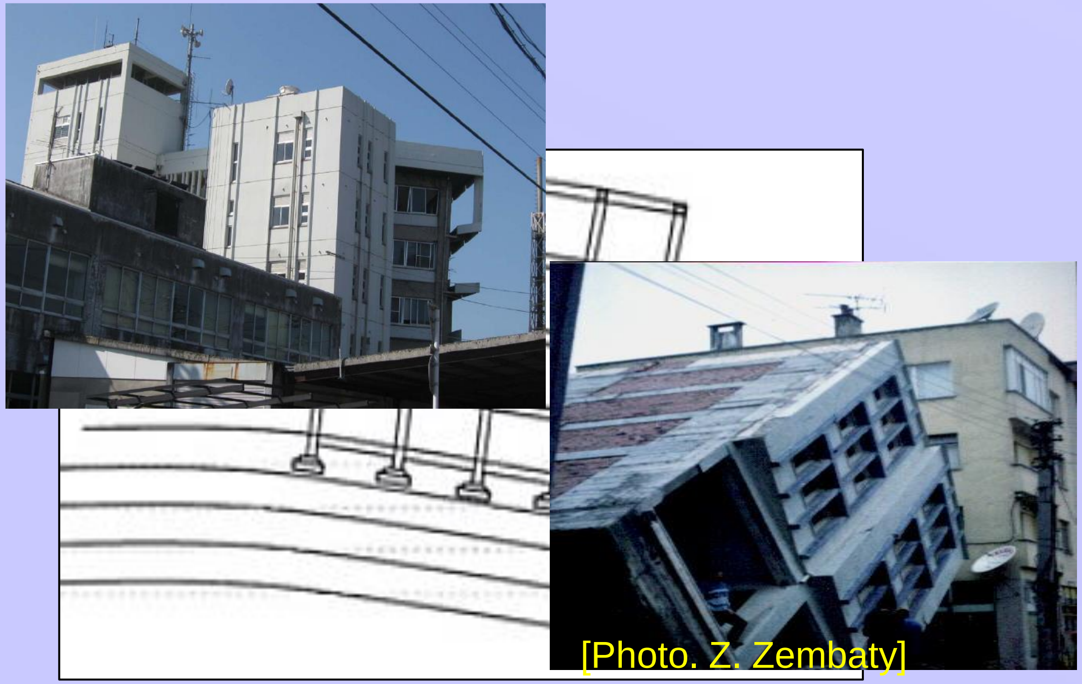


[https://www.outlookindia.com/website/story/major-quake-of-magnitude-8-likely-to-hit-north-india-says-chief-of-seismology-ce/304704]

# Influence of geological blocks rotation


High frequency content

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




Low frequency content

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

[Castellani, 2nd *IWGoRS workshop,* Masaryk's College Prague, 2010]

**„Seismological" applications**
[Bernauer et al., *J. Seism.*, **16**, (2012), 595-602]

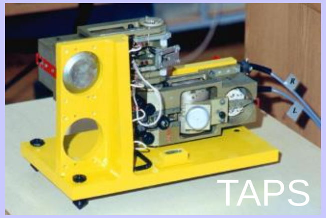
1. effectively insensitive to linear motion, or at any time, independent measurement of linear and rotational motions must be possible,
2. small (mobile) and stable with respect to ambient conditions, including changes of temperature,
3. the electrical power supply should be easily managed using batteries, at least combination with solar panels or fuel cells,
4. be able to measure amplitudes on the order of $10^{-8}$ rad/s at frequency range 0.01 Hz - 0.1 Hz.

**„Engineering" applications**
[Jaroszewicz et al., *Sensors*, **16**, (2016), 2161]

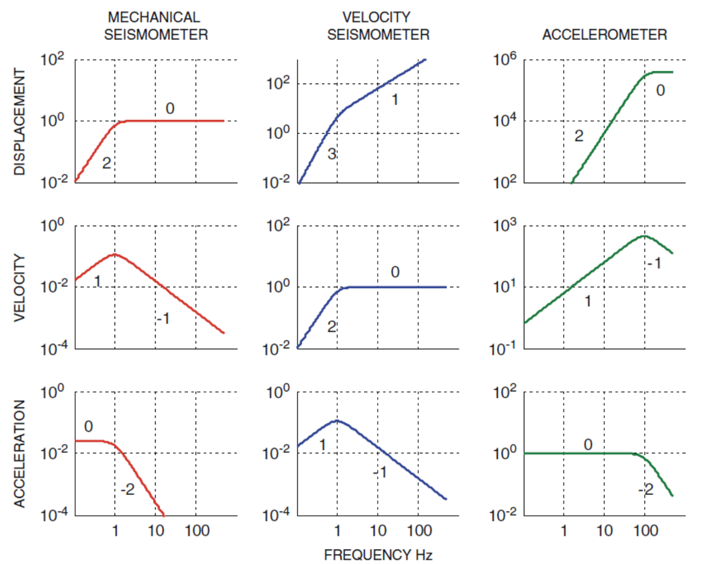
1. effectively insensitive to linear motion, or at any time, independent measurement of linear and rotational motions must be possible,
2. small (mobile) and stable with respect to ambient conditions, including changes of temperature,
3. the electrical power supply should be easily managed using batteries, at least in combination with solar panels or fuel cells,
4. be able to measure amplitudes up to a few rad/s at frequency range 0.01 Hz - 100 Hz.

**Rotational sensor → ROTATIONAL SEISMOMETER (1-, 2- or 3-axes)**
**field application → ROTATIONAL SEISMOGRAPH**
network of **seismometers +** precise time source + recording device + network

**1. Mechanical type (nondirect based on velocity or accelerometer type seismometer)**
Limited: frequency range, max. detectable rotation rate

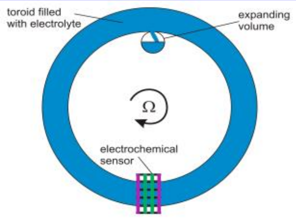


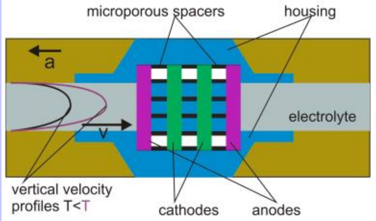



[Havskov, Alguacil, *Instrumentation in Earthquake Seismology.* Springer, 2016]

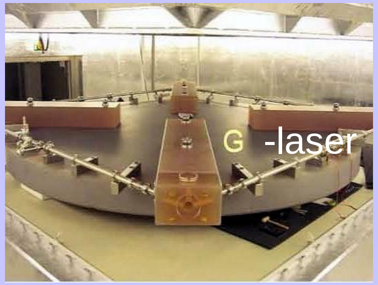
**2. Electro-chemical type (direct based on liquid inertia)**
high thermal instability, problem with electrolyte inertia



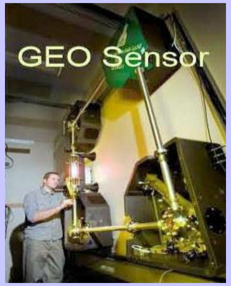





**3. Optical type (direct based on Sagnac/(von Laue) effect)**
optimal for seismological applications, but stationary system





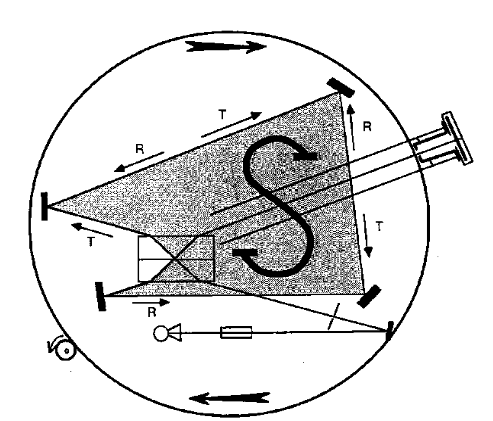



**Specialized system based on FOG**


µ-FOG-1


LCG-demonstrator

Sagnac (1913)/Von Laue (1911) effect is a result of a difference between two beams propagating around closed optical path, in oposite direction when this path is rotating.

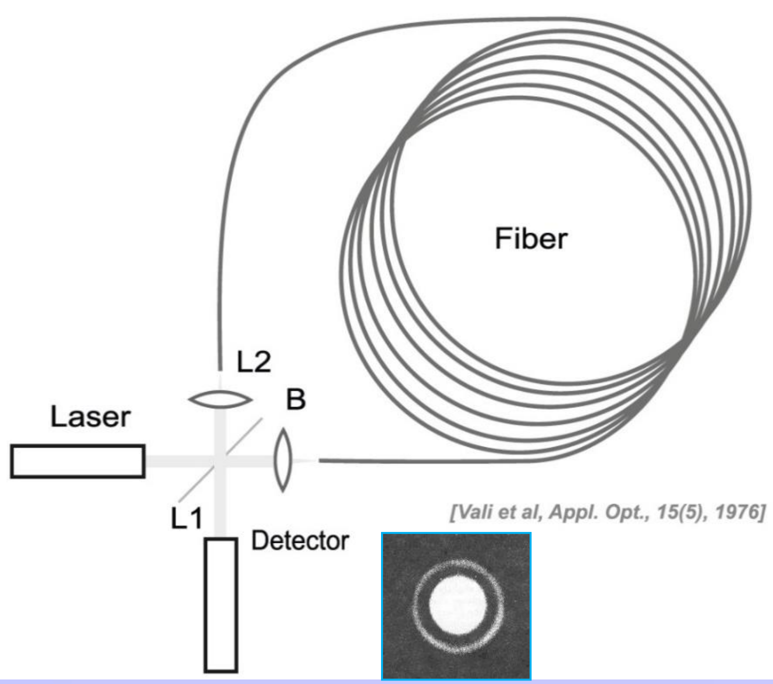



[Post, *Rev. Mod. Phys.*, ***39,*** *1967*]

The Sagnac phase shift (1976) induced by rotational rate $\Omega$ perpendicular to plane of fiber optic sensor loop is equal to:

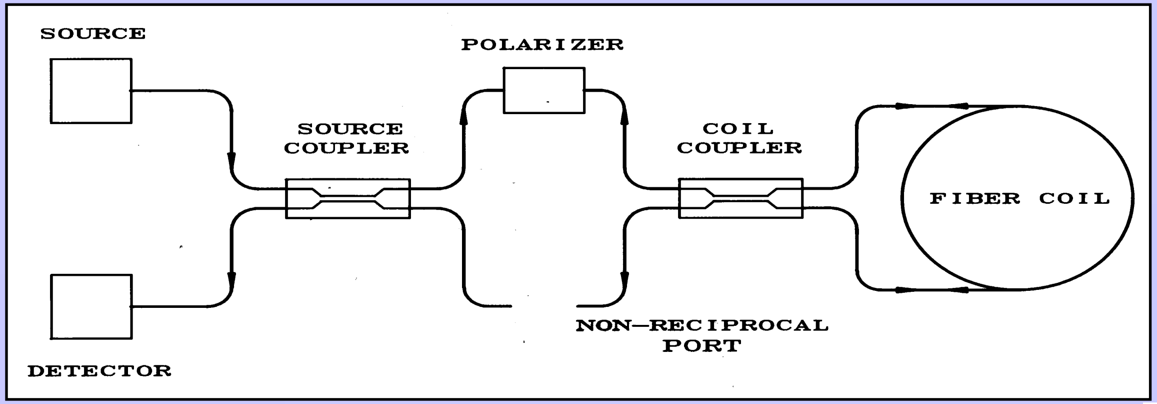
$$\Delta\varphi = \frac{4\pi RL}{\lambda c}\Omega = \frac{1}{S_0}\Omega$$

where:
L – length of the fiber in the sensor loop
R – sensor loop radius
λ – wavelength
c – velocity of the light in vacuum
$S_0$ – the optical constant of interferometer




*[Vali et al, Appl. Opt., 15(5), 1976]*

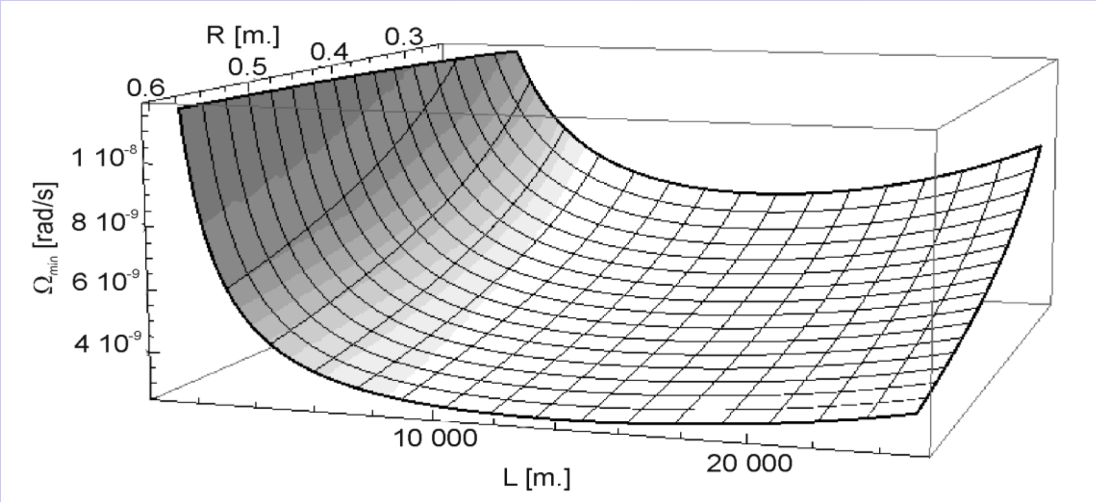
Minimum configuration → **FORS** optimization for **rotation rate** (**not angle**) detection



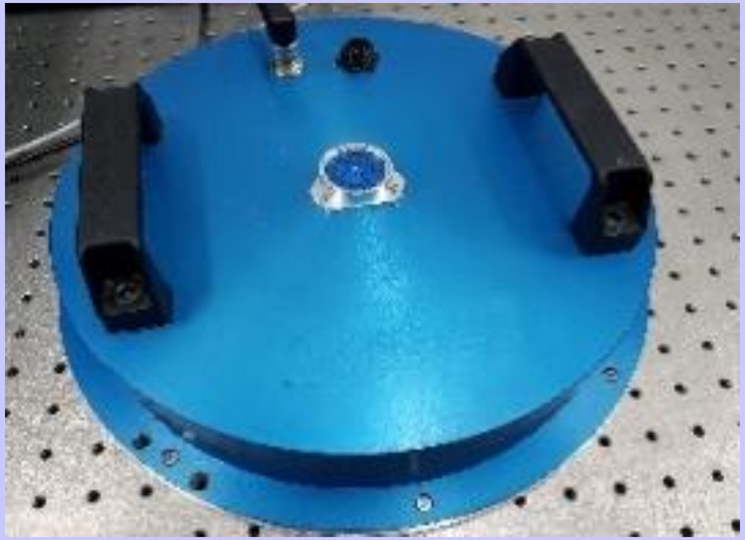


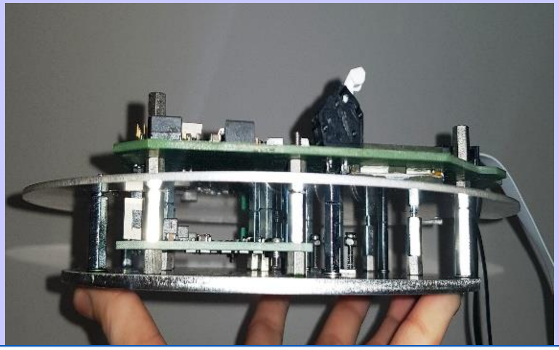

**AFORS – gain FOG optimization of optical head:**

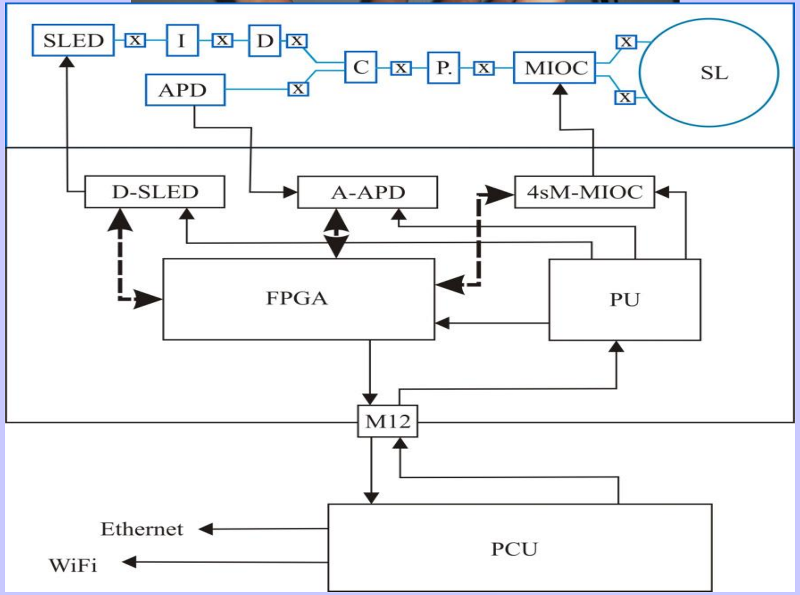
- **L= 15 000 [m],** 15 layers, quadrupole-bifilar winding,
- $\alpha$ =0.436 [dB/km],
- **loop R=0.34 [m]** with permalloy particles,
- **$\sigma$ = 13.16 [dB],**
- cascade polarizers (46 and 55 [dB]),
- depolarizer with P=0.002
- $\Delta\lambda$=31,2 [nm], $\lambda$=1326.9 [nm], $P_L$ =20 [mW],
- S=0.99 [ A/W], $I_A$ =0.06 [nA], $R_0$ =163 [k$\Omega$]
- open-loop architecture




**$\Omega_{min}$ =1.93·10$^{-9}$ [rad/sHz$^{1/2}$]**








FOS5:
- 5 km long SL
- 0.25 m diameter

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

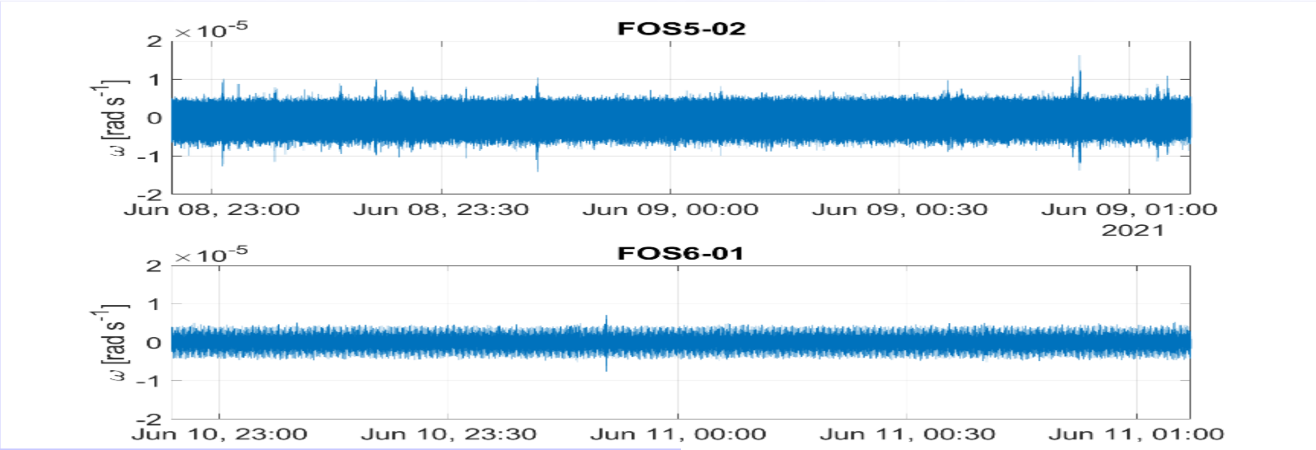
FOS6:
- 15 km long SL
- 0.60 m diameter

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

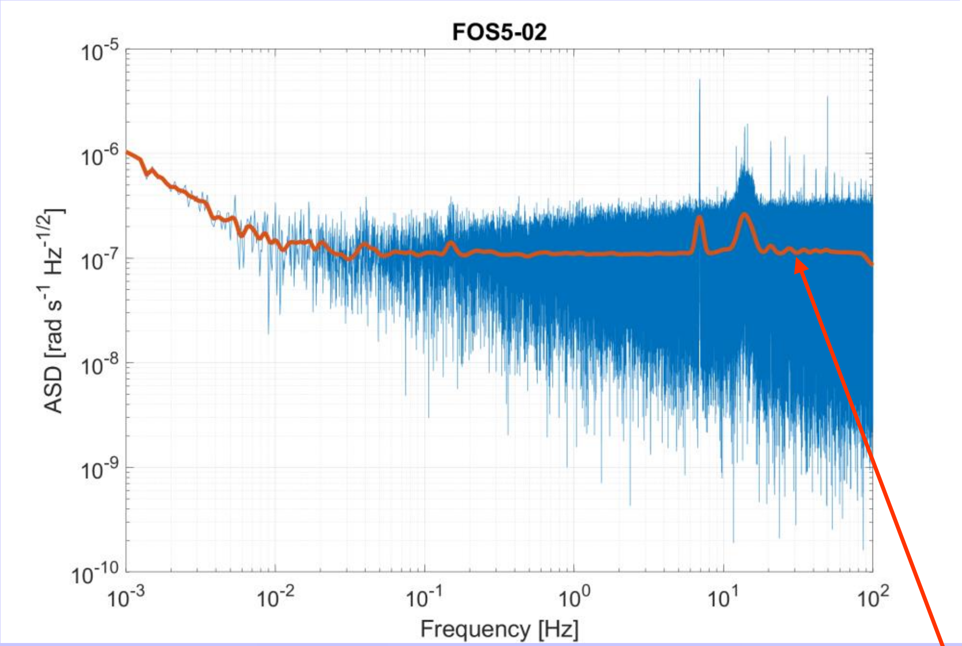
SLED – light source, I – fiber-optic isolator, D – fiber-optic depolarizer, C – fiber-optic coupler, P – fiber-optic polarizer, MIOC – multi-integrated optical circuit, SL - sensor loop, X -fused splice, APD – avalanche photodetector, D-SLED – SLED driver, A-APD – APD amplifier, 4sM-MIOC – four-step MIOC modulator, FPGA – general FPGA unit, PU – power unit, PCU – power and communication unit

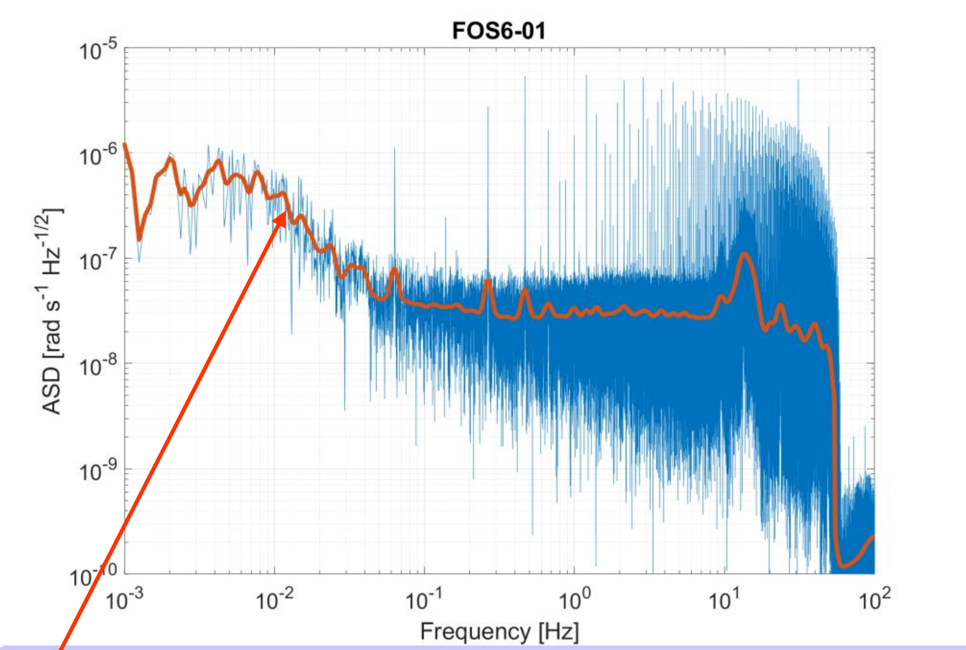
# NOISE ANALYSE

Allan variance analyse:
Angular Random Walk
$5.7 \cdot 10^{-7}$ rad/(s√Hz)



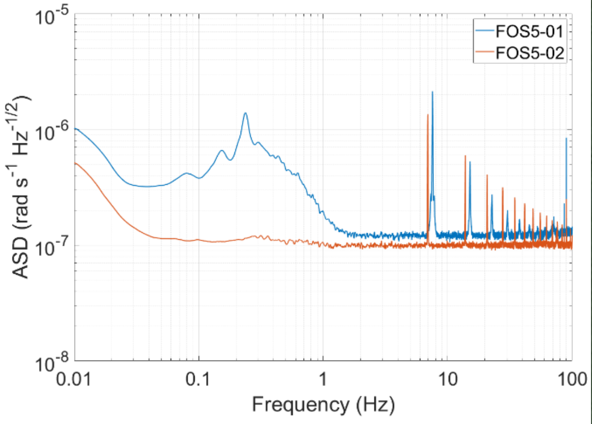

Allan variance analyse:
Angular Random Walk
$7.5 \cdot 10^{-8}$ rad/(s√Hz)



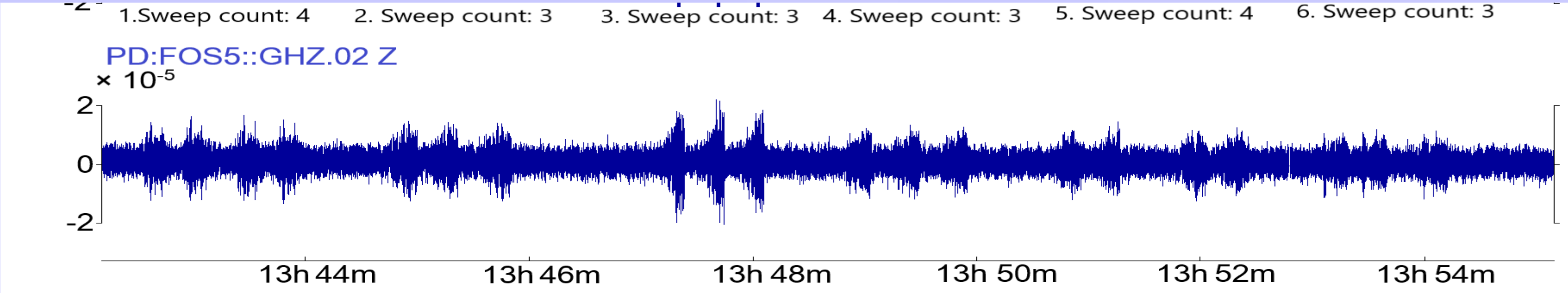



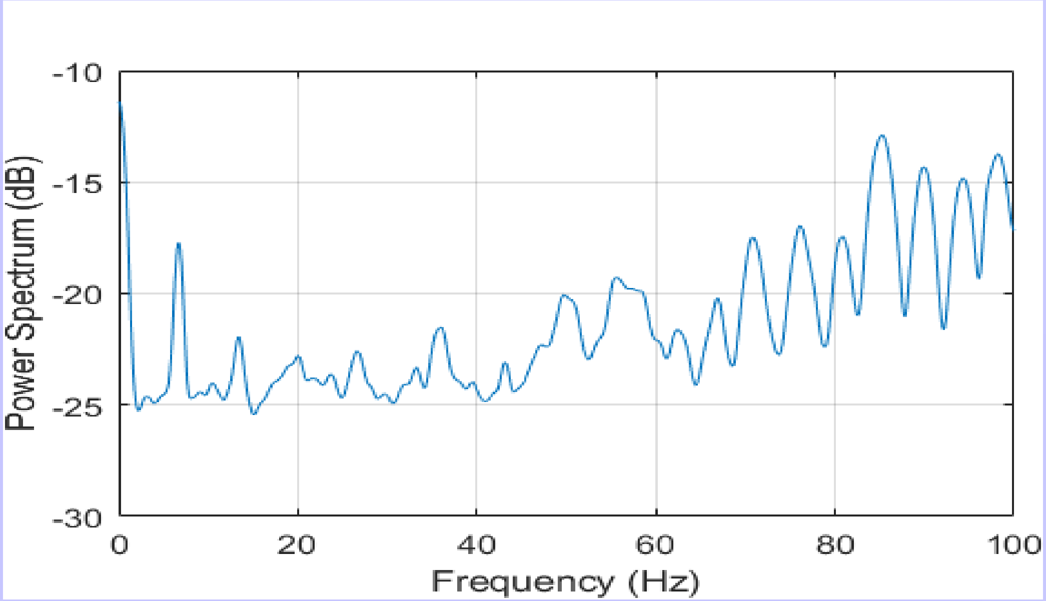

data filtered by Konno-Ohmachi filter with smoothing coefficient equal to 40

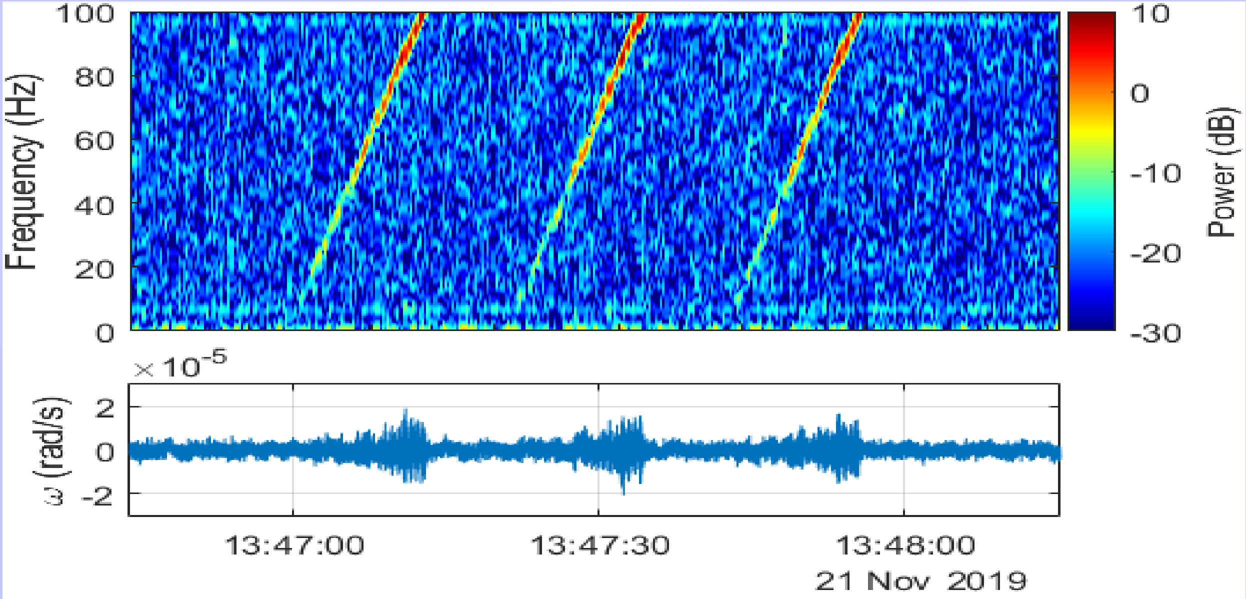
# FOS5 – Field test Fürstenfeldbruck 19-22.11.2019


VibtroSeis truck (peak force 275 kN) travelled in a distance (96-138 m from FOS5s) and generated seismic perturbations in the ground. Each series of ground impacts lasted 15 s with frequency increasing from about 7 Hz to 120 Hz

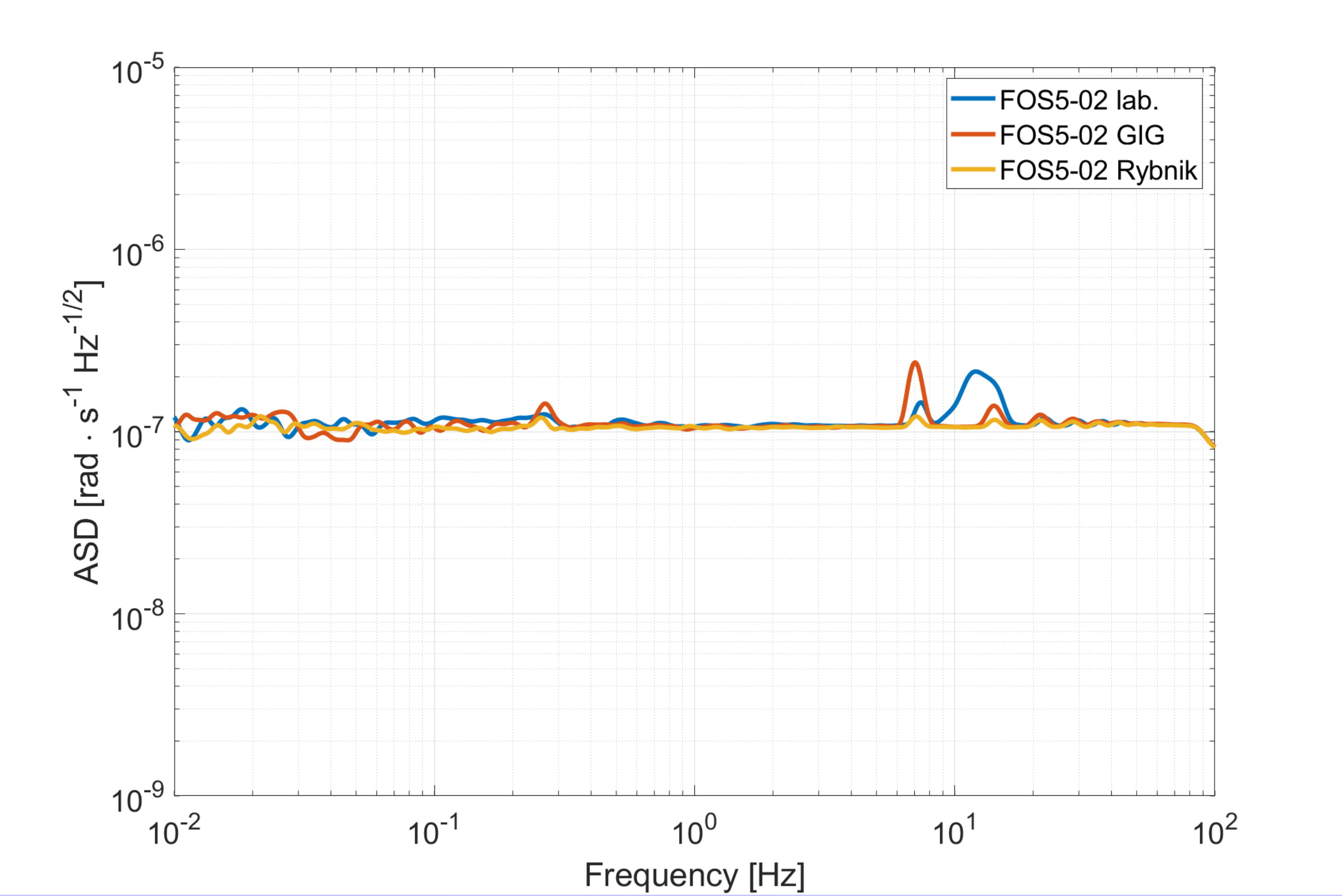


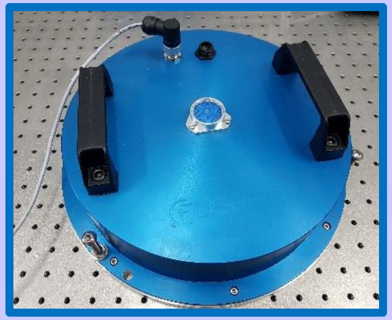



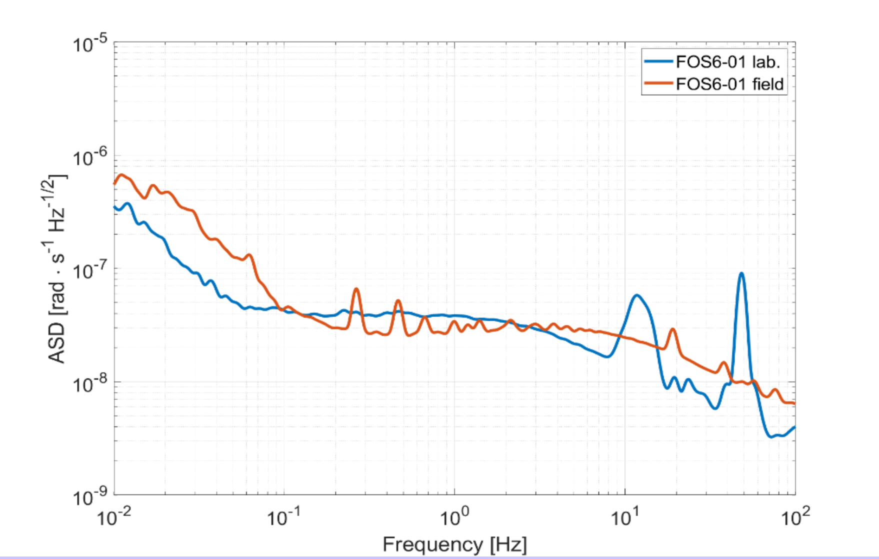

[Kurzych, et al., *Sensors*, **20**, (2020), 6107]

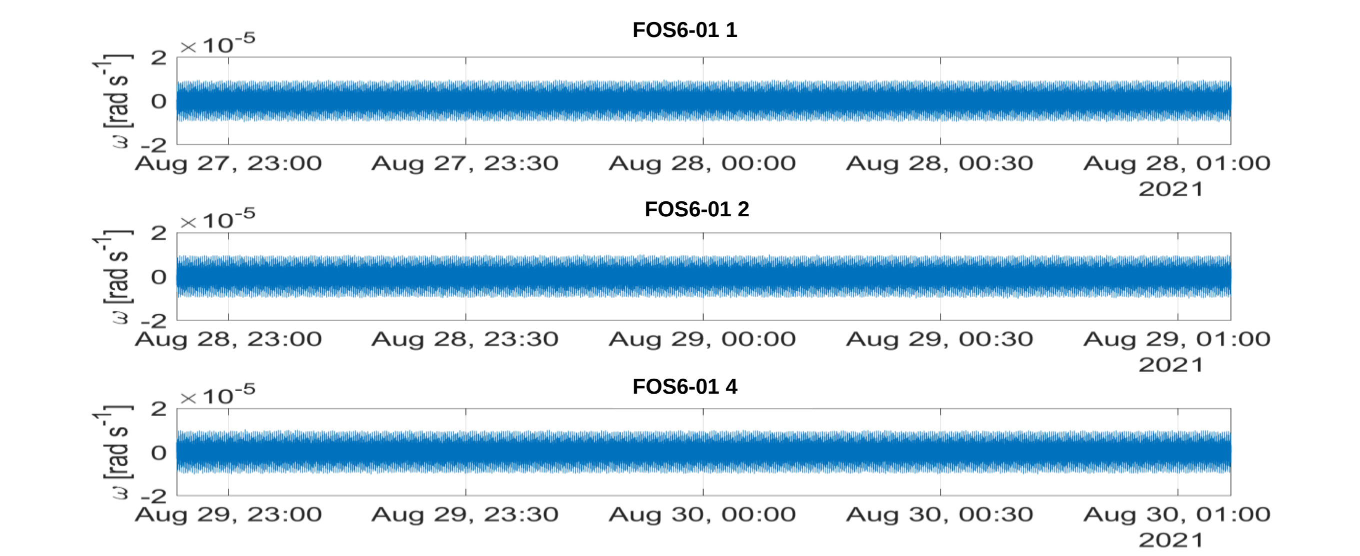
# FOS5 – Improvement of noise characteristic

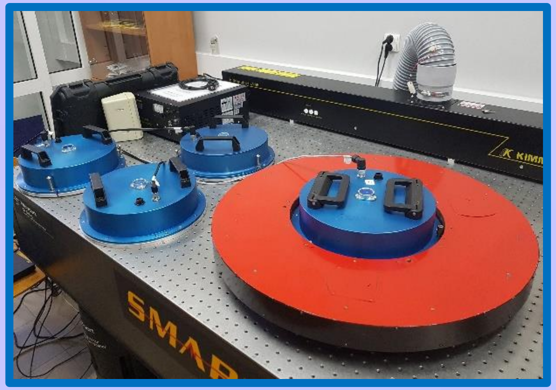


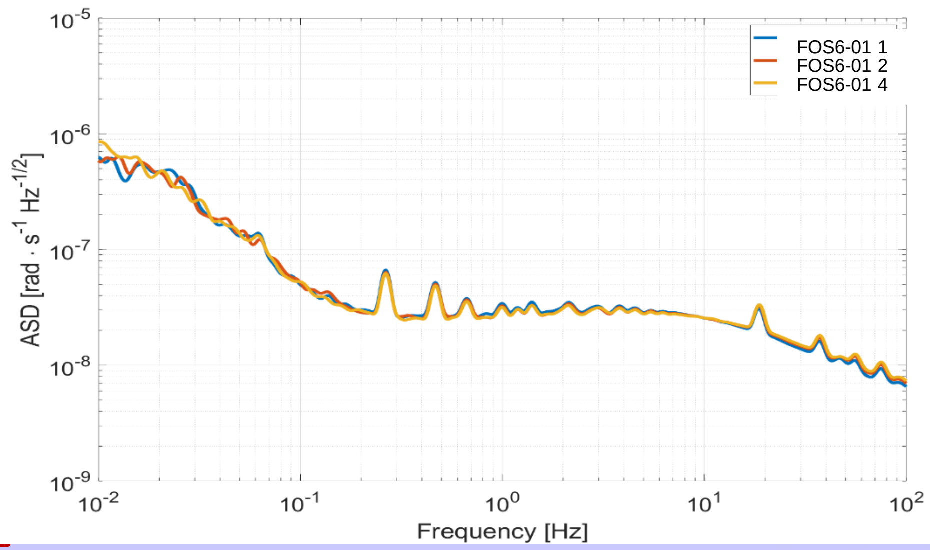



# FOS6 – noise characteristic

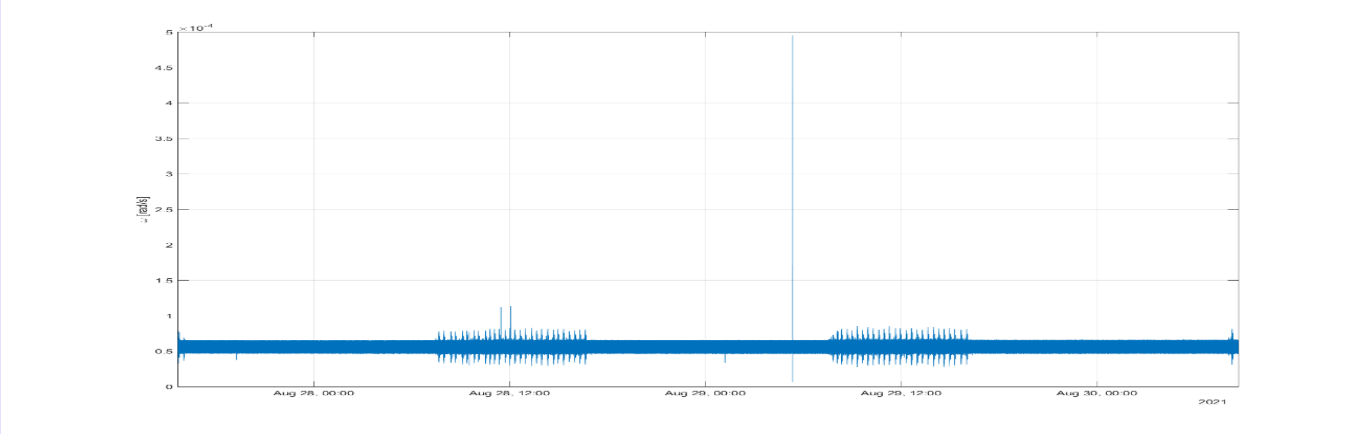


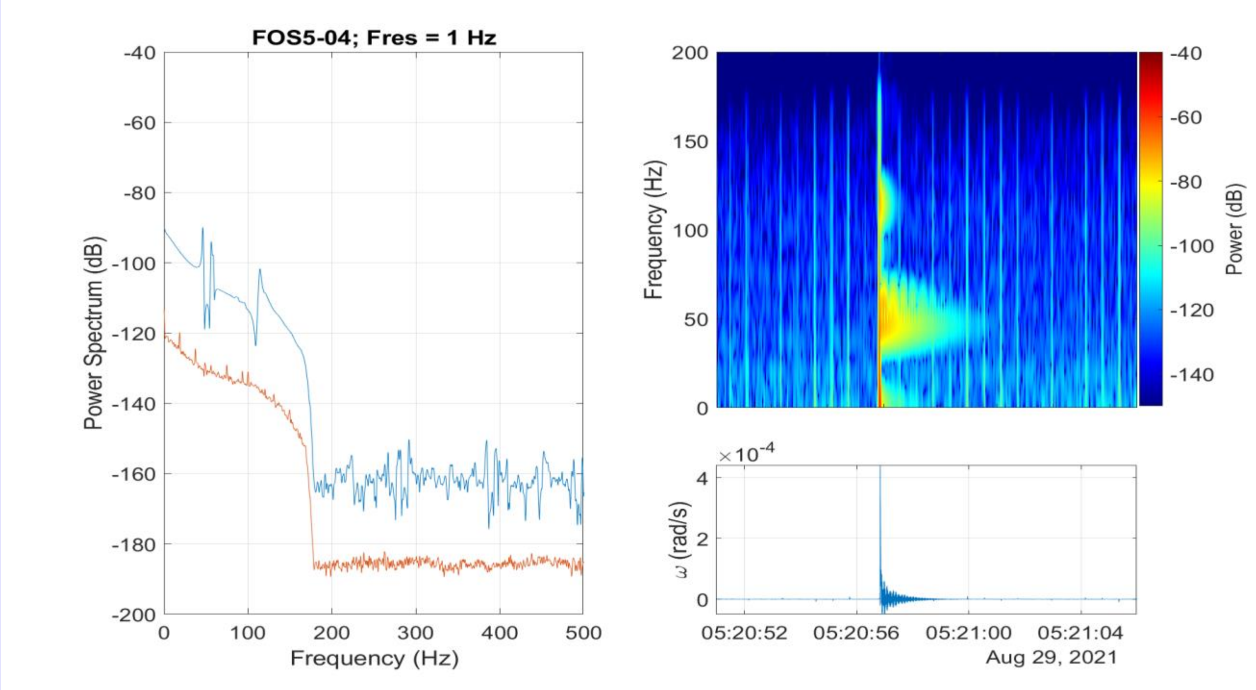



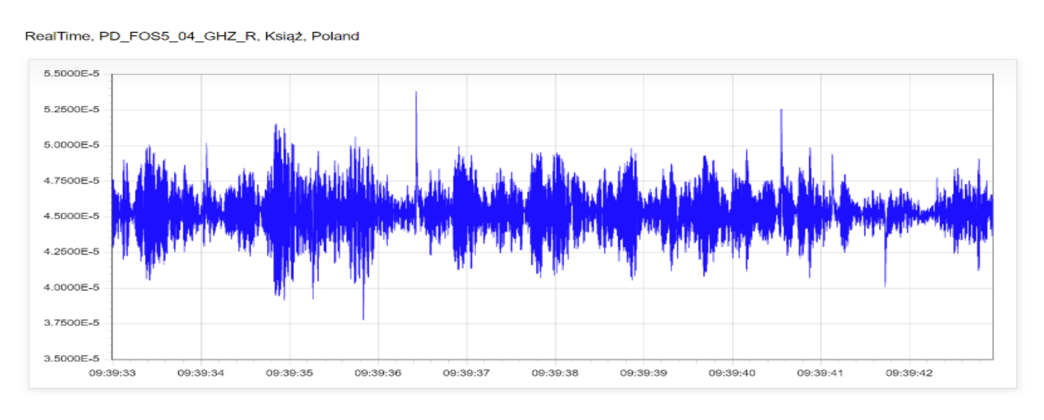





# FOS6 – field exploatation at Książ PAS laboratory



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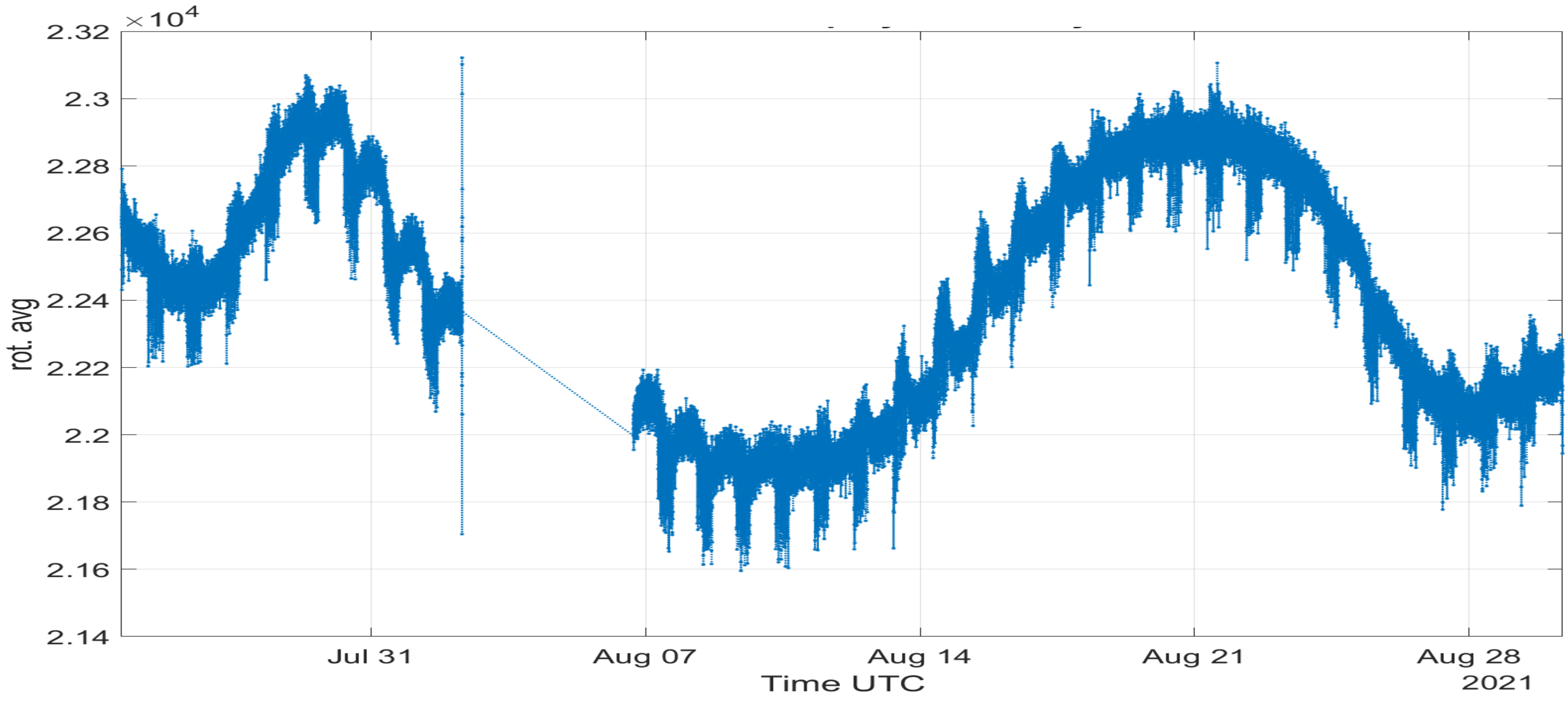

# ACKNOWLEGEMENTS

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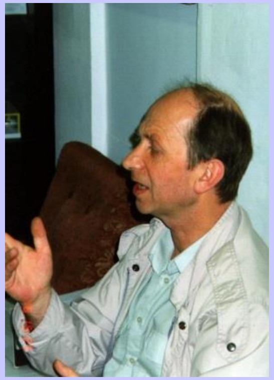

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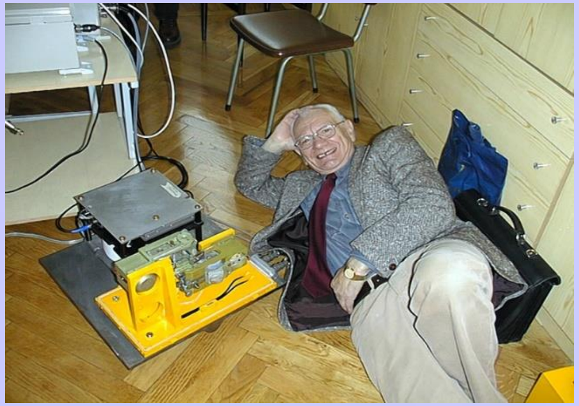

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# Thank you for your attention