Sejsmograf rotacyjny a adekwatność przenoszenia składowych rotacyjnych od sztucznych wymuszeń

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AGENDA

- Seismological investigation of rotational effects
- A short glossary for Rotational Seismology
- Rotational instrumentations
- Sagnac/(von Laue) effect – theoretical background
- Fiber-Optic Rotational Seismograph – innovative idea
- FORS types ofFOS3, FOS5 and FOS6
- FOS field test

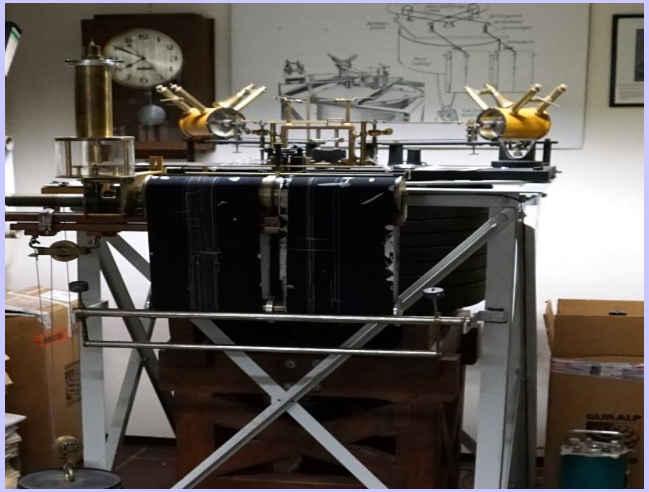
Rotational Seismology [Lee et al. *BSSA*, **2009**, *99*, 945-957] a new, emerging field for the study of all aspects of rotational ground motion induced by earthquakes, explosions, and ambient vibrations

Seismological application:

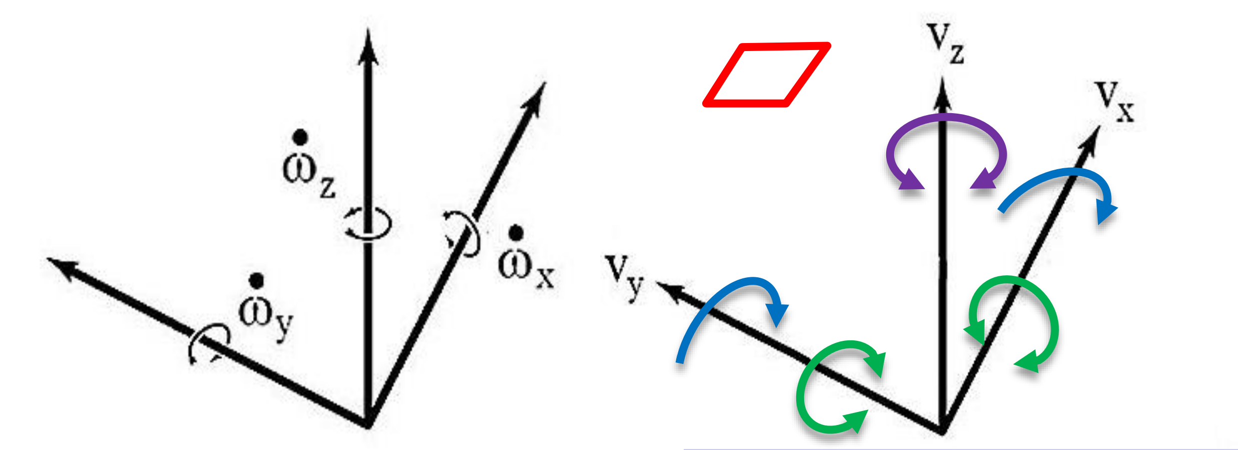
- broadband seismology [Igel et al., *Geophys. J. Int*., **168(1)**, (2006), 182–197],
- strong-motion seismology [Anderson, *The Intern. Handbook of Earthquake and Engineering Seismology*, 2003, Chap. 57, 937-965],
- earthquake physics [Teisseyre et al, Springer, 2006; Teisseyre et al., Springer, 2008],
- 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]

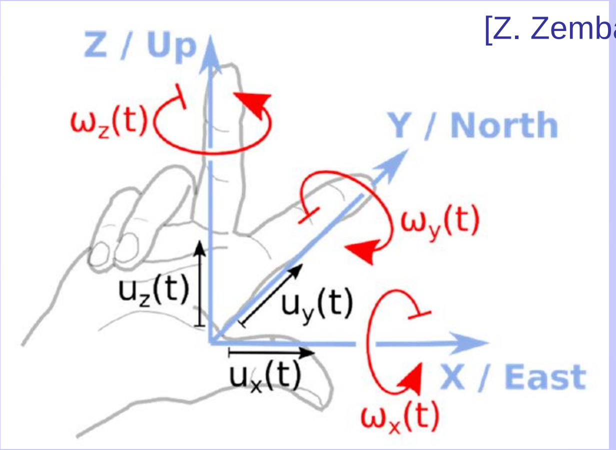
Engineering application:

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



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





[Z. Zembaty, et al., Editorial, *Sensors*, *21*, 5344, 2021]

6-component Seismic Ground Motion System:

- $\omega_z(t)$ – yaw, twist, torsion,
- $\omega_x(t)$ – rocking, roll,
- $\omega_y(t)$ – pitch

$$\begin{Bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{Bmatrix} = \frac{1}{2}\nabla \times \boldsymbol{u} = \frac{1}{2}\begin{pmatrix} \partial_y u_z - \partial_z u_y \\ \partial_z u_x - \partial_x u_z \\ \partial_x u_y - \partial_y u_x \end{pmatrix}$$

Tilt - means long-period rotations about a horizontal axis, to others **only static rotations** at any frequency.

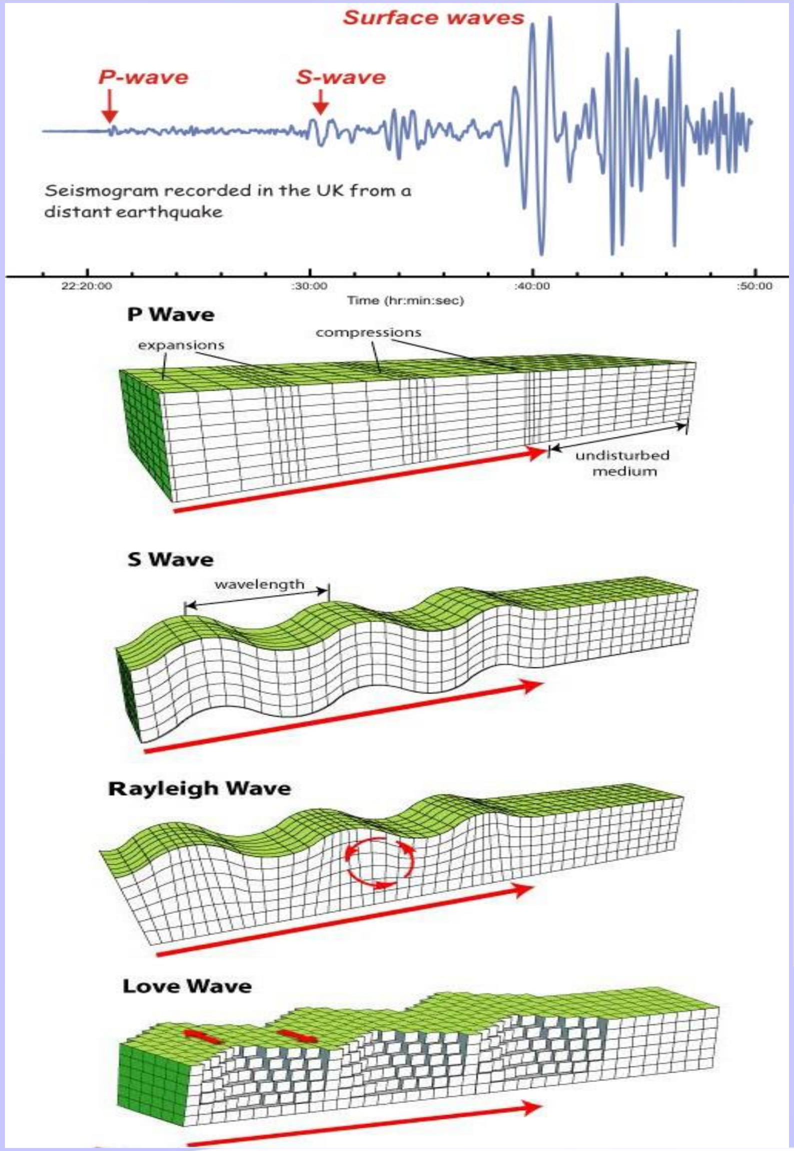
Rocking - rotation about horizontal axis or, as often used by engineers, of a whole structure about a given axis.

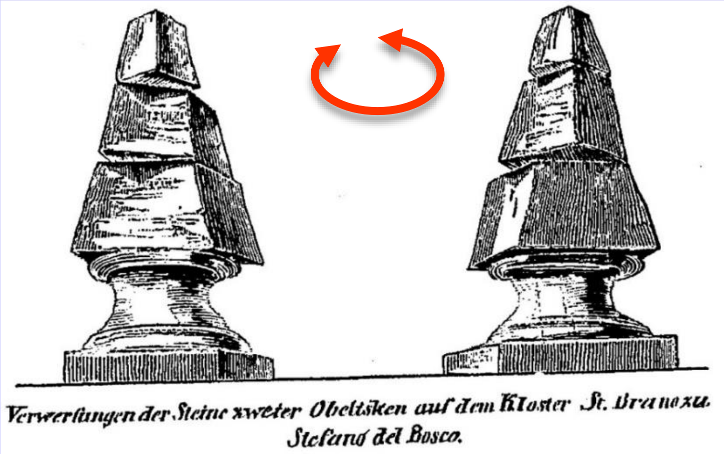
Torsion – rotations or strains about vertical axis of a structure.

Twist - a shear deformation caused by torsional moment.

Spin - a term that is unclear at present; in physics, it is used for rotational velocity; in continuum mechanics, it is the antisymmetric part of the velocity gradient tensor and may also be used for the proper kinetic moment of particles.

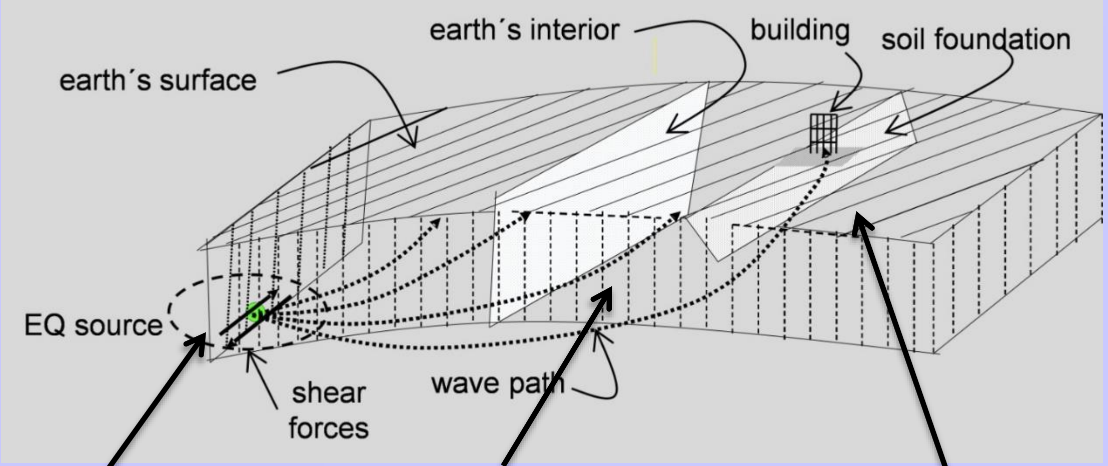
A SHORT GLOSSARY FOR ROTATIONAL SEISMOLOGY





CALABRIA, 05.02.1783

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



Finite size as near field effects

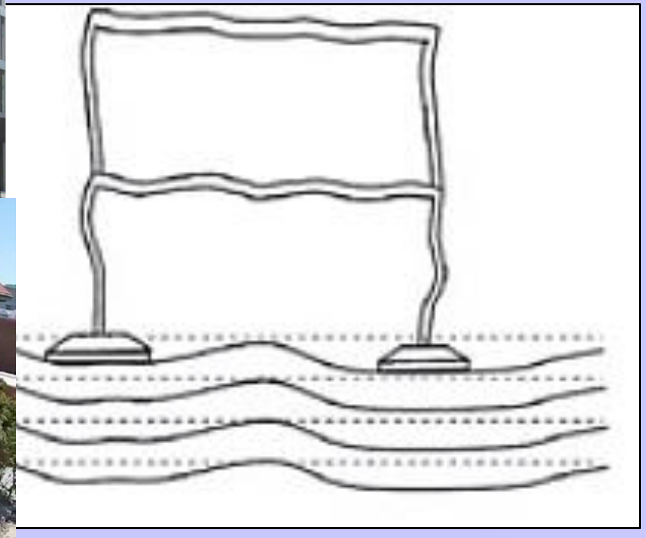
(hypothetic) rotational wave (Teisseyre Roman) "anti-Richter"

reflection &interference „rotation of geological blocks"

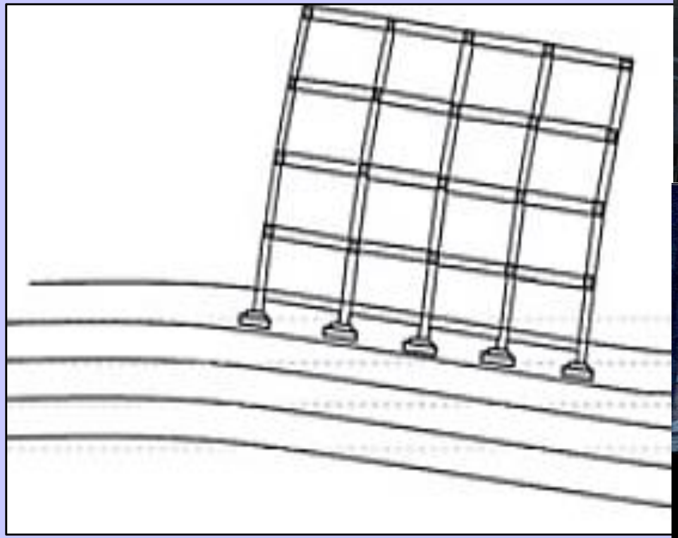
[prof. Z. Zembaty lecture, *SMOiO KM PAS* 14.10.2016]

Influence of geological blocks rotation


[Fujii, Chiba Int. of Techn., 2016/05/04]



High frequency content



Low frequency content


[Photo. Z. Zembaty]

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

- 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. Seisml.*, **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

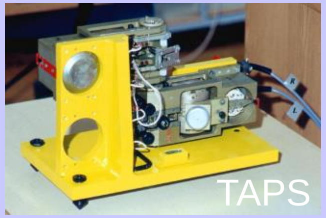
[Jaroszewicz et al., *Sensors*, **16**, (2016), 2161]

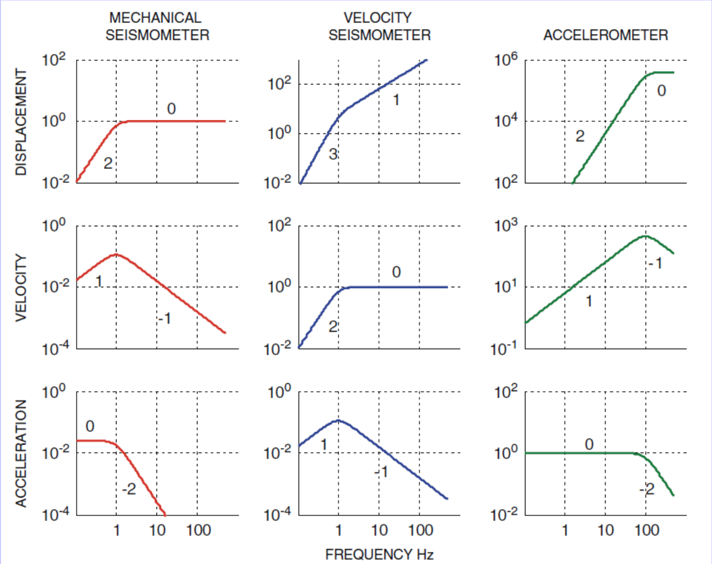
1. effectively insensitive to linear motion, or at any time, independent measurement of linear and rotational motions must be possible,
2. small (mobile) and stable with respect to ambient conditions, including changes of temperature,
3. the electrical power supply should be easily managed using batteries, 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

ROTATIONAL INSTRUMENTATIONS

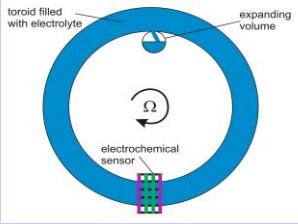
1. Mechanical type (nondirect based on velocity or accelerometer type seismometer)
Limited: frequency range, max. detectable rotation rate

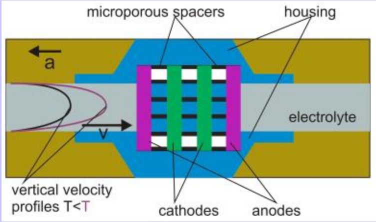




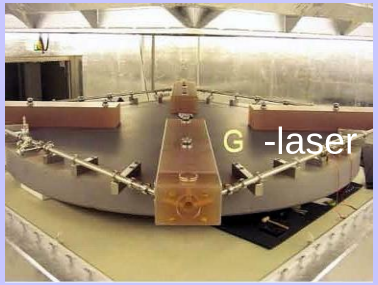
[Havskov, Alguacil, *Instrumentation in Earthquake Seismology.* Springer, 2016]

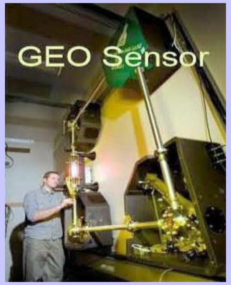
2. Electro-chemical type (direct based on liquid inertia)
high thermal instability, problem with electrolyte inertia





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



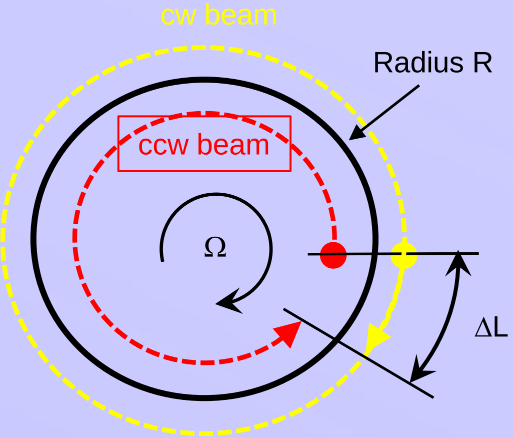


Specialized system based on FOG

THE SAGNAC – VON LAUE EFFECT

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

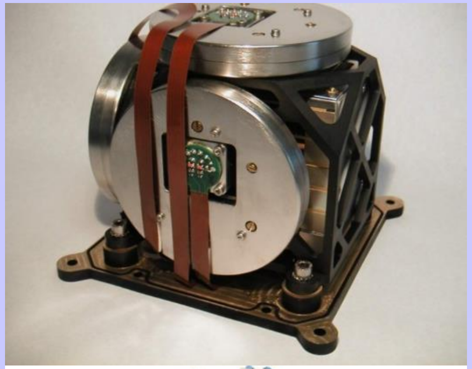
$$T_0 = \frac{Circum\,ference}{Speed\;of\;light} = \frac{2\,\pi\,R}{c}$$

When rotated at rate Ω

- cw beam travels father to catch up with the moving beam spliter, and its time of flight becomes:
- ccw beam travels a shorter distance:

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

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



- **Difference in times of flight:**

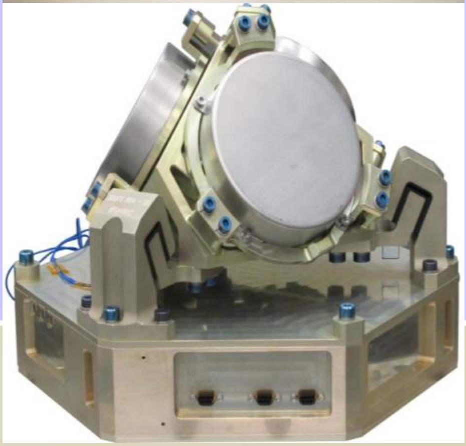
$$\delta T \;= |T_{cw} - T_{ccw}| = 2\frac{R\Omega T_0}{c}$$

- **Fringes shift (Sagnac-Von Laue effect):**

$$\Delta Z = 4\frac{\vec{\Omega}\cdot\vec{S}}{\lambda_0 c}$$

In optical fiber the two beams experience a Sagnac-Von Laue phase shift proportional to the rotation rate and the coil area

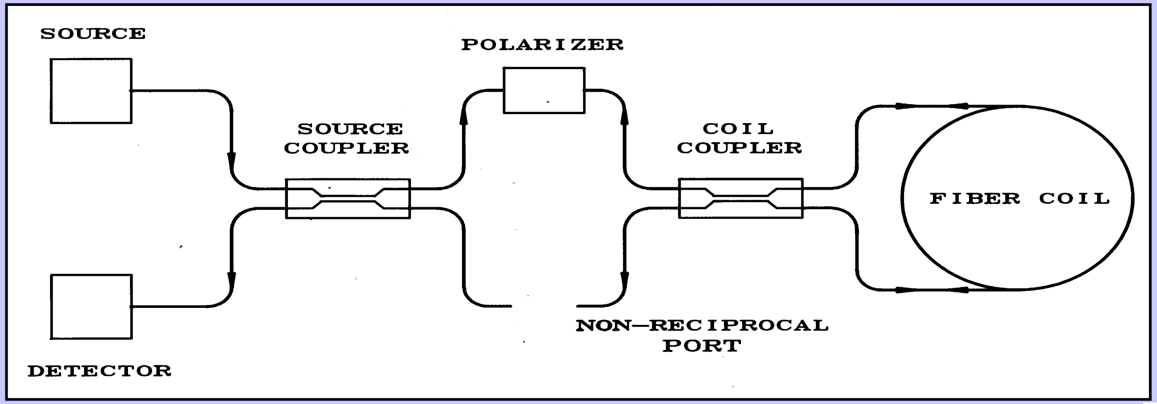
$$\varphi_s = \frac{4\pi RL}{c\lambda}\Omega = \frac{1}{S_o}\;x\;\Omega$$



$$\vartheta = \int \Omega dt$$

Ω – od **0,001 º/h** do **400 º /s**

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

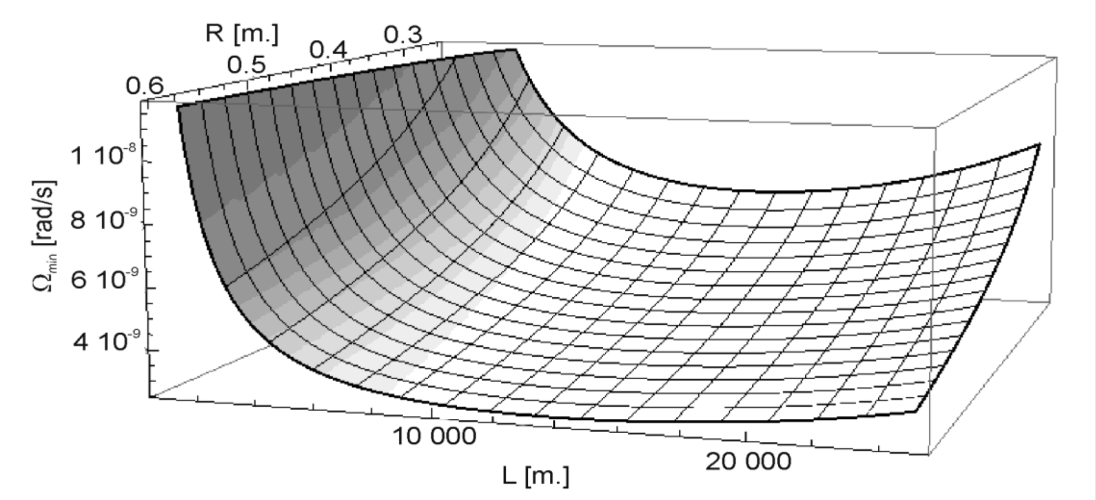



[private photo -*1999*]

[private photo -*1999*]

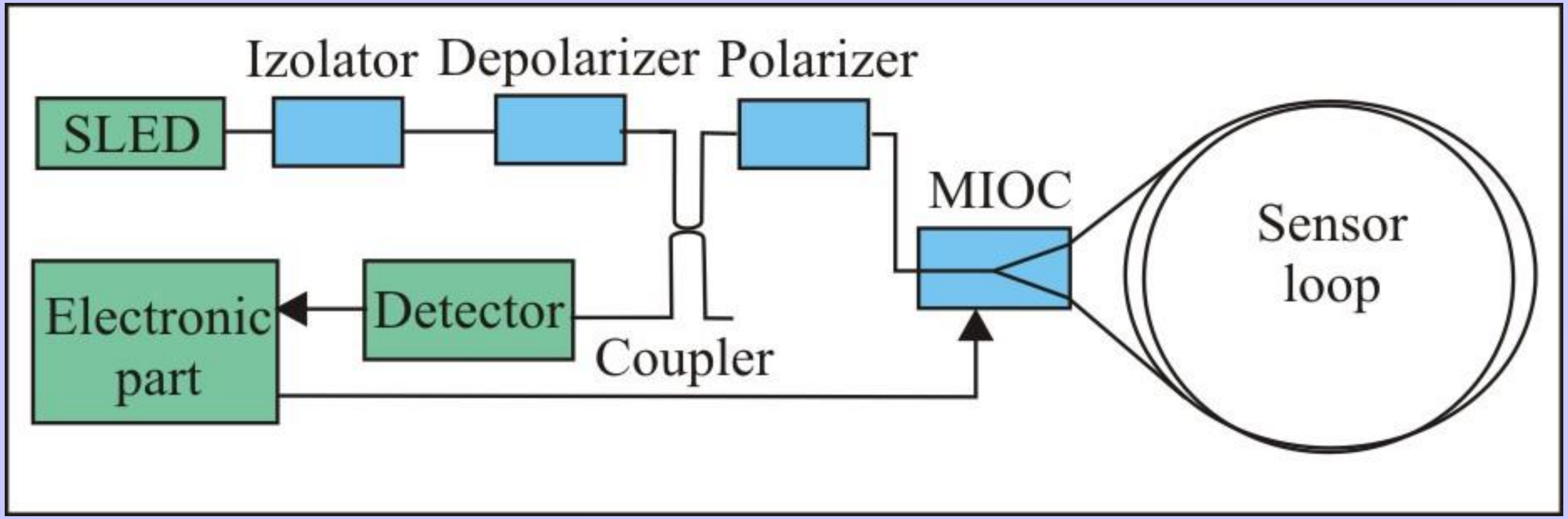
AFORS – gain FOG optimization of optical head:

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

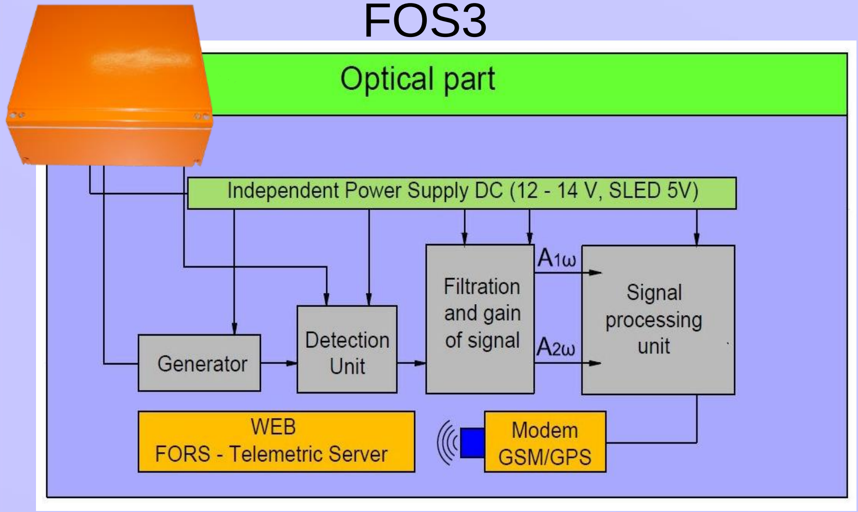


Ω_{min} **=1.93·10^{-9} [rad/sHz$^{1/2}$]**

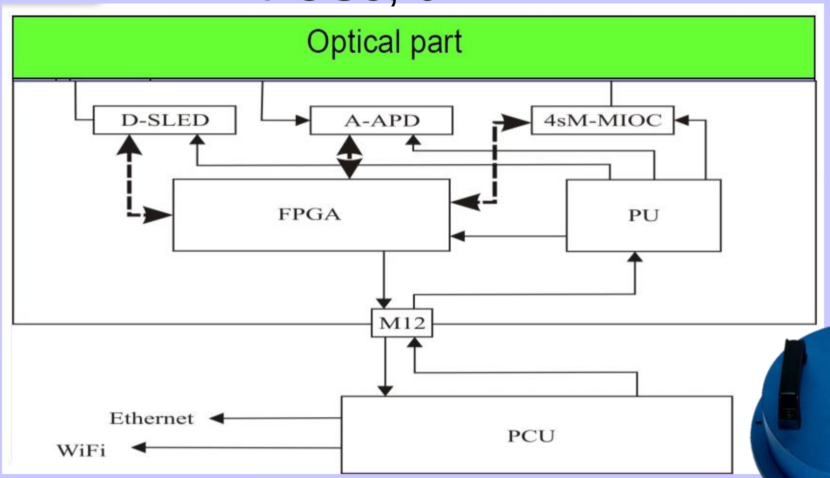
FORS TYPES OF FOS3, FOS5 and FOS6

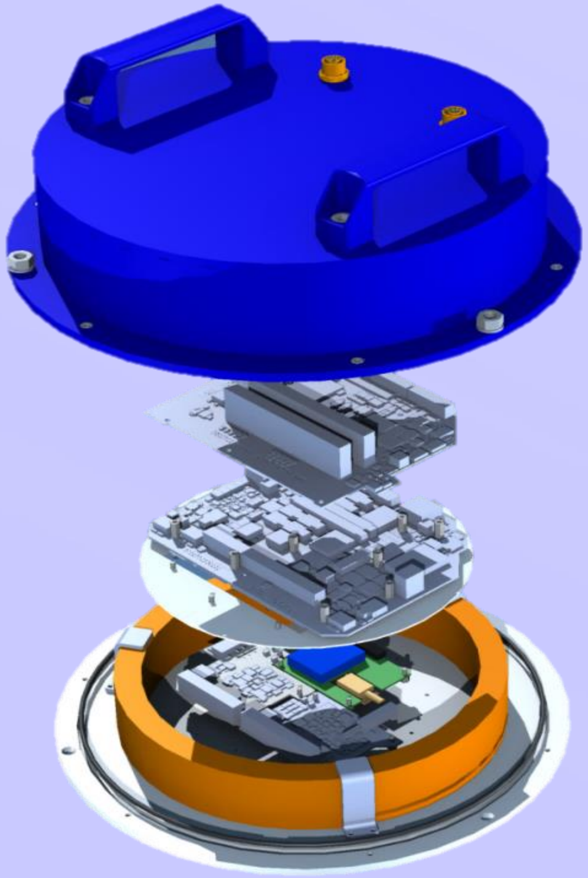


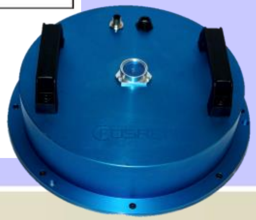
FOS3



FOS5, 6

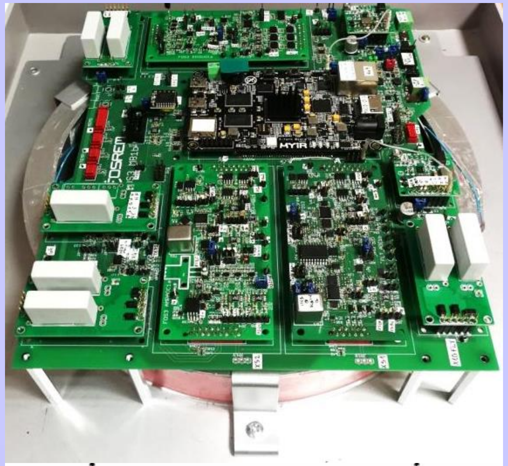


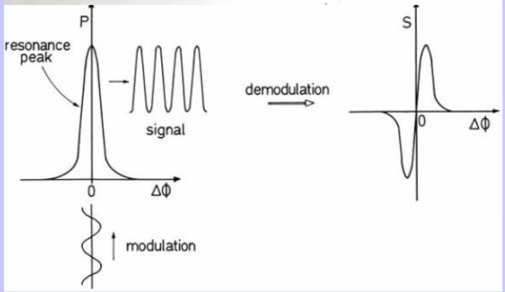




FORS TYPES OF FOS3, FOS5 and FOS6

Open-loop approach





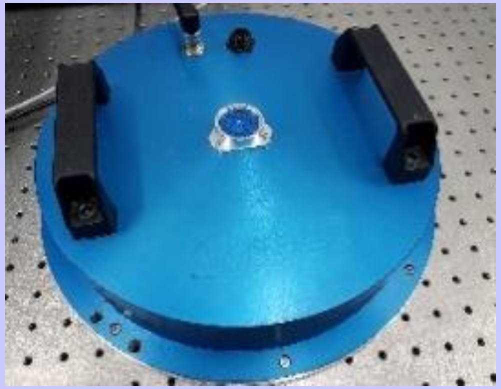
FOS3:
- 5 km long SL
- 0.25 m diameter

theoretical sensitivity:
$2 \cdot 10^{-8}$ rad/(s√Hz)

$$\Omega = S_o \tan^{-1}\left[\frac{u(t)}{S_e}\right], \qquad u(t) = \frac{A_{1\omega}}{A_{2\omega}}$$

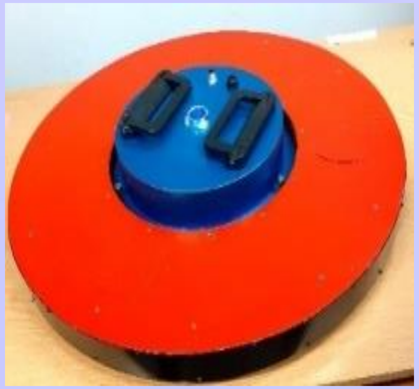
S_o, S_e – optical and electronic constant determines during scalling on Earth rotation

Closed-loop method



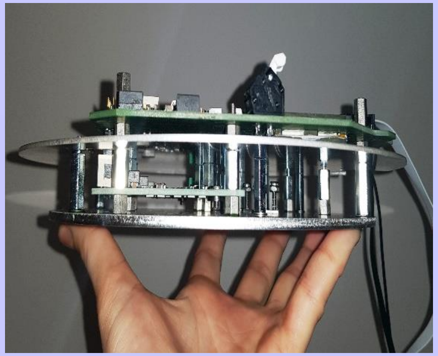
FOS5:
- 5 km long SL
- 0.25 m diameter

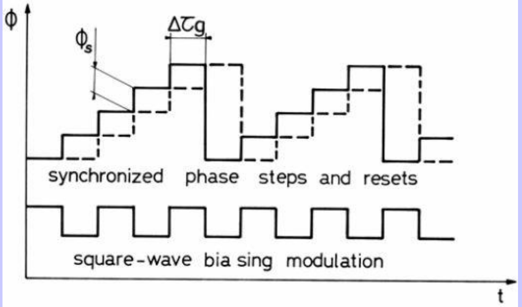
theoretical sensitivity:
$3.41 \cdot 10^{-8}$ rad/(s√Hz)



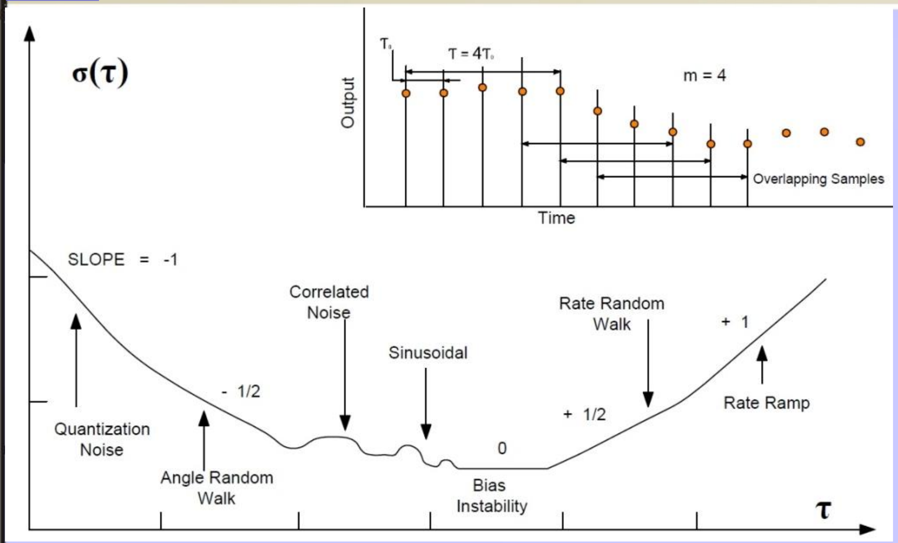
FOS6:
- 15 km long SL
- 0.60 m diameter

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



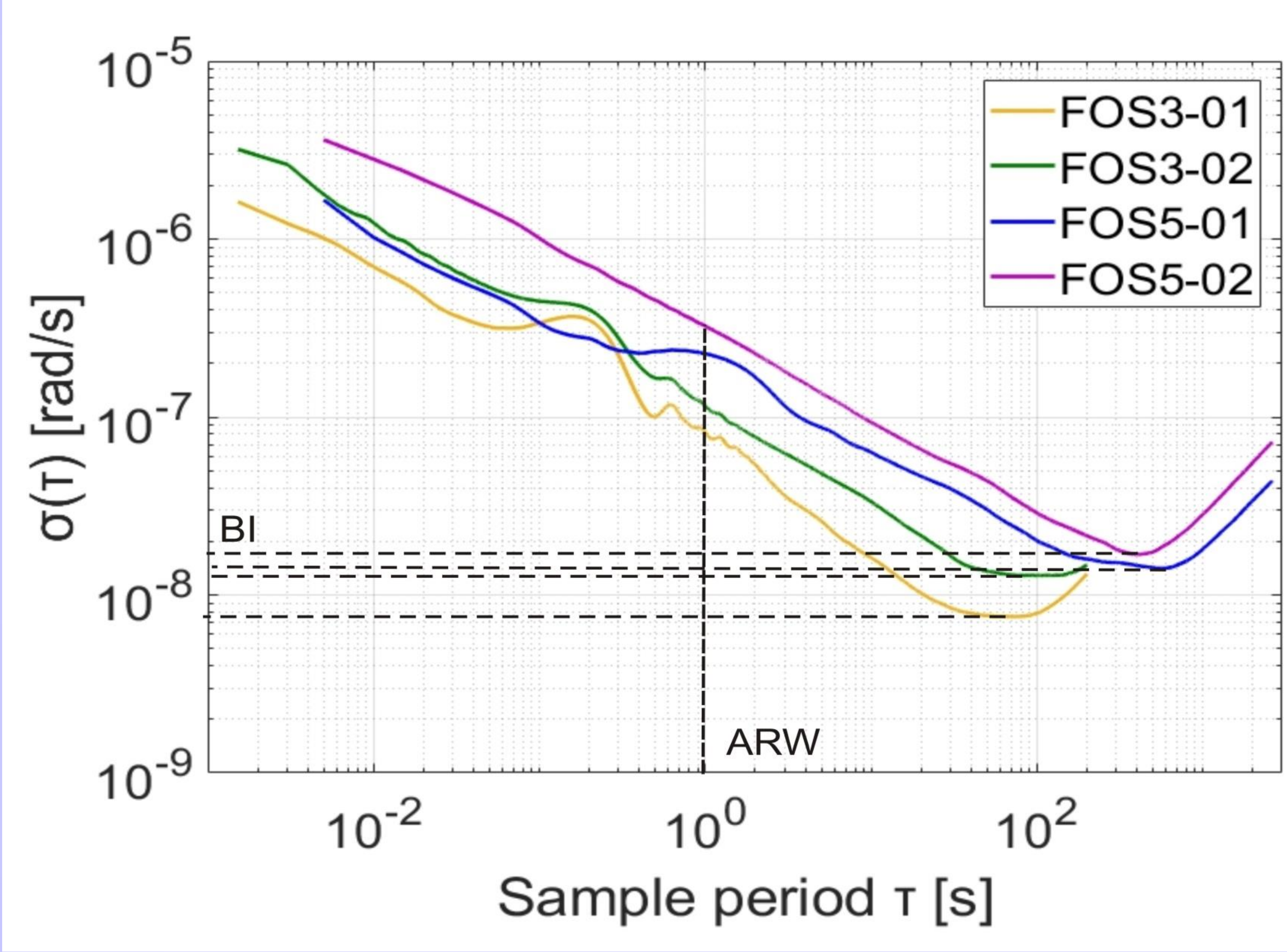


Digital Phase Ramp



AV is a method of analysing a sequence of data in the time domain, to measure the frequency stability of oscillators.

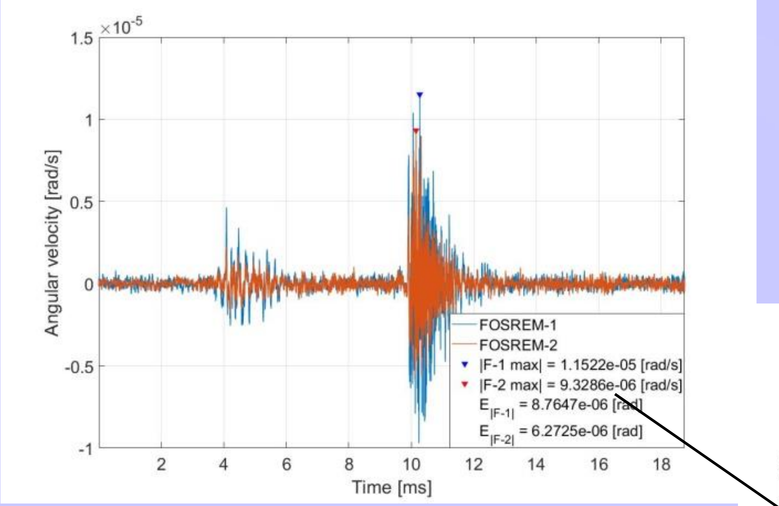
	ARW [rad/√s]	BI [rad/s]
FOS3-01	$8.70 \cdot 10^{-8}$	$1.13 \cdot 10^{-8}$
FOS3-02	$1.30 \cdot 10^{-7}$	$1.96 \cdot 10^{-8}$
FOS5-01	$2.16 \cdot 10^{-7}$	$2.28 \cdot 10^{-8}$
FOS5-02	$3.24 \cdot 10^{-7}$	$2.55 \cdot 10^{-8}$



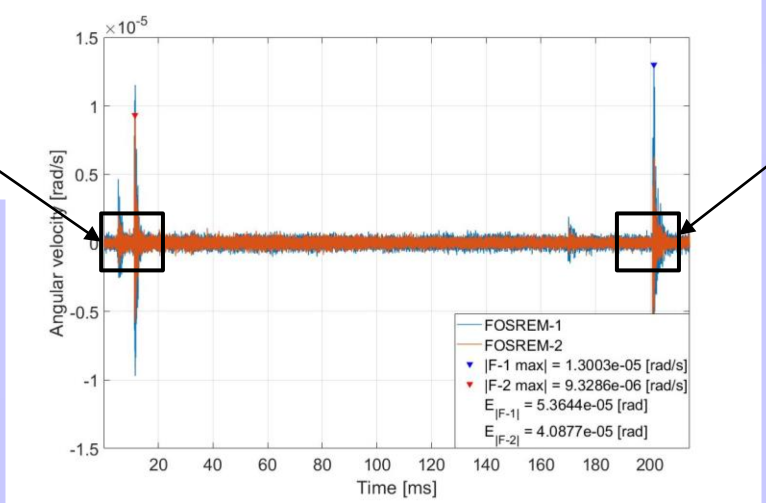

INSTYTUT GEOFIZYKI PAN


Gdynia
Słupsk
Gdańsk
Elbląg
Malbork
Kołobrzeg
Koszalin
Olsztyn
Ostróda
Giżycko
Suwałki
Ełk
Augustów
Grodno
Szczecin
Stargard
Chojnice
Bydgoszcz
Piła
Łomża
Białystok
Polska
Włocławek
Płock
Gorzów Wielkopolski
Gniezno
Poznań
Konin
Nowy Dwór Mazowiecki
Warszawa
Siedlce
Kutno
Biała Podlaska
Zielona Góra
Leszno
Kalisz
Łódź
Piotrków Trybunalski
Radom
Puławy
Lublin
Chełm
Legnica
Wrocław
Jelenia Góra
Zamek Książ
Częstochowa
Kielce
Opole
Sandomierz
Zamość
Stalowa Wola
Liberec
Hradec Kralove
Katowice
Praga
Pardubice
Kraków
Tarnów
Rzeszów
Lwów
Ostrawa
Bielsko-Biała
Wieliczka
Czechy
Nowy Sącz
Krosno
Przemyśl
Ołomuniec
Zakopane
Google
Dane mapy ©2017 GeoBasis-DE/BKG

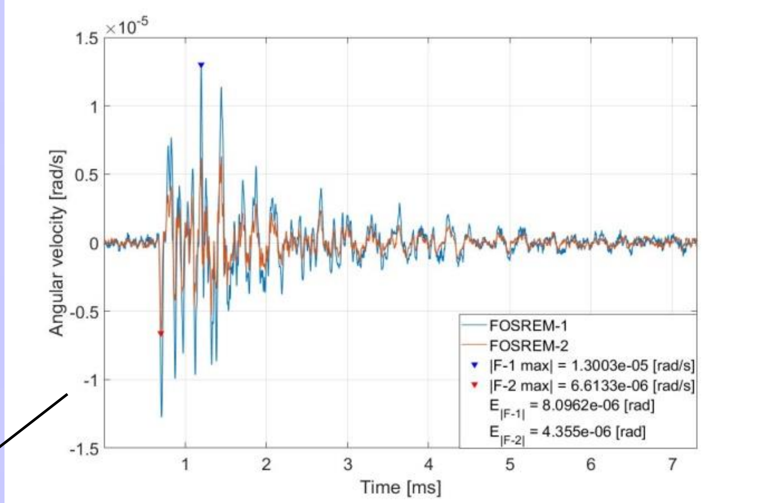

FOSREM
Fiber Optic Rotational Seismograph



Correlation coefficient: 0.74



Correlation coefficient: 0.64



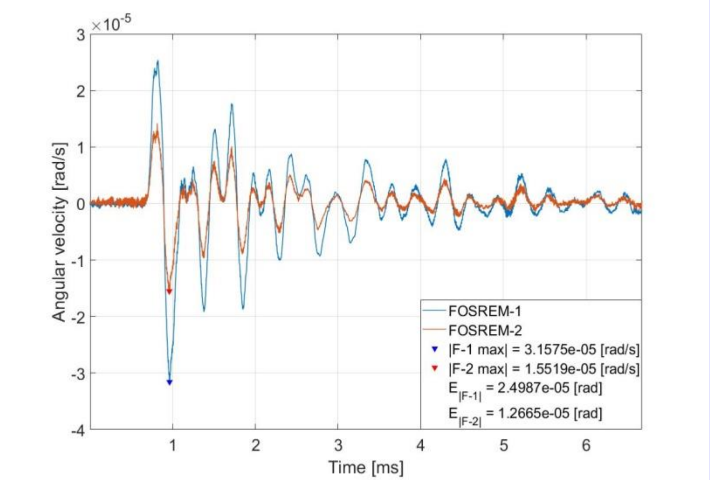
Correlation coefficient: 0.98

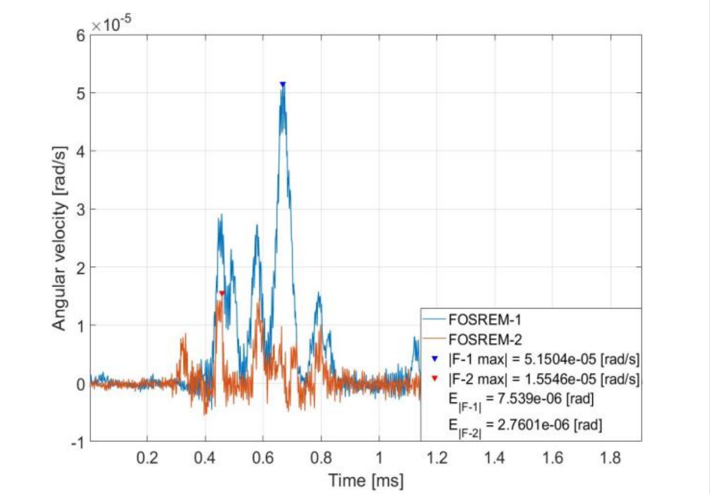
Min amplitude: **53.1431** [μrad/s]	Avg amplitude: **62.48864** [μrad/s]	Max amplitude: **69.1125** [μrad/s]
Start: **2017-12-01 12:19:51.674**	End: **2017-12-01 12:24:51.716**	Samples: **197 000**

FOS – KSIĄŻ OBSERVATORY (MINING ACTIVITY)

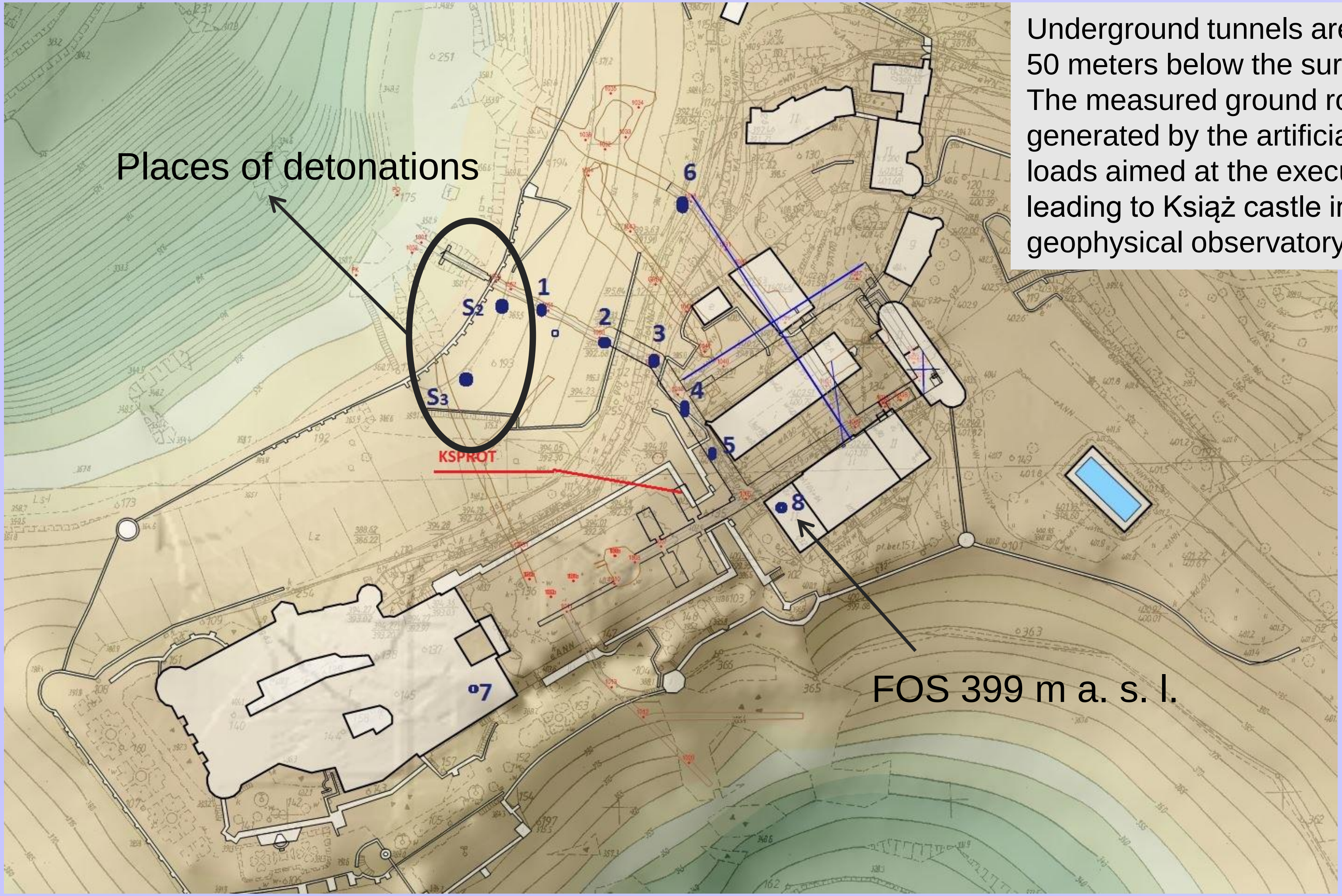
Data recorded by the FOSREMs in the geophysical observatory in Książ, Poland in period 8/01/2017 – 1/25/2018.

	Recordings of tilt			Recordings of torsion		
	Max. amplitude [rad/s]	Energy [rad]	Correlation coefficient	Max. amplitude [rad/s]	Energy [rad]	Correlation coefficient
FOS 1 FOS 2	$1.02 \cdot 10^{-4}$ $1.01 \cdot 10^{-4}$	$3.72 \cdot 10^{-5}$ $3.22 \cdot 10^{-5}$	0.59	$3.89 \cdot 10^{-6}$ $1.81 \cdot 10^{-6}$	$3.94 \cdot 10^{-6}$ $2.13 \cdot 10^{-6}$	0.82
FOS 1 FOS 2	$1.01 \cdot 10^{-4}$ $1.17 \cdot 10^{-4}$	$1.57 \cdot 10^{-5}$ $2.45 \cdot 10^{-5}$	0.53	$8.25 \cdot 10^{-6}$ $4.17 \cdot 10^{-6}$	$4.56 \cdot 10^{-6}$ $2.48 \cdot 10^{-6}$	0.95
FOS 1 FOS 2	$2.74 \cdot 10^{-5}$ $4.65 \cdot 10^{-5}$	$3.55 \cdot 10^{-6}$ $7.19 \cdot 10^{-6}$	0.51	$1.67 \cdot 10^{-5}$ $1.03 \cdot 10^{-5}$	$5.78 \cdot 10^{-5}$ $2.97 \cdot 10^{-5}$	0.94
FOS 1 FOS 2	$3.66 \cdot 10^{-5}$ $2.20 \cdot 10^{-5}$	$5.64 \cdot 10^{-6}$ $3.15 \cdot 10^{-6}$	0.56	$1.86 \cdot 10^{-6}$ $1.61 \cdot 10^{-6}$	$6.17 \cdot 10^{-7}$ $5.31 \cdot 10^{-7}$	0.84
FOS 1 FOS 2	$1.73 \cdot 10^{-5}$ $1.20 \cdot 10^{-5}$	$1.26 \cdot 10^{-5}$ $1.11 \cdot 10^{-5}$	0.78	$1.58 \cdot 10^{-6}$ $1.01 \cdot 10^{-6}$	$1.93 \cdot 10^{-6}$ $1.11 \cdot 10^{-6}$	0.79
FOS 1 FOS 2	$3.55 \cdot 10^{-5}$ $2.90 \cdot 10^{-5}$	$5.55 \cdot 10^{-6}$ $9.57 \cdot 10^{-6}$	0.72	$2.00 \cdot 10^{-5}$ $1.00 \cdot 10^{-5}$	$1.31 \cdot 10^{-5}$ $6.66 \cdot 10^{-6}$	0.98
FOS 1 FOS 2	$3.47 \cdot 10^{-5}$ $6.20 \cdot 10^{-5}$	$3.25 \cdot 10^{-5}$ $5.32 \cdot 10^{-5}$	0.73	$1.65 \cdot 10^{-6}$ $1.32 \cdot 10^{-6}$	$6.86 \cdot 10^{-7}$ $5.95 \cdot 10^{-7}$	0.86
FOS 1 FOS 2	$1.67 \cdot 10^{-6}$ $1.99 \cdot 10^{-6}$	$1.08 \cdot 10^{-6}$ $9.18 \cdot 10^{-7}$	0.67	$1.77 \cdot 10^{-6}$ $1.09 \cdot 10^{-6}$	$1.04 \cdot 10^{-6}$ $6.73 \cdot 10^{-7}$	0.88
Mean value	$4.6728 \cdot 10^{-5}$ $\pm 0.0002 \cdot 10^{-5}$	$1.4896 \cdot 10^{-5}$ $\pm 0.0003 \cdot 10^{-5}$	**0.63 ± 0.07**	$5.5226 \cdot 10^{-6}$ $\pm 0.0005 \cdot 10^{-6}$	$8.6772 \cdot 10^{-6}$ $\pm 0.0003 \cdot 10^{-6}$	**0.88 ± 0.03**



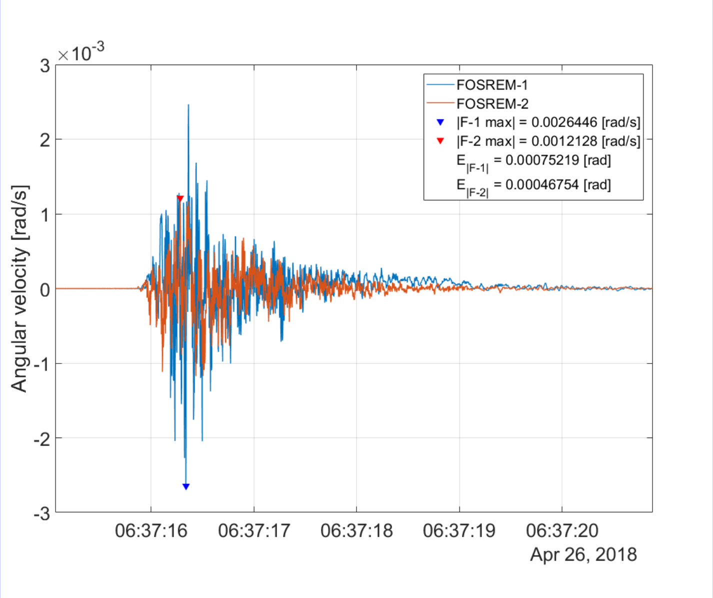


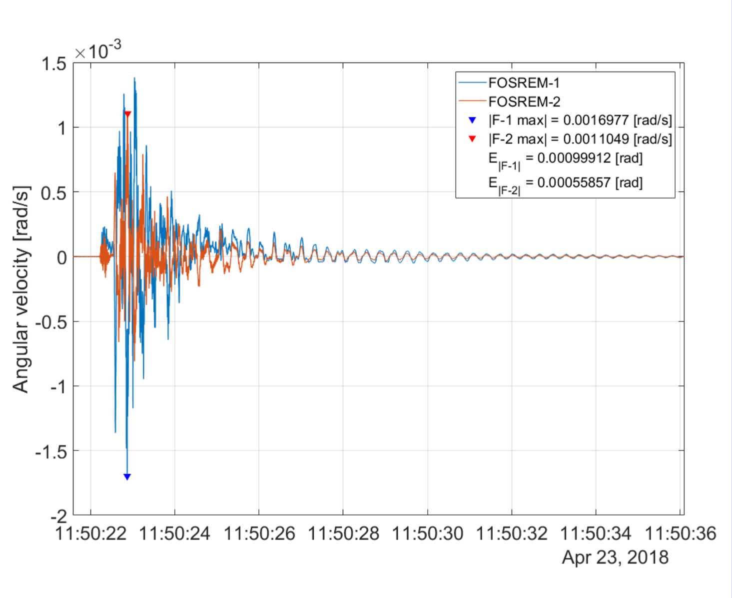
FOS – KSIĄŻ OBSERVATORY (MICROSHOCKS)

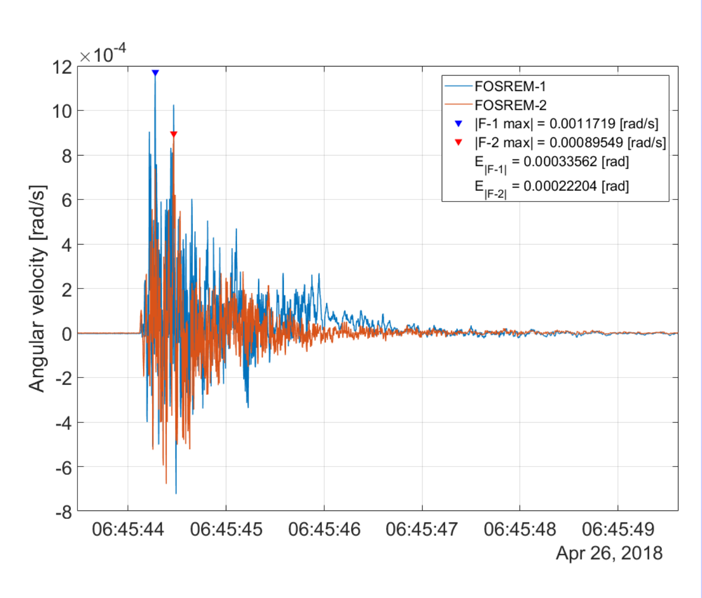


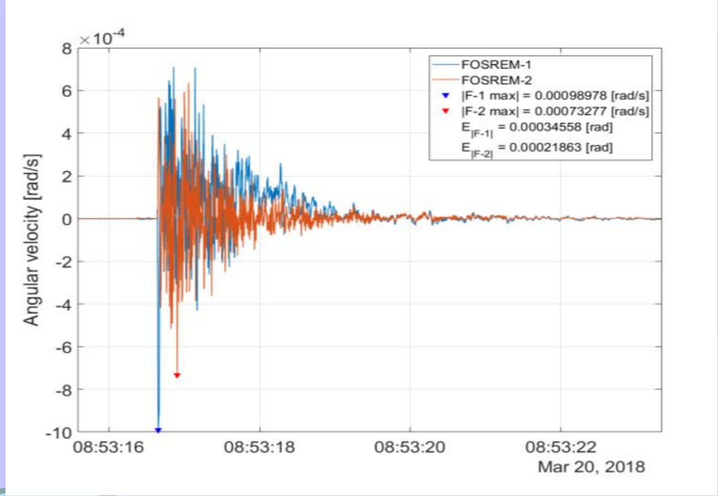
Underground tunnels are located at the level of -50 meters below the surface of the castle.
The measured ground rotational movements were generated by the artificial explosions by dynamite loads aimed at the execution of tourist tunnels leading to Książ castle in near field of the geophysical observatory.

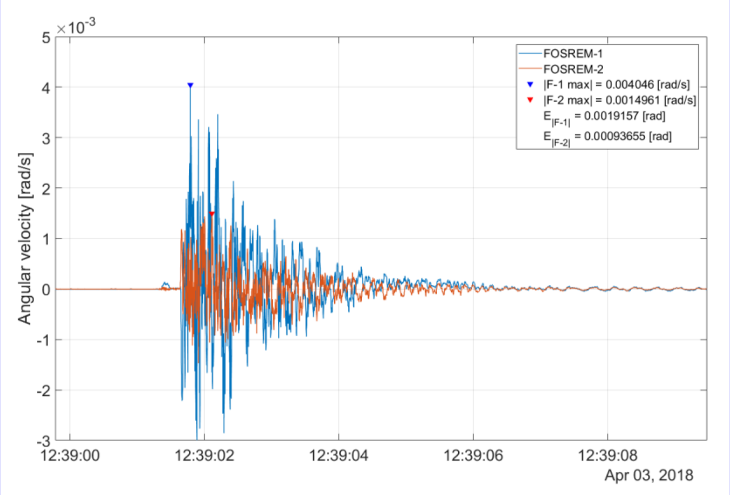
FOS – KSIĄŻ OBSERVATORY (MICROSHOCKS)

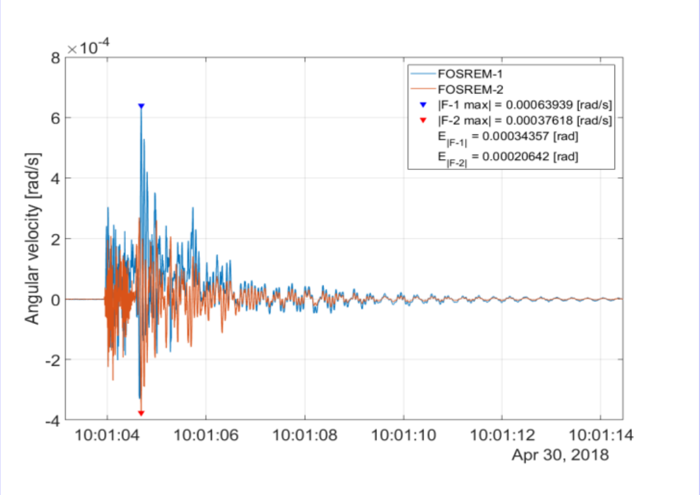




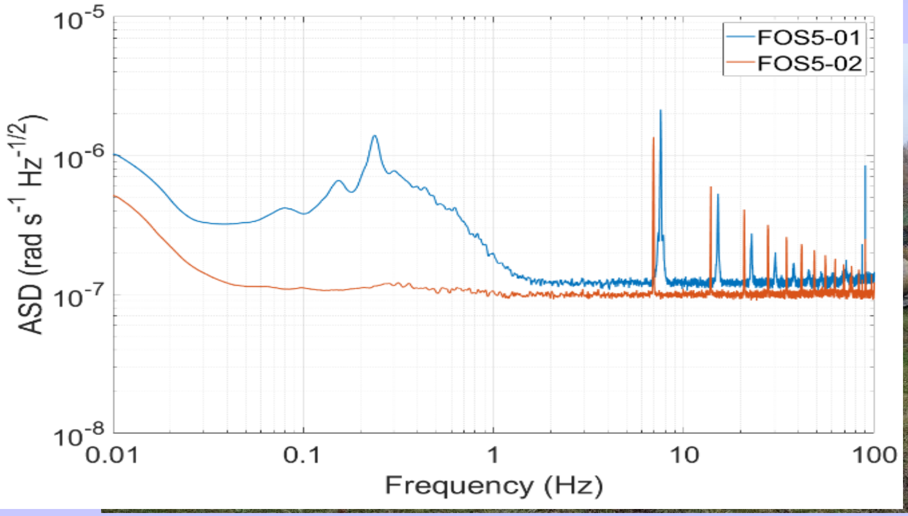


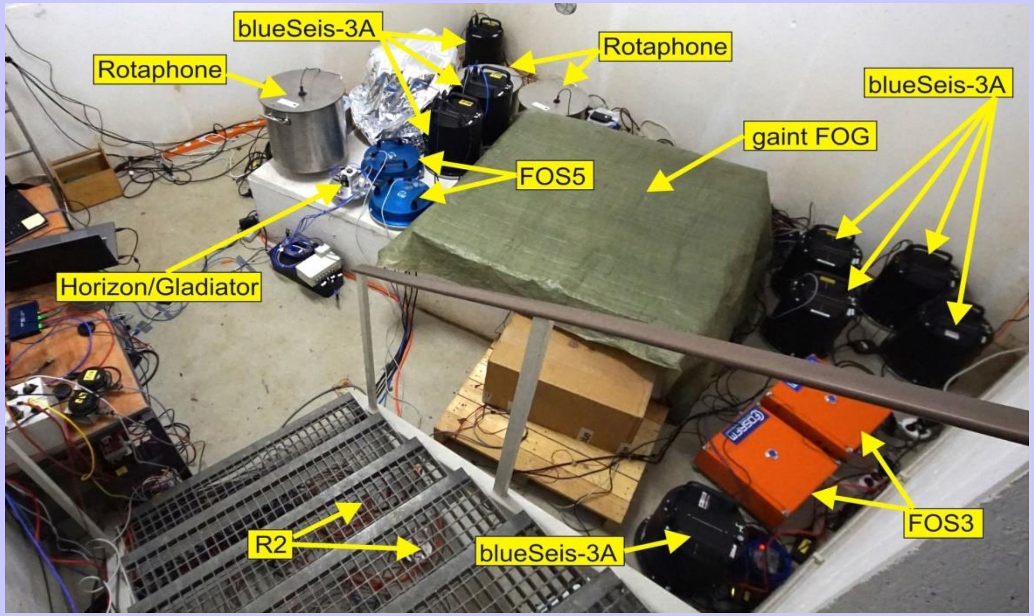


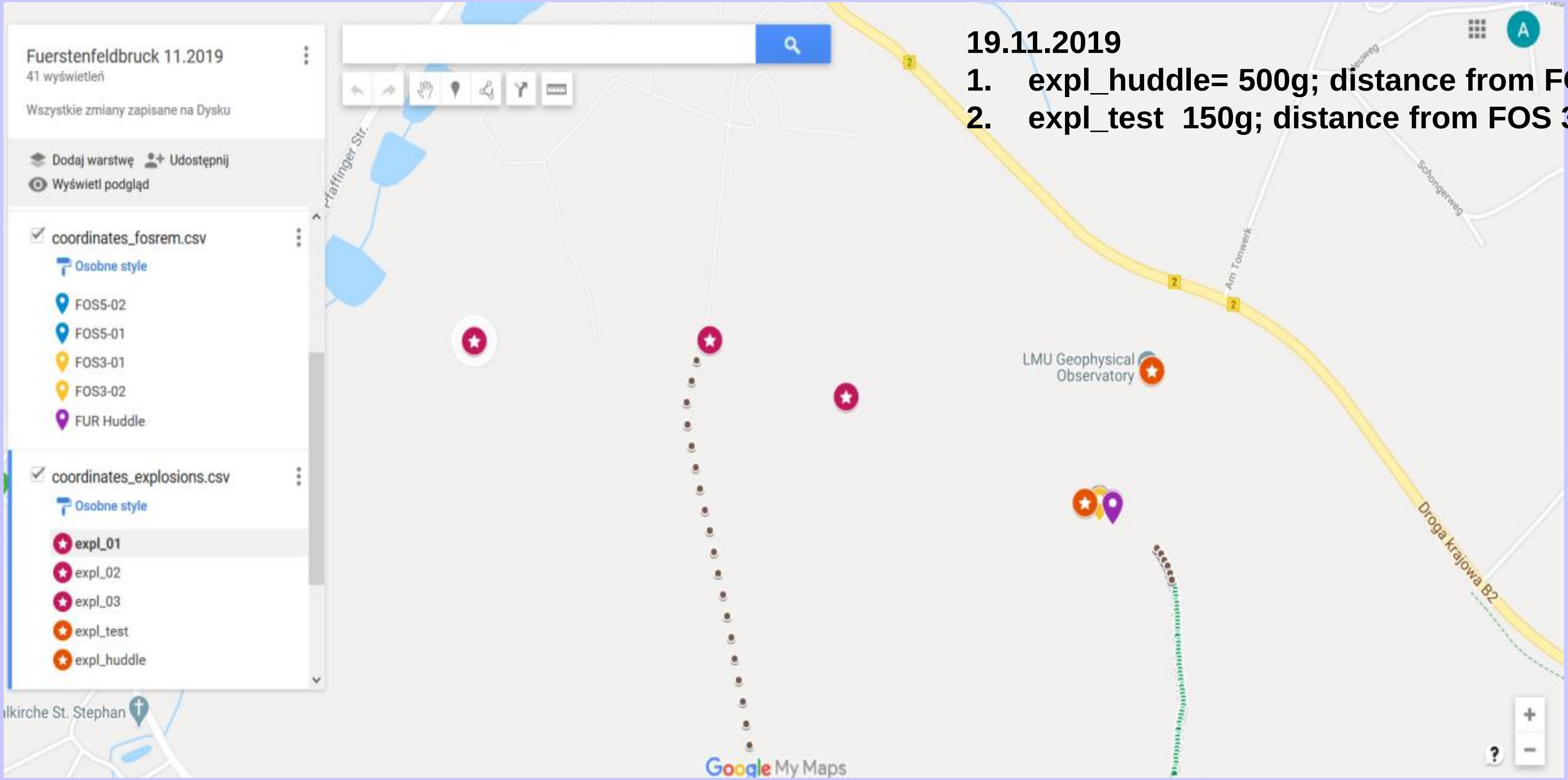




"ROTATION AND STRAIN IN SEISMOLOGY: A COMPARATIVE SENSOR TEST", FÜRSTENFELDBRUCK 19-22.11.2019



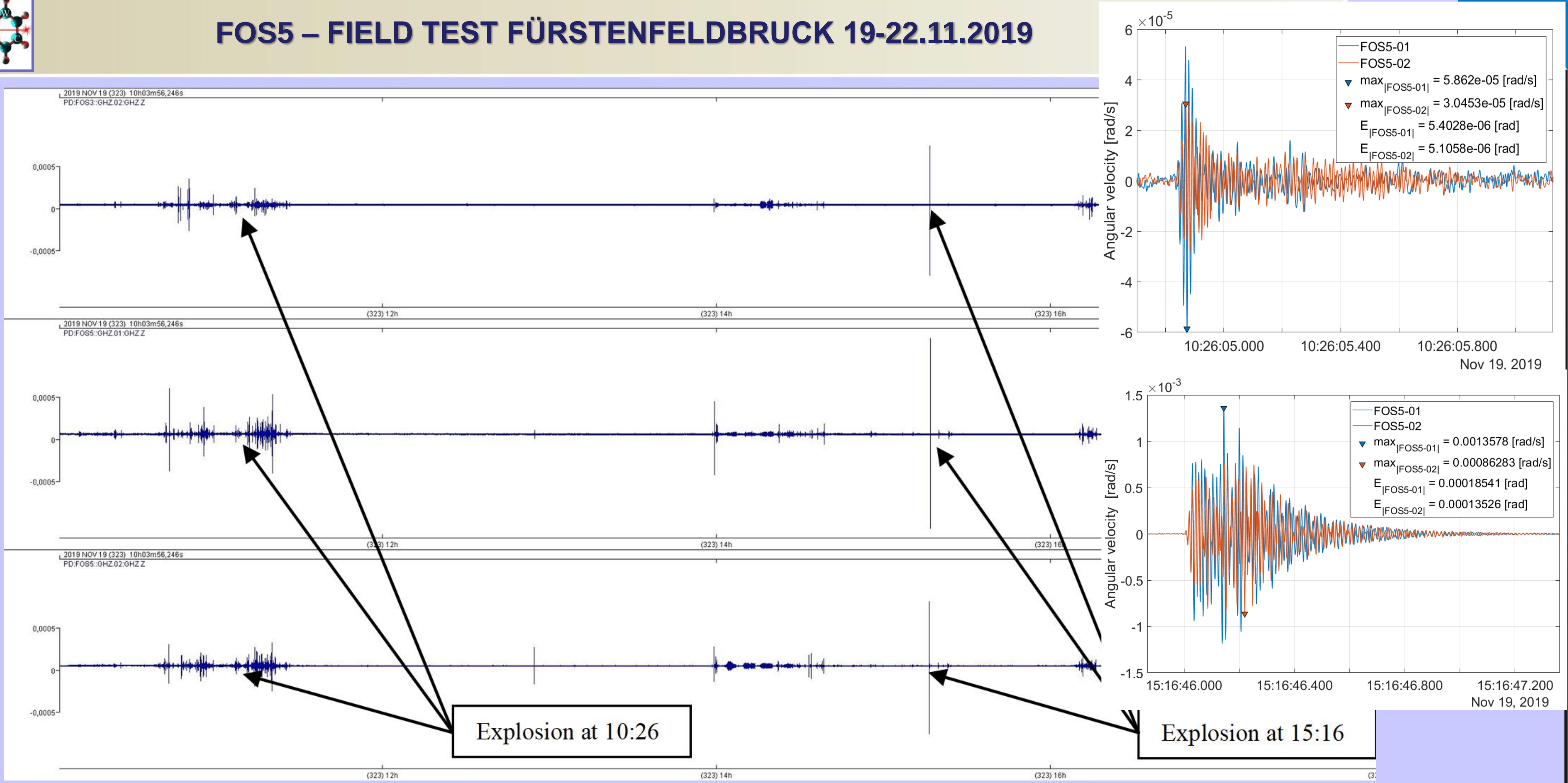




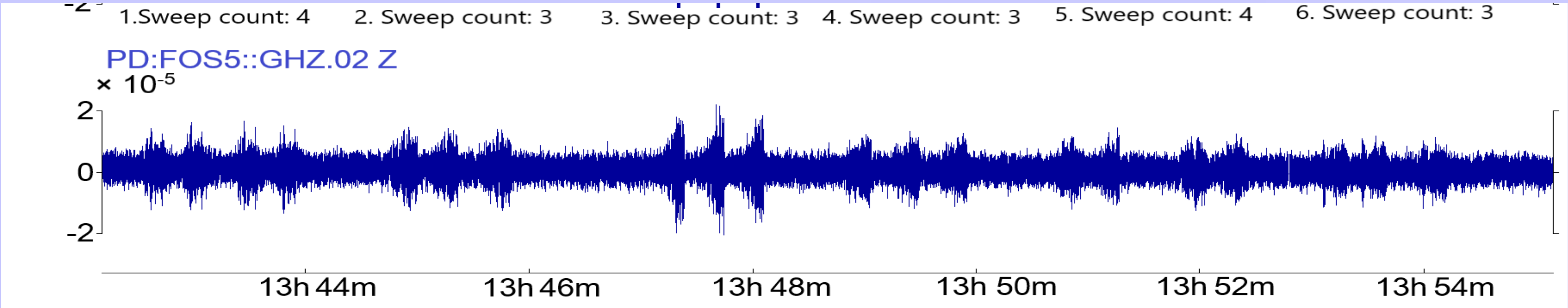
19.11.2019

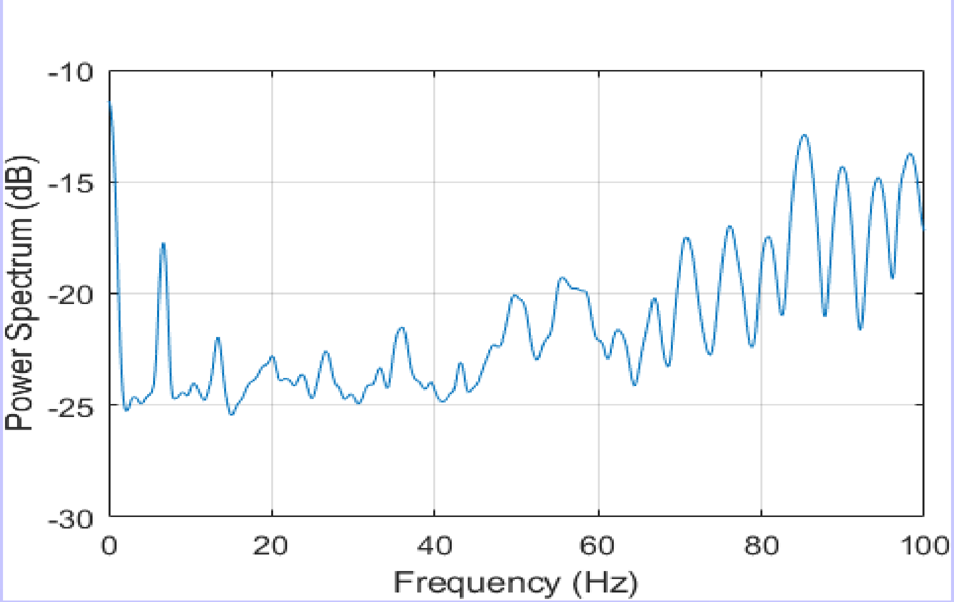
1. expl_huddle= 500g; distance from FOS 200m; 15:16
2. expl_test 150g; distance from FOS 33 m; 10:26

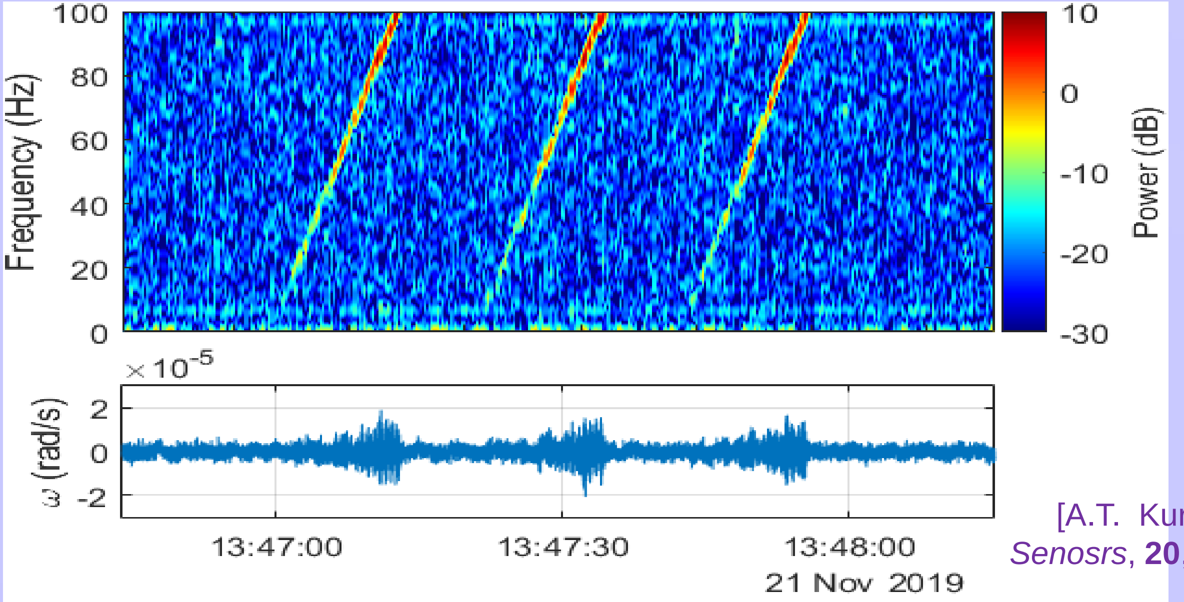
FOS5 – FIELD TEST FÜRSTENFELDBRUCK 19-22.11.2019



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

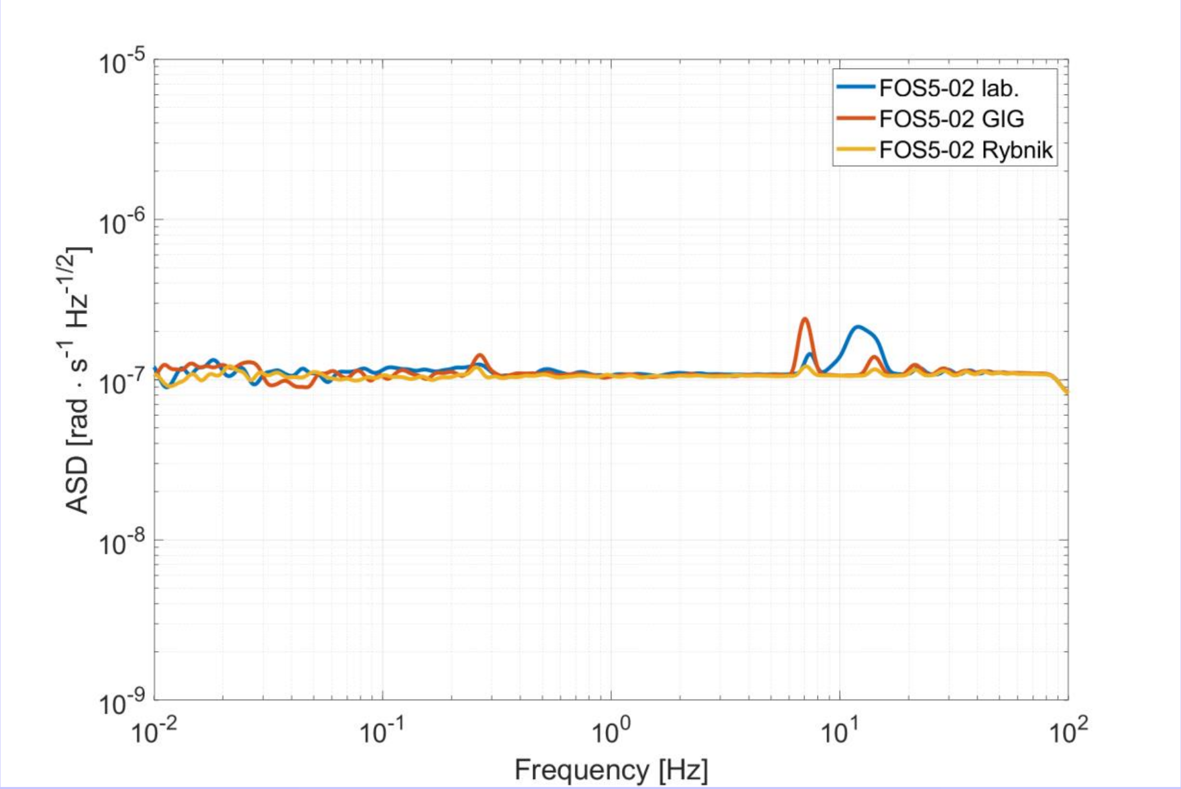


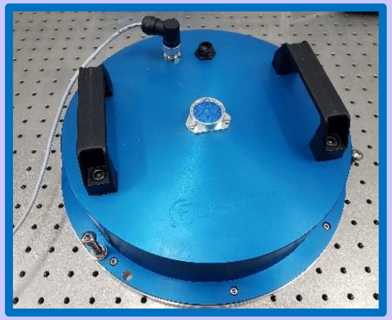




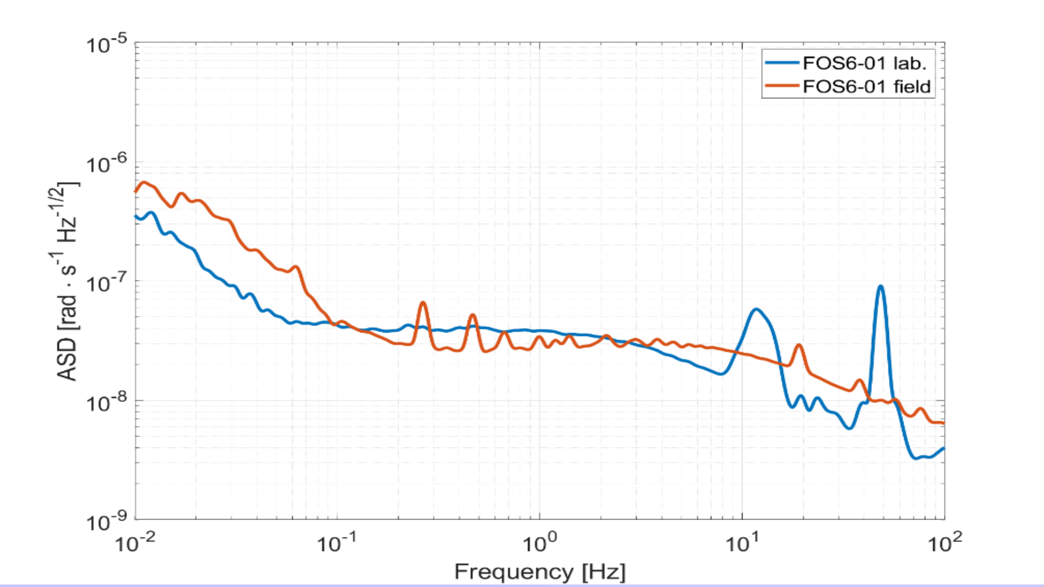
[A.T. Kurzych, et al, *Senosrs*, **20**, (2020), 6107]

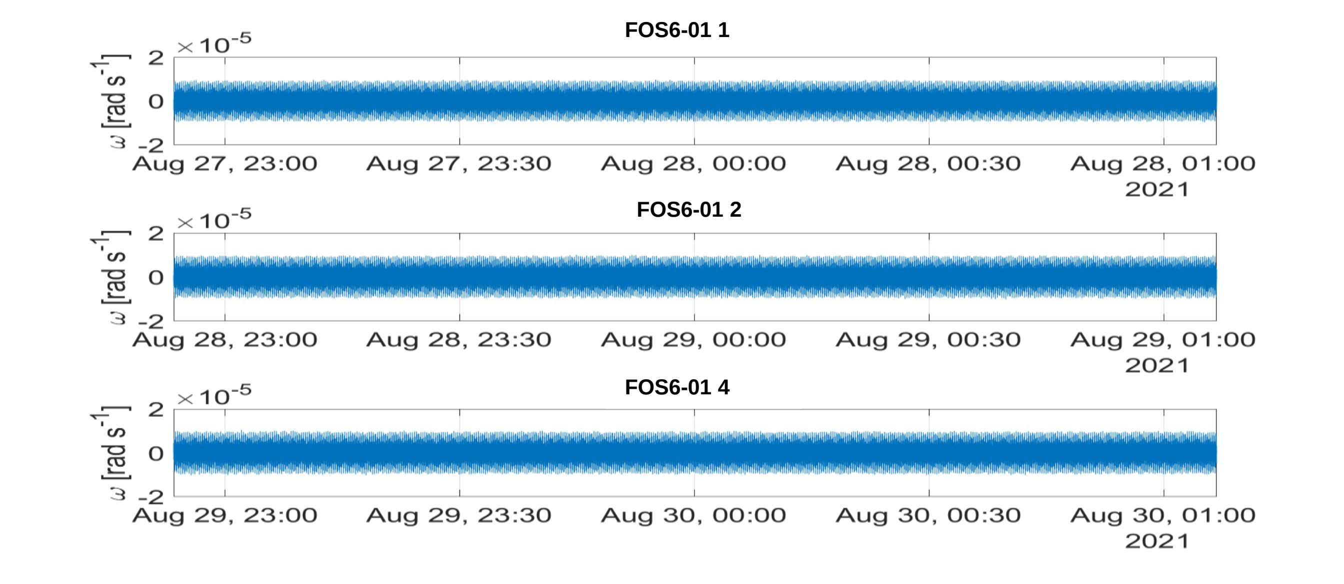
FOS5 – IMPROVEMENT OF NOISE CHARACTERISTIC

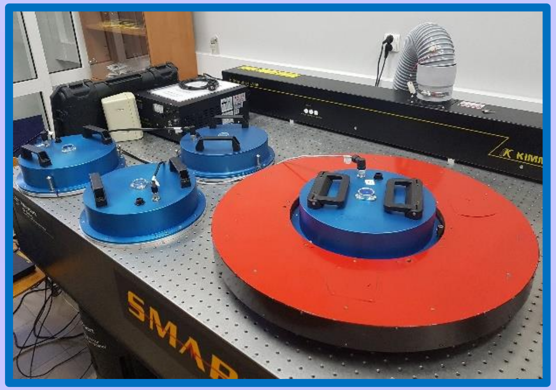


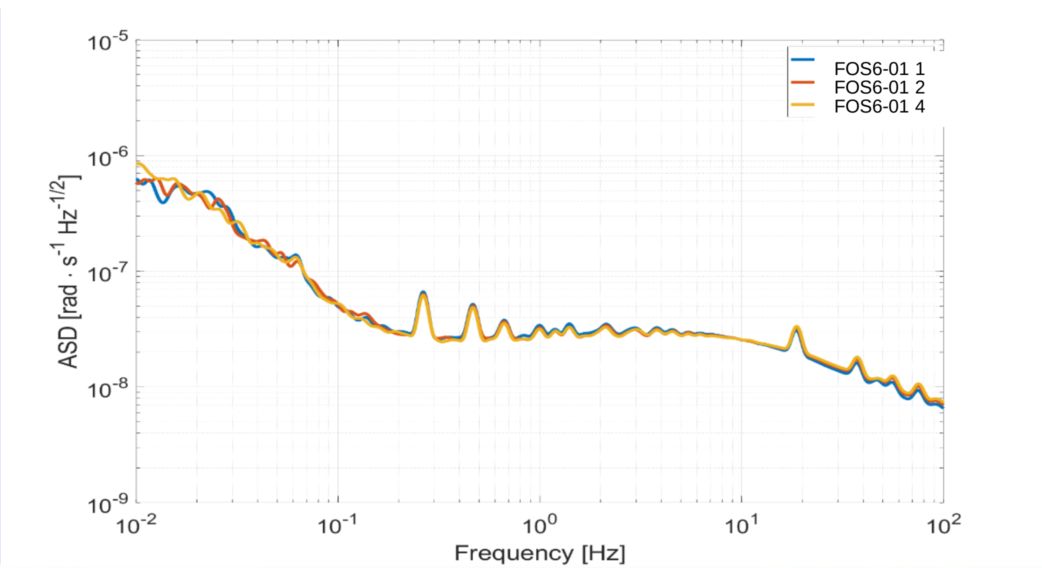


FOS6 – NOISE CHARACTERISTIC

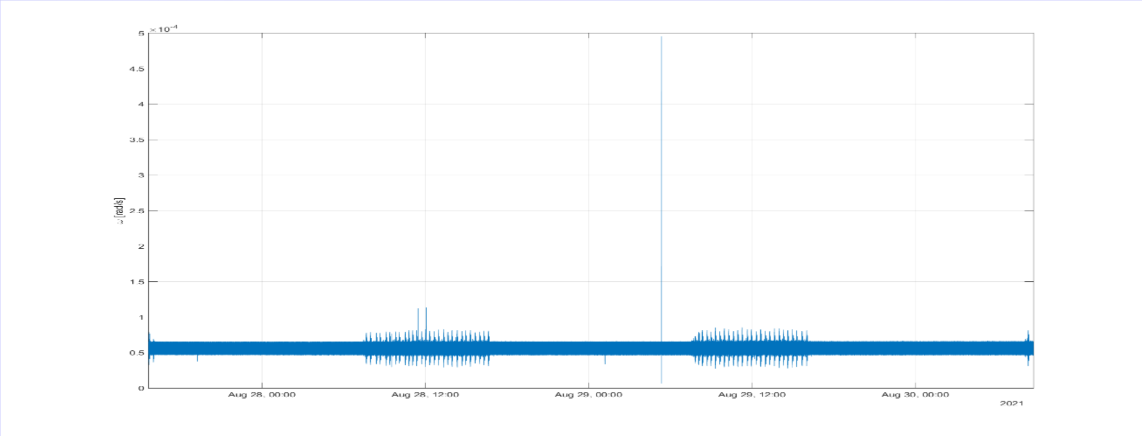


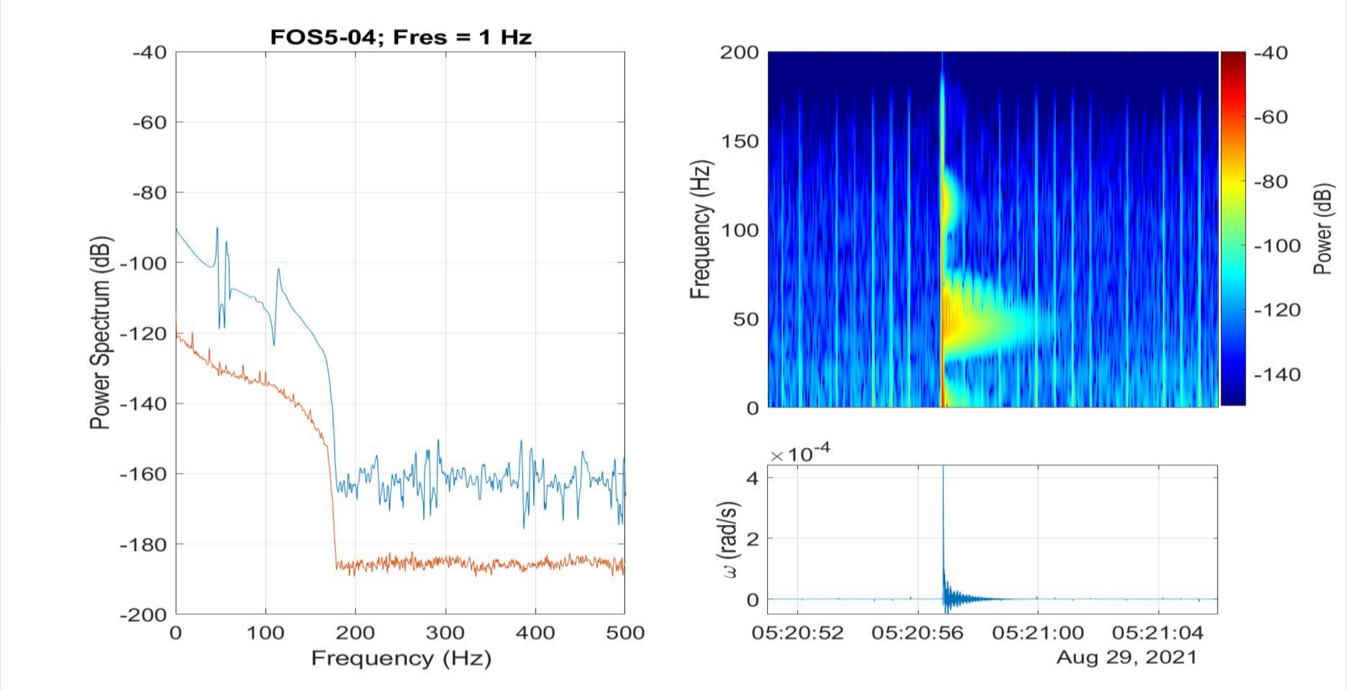


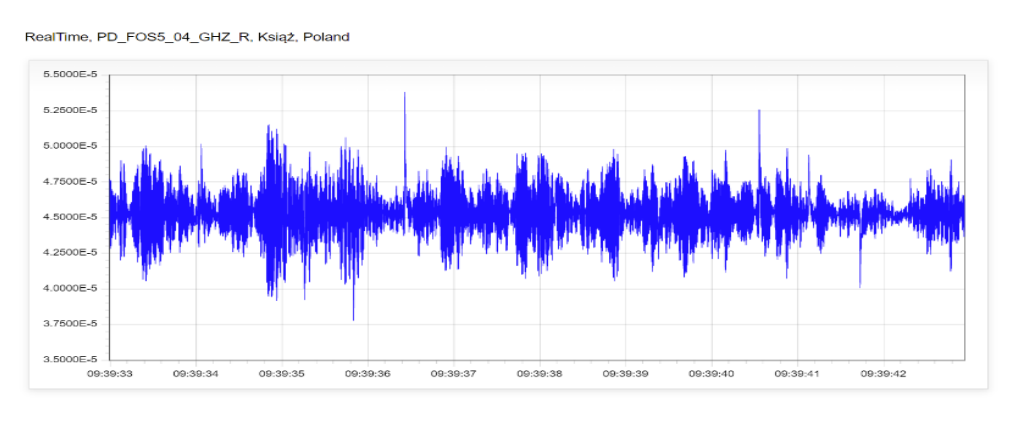




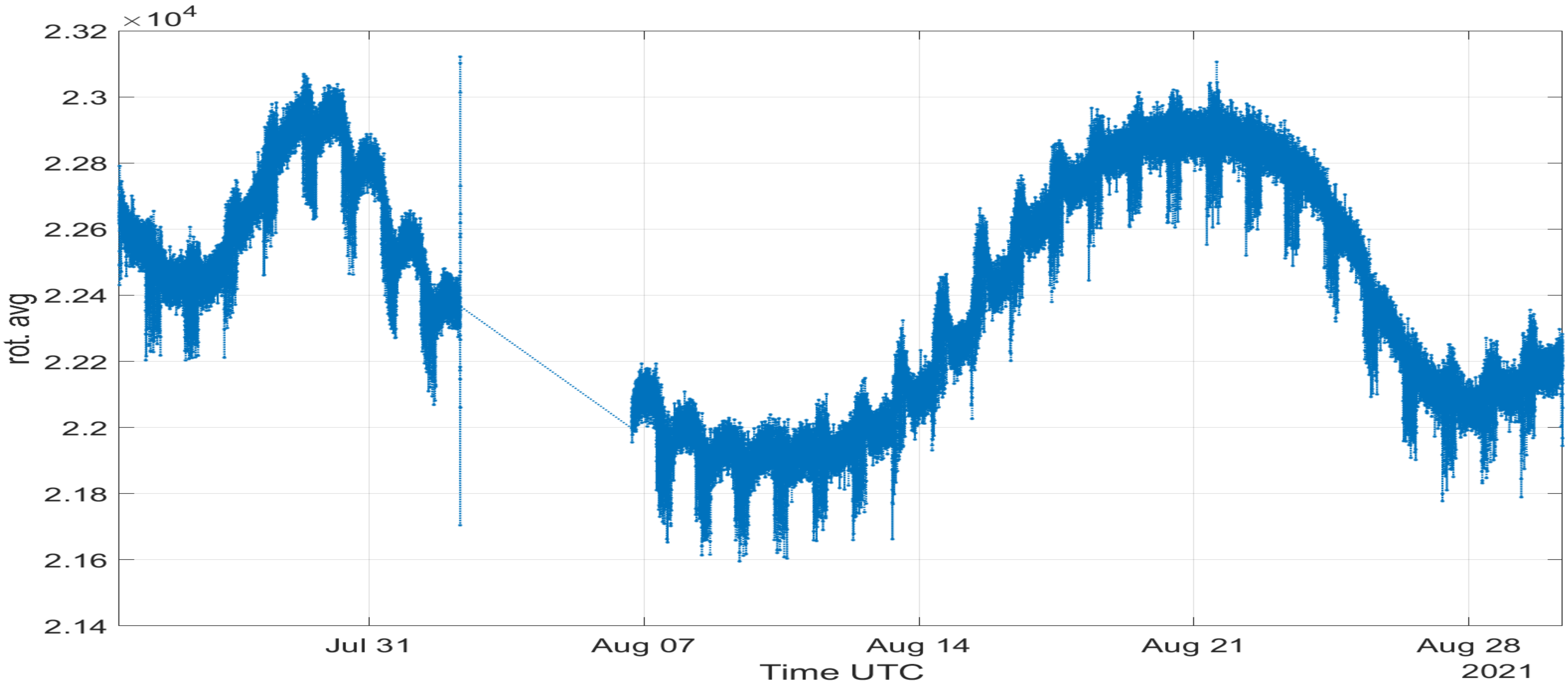
FOS6 – FIELD EXPLOATATION AT KSIĄŻ PAS LABORATORY







FOS6 – FIELD EXPLOATATION AT KSIĄŻ PAS LABORATORY



Dziękuje za uwagę

Prace w roku 2021 wykonano w ramach realizacji projektu NCBiR POIR.01.01-00-1553/20-00 „FOSREM- od nieba poprzez ziemię aż do podziemnych zastosowań”