Usefulness of different types of rotational seismometers for seismology as well as engineering applications

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Talk to the memory of Prof. Roman Teisseyre and Dr Wille Lee

Born April 14, 1929, in Lvov Poland, Prof. **Roman Teisseyre**, Ph.D., DSc, Emeritus Scientist Institute of Geophysics Polish Academy of Sciences (IGP PAS), passed away late November 2022.

Roman started his work as geophysicist in 1953 joining Leopold Infeld's team of theoretical physics. Almost to the end of life he worked in the Department, later: IGP PAS, Warsaw Poland. He was national professor, real member of PAS. Professor R. Teisseyre's field of interest was wide - from seismology to the fields of dislocations, macroscopic faults, electric and magnetic phenomena and the related measurements, generally: he contributed both to measurement methods and to the deep theories including the existence of rotational seismic waves.

Born October 6, 1940, in Quiping, Kwangsi province, China Dr. **William H. K. (Willie) Lee**, Emeritus Scientist U. S. Geological Survey, passed away late November 2022.

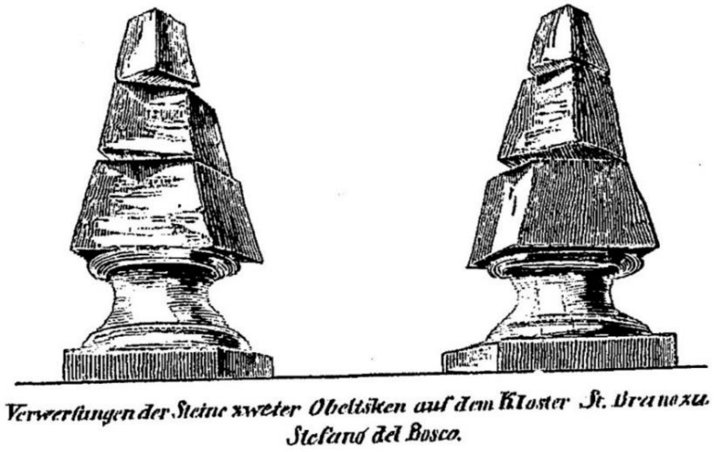
He was long career of leadership in seismology and studies of physics of the Earth's interior – a career marked by a strong emphasis on international cooperation and sharing of data and procedures and marked by organization of, and significant contributions to, important seismological projects. „Father" of large seismic network at San Francsco Bay Area. Willie was a driving force behind growing interest in rotational seismology – international conference in 2005 followed by special issue of the BSSA.

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

Spectacular visual examples

Seismological application:

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



CALABRIA, 05.02.1783

[Gordon et al., *BSSA*, 60, (1970), 953]

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

ELPROMA

FOSREM

Spectacular visual examples

Engineering application:

- seismic behaviour of irregular and complex civil structures [Trifunac, *BSSA, 99,* (2009), 968; Mustafa, InTech, 2015]- content:
  - low frequency (higher stress in structural element, horizontal displacement of the centre of mass – overturning moment),
  - high frequency (local vibration of beams & columns, meaningless motion of centre of mass – local destruction),
- damage control systems (drilling rig, pipe, wind tower),
- industry asset monitoring and management (sensing rotary@nuclear plant)

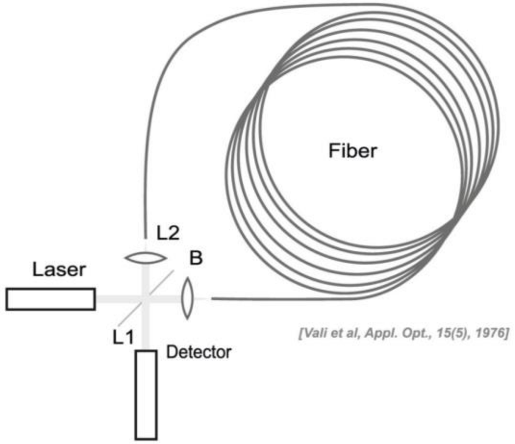
921 Earthquake Museum of Taiwan, Teichung. Effects of Chi-Chi earthquake, 1999 [private photo]

Review of Rotational Seismometer

3. Optical type (direct based on von Laue/ Sagnac effect)

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

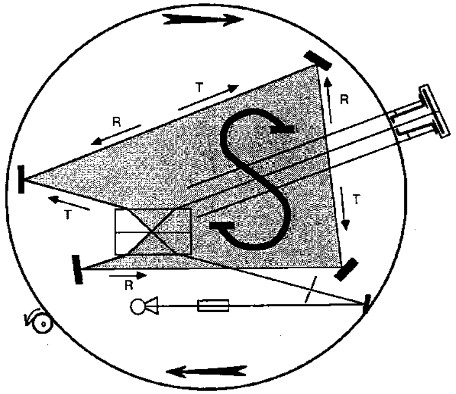
The Sagnac phase shift (1976) induced by rotational rate Ω perpendicular to plane of fiber optic sensor loop is equal to:



$$\Delta\phi = \frac{8\pi A}{\lambda c}\Omega = \frac{2\pi DL}{\lambda c}\Omega = \frac{1}{S_0}\Omega$$

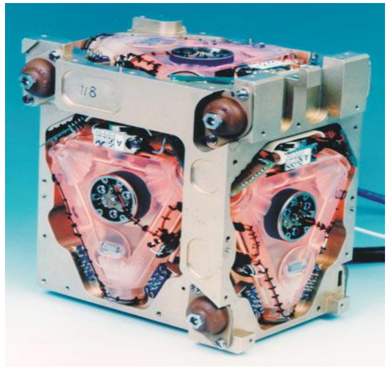
where:
A – optical area
L – length of the fiber in the sensor loop
D– sensor loop diameter
λ – wavelength
c – velocity of the light in vacuum
S_0 – the optical constant of interferometer

- Because device uses **massless particles** (photons) for the measurement, it is entirely **insensitive to linear accelerations**, **no-exist cross coupling** as well as it has **BB flat response**,
- There is **no moving part** except photons, it allows **maintenance free** and **small environment sensitivity**



[Post, *Rev. Mod. Phys.*, 39, (1967),475]

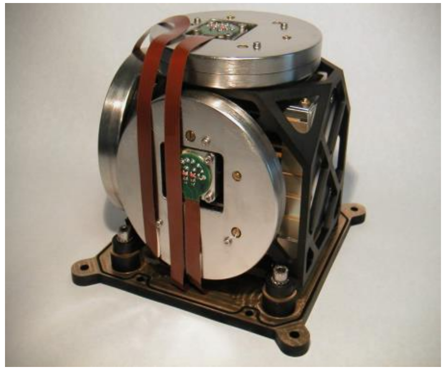
The laser-gyro (or RLG)



Resonant ring of 10-30 cm perimeter
He-Ne plasma laser with HV discharge

- V. simple read-out signal: freq. beating
- Dead zone about zero -> „dither”
- Improve lift time (5-7 years operating)

The fiber-gyro (or FOG)



Ring interferometer with fiber coil (0.1-10 km over 3-30 cm – A~ 0.7 – 700 m^2)

- Fully soilid-state components
- Much longer life time
- Low power, low voltage
- No acoustic noise

Requirements for rotational seismometer (RS)

Seismological application

[Bernauer et al., J. Seismol., 16, (2012), 595]

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,
- power consumption 5 – 8 W

Engineering application

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

Measuring range

signal amplitude:
up to a few rad/s,
frequency:
0.01 Hz – 100 Hz

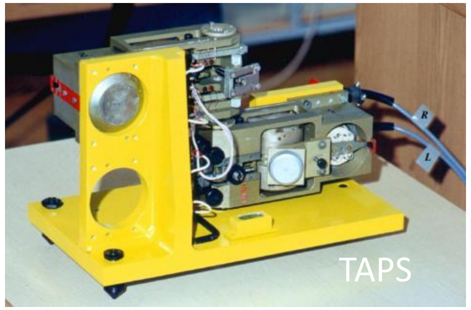
ROTATIONAL SEISMOGRAPH

set of RSs + precise time source + recording device + network

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

Review of Rotational Seismometer

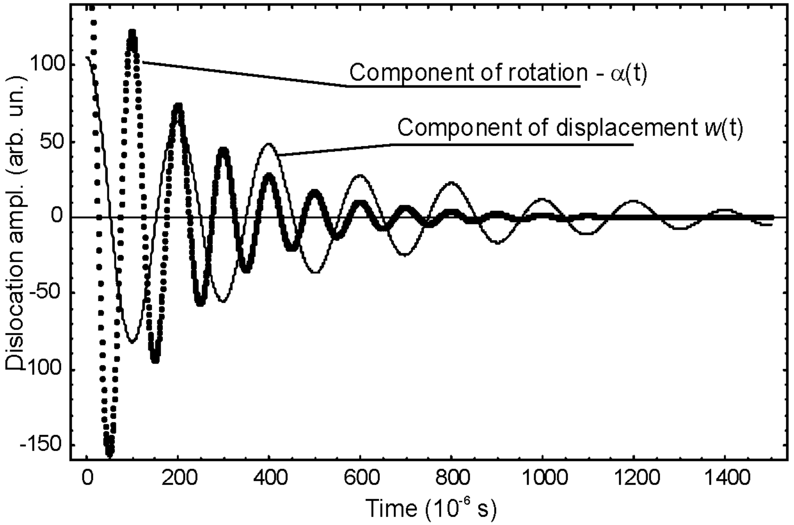
1. Mechanical type (nondirect based on velocity or accelerometer type seismometer) easy implementation to existing seismological recorder

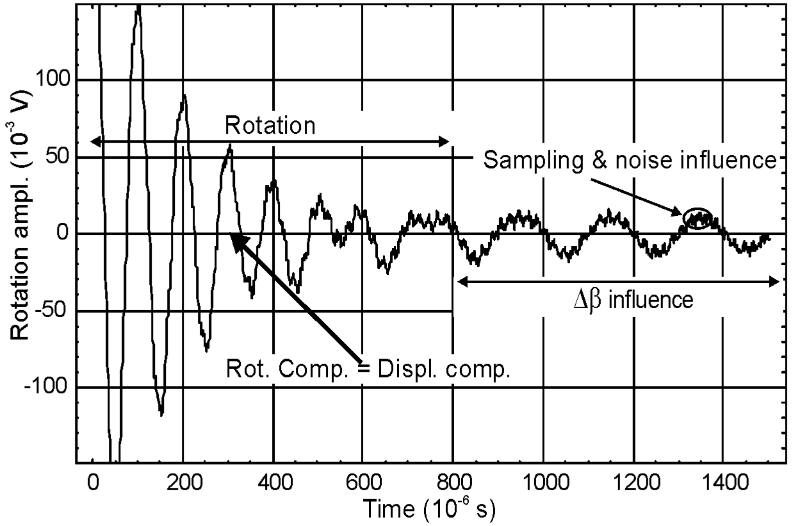


[Solarz et al., *AGP,* 52, (2002), 198]

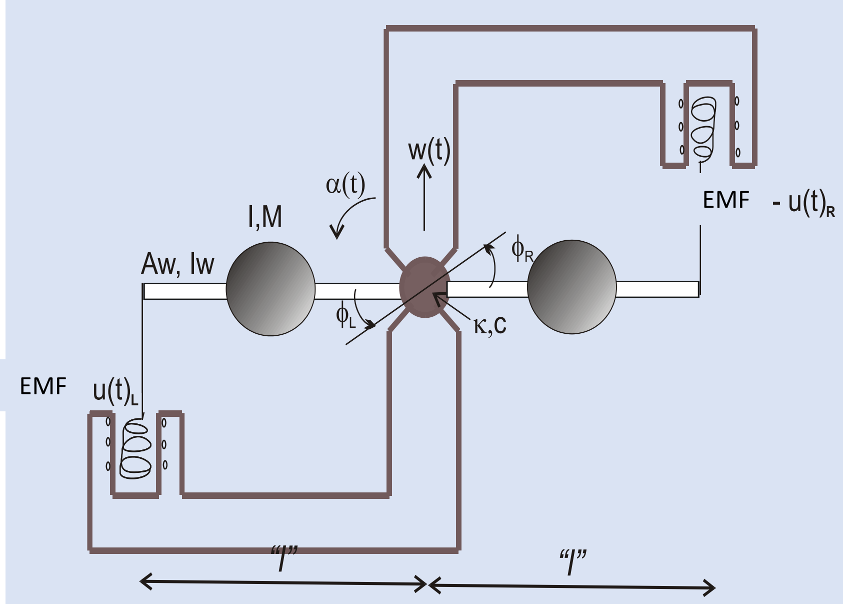
[Brokesova, Hab. Thesis, Charles Univ.2014]

[www.systron.com]





[Jaroszewicz et al., *Opt. Appl.,* XXXV, (2005), 383]



EMF recorder by components:

$$u(t)_{L,R} = \pm w(t) + l \cdot \alpha(t) \begin{cases} + & for R\ seismometer \\ - & for L\ seismometer \end{cases}$$

Rotation detection for identical components:

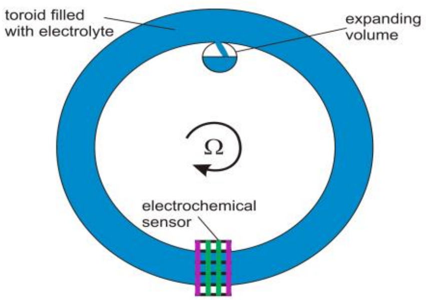
$$\alpha(t) = [u(t)_R + u(t)_L]/2l$$

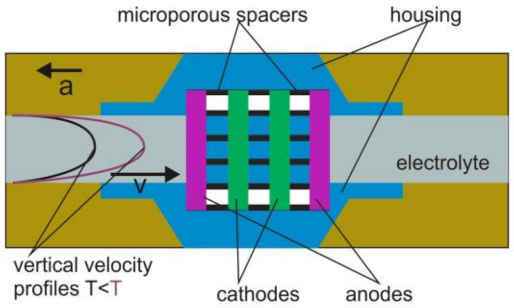
Limited: frequency range, max. detectable rotation rate, sensitivity

Review of Rotational Seismometer

2. Electro-chemical type (direct based on liquid inertia)

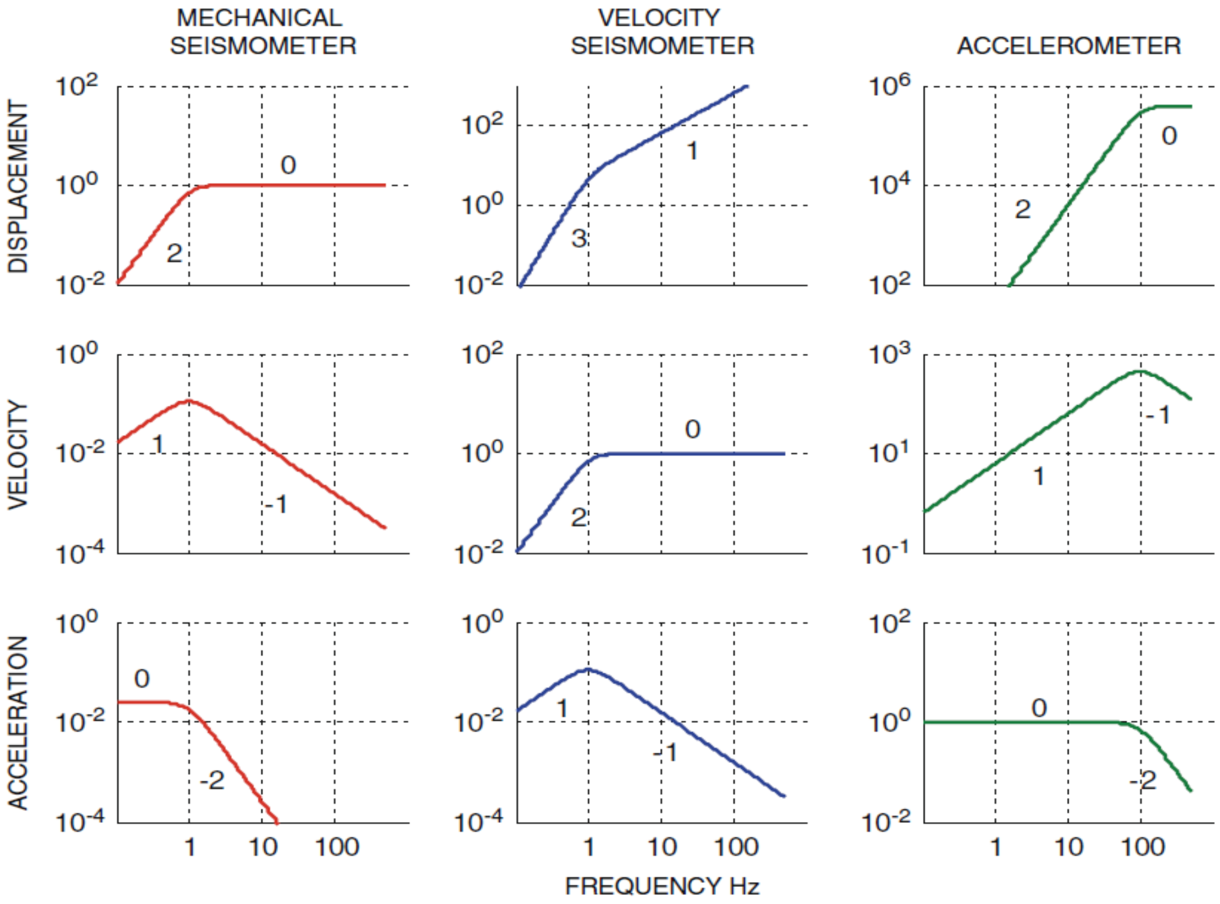
direct measurement the rotation velocity





[www.eentec.eu]

high thermal instability, problem with electrolyte inertia



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

[exail at 6th IWGoRS Meeting in Paris, IPGP, France, 21-23 November, 2022]

Sensitivy from Sagnac effec depends on enclosed area [A= (L D)/4]

RLG

Giant RLG > 10 m^2

Scalability of the Area

FOG

Large FOG up to ~1 000 m^2

Finesse is limited by mirror quality, gain, output optical power…

Increase the numer of turns

Optical fiber attenuation leads to a finite optimal length beams propagating

Square design => limited benefit

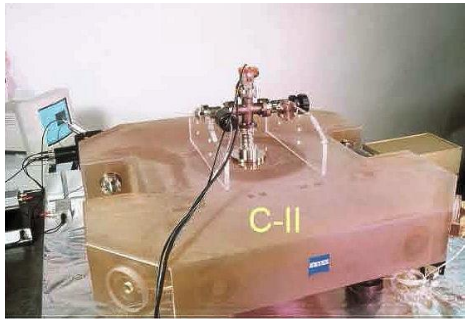
Winding capability limit

Perimeter longer than 30 cm => harder longitudal monomode

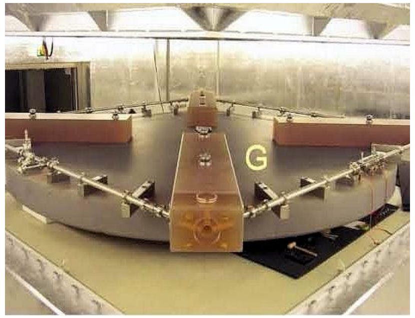
Increase the area of each turn

Homogenous environment harder to achieve for large coil

3a. RS as giant RLG (measure Ω from Sagnac effect) optimal for seismological application, stationary system



C-II Canterbury New Zealand 1997-2011 (A=1 m^2)



G ring laser Wettzell Germany since 2001 (A=16 m^2)

G-O Christchurch New Zealand (A~12 m^2)

GINGERino in LNGS tunel Gran Sasso Italy (A-13 m^2)

ROMY Munich Germany (A=4x ~ 62 m^2)

(ARW < 10^{-14}rad/s/√Hz) => sensitive to the spin of the planet and the twist of earthquakes

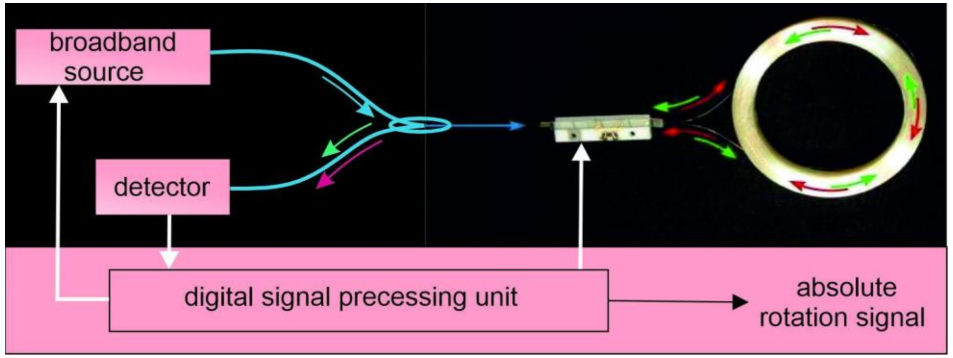
[Schreiber, Wells, Rotation Sensing with Large Ring Lasers, Cambridge Univ. Press, 2023]

Review of Rotational Seismometer

3b. RS as FOG for direct measure Ω (absolute, bradband, transportable) now probably the best solution

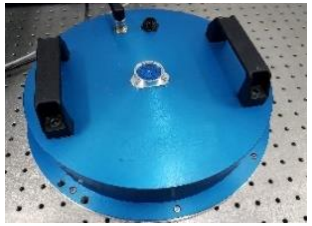
10^{-8} [rad/s] => ? $\Delta L = \frac{\lambda}{2\pi}\Delta\phi = \frac{LD}{c}\Omega = \frac{3\,000[m] * 0.2[m]}{3\;10^{8}[m/s]} 10^{-8}\left[\frac{rad}{s}\right] = 2\;10^{-14}[m]$

The range od hydrogen nuclei diameter !!!!



iXBlue -> axial (France)

MUT/ Elproma Elektronika Ltd (Poland)



blueSeis-3A:
- 3-axis
- 0.318 m diameter

Selfnoise: 20·10^{-9} rad/(s√Hz)
Broadband 0.01 Hz – 50 Hz

blueSeis-1C:
- 1-axis
- 0.40 m diameter

Selfnoise: 5·10^{-9} rad/(s√Hz)
Broadband: 0.001Hz – 100 Hz

FOS5-01, -02, -03:
- 1-axis
- 0.25 m diameter

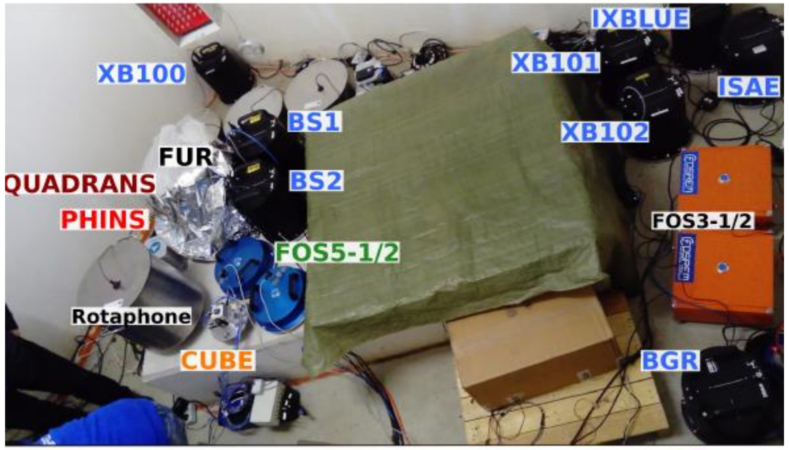
Selfnoise: 3.41·10^{-8} rad/(s√Hz)
Broadband: 0.01 HZ – 100 Hz

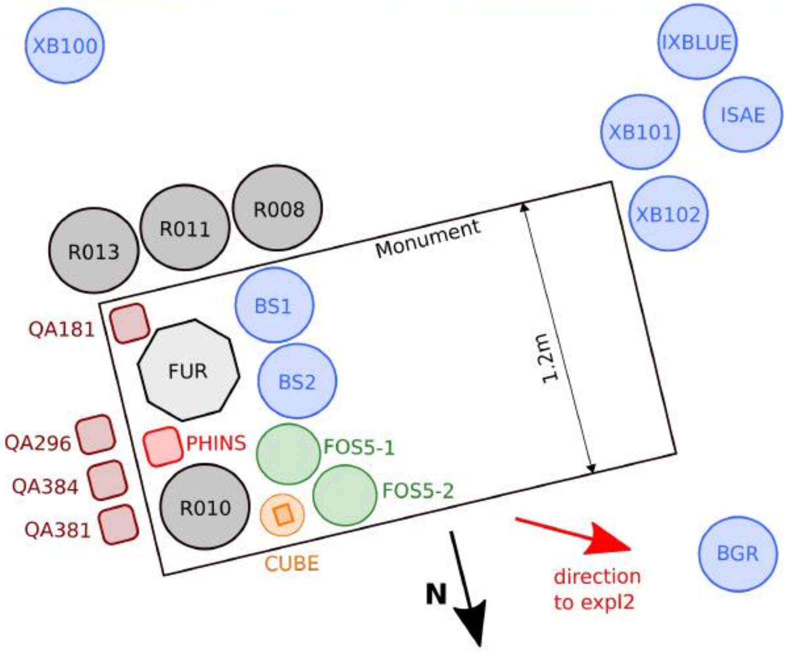
FOS5-04:
- 1-axis
- 0.60 m diameter

Selfnoise: 5.67·10^{-9} rad/(s√Hz)
Broadband: 0.01 Hz – 100 Hz

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

IWGoRS test in November 2019
Furstenfeldbruck, Germany

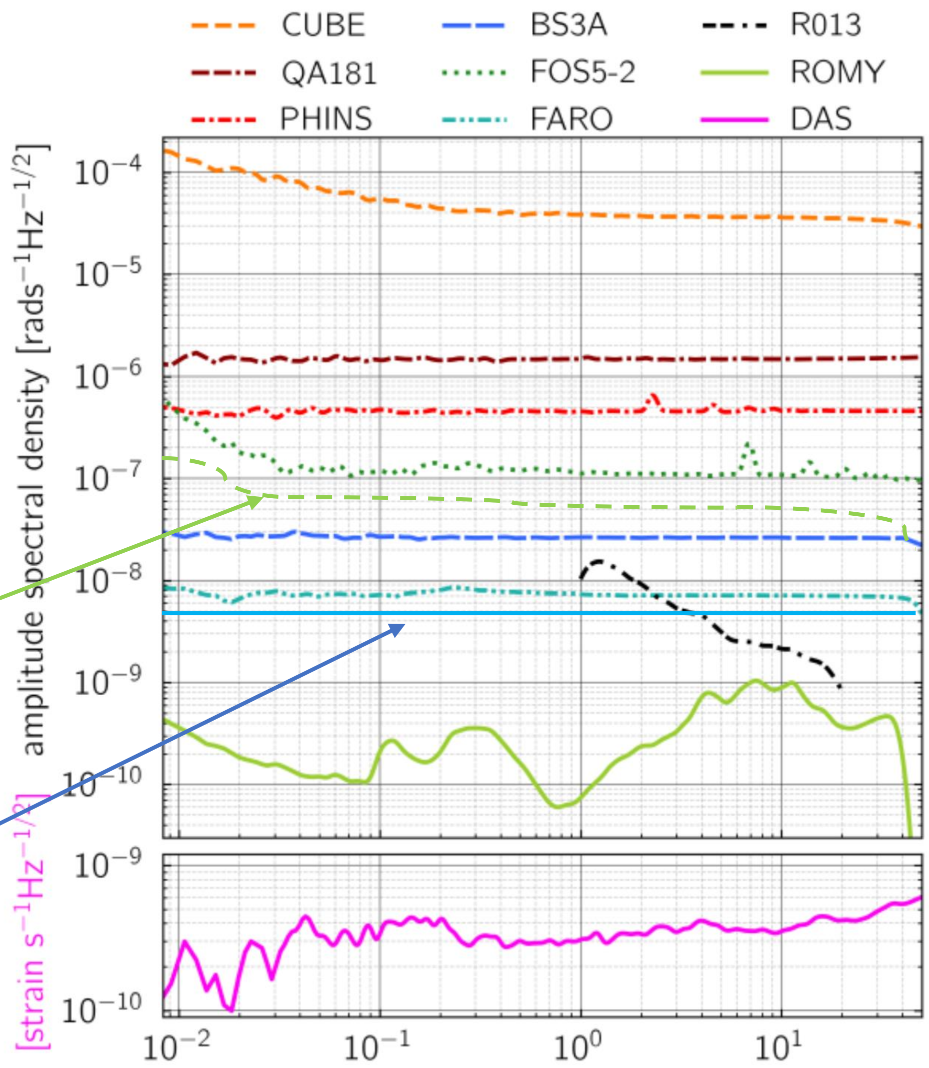




[Bernauer et al., Sensors, 21 (2021), 264]

More than 24 different sensors:

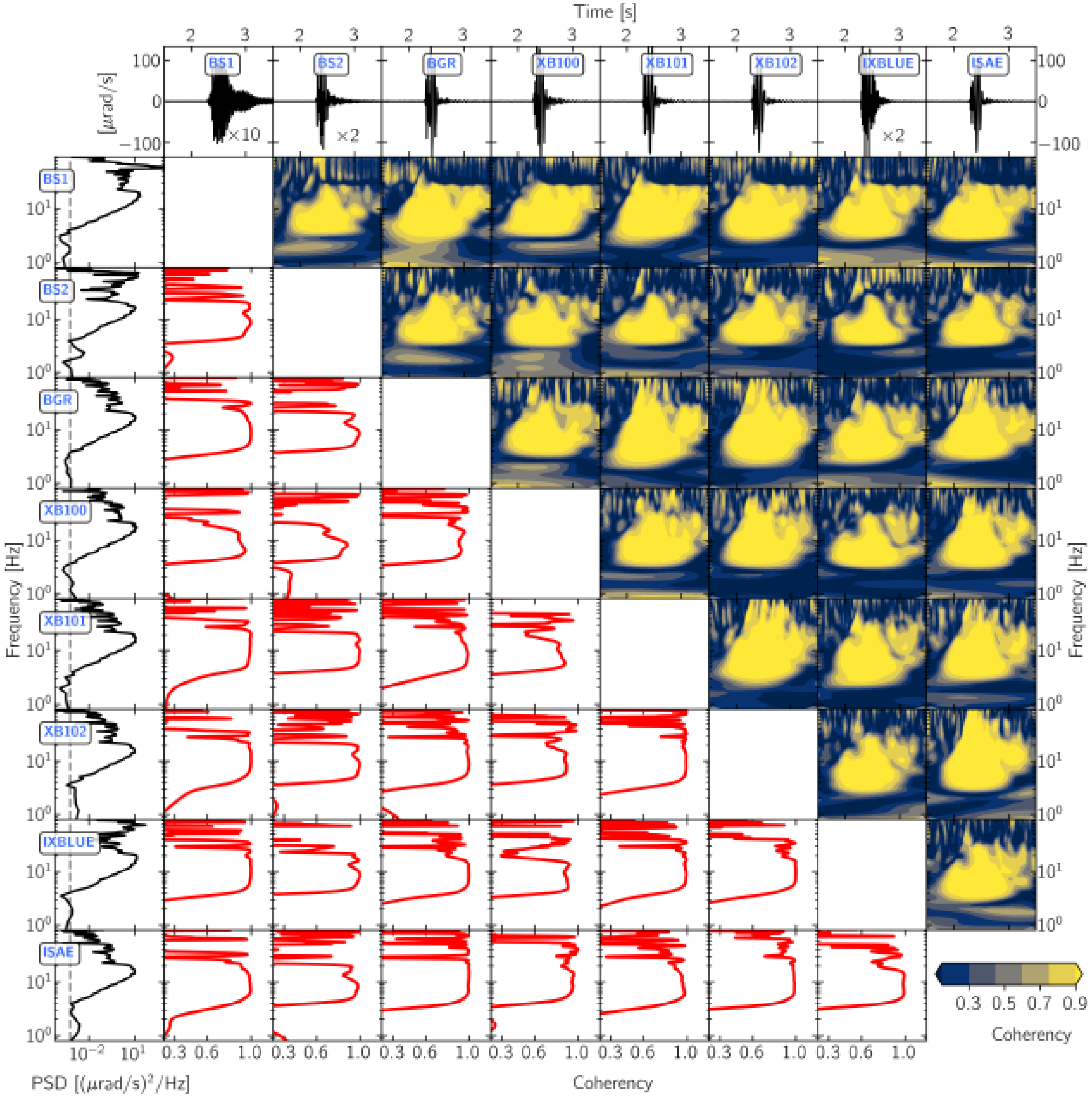
- bb Seismometer
- ROMY
- blueSeis-3A - eight
- FOS3 – two
- FOS5 - two
- Rotaphone
- Phins - one
- Quadrans - four
- Cube – four HORIZON
- Geophone
- DAS

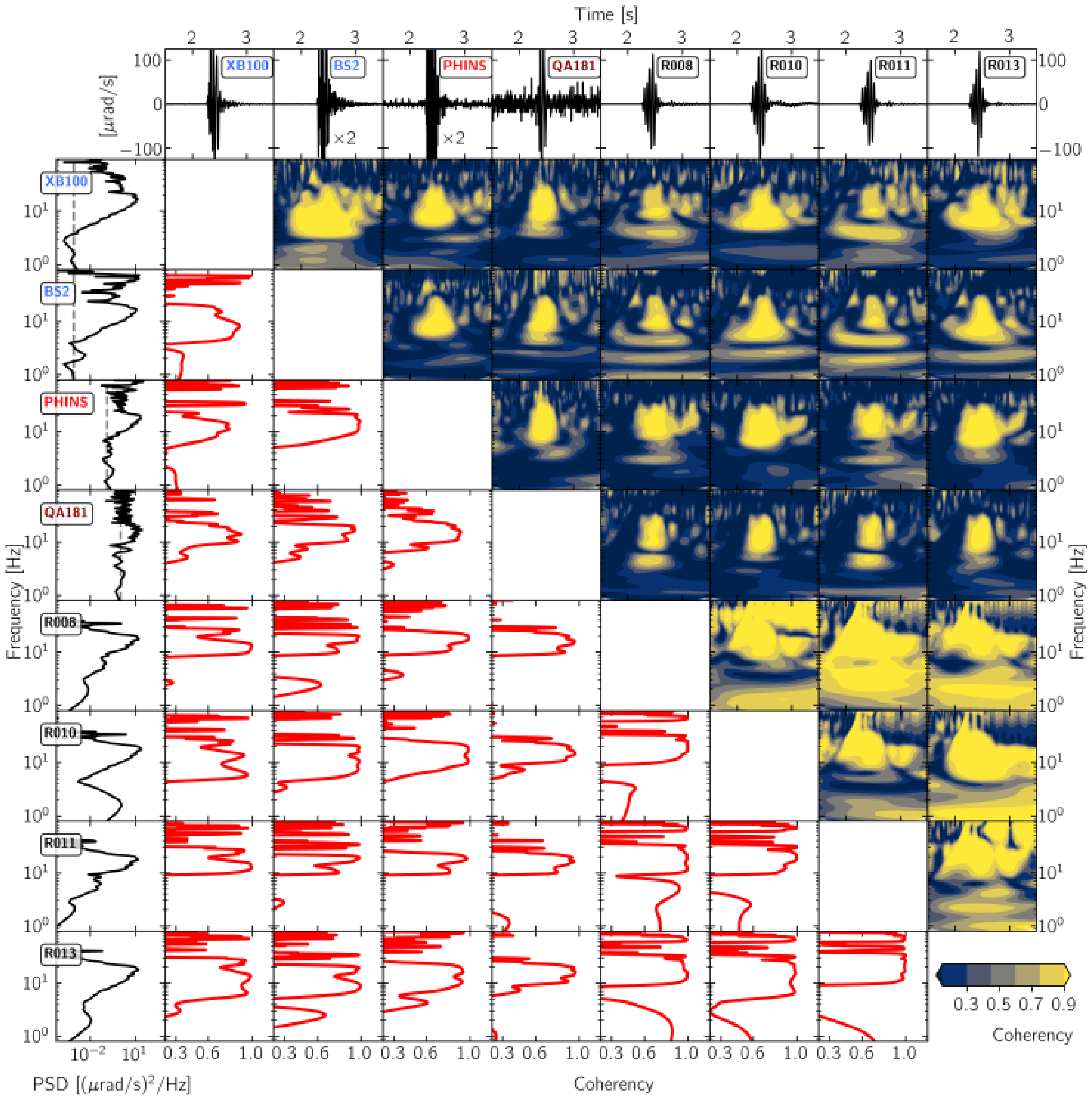


frequency [Hz]

[Bernauer et al., Sensors, 21 (2021), 264]

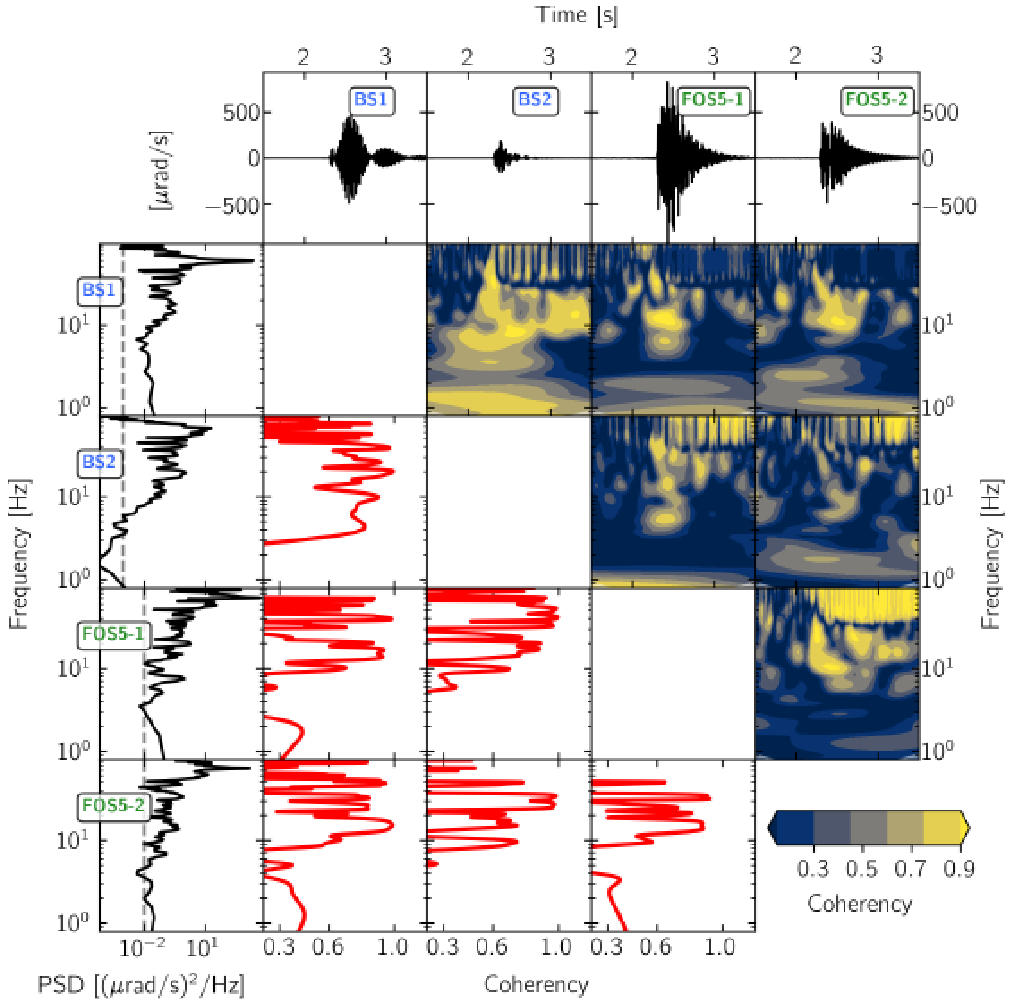
Waveform coherency during huddle test

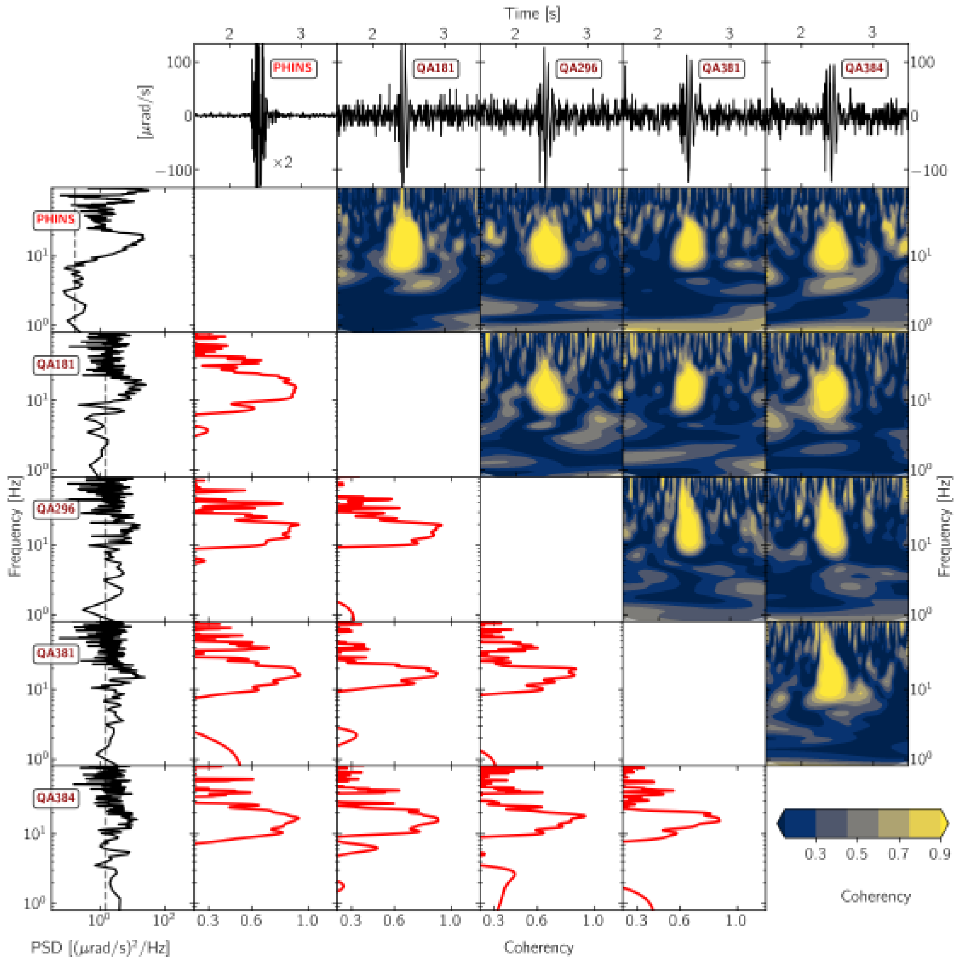




[Bernauer et al., Sensors, 21 (2021), 264]

Waveform coherency during huddle test

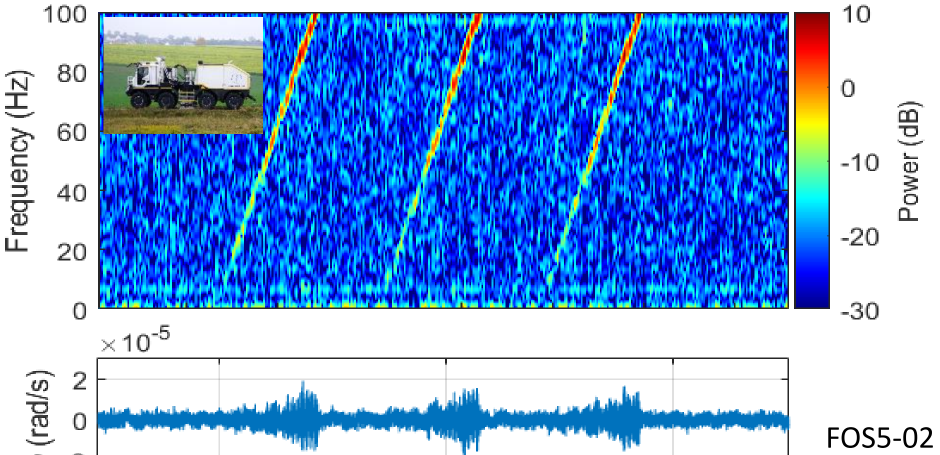




[Bernauer et al., Sensors, 21 (2021), 264]

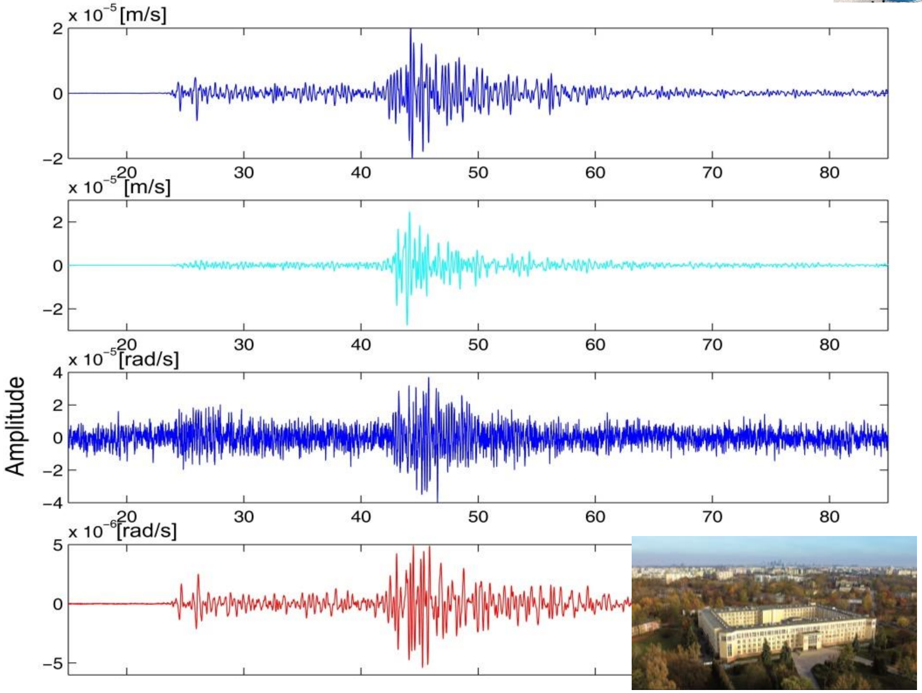
A high level of coherency and waveform similarity within a narrow frequency range (10 Hz - 20 Hz) for recordings from a nearby explosion signal

Real examples



FOS5-02

[Kurzych et al., Opto-Elect. Rev, 29 (2021), 39]

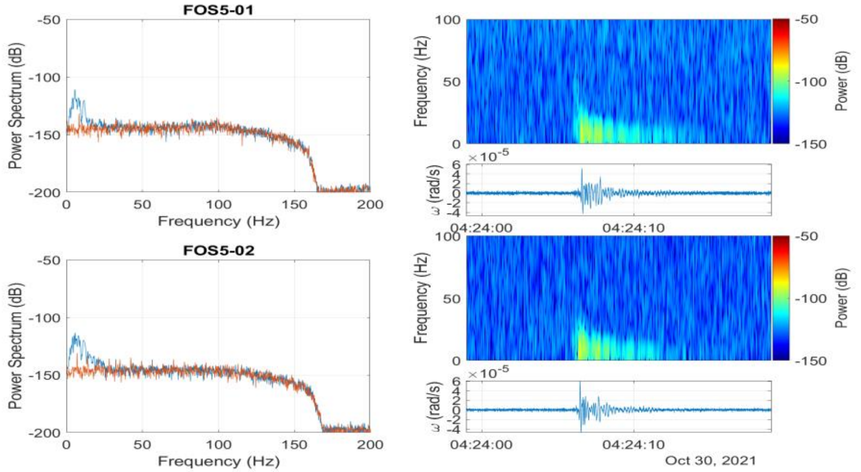


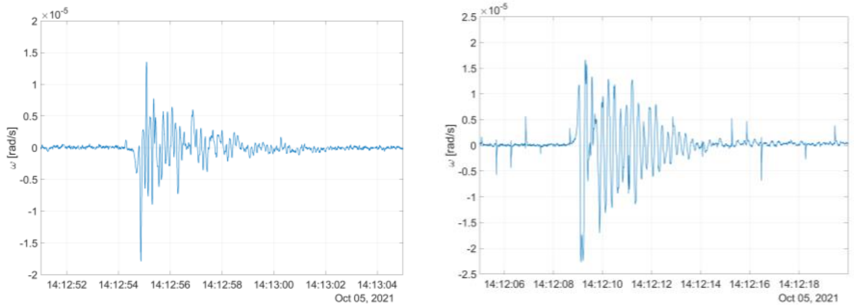
[Kurzych et al., Opto-Elect. Rev, 28 (2020), 69]

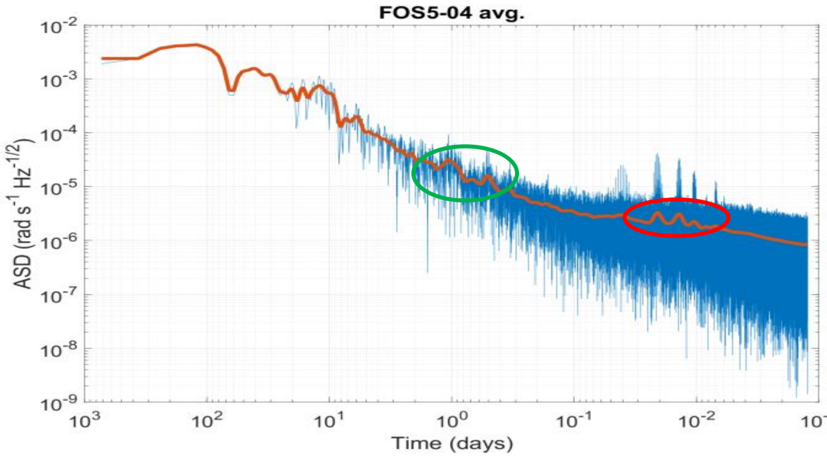
Coalmine “Ignacy” in Rybnik

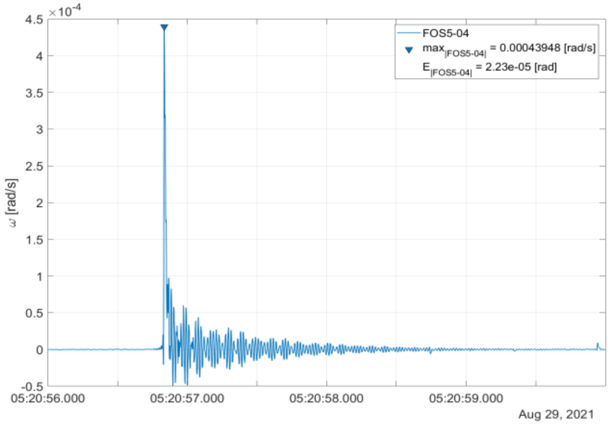
Książ Castle

- touristic activity
- changes of Earth’s rotation rate due to diurnal polar motions, as well as diurnal and semidiurnal tides.



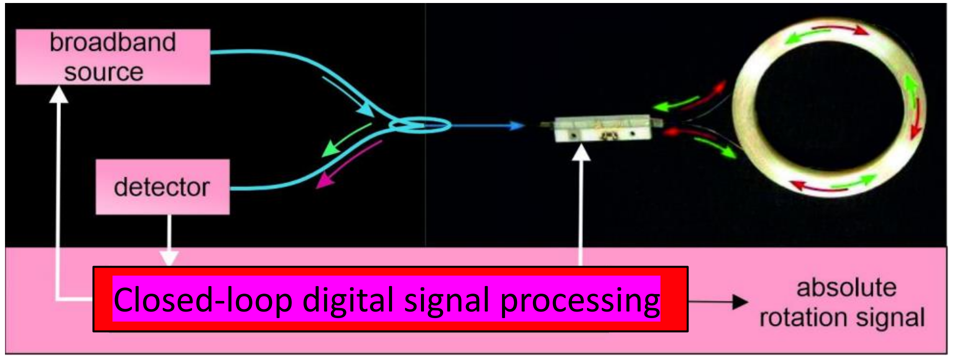






[Jaroszewicz et al., Opto-Elect. Rev, 29 (2021), 213]

End of this year !!



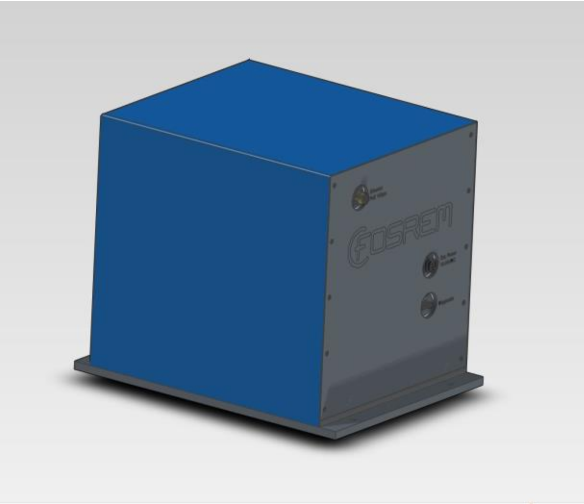
FOSREM - 6DoF (3 rotations - FOG & 3 displacements - MEMS)

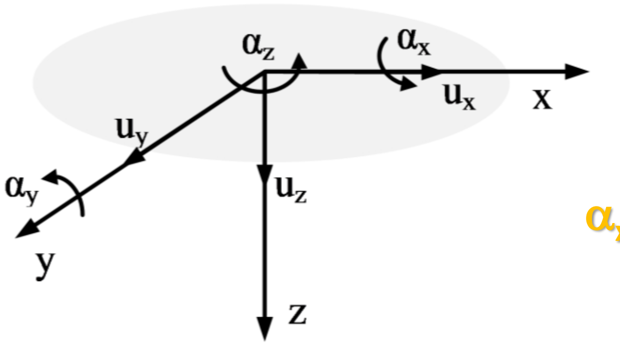
Broadband – 0.01 Hz – 100 Hz

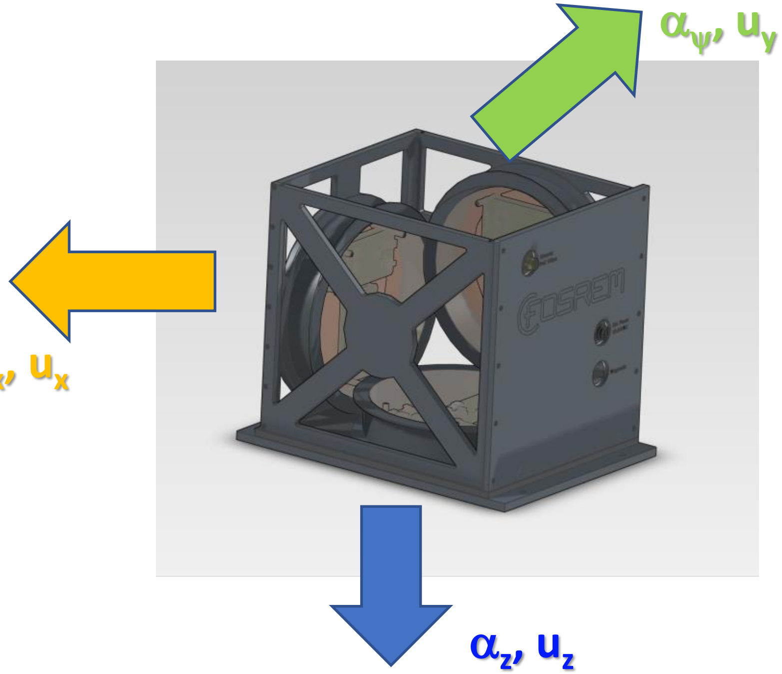
Sensitivity – several dozen nrad/s up to a few rad/s

Output data – miniSEED 200 bps with automatic event detection

Devices coherency - P> 0.9







This work was supported by the National Centre for Research and Development as project POIR.01.01.01-00-1553/20 „FOSREM – from Sky across Gound up to Underground”

ELPROMA FOSREM

Thank you for your attention