18TH WORLD CONFERENCE ON EARTHQUAKE ENGINEERING
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MILAN

Three-Axial Rotational Fibre-Optic Seismograph for Seismic Exploration

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https://fosrem.eu/

Motivation

01 Rotational Seismology

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

02 Engineering application

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

03 Seismological application

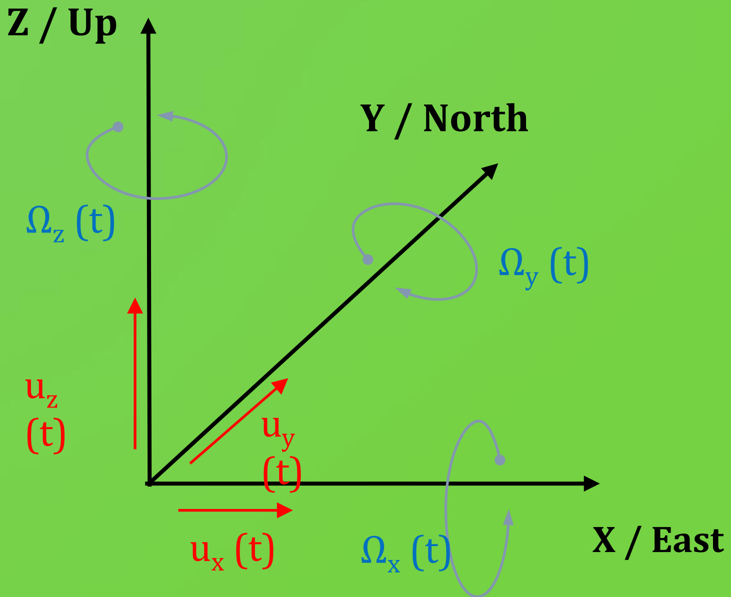
broadband seismology [Igel et al., Geophys. J. Int., 168(1), (2006), 182–197], **strong-motion seismology** [Anderson, 2003, Chap. 57, 937-965], **earthquake physics** [Teisseyre et al. Springer, 2006; Springer, 2008], **seismic hazards** [McGuire, Earthq. Eng. Struct. D., 37, (2008), 329–338], **seismotectonics** [www.geophysik.uni-muenchen.de/~igel/ Lectures/Sedi/sedi_tecto nics.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]

04 6-DoF

earthquake sources, tilt correction, wavefield separation, wave direction, wave dispersion,sScattering properties, seismic imaging

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

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



Requirements

for rotational seismology

Engineering application

Measuring range

signal amplitude:
up to 10 rad/s,
frequency:
0.01 Hz – 100 Hz

Seismological application

Measuring range

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

COMMON

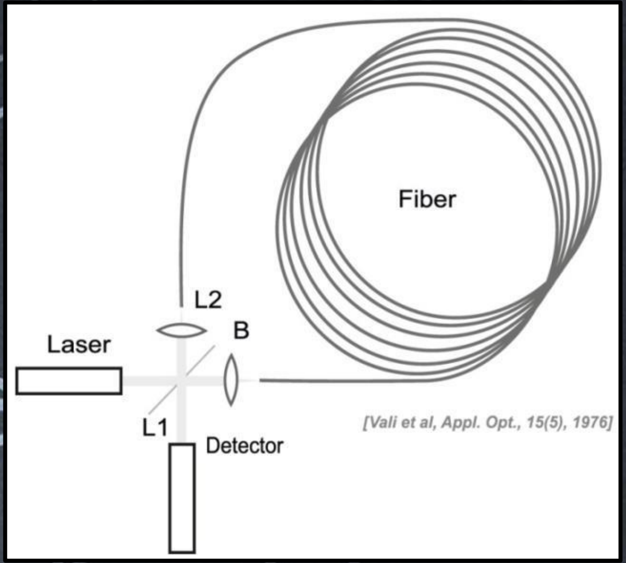
ROTATIONAL SEISMOGRAPH
network of seismometers + precise time source + recording device + network

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% / °C

BACKGROUND

The direct 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 fibre-optic implementation the rotation rate Ω is expressed by induced phase shift Δφ as:

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

L – length of the fibre 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

FORS - Fibre-Optic Rotational Seismograph historical brief

1998

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

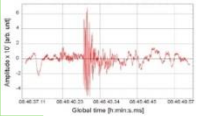
2001

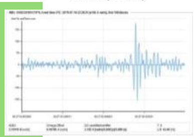
FORS-I
Ω_{min}: $2.2 \cdot 10^{-6}$ rad/s
Ω_{max}: $4.8 \cdot 10^{-4}$ rad/s
SL: 400 m PANDA
Radius: 0.1 m

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

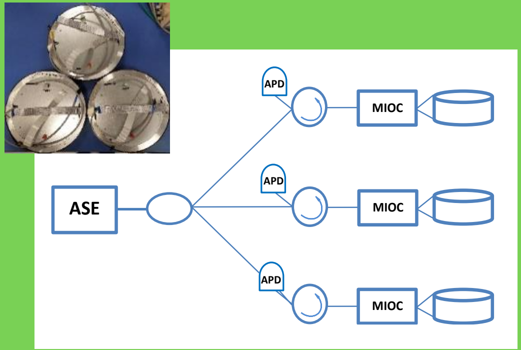
FOSREM – FOS3 & FOS4
Ω_{min}: $2 \cdot 10^{-8}$ rad/s,
Ω_{max}: few rad/s
SL: 5 000 m SMF
Radius: 0.125 m

2018

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

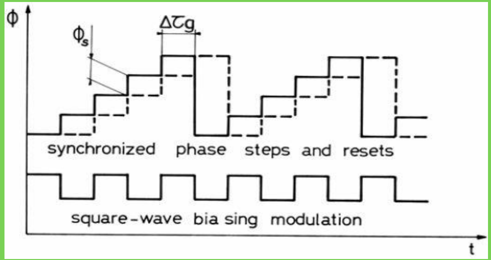
Fibre-Optic Seismograph FOS6
3- Axis with 100 nstime synchronization
Ω_{min}: several dozen nrad/s
Ω_{max}: 10 rad/s
SL: 6 000 m SMF
Radius: 0.125 m
Weight: 10 kg

Fibre-Optic Seismograph



OPTICAL PART

generates the phase shift $\Delta\varphi$ proportional to the measured rotation rate Ω which is perpendicular to the sensor loop plane



ELECTRONIC PART

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

Laboratory analysis of FORS’ parameters

Allan Variance analysis

Theoretically

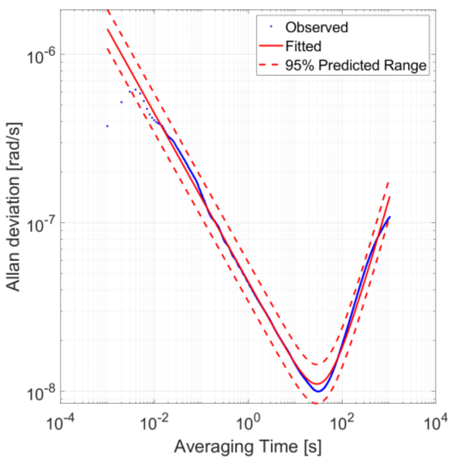
$$ARW = \frac{\sqrt{2}\lambda c}{2\pi DL}\sqrt{\frac{4kT}{R\eta^2P^2}+\frac{ei_d}{\eta^2P^2}+\frac{e}{\eta P}+\frac{\lambda^2}{4c\Delta\lambda}}$$

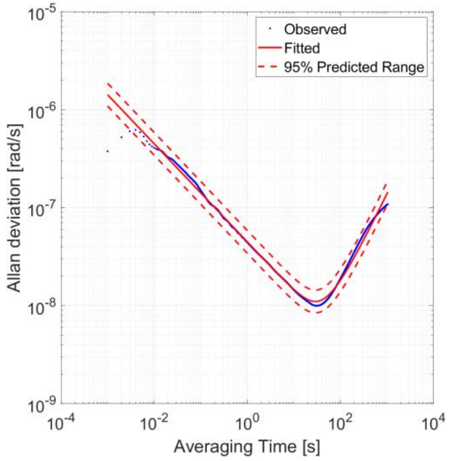
where: λ – central light wavelength (1 550 nm), c – speed of light, D – loop diameter (0.25 m), L – loop length (about 6 000 m), k – Boltzmann's constant, T – temperature (293 K), R – resistance of the trans-impedance transducer of the photodetector device (20 kΩ), η – efficiency ratio of the photodiode (0.85 A/W), P – incident optical power on the APD, e – elementary charge, i_d – photodiode dark current (80 nA), $\Delta\lambda$ – spectral width of the light source (40 nm).

The calculated theoretical values of ARW for each optical head for four FORS type FOS6 were in the range of 4.49-4.85 nrad/√s, depending on total optical losses and fiber length in the given optical head.

Allan Variance analysis

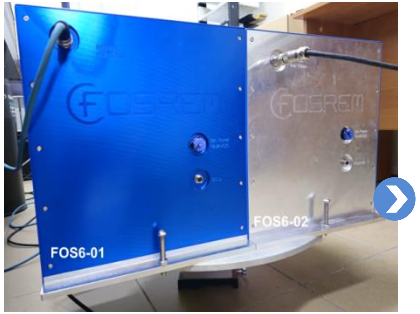
Data gathered in the Military University of Technology, Poland





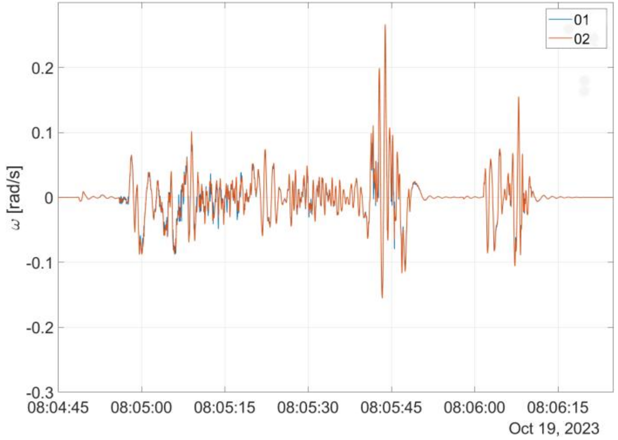
FOS6-01: ARW: 35 nrad/√s, BI: 10.0 nrad/s
FOS6-02: ARW: 45 nrad/√s, BI: 51.0 nrad/s

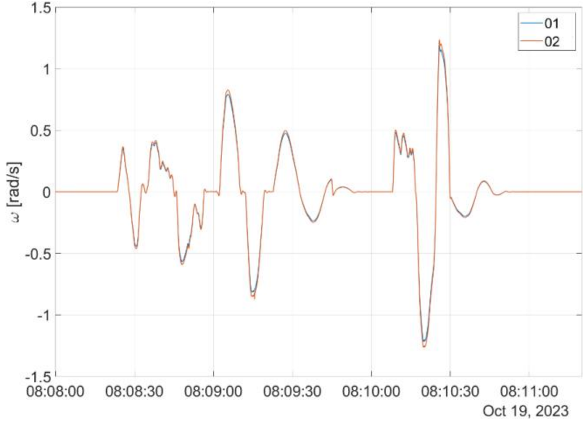
Correlation verification



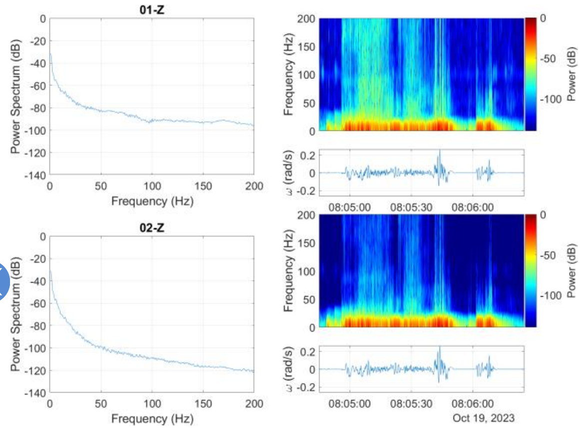
FOS6-01 and FOS6-02 in the MUT laboratory on the rotary table

Signals recorded by FORSs Z-axes during the medium high-amplitude and fast-changing excitations as well as high-amplitude amplitude excitations

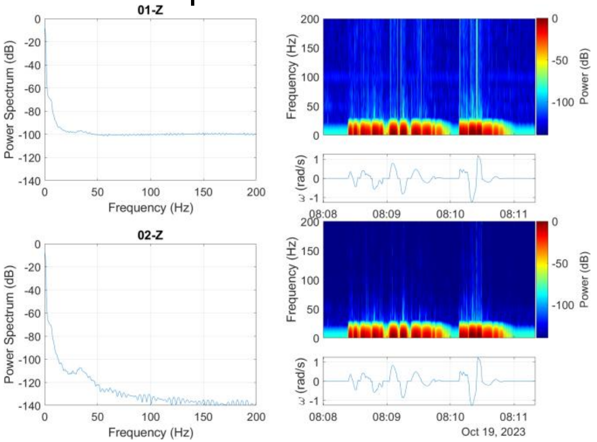




Pearson correlation coefficient equal to 99.42%



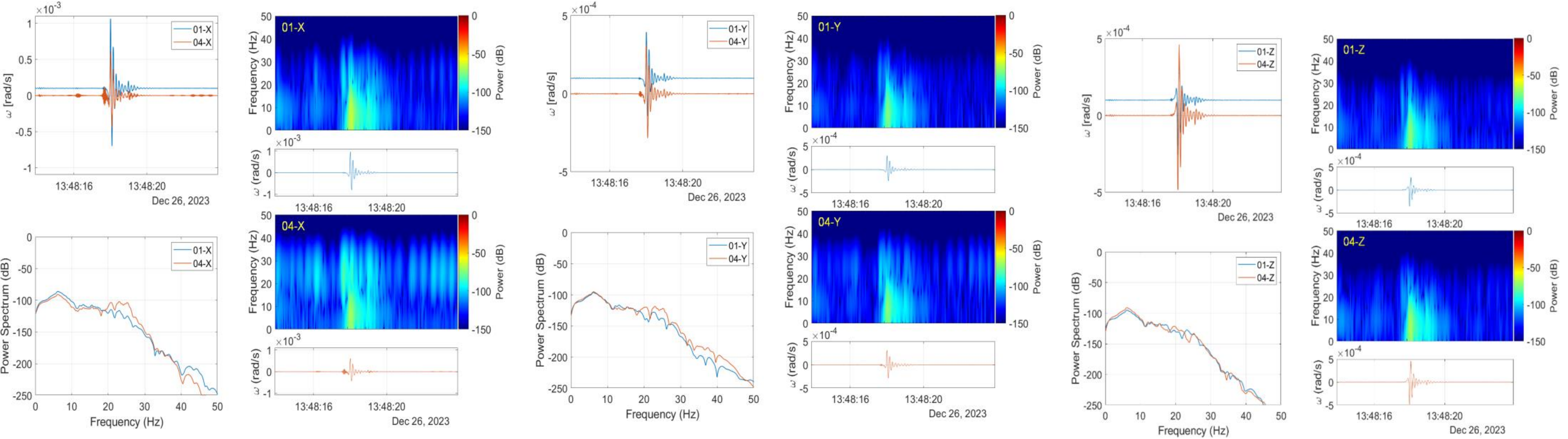
Pearson correlation coefficient equal to 99.99%



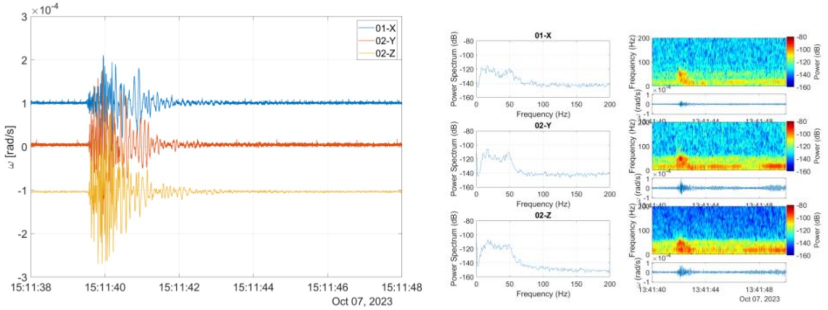
Correlation verification

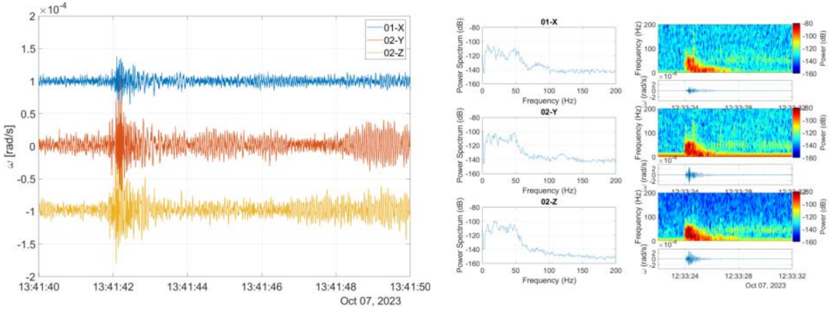
Field test in the Kampinos Nature Park by a pair of FORSs (FOS6-01 and FOS6-04)

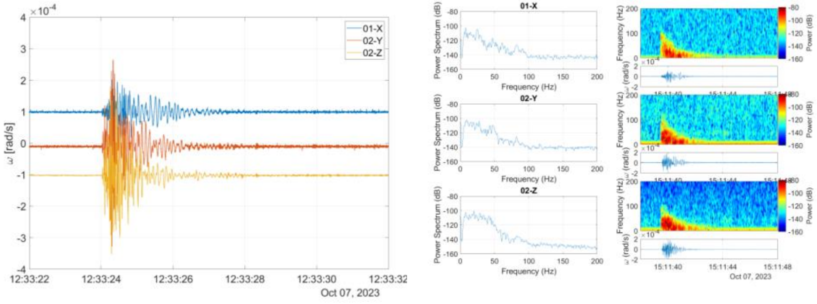
A weak rotational disturbance recording (with an amplitude of about 0.5 mrad/s) generated by the wild animal (elk) moving in the field close to the FORSs location.



Correlation of about 95% for the X axis, about 99% for Y axis, and about 99% for the Z axis







ROTATION DETECTION DURING DETONATION OF AN EXPLOSIVE CHARGE

On the 7th of October 2023 there were three explosions performed:

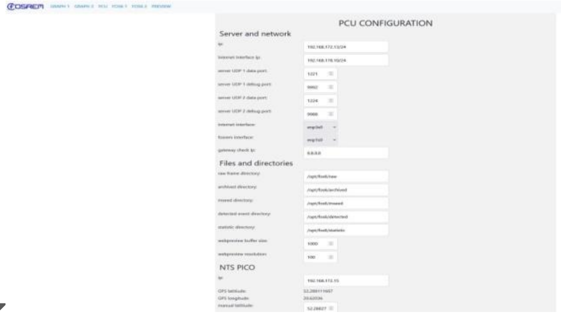
1. 12:33 UTC, 5 kg of explosive, 3 m below the ground surface with surface discharge.
2. 13:41 UTC, 5 kg of explosive, 4.5 m below the ground surface without surface discharge.
3. 15:11 UTC, two 5 kg explosive charges installed 5 meters apart were detonated one after the other, 4.5 m below the ground surface, with a distance of 5 m between loads.

	A_{max} [μrad/s]			E_f [μrad]		
Explosion number/ Axis of FORS	X	Y	Z	X	Y	Z
Explosion 1	140	327	281	69	163	104
Explosion 2	38	108	83	41	98	94
Explosion 3	119	177	170	65	111	106

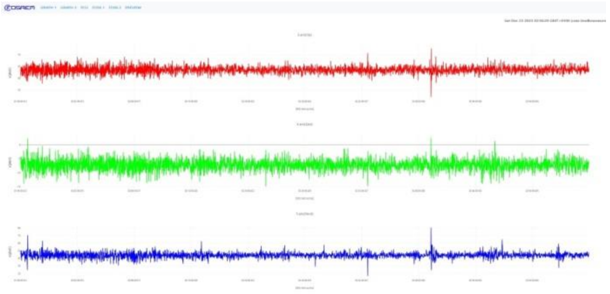
Remote control by webpage

System control

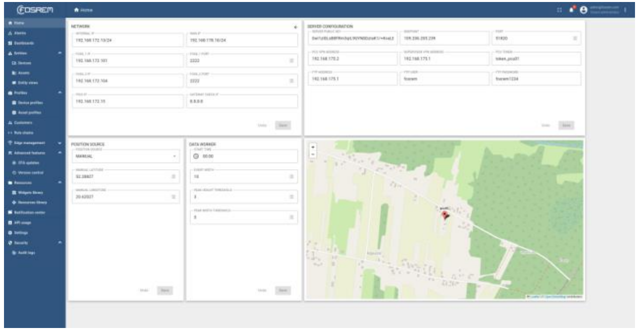
Paramters change



Data downloading



Localization



Conclusions

1 Data confirmed high reliability of recordings gathered by 3-axial Fibre-Optic Rotational Seismograph (correlation coefficient was near the value of 100%)

2 FORS recorded successfully artificial explosions in field test carried out in Szopowe, Poland which confirmed its usefulness of monitoring detonation tests, especially in border areas.

3 FORS main paramters:

- dynamics of 180 dB
- frequency detection bandpass: from 0.01 to 100 Hz
- built-in time scale synchronization system (accuracy 100ns)
- weight: less than 10 kg
- web-Based Management Interface
- possibility of mobile, autonomous operation

4 Future plans – 6 DoF recordings

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Polish Agency for Enterprise Development project FENG.01.01-IP.02-1714/23 (FOM-MEM)
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Meet Our Team

https://fosrem.eu/

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Thank You

FOSREM - FROM SKY ACROSS GROUND UP TO UNDERGROUND

FOM-MEM - FIBRE-OPTIC MATRIX FOR MECHANICAL EVENTS MAPPING

WAT

ELPROMA ELECTRONICS