Perspective instrumentation for rotational motion investigation in seismology

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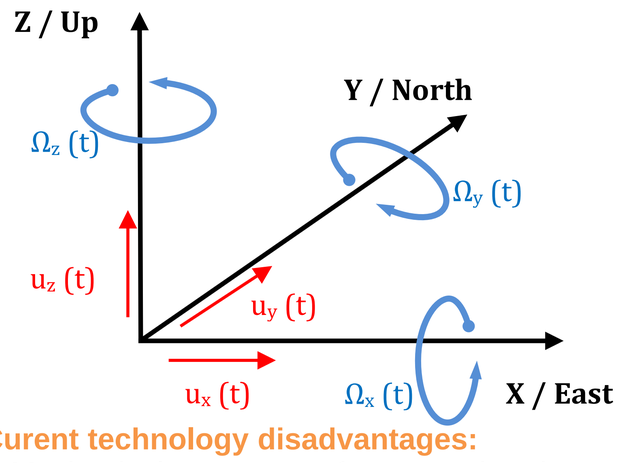
Rotational Seismology is an emerging field for the study of all aspects of rotational ground motion induced by earthquakes, explosions, and ambient vibrations [Lee et al. *BSSA*, 2009, *99*, 945-957].

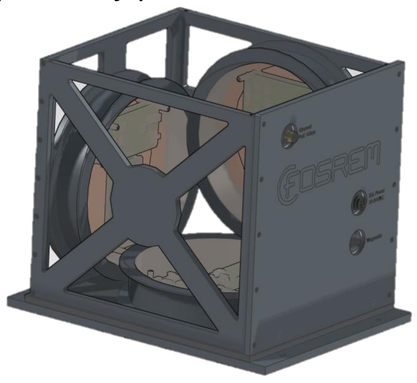


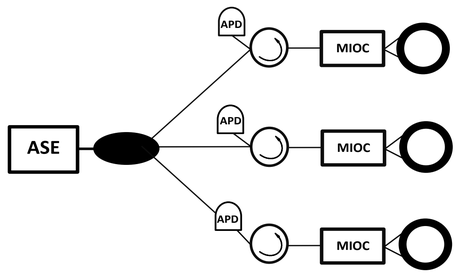
Curent technology disadvantages:

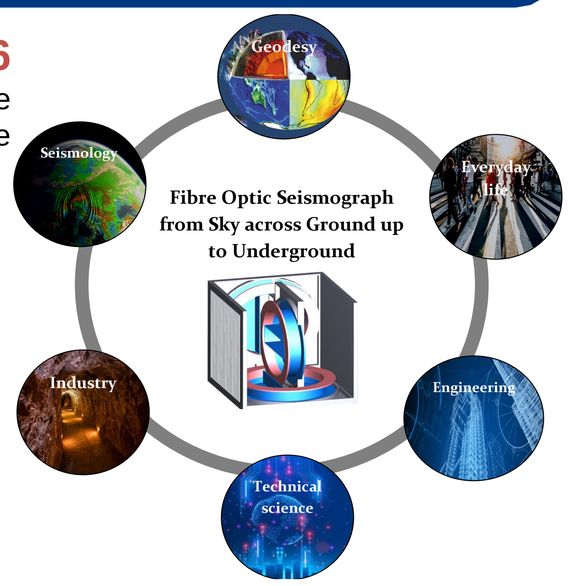
- Mechanical: too narrow frequency band or too low maximal detected rotation rate
- Electromechanical: due to its liquid inertia their application will be limited in the case of the loads
- Optical: large RLGs with sensitivity below 10^{-9} rad/s but they are stationary systems

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

Fibre-Optic Rotational Seismograph (FORS) type FOS6 is a 3-axes interferometric optical fiber sensor designed to continuously observe rotational effects. It uses closed-loop configuration which is based on the compensatory phase measurement method as well as specific electronic system.







Allan Variance analysis (AV) was applied to determine the basic parameters of the random errors of FOS

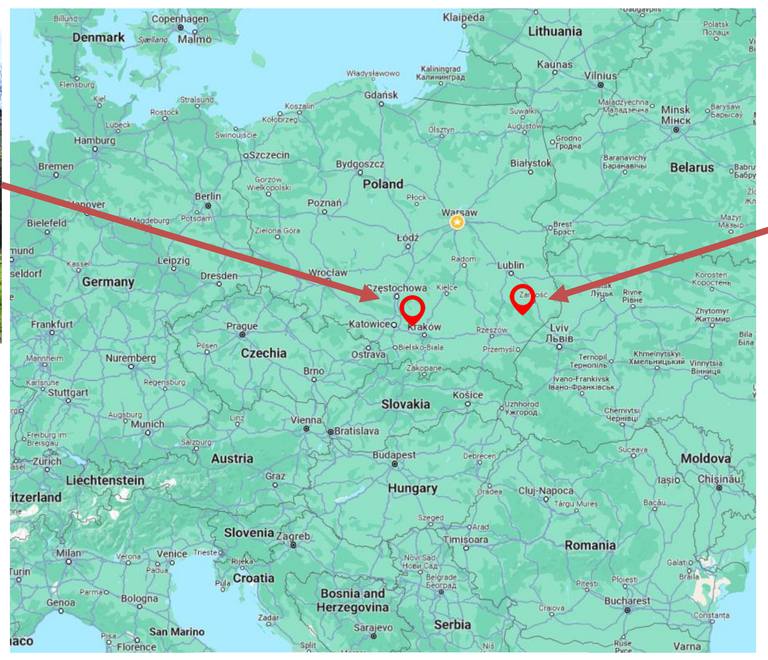
$$ARW = \frac{\sqrt{2}\lambda c}{2\pi DL}\sqrt{\frac{4kT}{R\eta^2P^2} + \frac{ei_d}{\eta^2P^2} + \frac{e}{\eta P} + \frac{\lambda^2}{4c\Delta\lambda}}$$

λ – central light wavelength, c – speed of the light, D – loop diameter, L - loop length, k - Boltzmann's constant, T – temperature, R - resistance of the transimpedance transducer of the photodetector device, η - efficiency ratio of photodiode, P - incident optical power on the APD, e - elementary charge, i_d - photodiode dark current, $\Delta\lambda$ - spectral width of the light source. The theortecially calculated values of ARW for optical heads are equal to **2.03 nrad/√s**

Field measurements

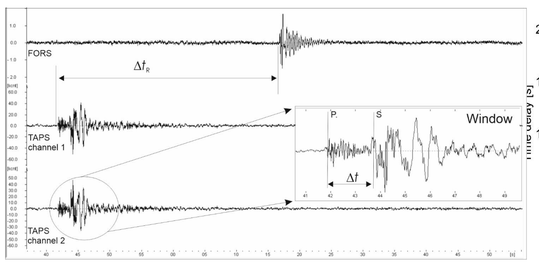
Observing time delays between the linear and rotational components

Geophysical Observatory of the Institute of Geophysics of the Polish Academy of Sciences in Ojców, Poland
Coordinates: 50.2196 N 19.7984° E
Height: 391 m a.s.l.
Localization: Ojców National Park, Sąspówka valley, free from disturbances caused by human activity

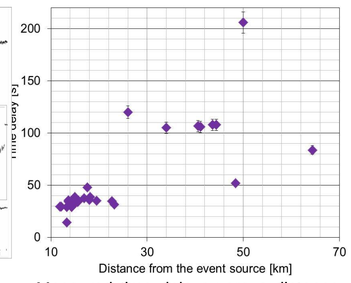


Observing rotational motions during explosions

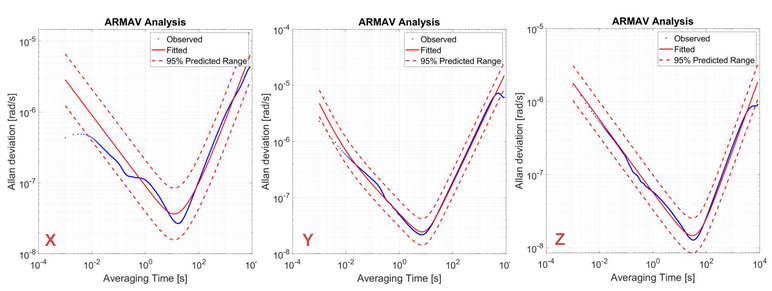
Szopowo, Poland (near the Ukrainian border)
Coordinates: 50.5177 N 23.0638° E
11 different rotational fibre optic sensors were used in the tests, including 2xFOS6 (3D-6C), 3xFOS5 (1D-1C), 3xMSMS1 (3D-6C) and 3xMSMS2 (3D-3C); Sensors were placed at a distance of 150 to 1000 m from point of two explosions:
1– 5 kg, 3 m below the ground surface with surface discharge
2 – 2 x 5kg, 4.5 m below the ground surface with a distance of 5 m between loads



Example of seismograph recorded by FORS and two channels of TAPS, the inside small bottom-right window shows idea of estimation time delay between S- and P-waves

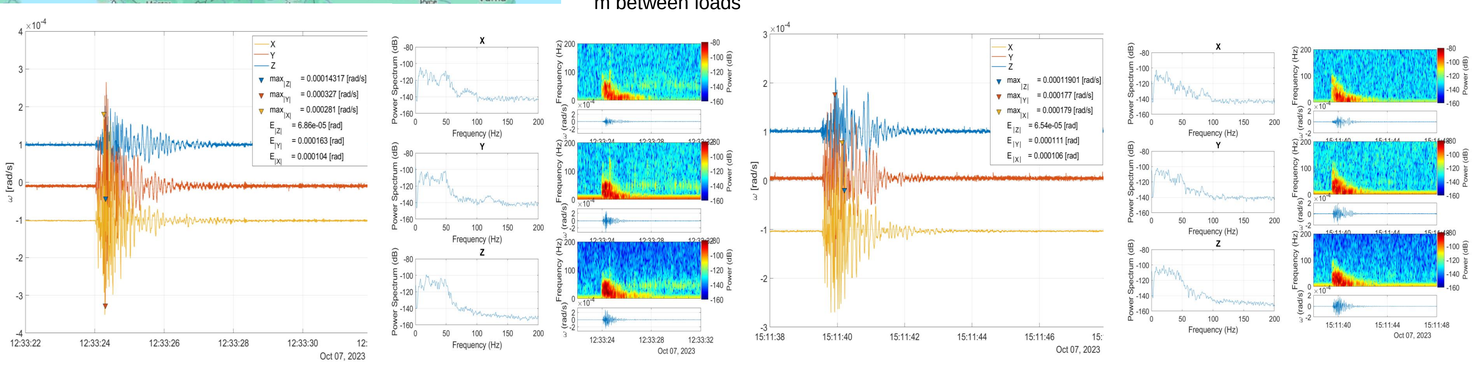


Measured time delays versus distance from the event source



Axis	ARW [nrad/√s]	BI [nrad/s]
X	100	40
Y	50	35
Z	60	20

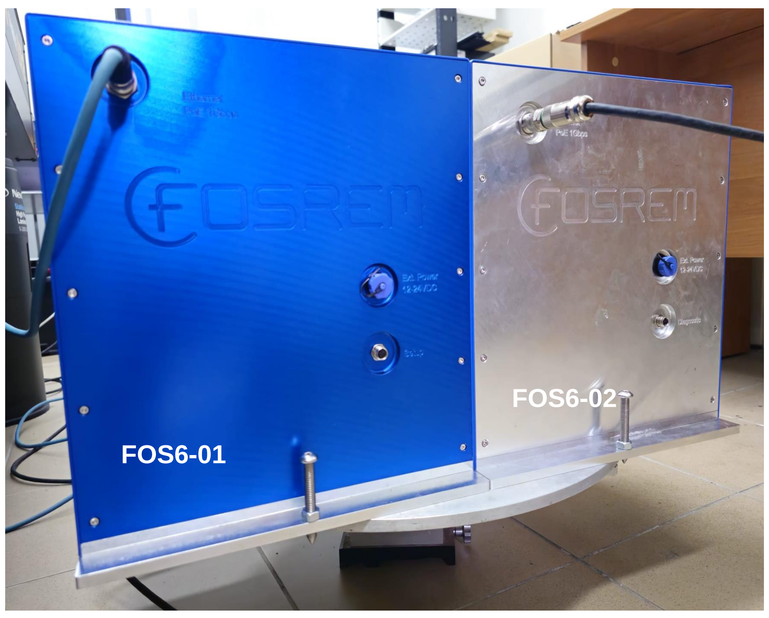
Angle/velocity random walk (ARW) and bias instability (BI) determined by AV analysis for particular axis

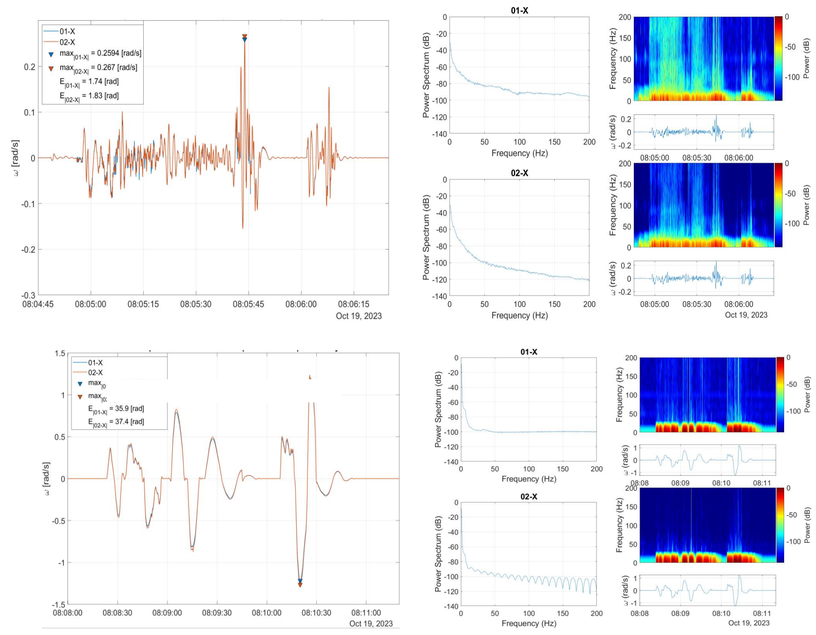


Technical parameters

Max. measurable rotational rate	10 rad/s
Sensitivity	dozens nrad/s/√Hz
Frequency bandpass	0.01 - 100 Hz
Configuration	Closed-loop configuration with digital processing
Communication	Ethternet, WiFi, 4G/5G/SAT WWAN, miniSSED (TCP/UDP), PTP for time stamping, GNSS
Data storage	Up to 512GB SSD in PCU can store up to 30 days of measurement data
Interfaces	1Gbps RJ-45 with PoE and PTP
Management	Local and remote management and data acquisition over Internet
Power supply	12 - 24 VDC, via Power Communication Unit over PoE
Power consumption	less than 20W
Dimensions, weight	360 x 300 x 295mm, 20 kg
Ingress protection	IP66

Pearson correlation coefficient between signals from two FOS6: 99.42%; 99.99%





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