A historical perspective of the fibre-optic seismographs and their field application: the past, present and exciting future

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- Sensors, Sensing Structures and Methods
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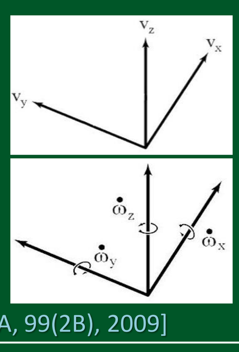
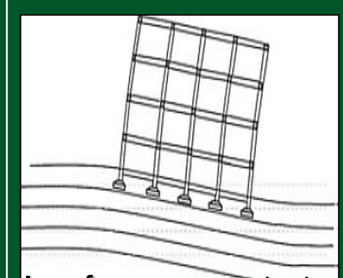
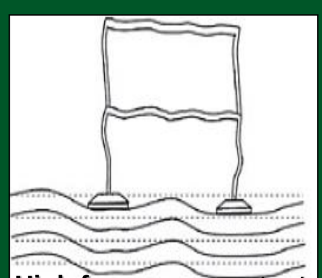
MOTIVATION

Rotational Seismology [Lee et al., *BSSA*, 2009, 99, 945-957]

an emerging field for the study of all aspects of rotational ground motion induced by earthquakes, explosions, and ambient vibrations

Requirements for rotational seismometer

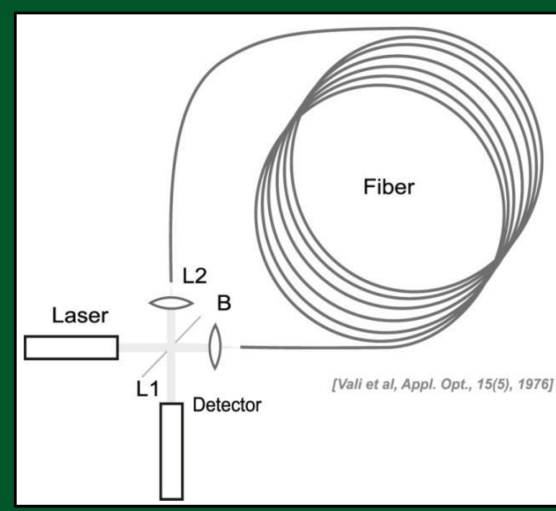
Seismological application	Engineering application
  [Evans, J. R. BSSA, 99(2B), 2009]	  [Castellani, G. 2nd workshop of IWGoRS, 2010]
Insensitivity to linear motion, or at any time opportunity to detect linear and rotational motions independently	
Mobility, stability with respect to environmental conditions, including changes of temperature	
Independent power supply	
Measuring range: signal amplitude: from 10^{-8} rad/s, frequency: 0.01 Hz – 0.1 Hz	Measuring range: signal amplitude: up to 10 rad/s, frequency: 0.01 Hz – 100 Hz

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

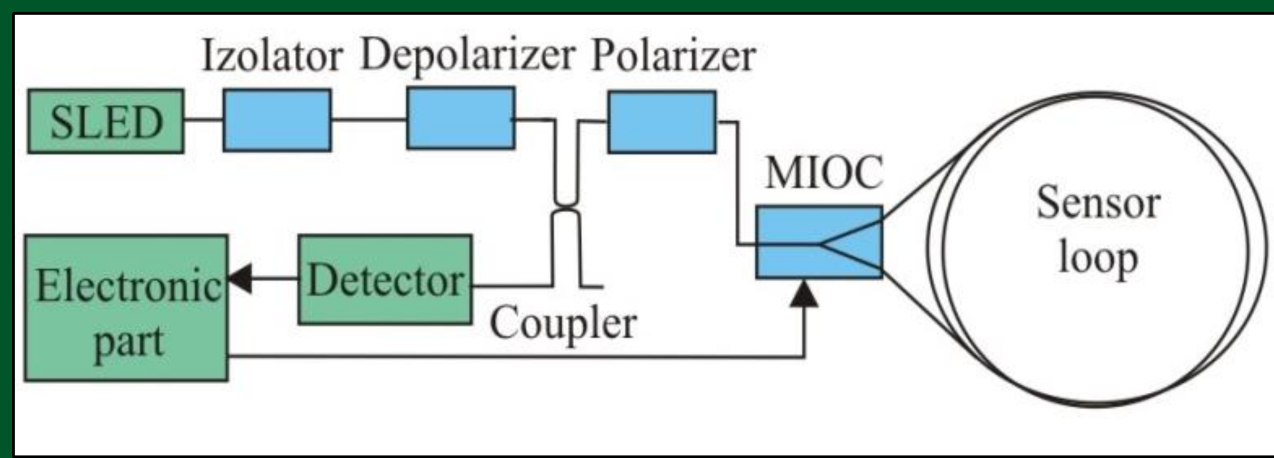
BACKGROUND

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

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

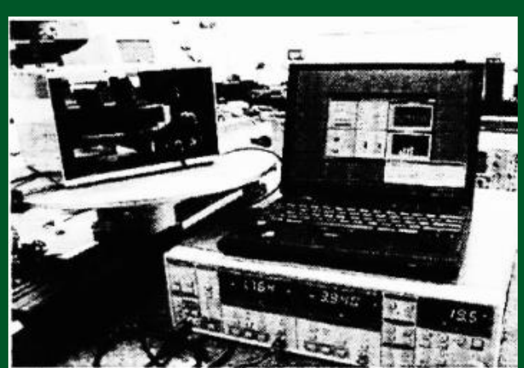


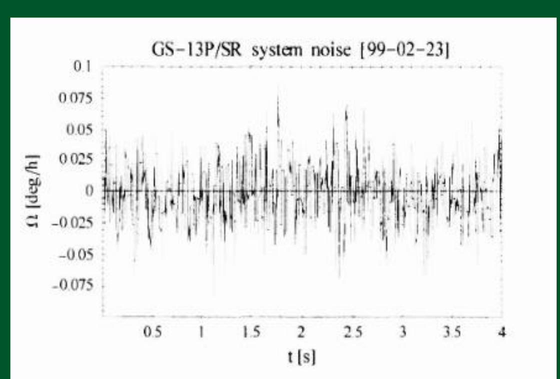
L – length of the fiber in the sensor loop, R – sensor loop radius, λ – wavelength of used source, c – velocity of the light in vacuum, S_0 – the optical constant of interferometer



CONSTRUCTION

1. Gyro System for Platform Investigation (GS-13P), 1998

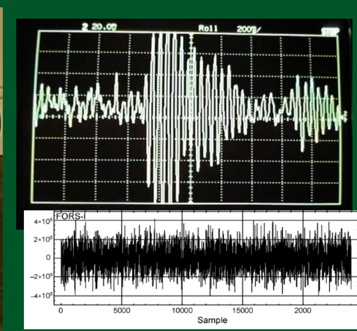




Sensitivity: $9.7 \cdot 10^{-7}$ rad/s
Max. detectable signal: $4.8 \cdot 10^{-4}$ rad/s
Sensor loop: a 380 m length of PANDA fiber, radius of 0.1 m

[Jaroszewicz, L. R. et al., Proc. SPIE 3479, 1998]

2. Fibre-Optic Rotational Seismometer (FORS-I), 2001



I. Sensitivity: $2.2 \cdot 10^{-6}$ rad/s
Max. detectable signal: $4.8 \cdot 10^{-4}$ rad/s
Sensor loop: a 400 m length of PANDA fiber, radius of 0.1 m

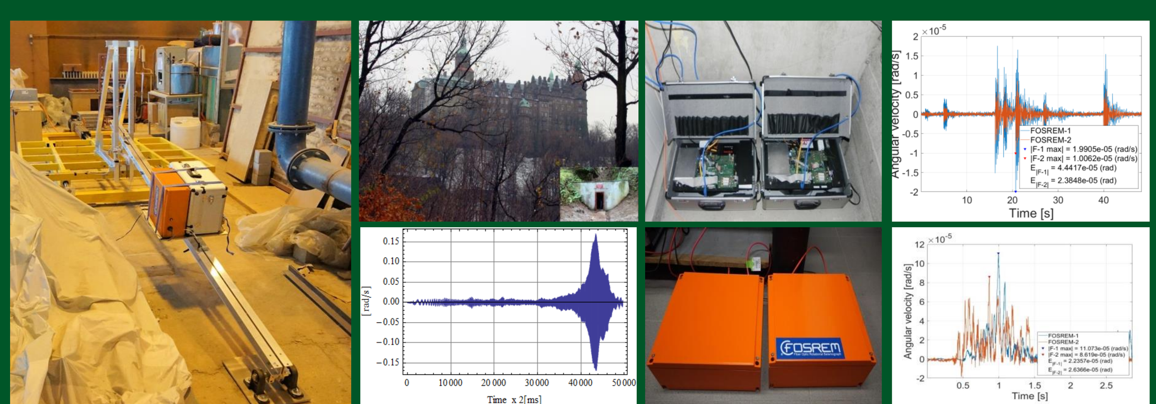
[Jaroszewicz, L. R., et al., Molecular and Quantum Acoustics, 22, 133-144, 2001]
[Krajewski, Z. et al., Proc. SPIE, 5484, 2004]

3. Autonomous Fibre-Optic Rotational Seismograph (FORS-II or FOS1, AFORS or FOS2), 2004, 2010

FOS1: II.Sensitivity: $4.2 \cdot 10^{-8}$ rad/s
Max. detectable signal: $4.85 \cdot 10^{-4}$ rad/s
Sensor loop: a 11 000m length of SMF, radius of 0.34 m
FOS2: Sensitivity: $4 \cdot 10^{-9}$ rad/s
Max. detectable signal: $6.4 \cdot 10^{-3}$ rad/s
Sensor loop: a 15 000 m length of SMF, radius of 0.34 m

[Jaroszewicz, L. R. et al., Acta Geophysica, 59, 578-596, 2011] [Kurzych, A. et al., Sensors, 14(3), 5459-5469, 2014]

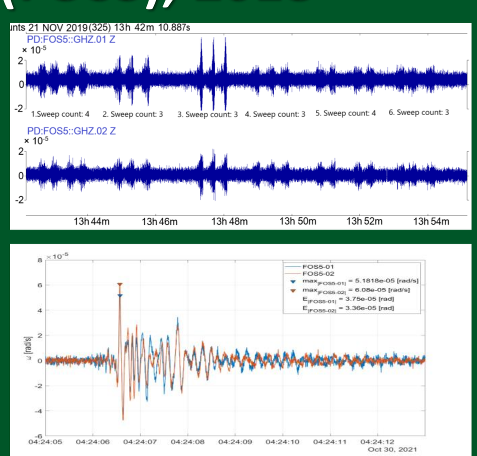
4. Fibre-Optic System for Rotational Events and Phenomena Monitoring (FOSREM – FOS3 & FOS4), 2015

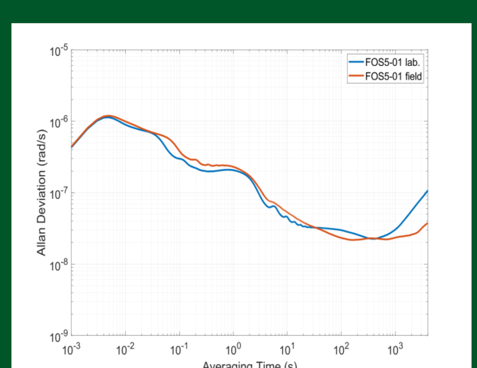


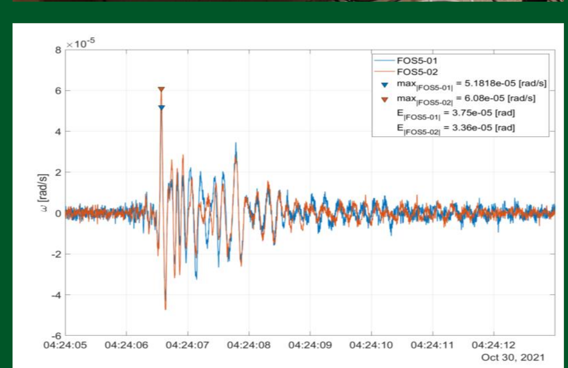
Sensitivity: $2 \cdot 10^{-8}$ rad/s
Max. detectable signal: few rad/s
Sensor loop: a 5 000 m length of SMF, radius of 0.125 m

[Kurzych, A. T. et. al., JLT, 36, 879-884, 2018] [Jaroszewicz, L. R. et. al.,Sensors,19, 2699, 2019]
[Kurzych, A. T. et. al., JLT 37(18), 4851-4857, 2019]

5. Fibre-Optic Seismograph (FOS5), 2018







[Kurzych, A.T. et al., Sensors, 20, 6107, 2020]
[Bernauer, F. et al., Sensors, 21, 264, 2021]
[Jaroszewicz, L. et al., Opto-electron Rev. 29(4), 2021]

Sensitivity: $7 \cdot 10^{-8}$ rad/s
Max. detectable signal: 10 rad/s
Sensor loop: a 5 000 m length of SMF, radius of 0.125 m

6. FOSREM-3D (FOS6) main parameters:

- Three axes
- Measuring range from several dozen nrad/s to 10 rad/s (dynamics of 180 dB)
- Frequency detection bandpass: from DC to 100 Hz
- Built-in time scale synchronization system (accuracy 10 µs)
- Weight: less than 10 kg
- Web-Based Management Interface
- Possibility of mobile, autonomous operation; equipped with photo-solar cells, battery or wind generator

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