# Rotational Seismology Measurement Possibilities Based on Fiber-Optic Rotational Seismometer

# Outline

# Rotational Seismology
# Physical investigation
# Instrumental requirements
# Review of existing solutions
# Fiber-optic seismometer
# AFORS – critical remarks
# FOSREM – towards final success
# Acknowledgements

# 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 all, *BSSA*, **99,** (2009), 945-957].

Rotational seismology areas of interest [Lee et all, *Seis. Res. Let.*, **80**(3), (2009), 479-489]:

1. wide range of geophysical disciplines:

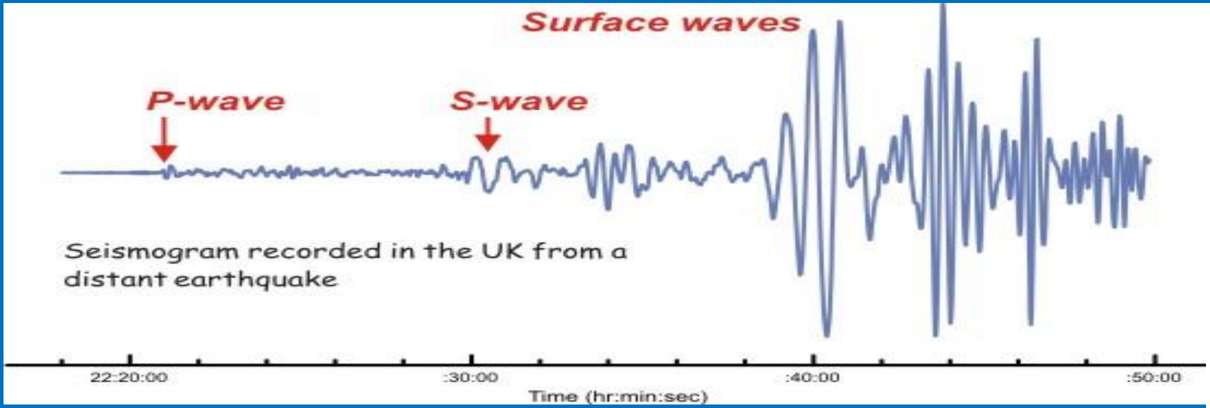
- broadband seismology [Igel et all, Geophys. J. Int., **168**(1), (2006), 182–197],
- strong-motion seismology [Anderson, *The International Handbook of Earthquake and Engineering Seismology*, 2003, Chap. 57, 937-965],
- earthquake physics [Teisseyre et all, Springer, 2006; Teisseyre i inni, Springer, 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 all, *Rep. Prog. Phys.*, **63**, (2000), 1317–1427; Lantz i inni, *BSSA*, **99, (**2009), 980-989];

2. earthquake engineering:

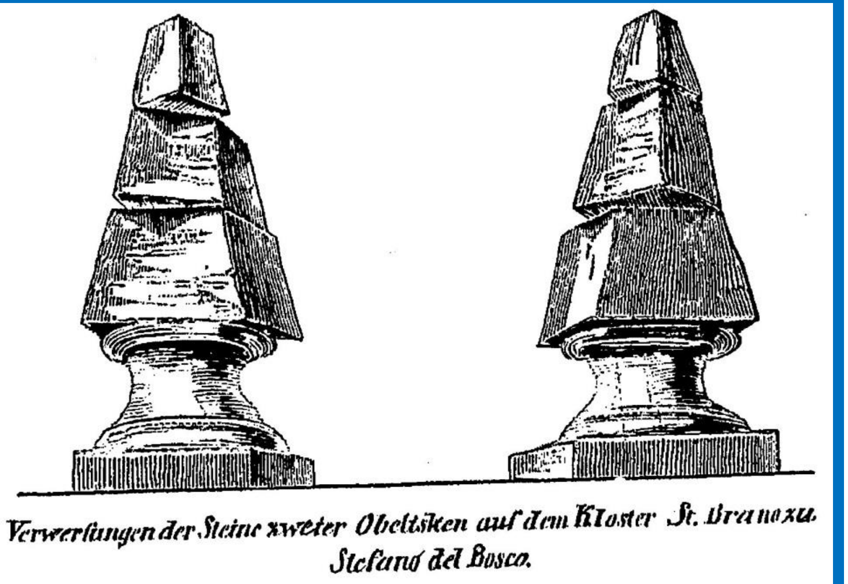
- seismic behaviour of irregular and complex civil structures [Trifunac, *BSSA*, **99, (**2009), 968-97; Mustafa, InTech, 2015].

# Physical investigation

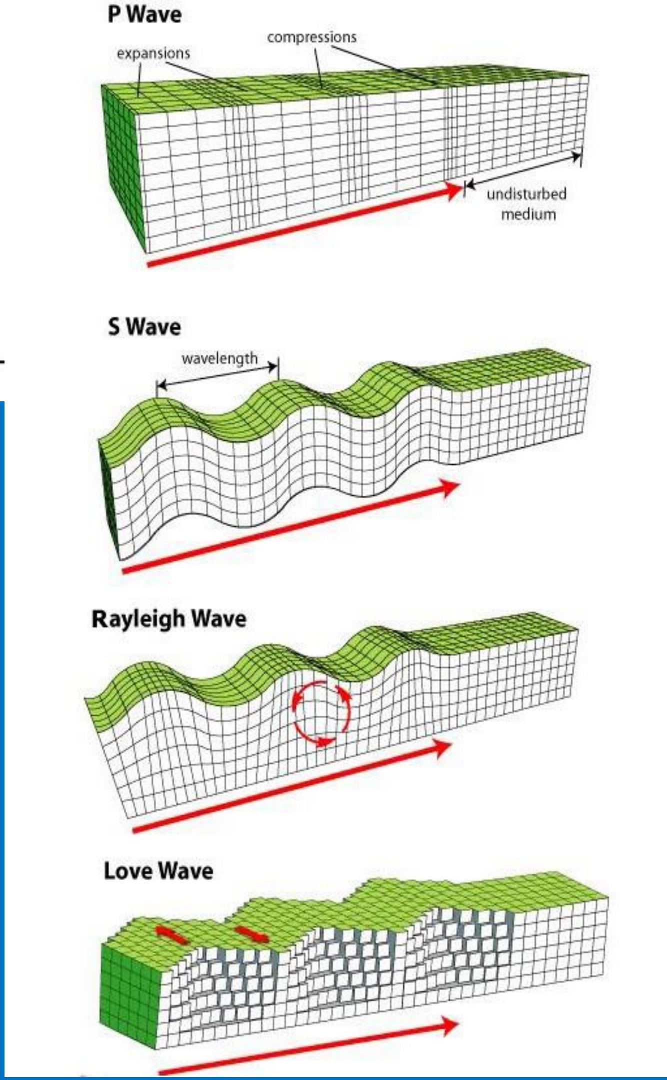
1. Geophysical aspects of rotation in earthquakes




Kushiro, 2003



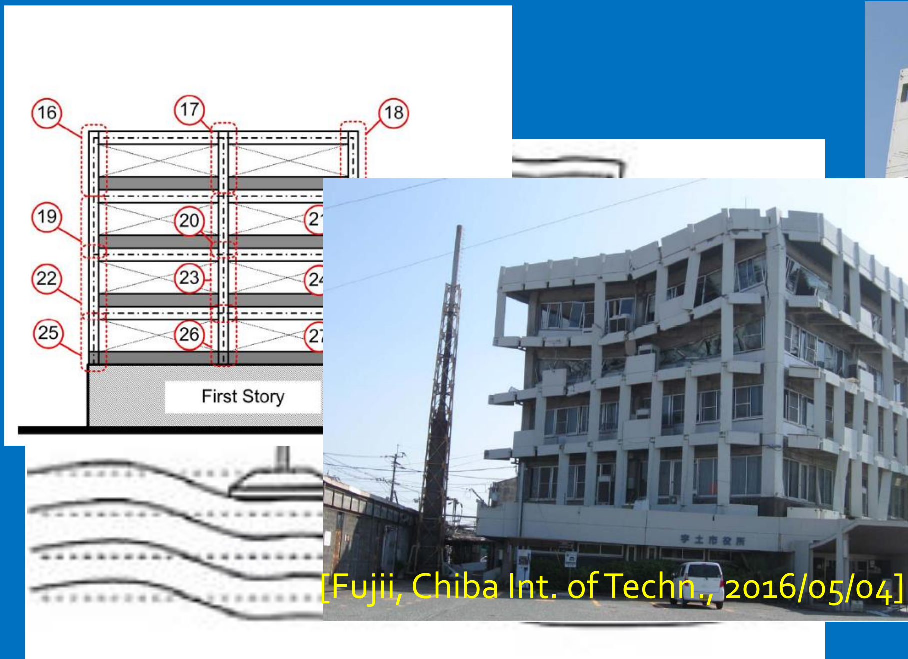

CALABRIA, 05.02.1783




[Hinzen, *J. Seisml.*, **16**(4), (2012), 797–814 ]

# Physical investigation

2. Effect of rotation motion on engineering structures




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

[Photo. Z. Zembaty]

## High frequency content

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

## Low frequency content

- Higher stress in structural element
- **Overturning moment**
- Horizontal displacement of the center of mass

[Castellani, *2nd IWGoRS workshop*, Masaryk's College Prague, (2010)]

# Instrumental requirements

**1. „Seismological" applications**

[Bernauer et all, *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.

**2. „Engineering" applications**

[Jaroszewicz et all, *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

# Review of existing solutions

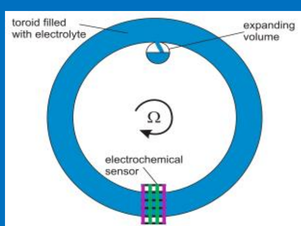
**1. Mechanical type (nondirect based on velocity or accelerometer type seismometer)**

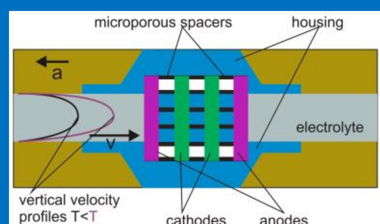
Limited: frequency range, max. detectable rotation rate




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

hight thermal instability, problem with electroliyte inertia



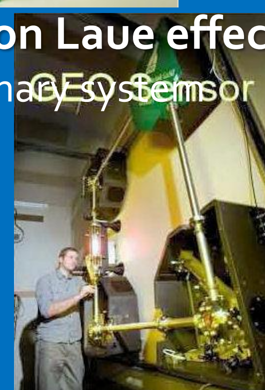



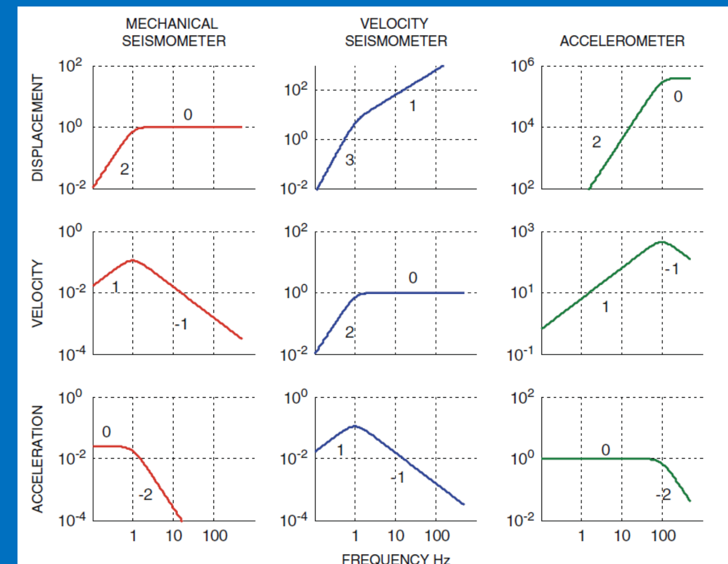


**3. Optical type (direct based on Sagnac-von Laue effect)**

opimal for seismological applications, but stationary systems





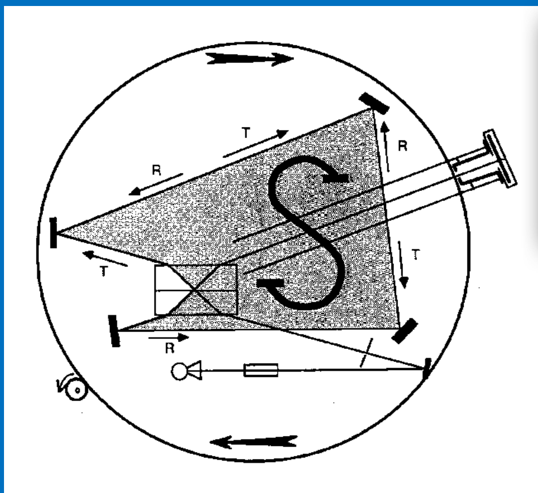



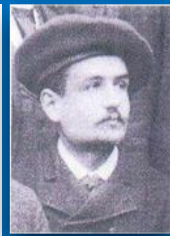

[Havskov, Alguacil, *Instrumentation in Earthquake Seismology*. Springer, 2016]

**Specialized system based on FOG**

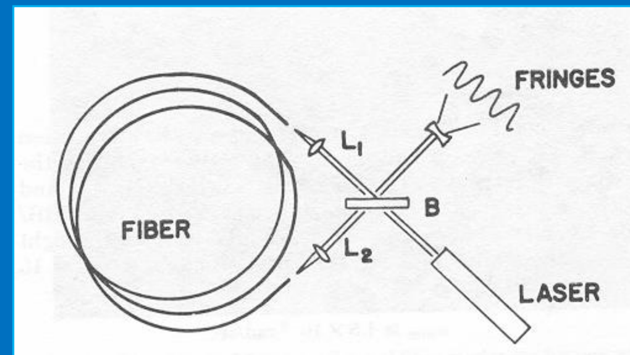

# Fiber-Optic seismometer

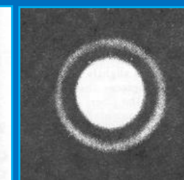
Sagnac – von Laue (1913/1911) effect in F-O technology



$$\Delta Z = 4\frac{\mathbf{\Omega.S}}{\lambda_0 c}$$



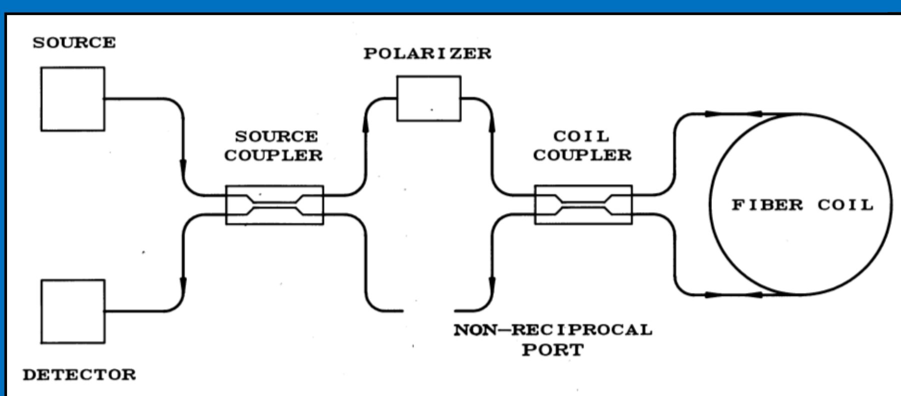



$$\Delta\varphi = \frac{4\pi RL}{\lambda c}\Omega = \frac{1}{S_0}\Omega$$

[Post, *Rev. Mod. Phys.*, ***39,*** *1967*]

[Vali, Shorthil, *Appl. Opt., 15(5), 1976*]

Minimum configuration → FOG system optimisation for angle (not rotation rate) detection





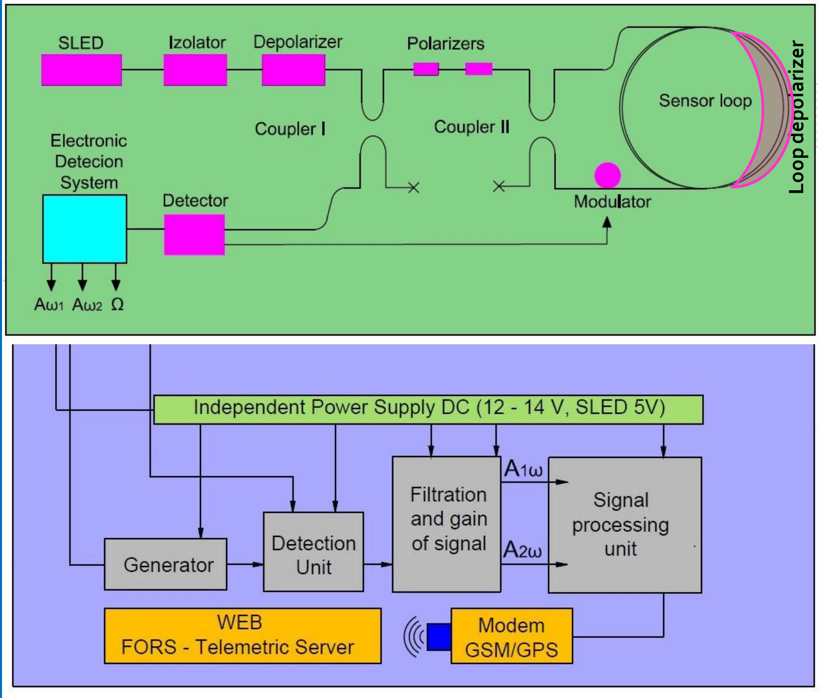
[private photo -*1999*]

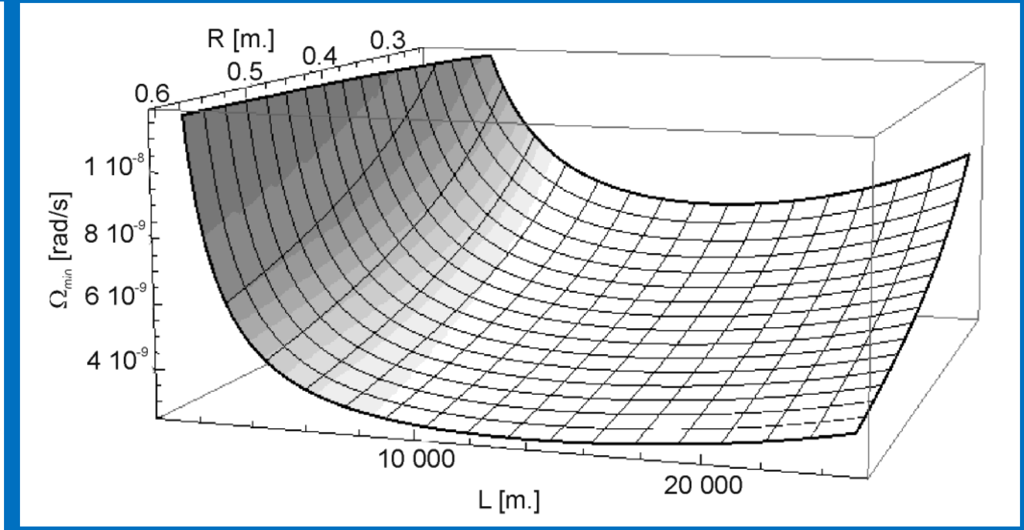
[private photo -*1999*]

# AFORS – critical remarks

1. Autonomous Fiber-Optic Rotational Seismograph

[Jaroszewicz et all, *Acta Geophys.*, **59**, (2011), 578-596]




- applied depolarised light for cost minimisation,
- ESPU optimised for detection rotation rate instead of angle (FOG):

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

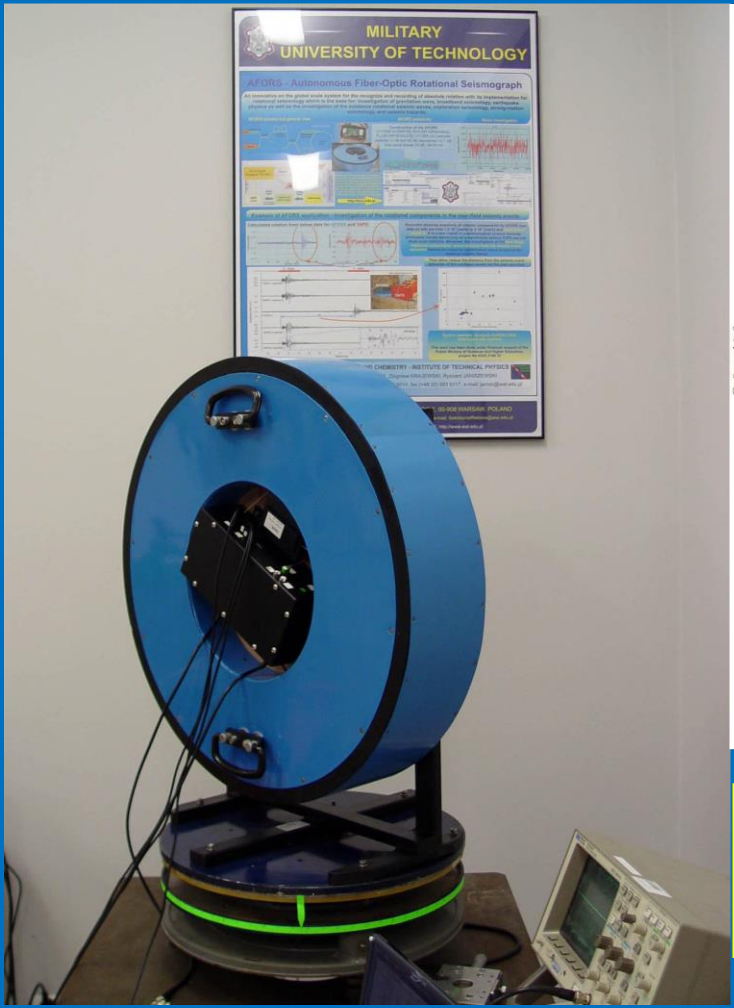
**AFORS optimisation of optical head:**

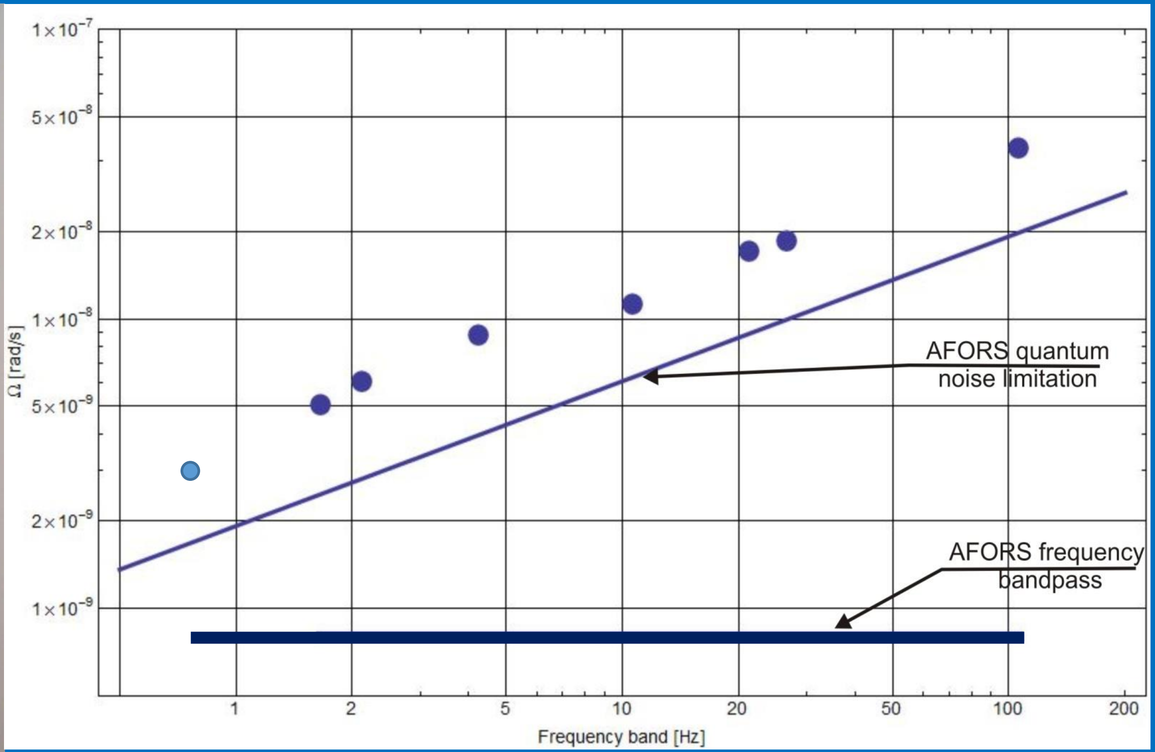
- L= 15 000 [m], 15 layers, quadrapole-bifilar winding,
- $\alpha$ =0.436 [dB/km],
- loop R=0.34 [m] with permaloy particles,
- $\sigma = 13.16$ [dB],
- cascade polarisers (46 and 55 [dB]),
- depolariser with P=0.002
- $\Delta\lambda$=31,2 [nm], $\lambda$=1326.9 [nm], $P_L$ =20 [mW],
- S=0.99 [ A/W], $I_A$ =0.06 [nA], $R_0$ =163 [k$\Omega$].

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

# AFORS – critical remarks

2. Optical/electronic constant ($S_o$, $S_e$) – system callibration on Earth rotation



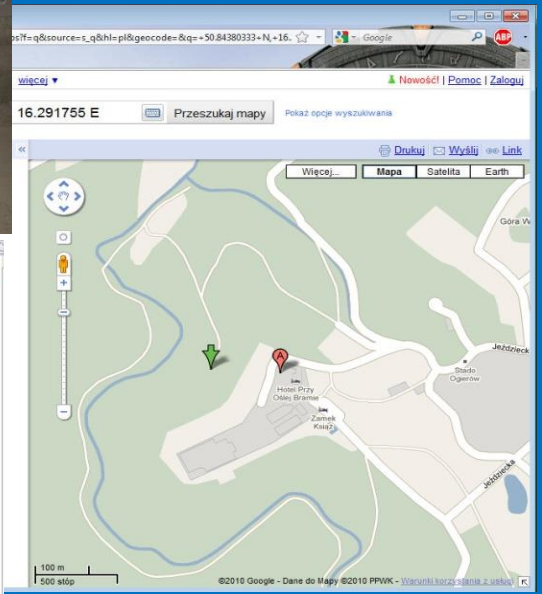



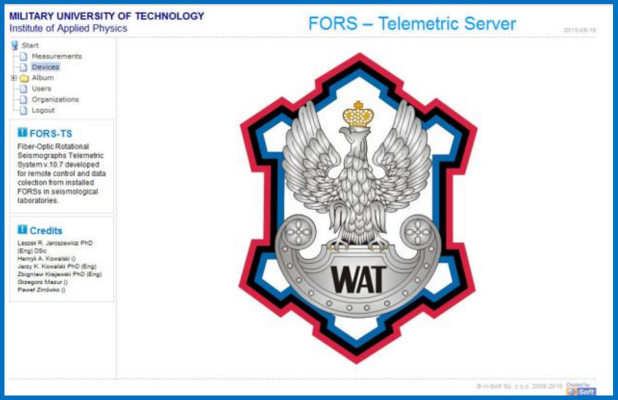

| | Accurcy | | |
|---|---|---|---|
| ΔB= | 0.83 [Hz] | 21.2 [Hz] | 106.15 [Hz] |
| | $3.6\ 10^{-9}$ [rad/s] | $1.7\ 10^{-8}$ [rad/s] | $3.9\ 10^{-8}$ [rad/s] |

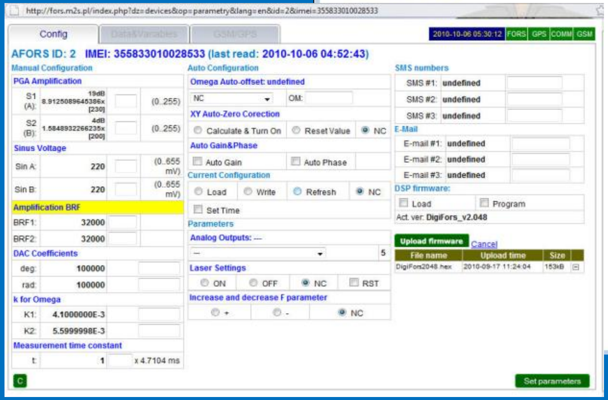
[Jaroszewicz et all, *J. Seismol.*, 16, (2012), 573-586]

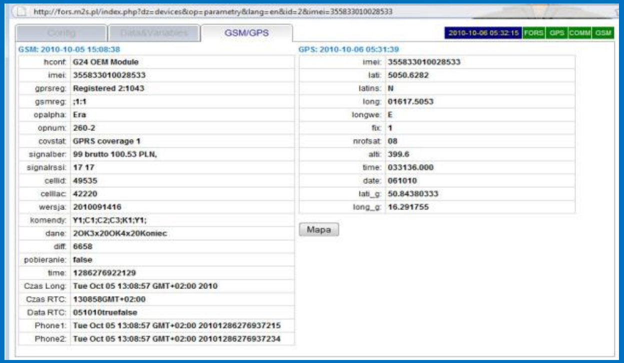
# AFORS – critical remarks

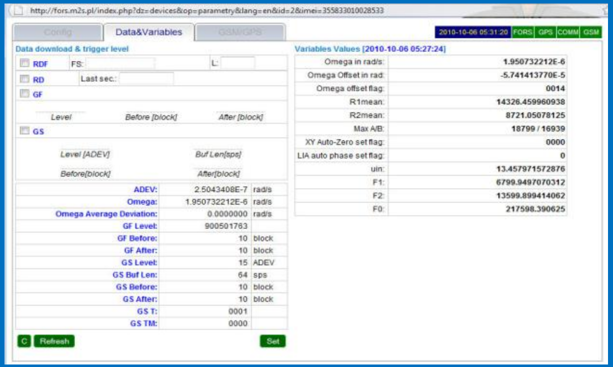
3. Operation as seismograph in real field application



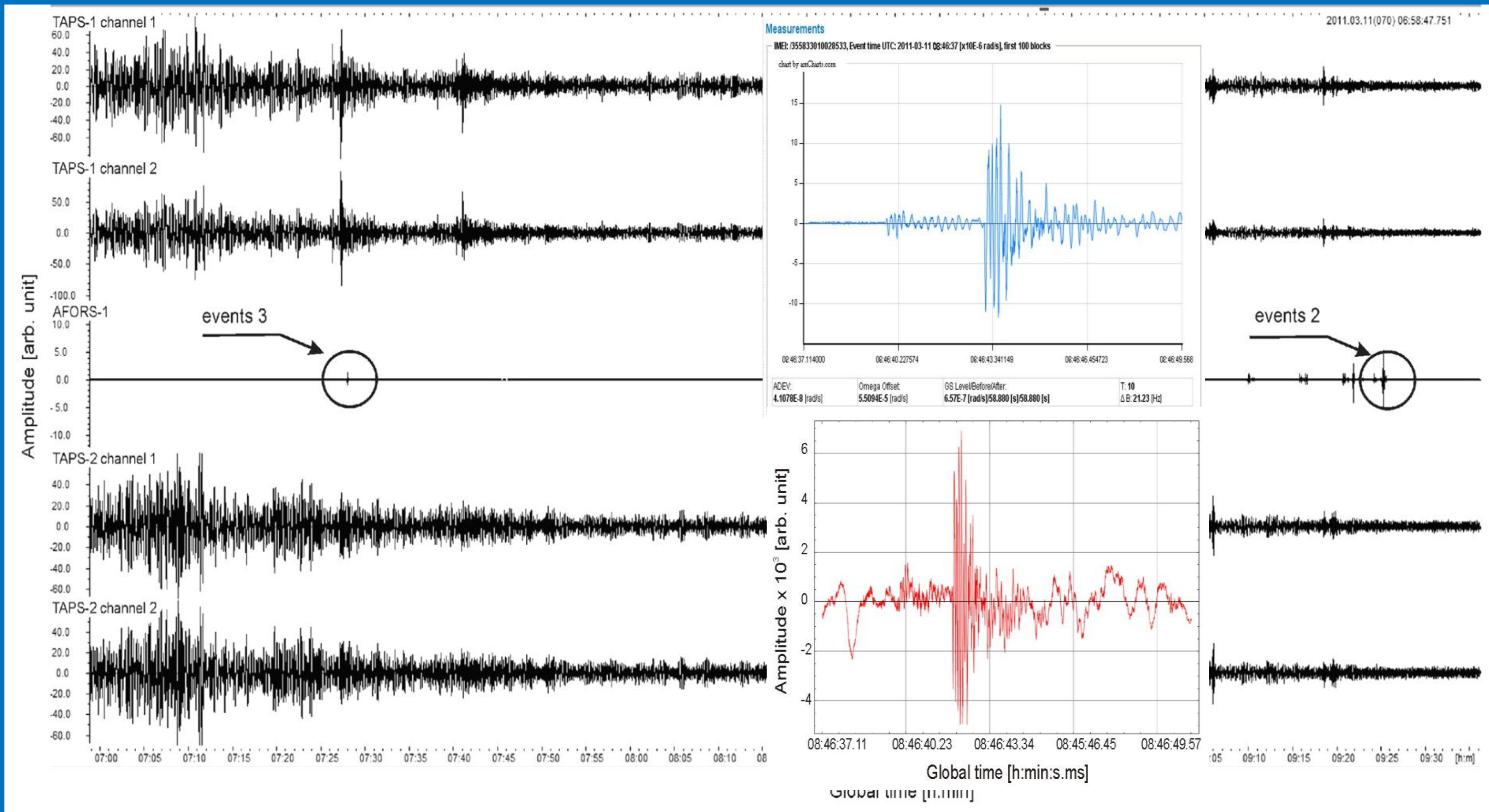




# AFORS – critical remarks

4. Seismogram recorded in Książ from Honshu earthquake (M=9.0) at 6:58, 11-03-2011



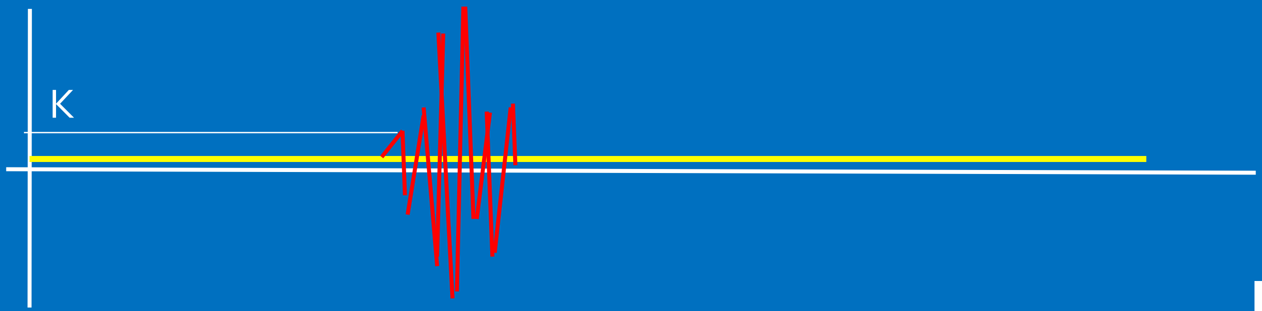

[Jaroszewicz et all, *J. Seismol.*, **16,** (2012), 573-586]

# AFORS – critical remarks

5. Special numerical approch to Ω detection on „drifting signal"

[Kurzych et all, *Sensors*, **14**, (2014), 5459-5469]

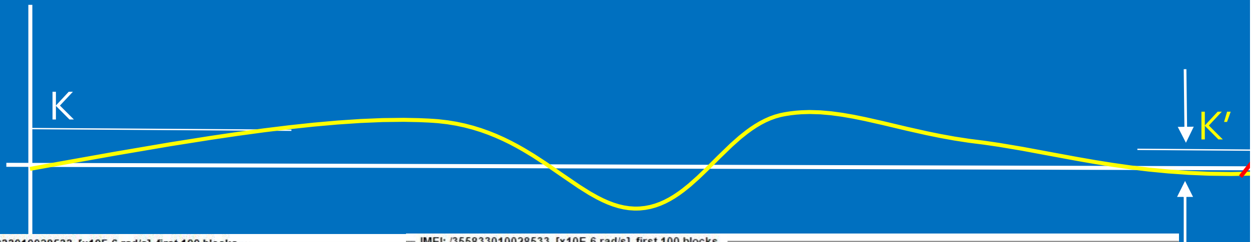
Ideal approach (without drift connected with bias phenomena)

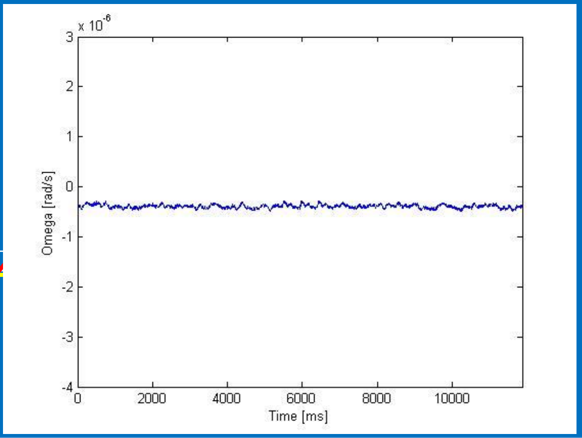


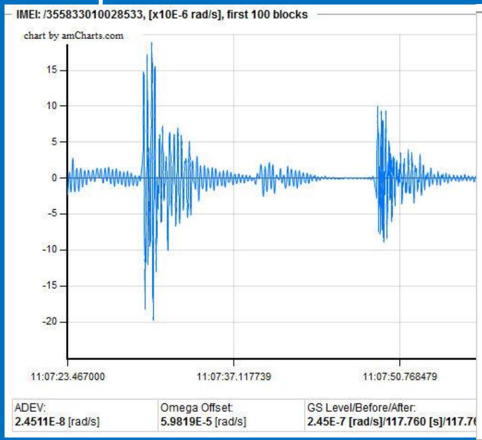

K – definied Ω level for start to recording data

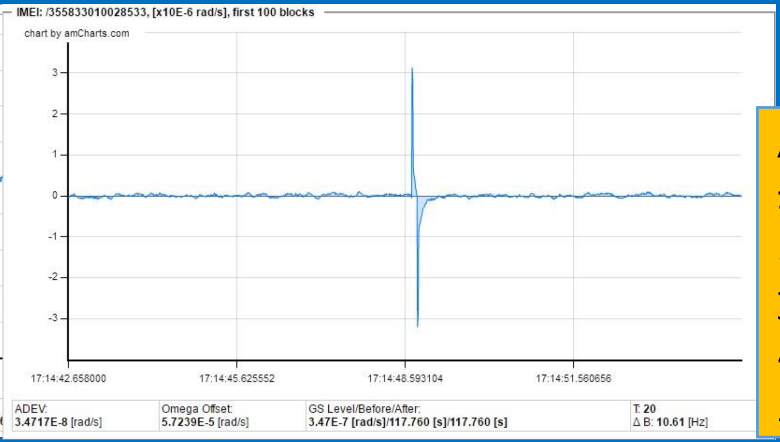
2. K" – definied for artefactes elimination

Real situation `drifting signal` (bias connected with enviroment)




**AFORS:**

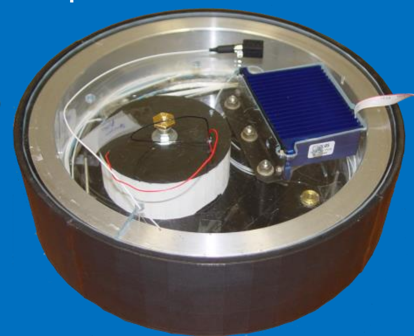
1. Too big size (0.6 m diameter)
2. Too big low frequency (0.83 Hz)
3. Too low max. Ω (0.006 rad/s)
4. Expensive device
5. Limited number of devices

# FOSREM – towards final success

Fibre-Optic System for Rotational Events & Phenomena Monitoring

FOSREM-SS

Optical module



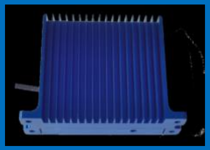
[Kurzych et all, *Opto-Electron.Rev.*, 24, (2016), 134-143]


FOSREM-BB

Electronic module

Analog & ADC

DSP & μ–computer



Laser

Power supply

[Pat. Appl. Pat. PCT/IB2015/059521, 10-12-2015]

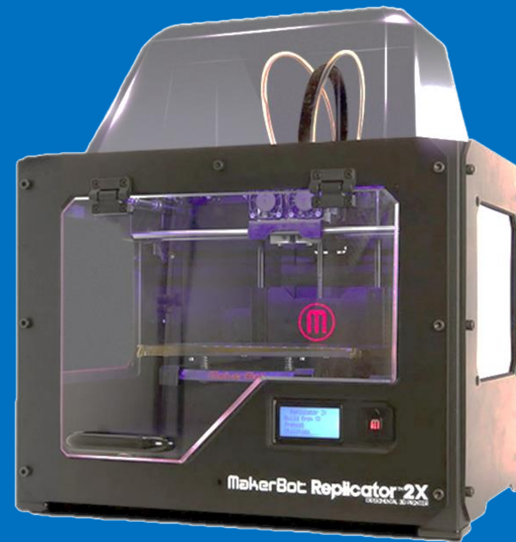
**FOSREM advantages:**

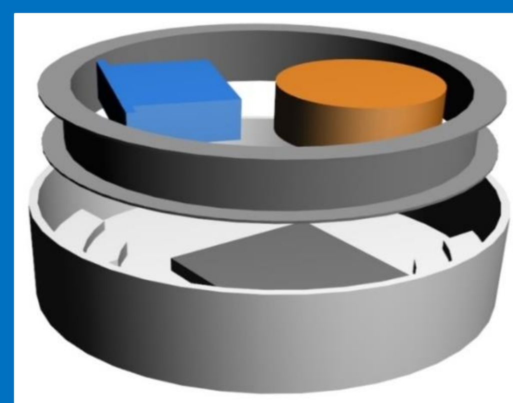
- Optimised optical head (5 km SMF-28, diameter 0,25 m);
- 3D printing structure – low cost;
- Long-life source (SLED);
- Theoretical sensitivity $2 \cdot 10^{-8}$ rad/s/$Hz^{1/2}$;
- Open-loop, digital processing
- Passband from DC to discrete value from 2.56 - 328.12 Hz);
- Max. rotation rate a few rad/s;
- Mobility (36x 36x16 cm, weight: 10 kg);
- Remote control via internet;
- Power supply: 230AC PCU, PoE 48V from PCU (3 seismometers)

# FOSREM – towards final success

1. Optimisation  of optical head fabrication cost


Special set-up for quadrapole-bifilar loop winding



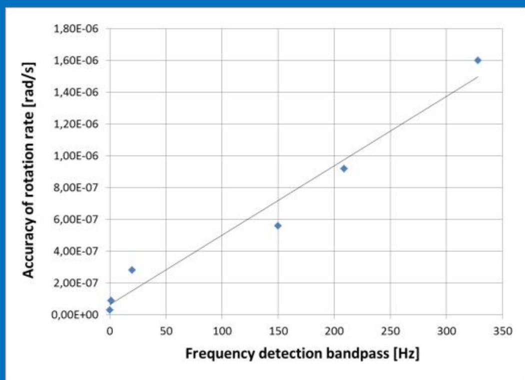




3D printer:  MakerBot Replicator 3X i Replicator Z18

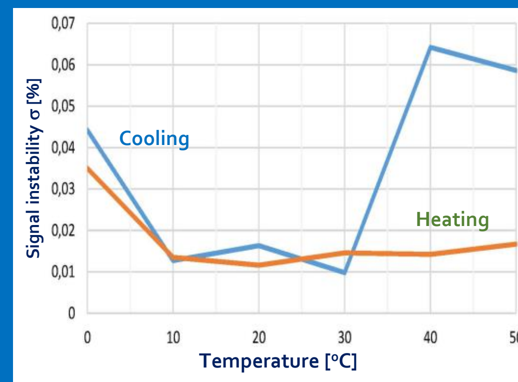
# FOSREM – towards final success

2. Laboratory investigation (thermal stability and bandpass accuracy)

FOSREM accuracy

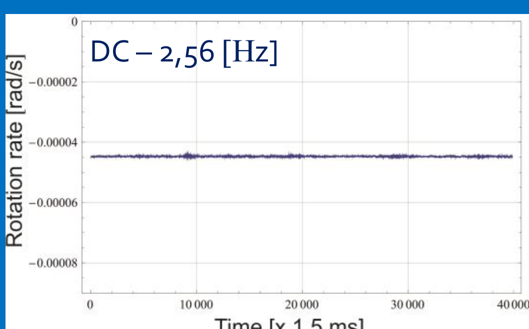


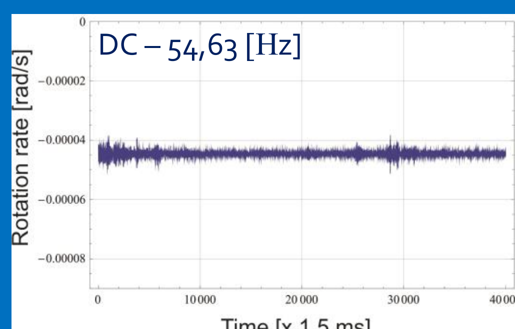

FOSREM thermal instability

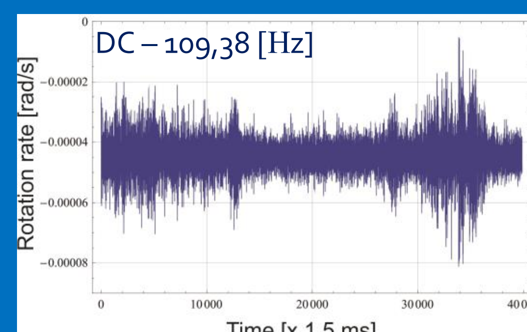



Climate chamber VCL 7010

Ω of Earth for Warsaw (4,45 $10^{-5}$ [rad/s]



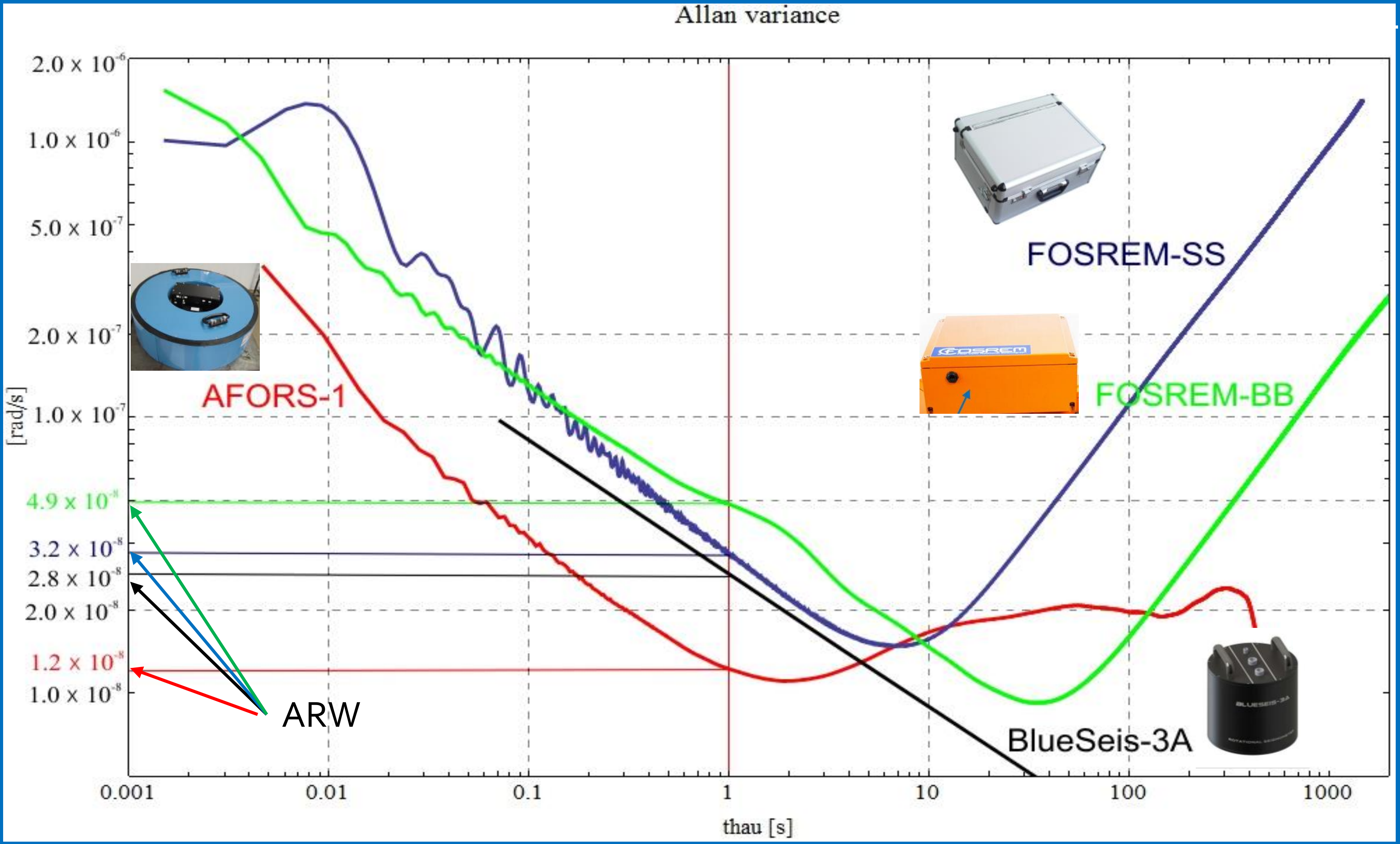




[Kurzych et all, *Opto-Electron. Rev.*, **24**, (2016), 134-143]

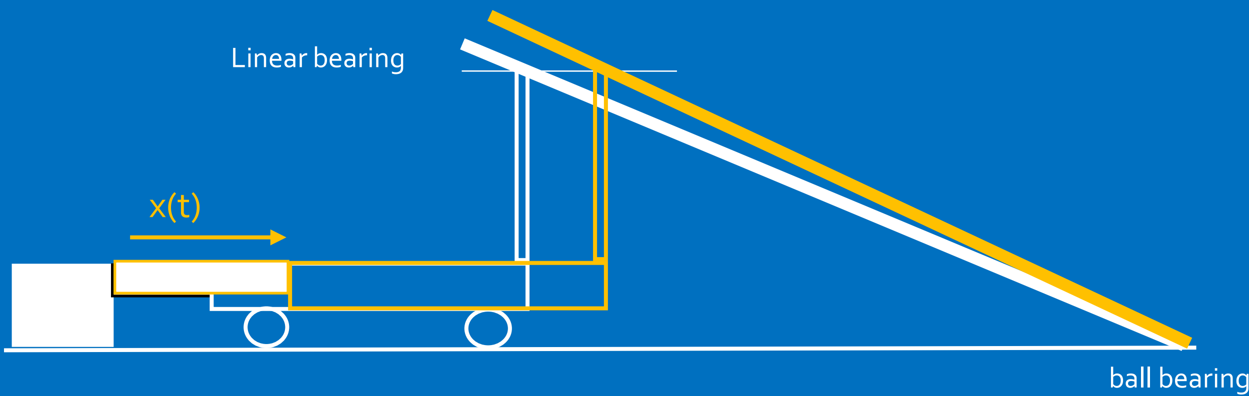
# FOSREM – towards final success

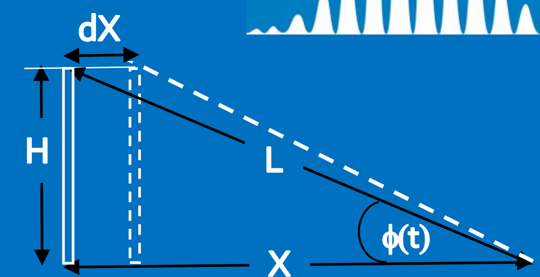
3. Noise analysis in Allan Variance approach



# FOSREM – towards final success

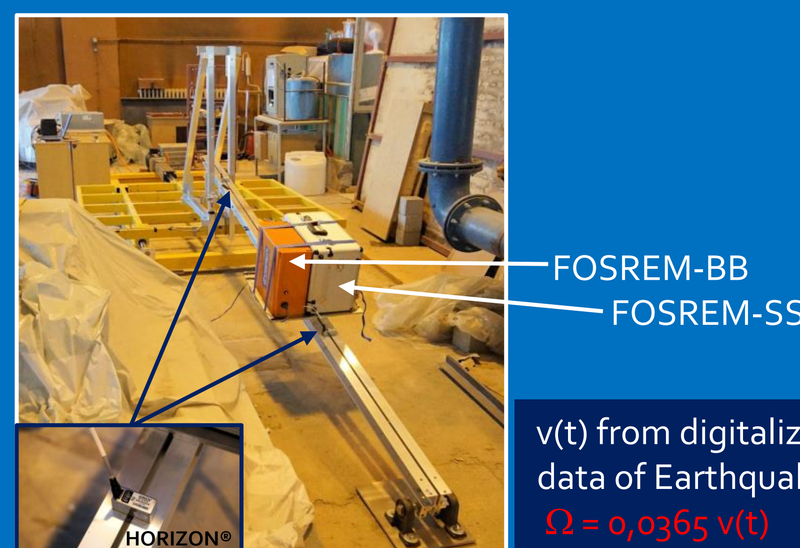
4. Earthquakes simulation in laboratory conditions




$$\phi(t) = \text{ctan}^{-1}\left[\frac{X-dX}{H}\right]$$

$$\Omega \equiv \frac{d\phi(t)}{dt} = \frac{1}{1+\left(\frac{X-dX}{H}\right)^2 H}\frac{dX}{dt}\Big|_{dX \ll X} = \frac{H}{\left[H^2+\left(\frac{X}{H}\right)^2\right]H}\, v(t) = \frac{H}{L^2}\, v(t) = 0{,}0365\, v(t), \qquad L = 3{,}7\ \text{m}, H = 0{,}5\ \text{m}$$

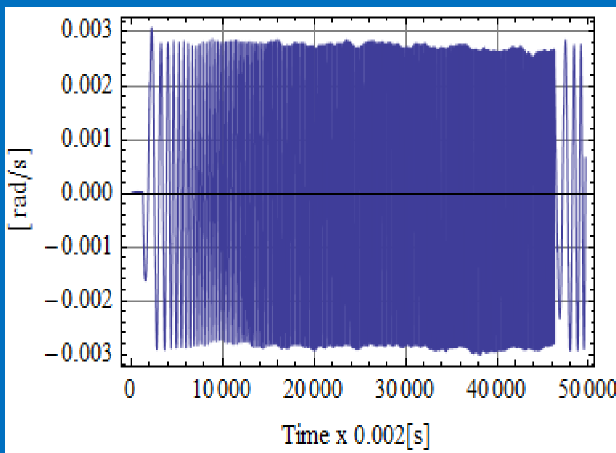




v(t) from digitalized data of Earthquakes
$\Omega = 0{,}0365\, v(t)$ (1)

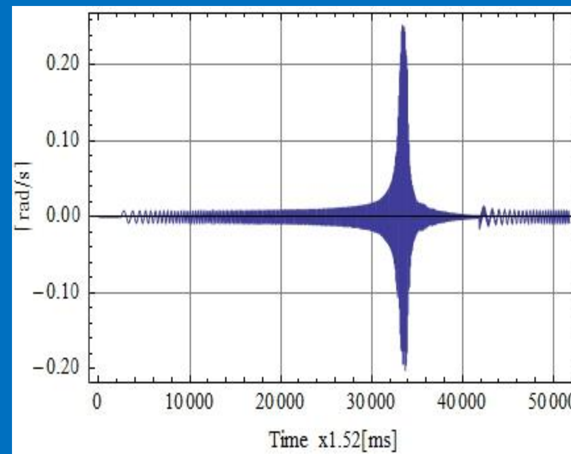
# FOSREM – towards final success

## 4. Earthquakes simulation in laboratory conditions

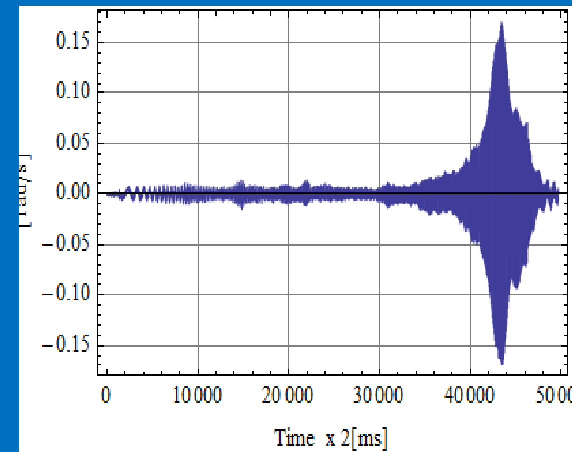
Calculation from formule (1)



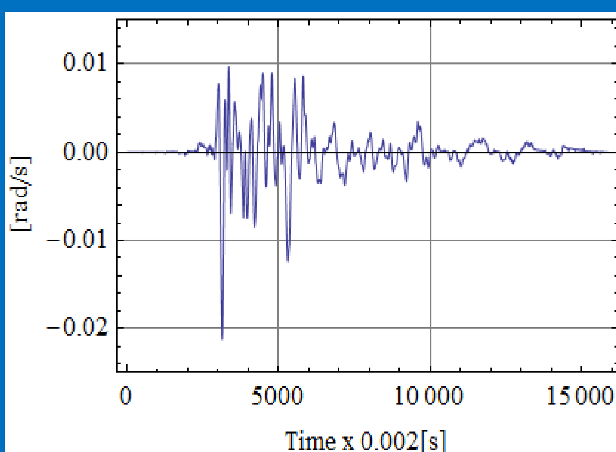

Data from FOSREM-BB

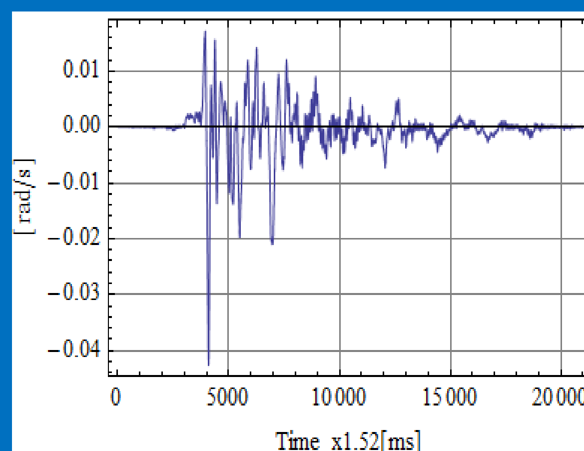


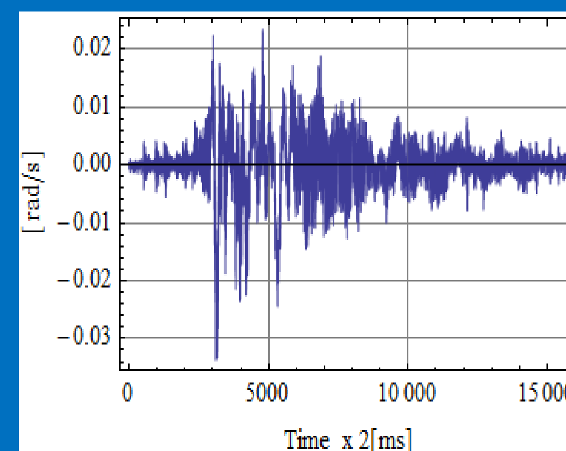

Data from Horizon HZ1-100-100




sweep sine 0.25-10 Hz



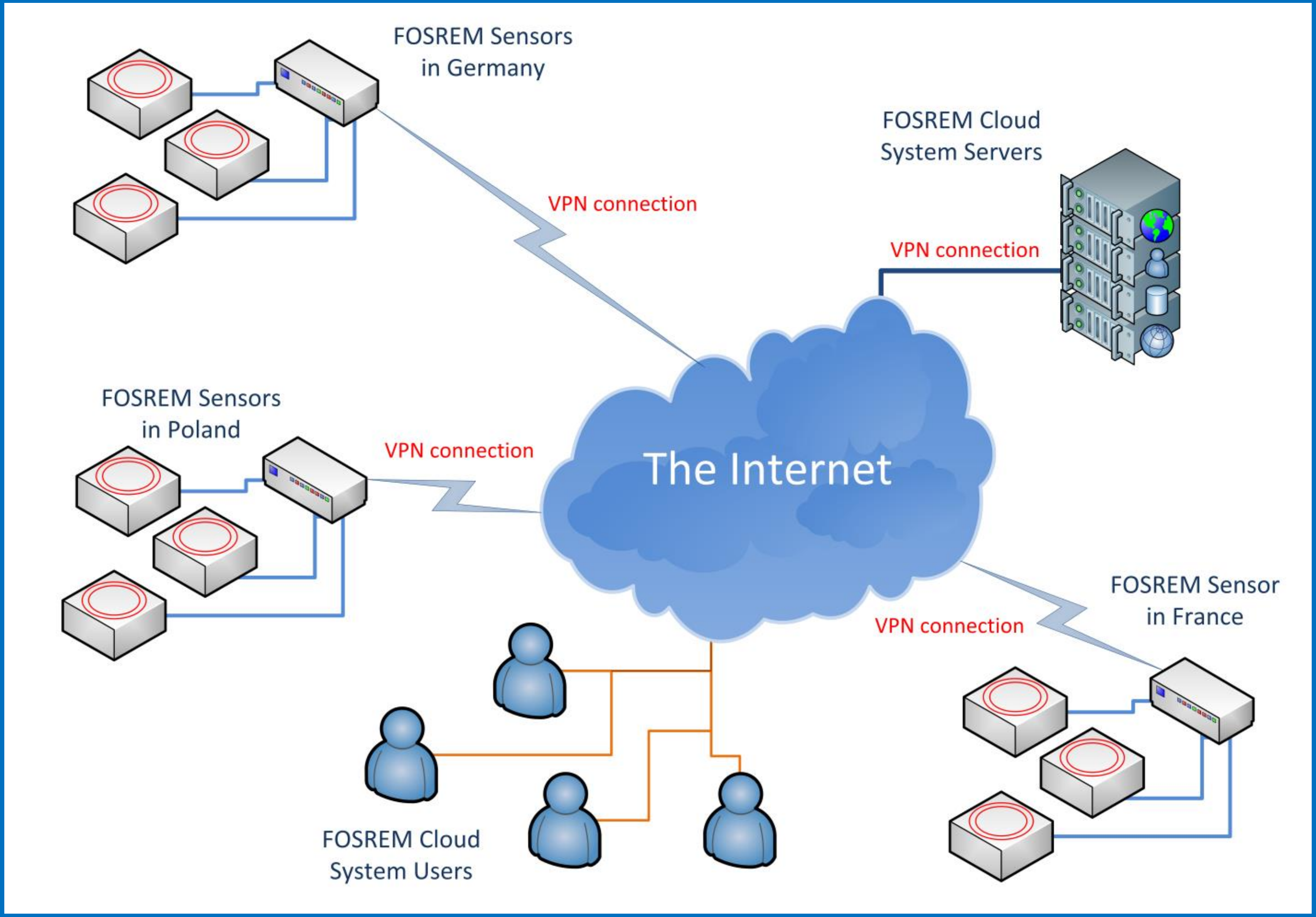




Eartquake Loma Prieta 17.09.1989

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

# FOSREM Cloud System

**POIR.04.02.00-14-A003/16, EPOS – System Obserwacji Płyty Europejskiej 19/01/2017**




[Jaroszewicz et all, 4th Meeting of IWGoRS, Tutzing, Germany, 23rd june, 2016]

Dozens of sensors can operate in one worldwide network, transferring data to a central cloud-based system. The data can be viewed and analyzed from anywhere in the world via the Internet.

# Acknowledgements

Ryszard Świłło
PhD, Eng.

Ryszard
Janiszewski

Zbigniew Krajewski
Mjr, Dr Eng.,

Anna Kurzych
M.Sc., Eng.

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Piotr Bobra
M.Sc., Eng.,

Prof. Zbigniew Zębaty
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Opole Univ. of Technology

Jerzy Kowalski
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m-Soft Ltd

Robert Jankowski
PhD, D.Sc.
Gdansk Univ. of Technology