

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

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

1. wide range of geophysical disciplines:

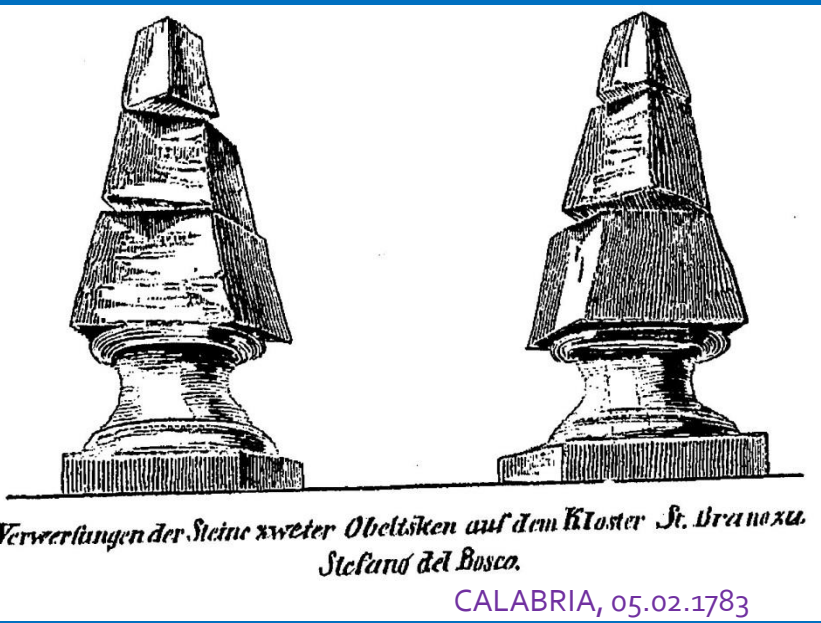
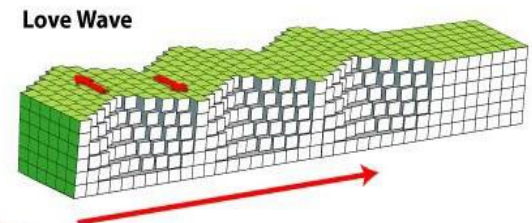
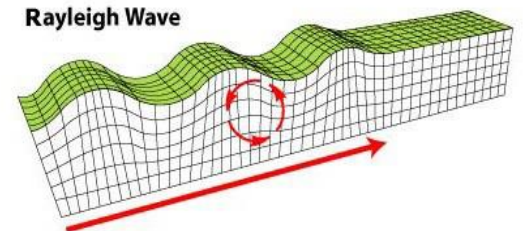
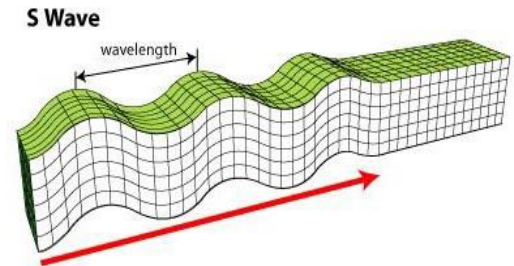
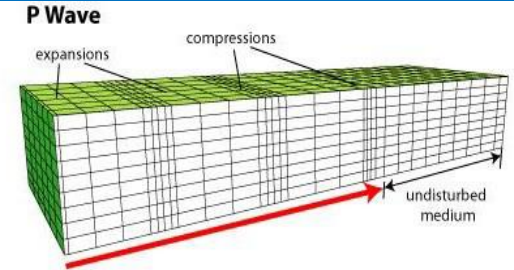
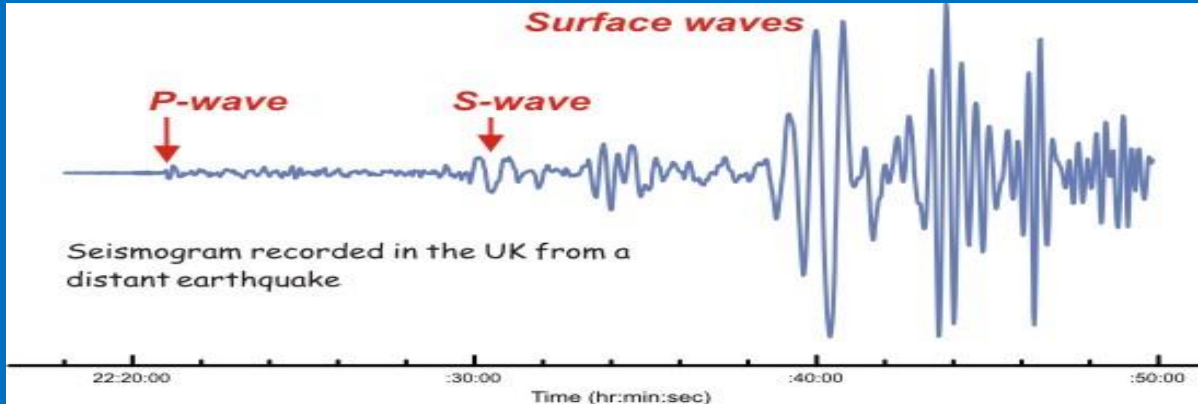
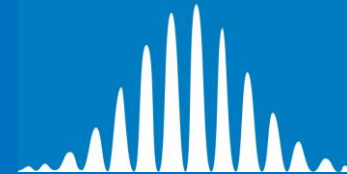
- broadband seismology [Igel et al, *Geophys. J. Int.*, **168**(1), (2006), 182–197],
- strong-motion seismology [Anderson, *The International Handbook of Earthquake and Engineering Seismology*, 2003, Chap. 57, 937-965],
- earthquake physics [Teisseyre et al, Springer, 2006; Teisseyre i inni, Springer, 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 al, *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), 968-977; Mustafa, *InTech*, 2015].

Physical investigation

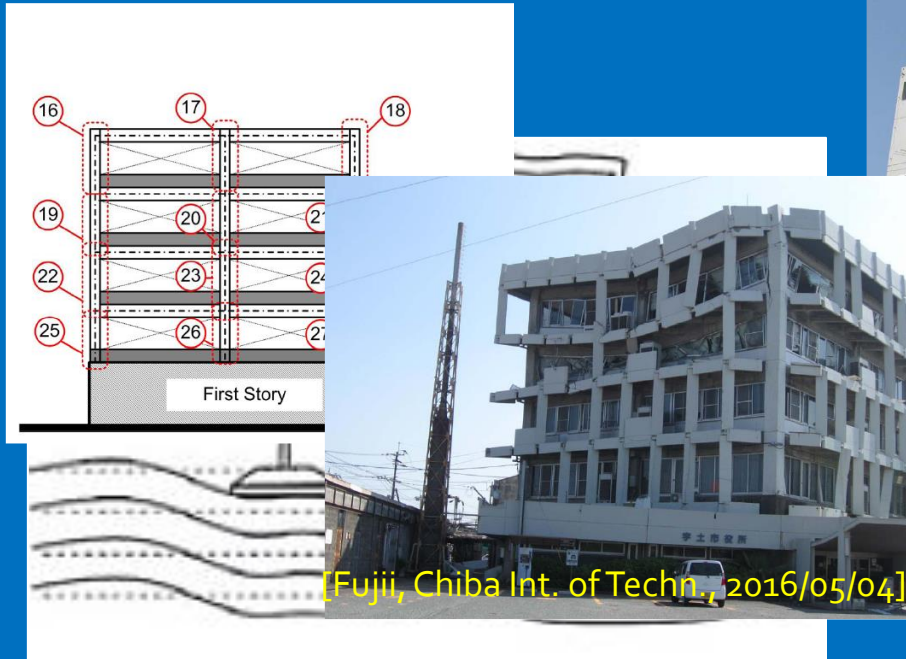
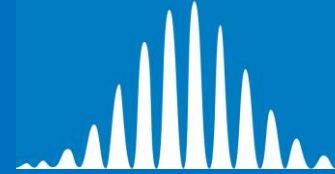
1. Geophysical aspects of rotation in earthquakes



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

Physical investigation

2. Effect of rotation motion on engineering structures



High frequency content

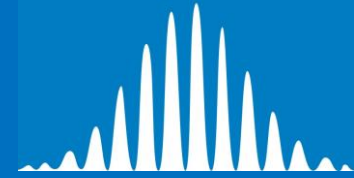
- Local vibration of beams and columns
- Meaningless motion of the building center of mass

Low frequency content

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

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

Instrumental requirements



1. „Seismological“ applications

[Bernauer et al, *J. Seismol.*, **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 al, *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)

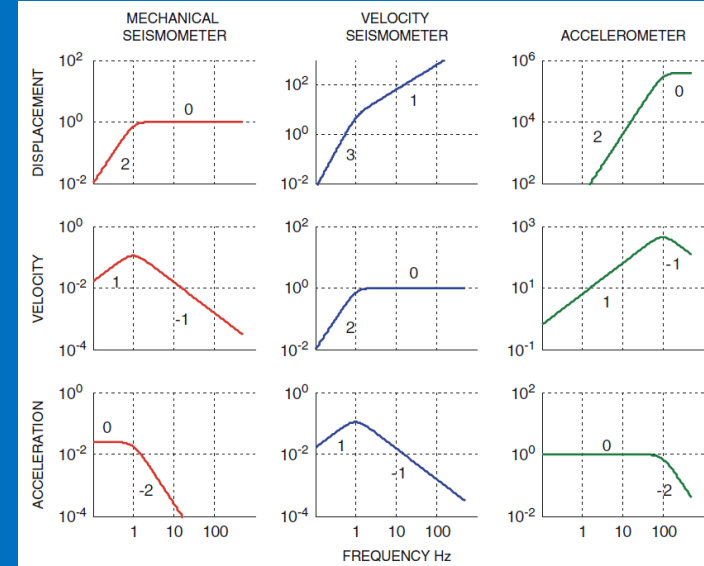
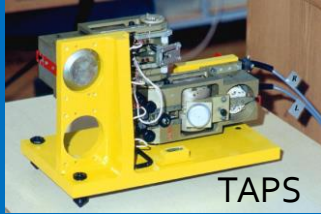
field application → ROTATIONAL SEISMOGRAPH

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

Review of existing solutions

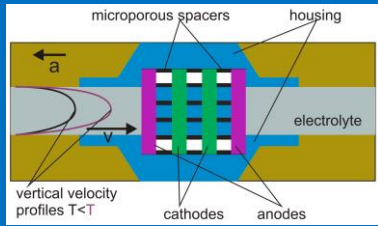
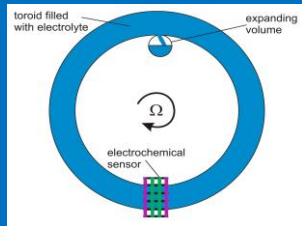
1. Mechanical type (nondirect based on velocity or accelerometer type seismometer)

Limited: frequency range, max. detectable rotation rate



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

high thermal instability, problem with electrolyte inertia



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

optimal for seismological applications, but stationary GEO systems



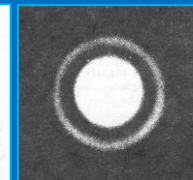
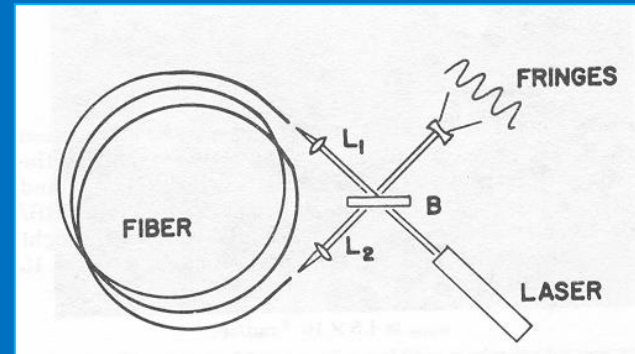
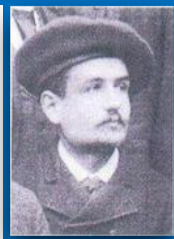
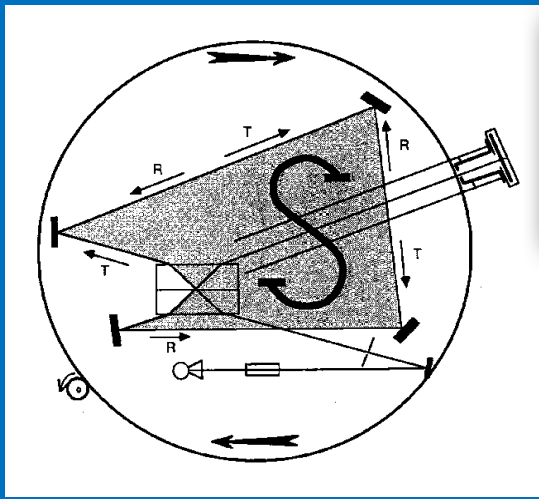
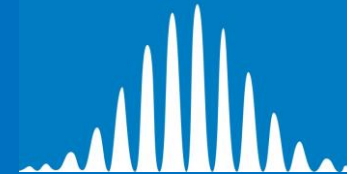
Specialized system based on FOG



Fiber-Optic seismometer

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

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

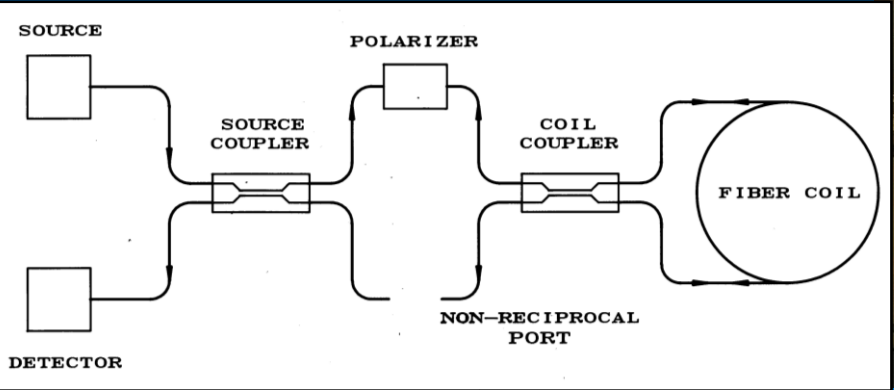


$$\Delta \phi = \frac{4\pi RL}{\lambda c} \Omega = \frac{1}{S_0} \Omega$$

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

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

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



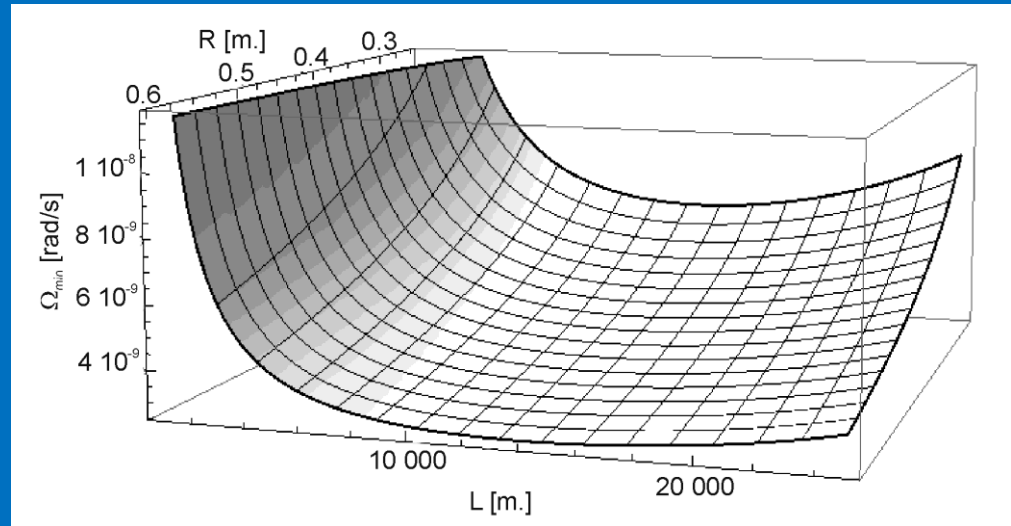
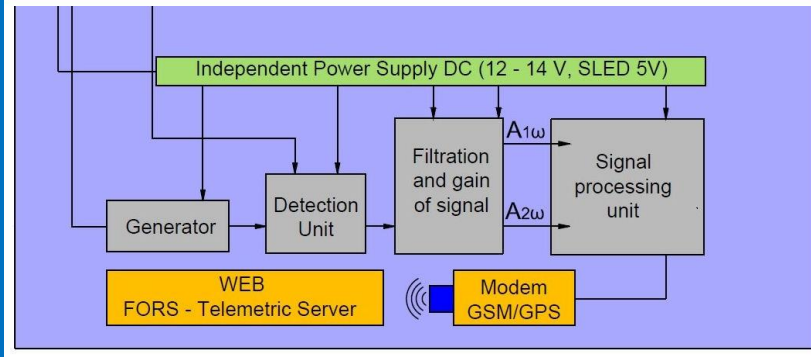
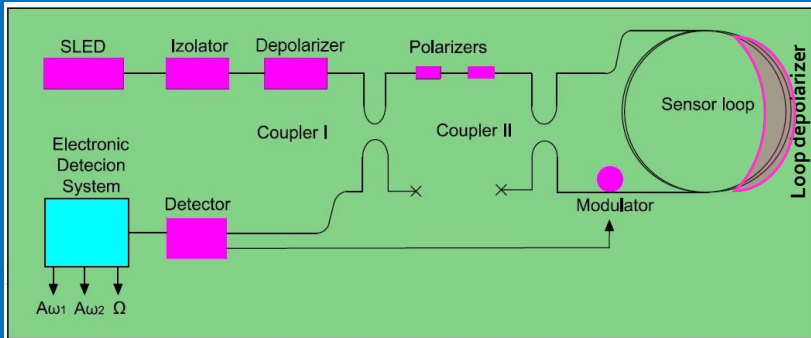
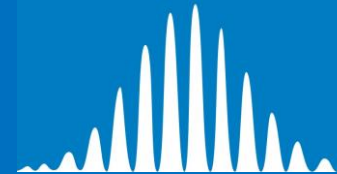
[private photo -1999]

[private photo -1999]

AFORS – critical remarks

1. Autonomous Fiber-Optic Rotational Seismograph

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



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], $R_0 = 163$ [kΩ].

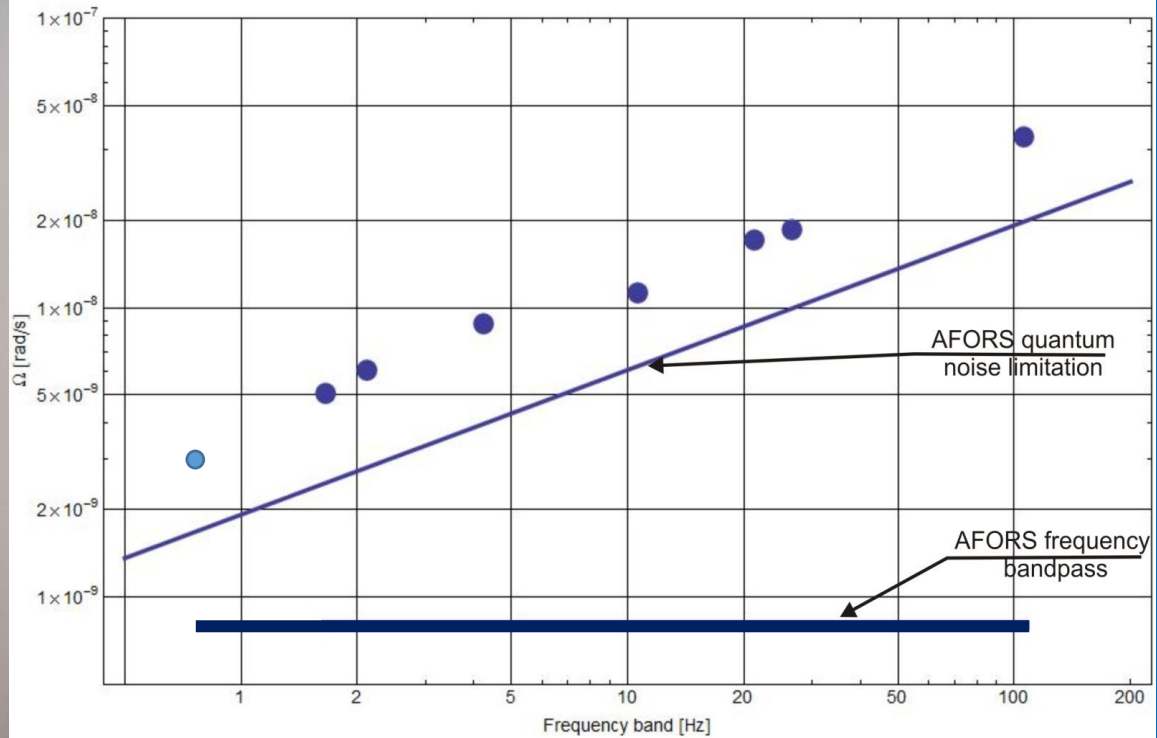
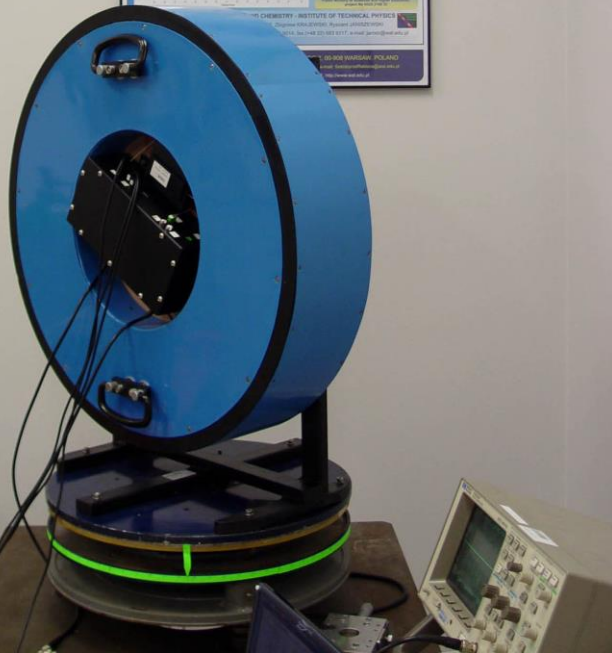
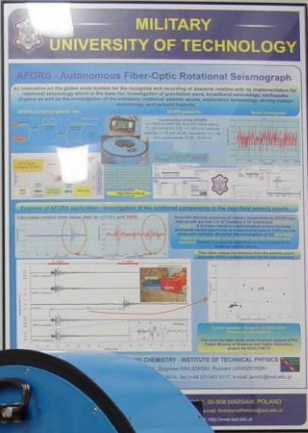
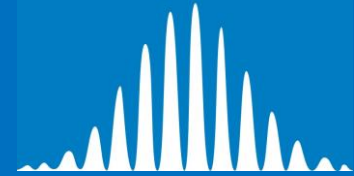
- applied depolarised light for cost minimisation,
- ESPU optimised for detection rotation rate instead of angle (FOG):

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

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

AFORS – critical remarks

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

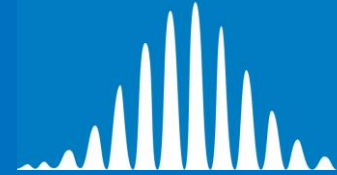


	Accuracy		
$\Delta B =$	0.83 [Hz]	21.2 [Hz]	106.15 [Hz]
	3.6 10 ⁻⁹ [rad/s]	1.7 10 ⁻⁸ [rad/s]	3.9 10 ⁻⁸ [rad/s]

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

AFORS – critical remarks

3. Operation as seismograph in real field application



MILITARY UNIVERSITY OF TECHNOLOGY
Institute of Applied Physics

FORS – Telemetric Server

2010-06-15

FORS-TS
Fiber-Optic Rotational Seismographs Telemetric System v.10.7 developed for remote control and data collection from installed FORS in seismological laboratories.

Credite
Leszek R. Janczewski PhD (Eng) DSc
Henryk A. Kowalek (J) Jerzy K. Kowalek PhD (Eng) DSc
Dariusz Krawiec PhD (Eng) DSc
Dawid Krawiec (J) Paweł Zimoch (J)

http://fors.m2s.pl/index.php/dz=device&op=parametry&lang=en&id=2&imei=355833010028533

2010-10-06 05:30:12 FORS GPS COMW GSM

AFORS ID: 2 IMEI: 355833010028533 (last read: 2010-10-06 04:52:43)

Manual Configuration

S1 (A)	8.912508944255E-330	(0.255)	NC	OM:	
S2 (B)	1.544893226623E-3300	(0.255)	Calculate & Turn On	Reset Value	NC

Sines Voltage

Sin A:	220	(0.555 mV)	
Sin B:	220	(0.555 mV)	

Amplification BRF

BRF1:	32000
BRF2:	32000

DAC Coefficients

deg:	100000
rad:	100000

k for Omega

K1:	4.1000000E-3
K2:	5.9999998E-3

Measurement time constant

t:	1	x 4.7104 ms
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Get parameters

16.291755 E Przeszukaj mapy

100 m
500 satip

©2010 Google - Dane do Mapy ©2010 PPKW - (licencja: bezcenne)

http://fors.m2s.pl/index.php/dz=device&op=parametry&lang=en&id=2&imei=355833010028533

2010-10-06 05:32:15 FORS GPS COMW GSM

GSM: 2010-10-05 15:08:38

hconf:	G24 OEM Module
imei:	355833010028533
simreg:	Registered 21043
gsmreg:	11
opalph:	Era
opnum:	260-2
covstat:	GPRS coverage 1
signalbar:	99 brutto 100.53 PLN,
signalstat:	17 17
cellid:	49535
cellacc:	42220
wersja:	2010091416
komentarz:	Y1C1C2C3K1Y1;
date:	20K3x20K4x20Komic
diff:	6558
popieranie:	false
time:	1286276922129
Czas Long:	Tue Oct 05 13:08:57 GMT+02:00 2010
Czas RTC:	1306880GMT+02:00
Data RTC:	05/10/09wlab
Phone1:	Tue Oct 05 13:08:57 GMT+02:00 20101286276937215
Phone2:	Tue Oct 05 13:08:57 GMT+02:00 20101286276937224

Mapa

http://fors.m2s.pl/index.php/dz=device&op=parametry&lang=en&id=2&imei=355833010028533

2010-10-06 05:27:24 FORS GPS COMW GSM

Data download & trigger level

RF	FS:	L:
RD	Last sec:	
GF		

Level Before [block] After [block]

Level (ADEV)	Buf Len(sps)
Before[block]	After[block]
ADEV:	2.5043408E-7 rads
Omega:	1.950732212E-6 rads
Omega Average Deviation:	0.0000000 rads
GF Level:	900501783
GF Before:	10 block
GF After:	10 block
GS Level:	15 ADEV
GS Buf Len:	64 sps
GS Before:	10 block
GS After:	10 block
GS T:	0001
GS TM:	0000

Variables Values (2010-10-06 05:27:24)

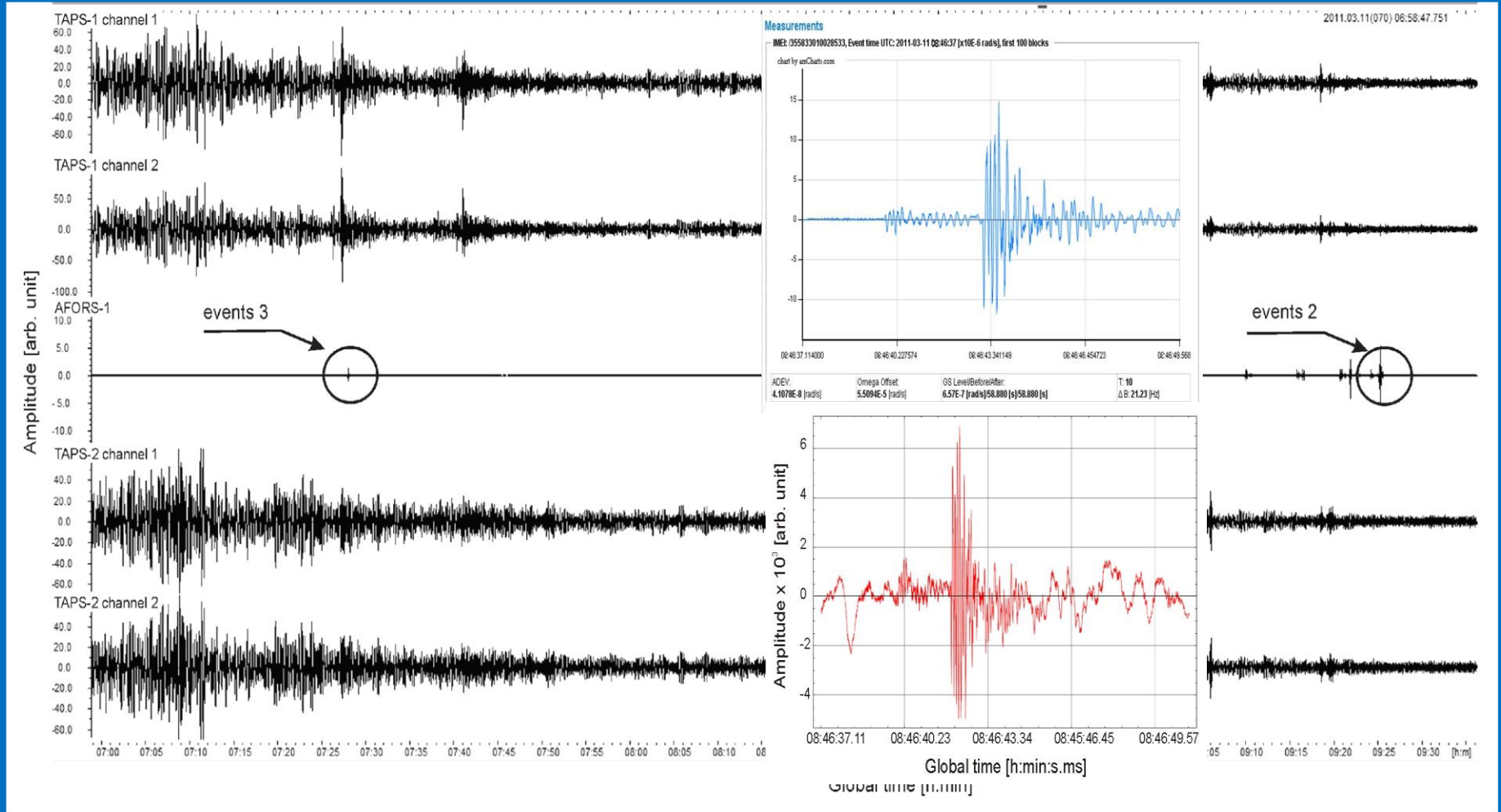
Omega in rads:	1.950732212E-6
Omega Offset in rad:	-5.741413770E-5
Omega offs flag:	0014
R1mean:	14326.459969038
R2mean:	8721.05078125
Max AB:	18799 / 16939
XY Auto-Zero set flag:	0000
Lik auto phase set flag:	0001
F1:	6798.9497070312
F2:	13599.899414062
F0:	217598.390625

Get



AFORS – critical remarks

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

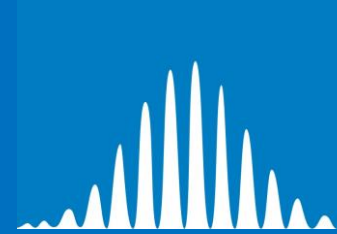


[Jaroszewicz et al, *J. Seismol.*, **16**, (2012), 573-586]

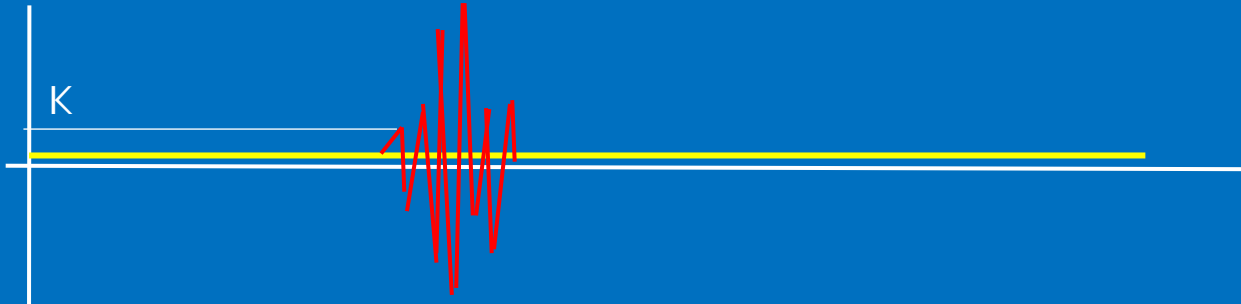
AFORS – critical remarks

5. Special numerical approach to Ω detection on „drifting signal“

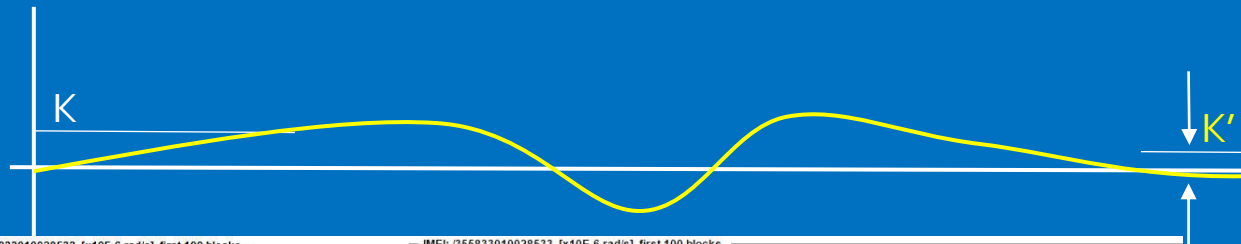
[Kurzych et al, *Sensors*, 14, (2014), 5459-5469]



Ideal approach (without drift connected with bias phenomena)

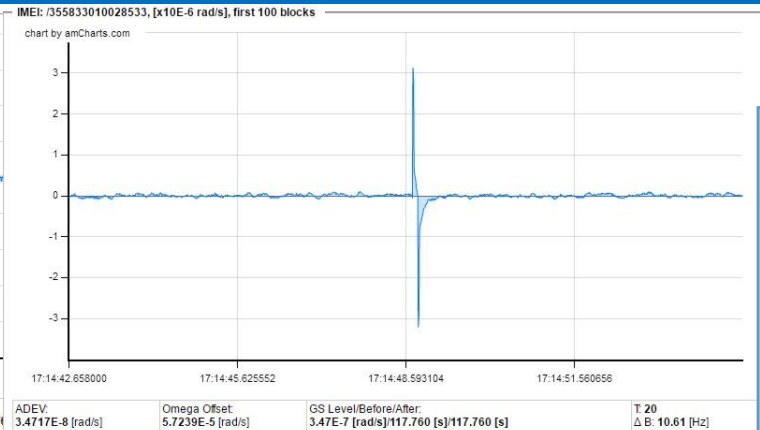
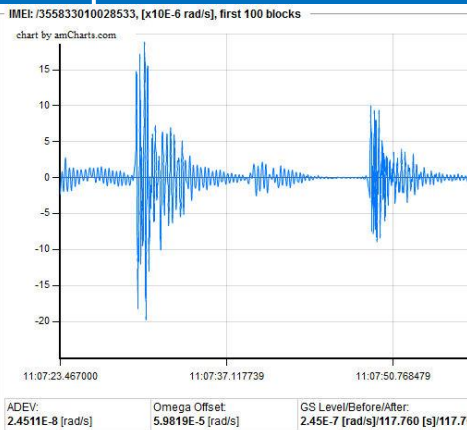
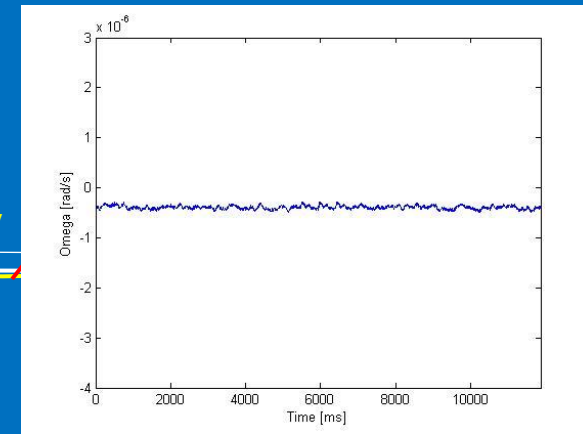


Real situation `drifting signal` (bias connected with environment)



K – defined Ω level for start to recording data

2. K'' – defined for artefactes elimination

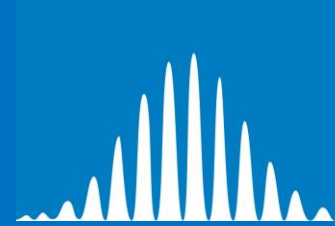


AFORS:

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

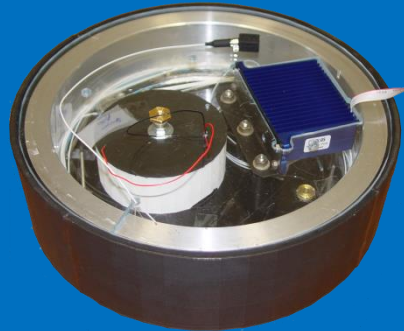
Fibre-Optic System for Rotational Events & Phenomena Monitoring



FOSREM-SS

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

Optical module



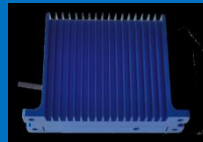
Electronic module



Analog & ADC



DSP & μ-computer



Laser



Power supply



FOSREM-BB

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

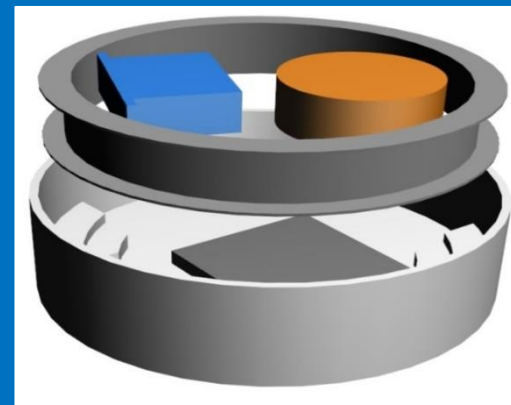
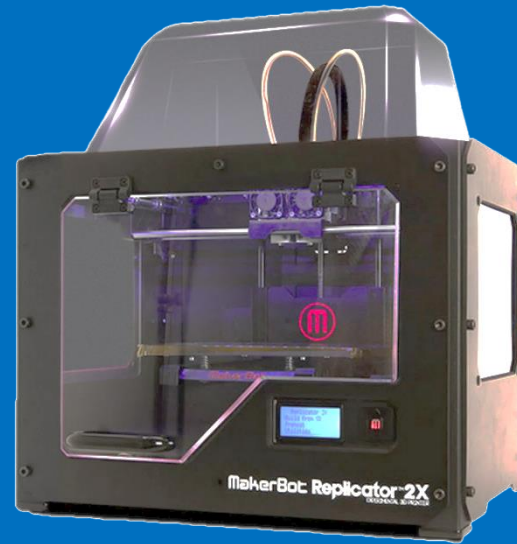
FOSREM advantages:

- 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

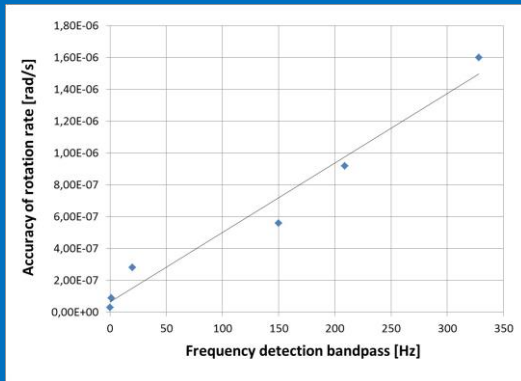
3D printer: MakerBot Replicator 3X i Replicator Z18

FOSREM – towards final success

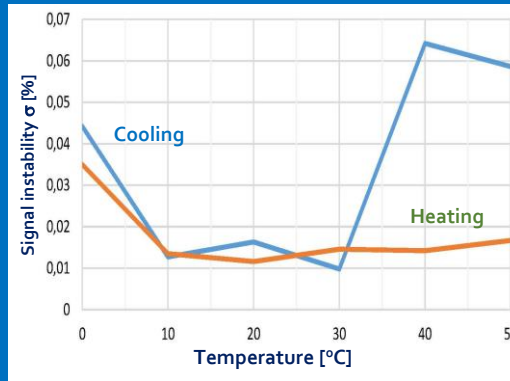
2. Laboratory investigation (thermal stability and bandpass accuracy)



FOSREM accuracy

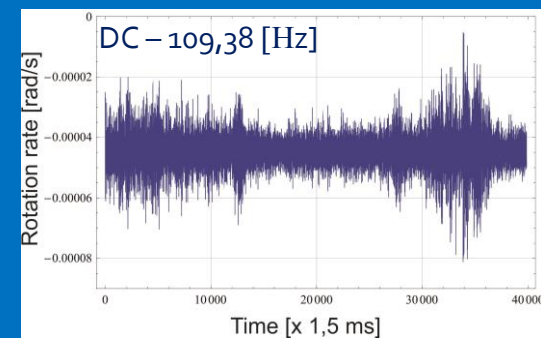
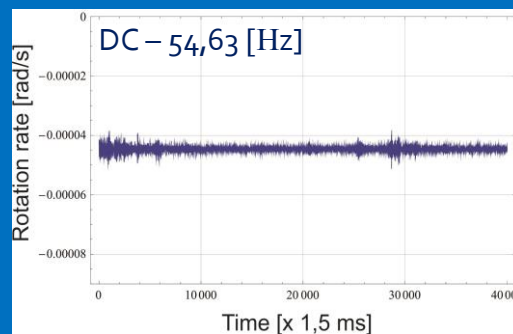
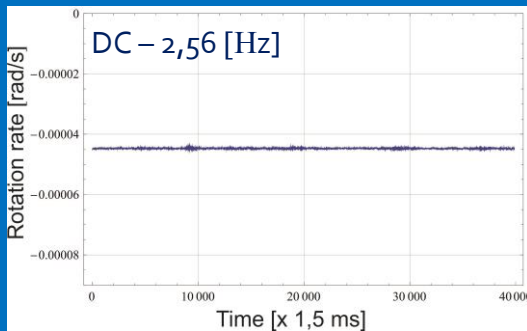


FOSREM thermal instability



Climate chamber VCL 7010

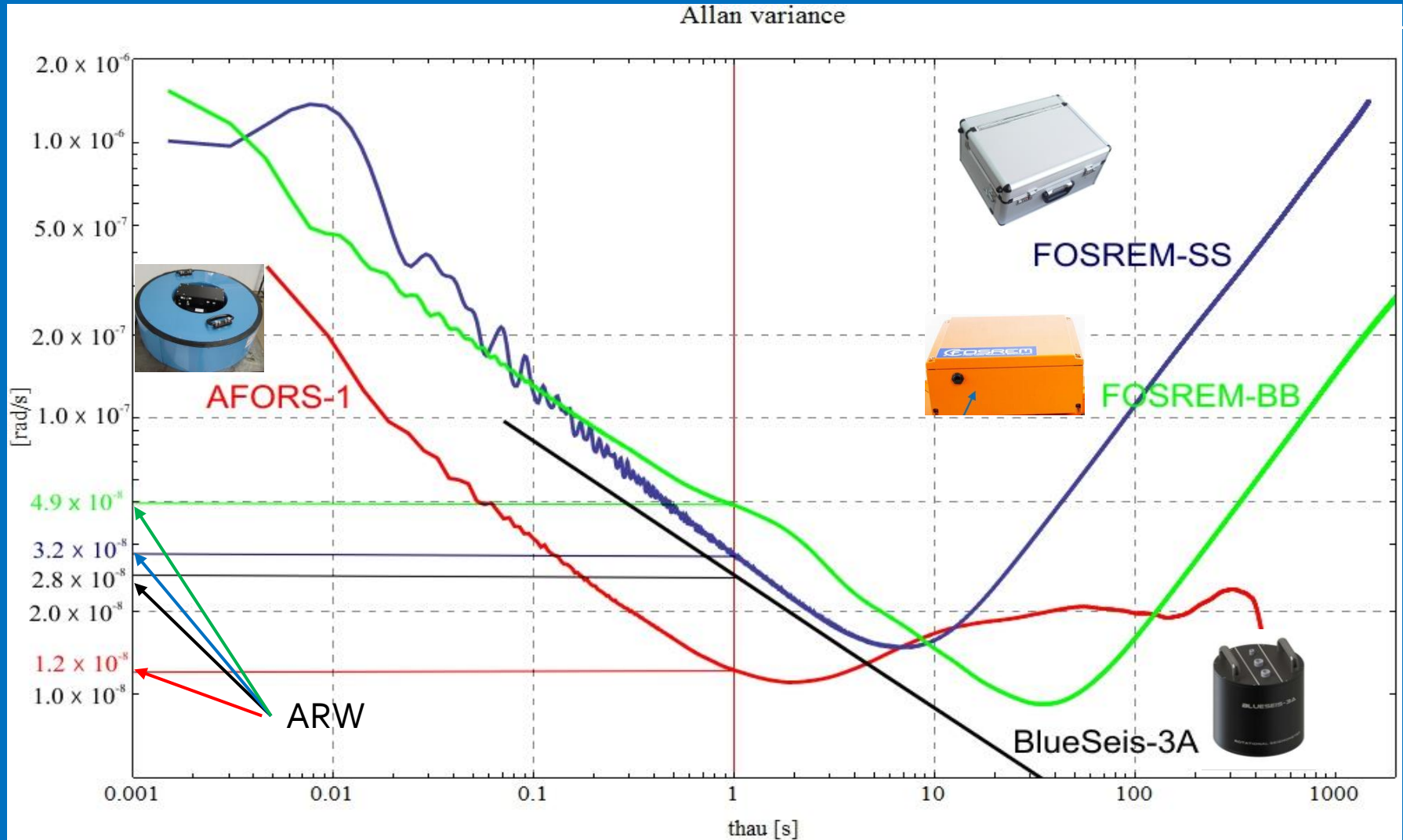
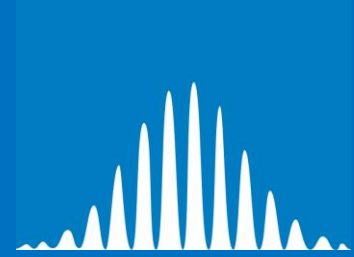
Ω of Earth for Warsaw ($4,45 \cdot 10^{-5}$ [rad/s])



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

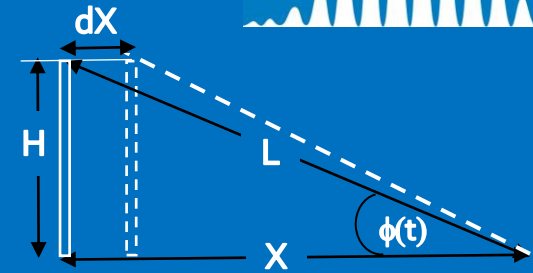
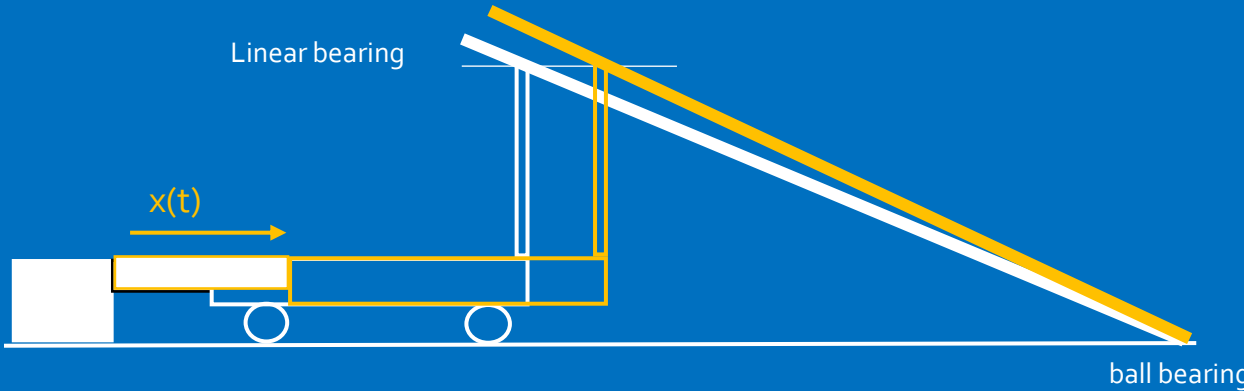
FOSREM – towards final success

3. Noise analysis in Allan Variance approach



FOSREM – towards final success

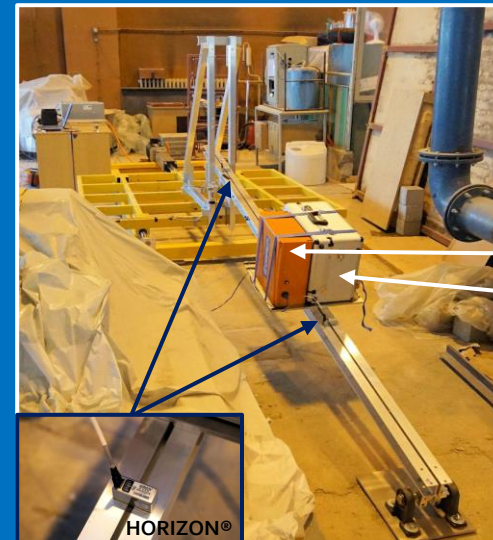
4. Earthquakes simulation in laboratory conditions



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

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

$$L = 3,7 \text{ m}, H = 0,5 \text{ m}$$

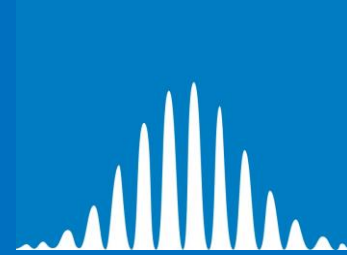


FOSREM-BB
FOSREM-SS

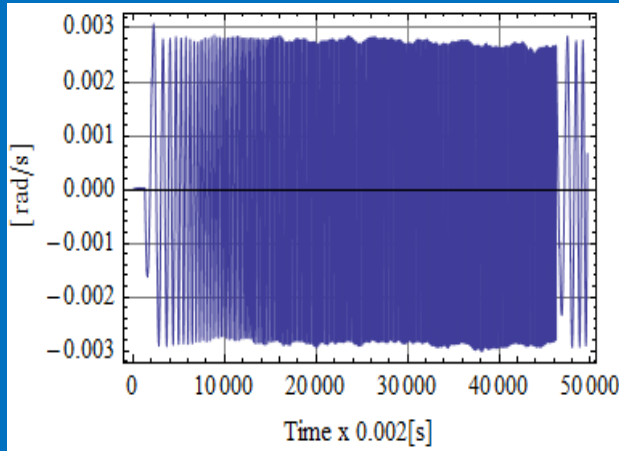
$v(t)$ from digitalized data of Earthquakes
 $\Omega = 0,0365 v(t) \quad (1)$

FOSREM – towards final success

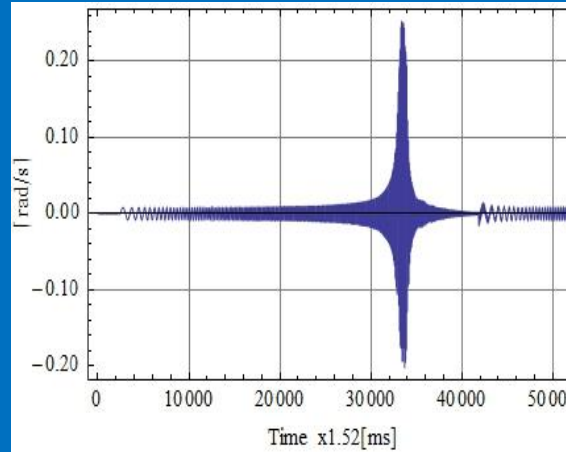
4. Earthquakes simulation in laboratory conditions



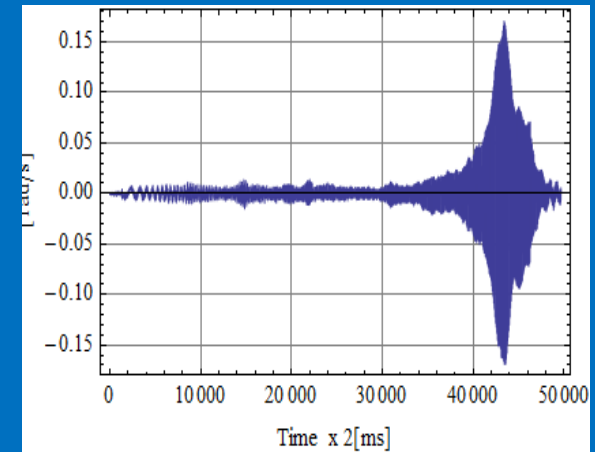
Calculation from formule (1)



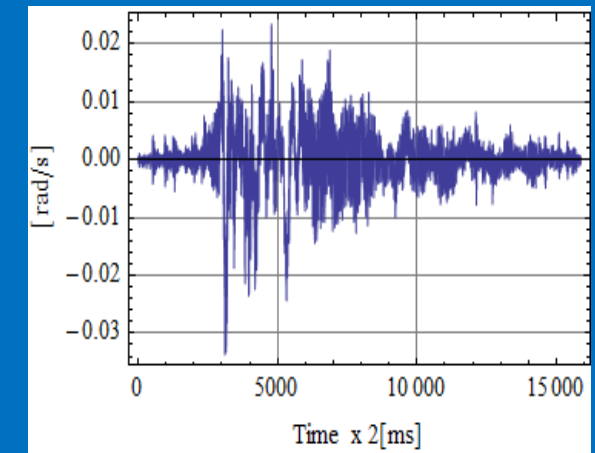
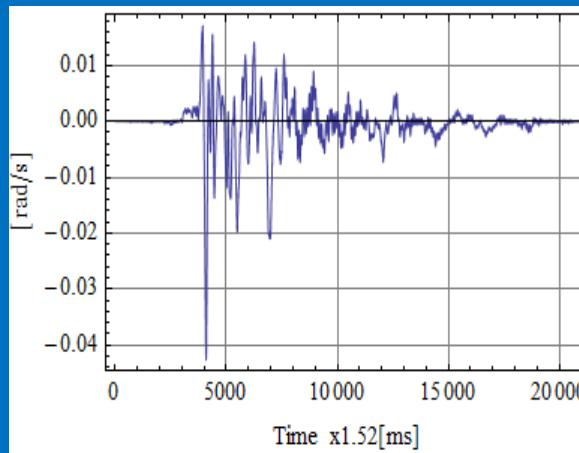
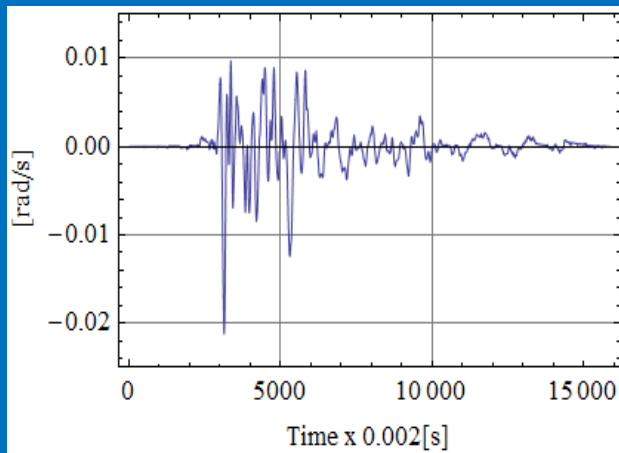
Data from FOSREM-BB



Data from Horizon HZ1-100-100



sweep sine 0.25-10 Hz

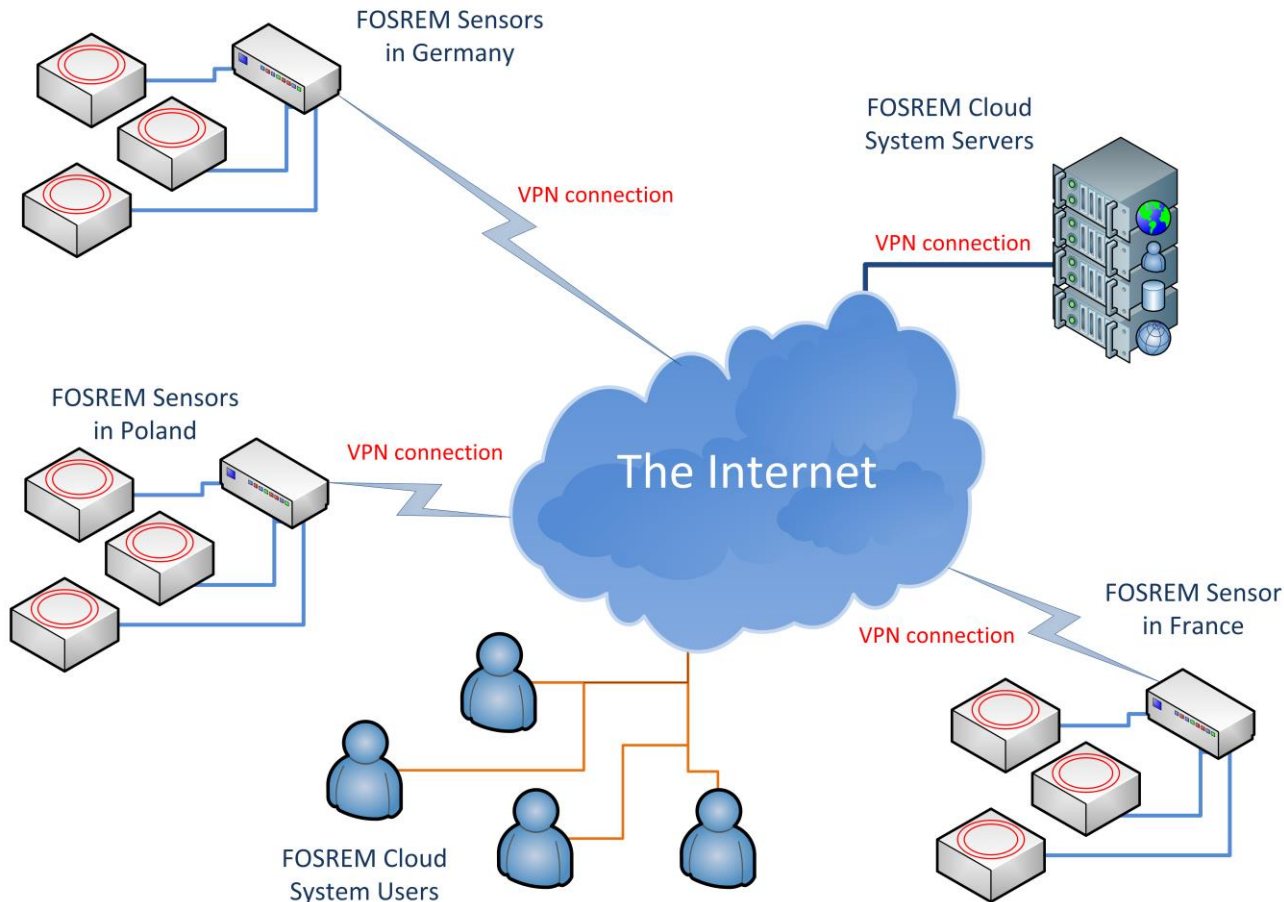


Eartquake Loma Prieta 17.09.1989

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

FOSREM Cloud System

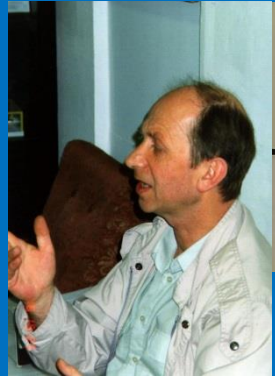
POIR.04.02.00-14-A003/16, EPOS – System Obserwacji Płyty Europejskiej 19/01/2017



[Jaroszewicz et al, 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.

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