Recording Rotational Motions at a New Set-up Uses `Earthquakes Simulation`

(simple modification of typical shaking table to cover rotation)

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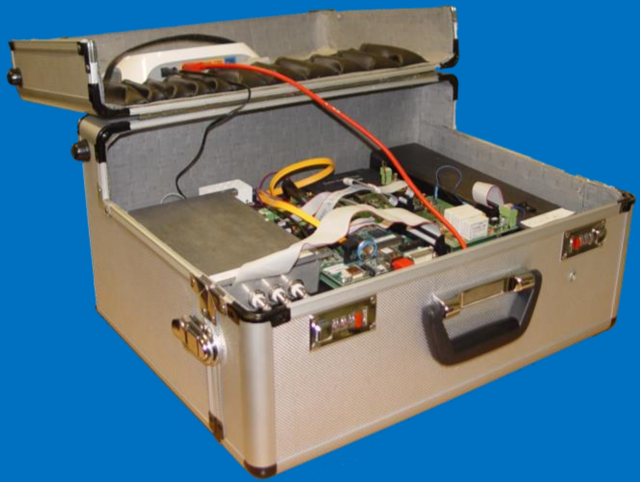
Fiber - Optic Seismograph for Rotational Events Monitoring (FOSREM)



FOSREM-SS

FOSREM-BB for strong motion (see example)

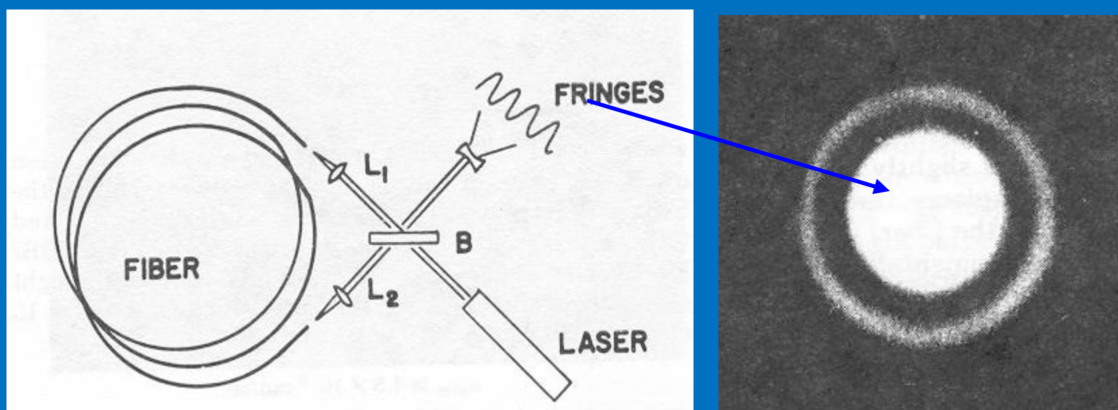
- **Optical part:**
  5 km SMF-28, α_{total}=16,37 dB, P=11 mW, min. FOG configuration → sensitivity: $2{,}06{\cdot}10^{-8}$ rad/s/Hz$^{1/2}$, max. rotation rate about 10 mrad/s
- **Electronic part:**
  Open-loop, digital processing, remote control via internet, passband from DC to- $2{,}56 \cdot 2^{n}$ Hz n=1,..,7)
- **Mechanical part:**
  size: 47x36x23 cm, weight: 7 kg,
  power supply: 230V AC + 14,4V/20Ah Li-On battery (12 hours system work)

Optical part:

- **5** km SMF-28, α_{total}=16,89 dB, P=0.5 mW, min. FOG configuration → sensitivity $2{,}18{\cdot}10^{-6}$ rad/s/Hz$^{1/2}$, max. rotation rate a few rad/s
- **Electronic part:**
  Open-loop, digital processing, remote control via internet, passband from DC to $2{,}56 \cdot 2^{n}$ Hz (n=1,..,7)
- **Mechanical part:**
  size: 36x36x16 cm, weight: 10 kg,
  power supply: 230AC PCU, PoE 48V from PCU (3 AFORSs)

The Fiber Optic Gyroscope's 40th Anniversary

- Prolific field launched by pivotal paper by Vali and Shorthill published in May 1976
  - Raport first use of an optical fiber for mesure a rotation rate
  - Sensitivity to rotation is enhanced by the numer of turns in a multi-turn, single-mode fiber coil



$$\varphi_s = \frac{2\,\pi\,L\,D}{\lambda\,c}\,\Omega$$

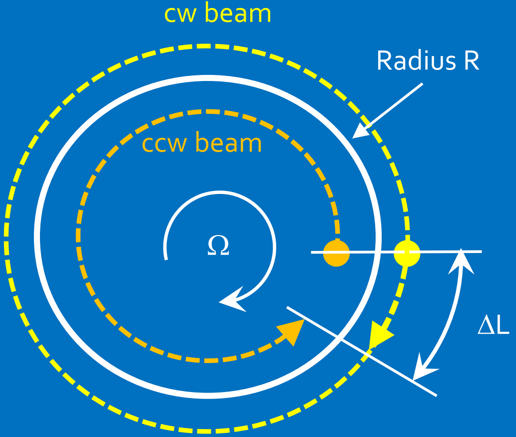
„This experiment show that a ring interferometer gyroscope having sufficient sensitivity for navigation can be bulit."

A.Vali nad R. Shorthill, „Fiber ring interferometer," *Appl. Opt.* 15(5) 1099-1100 (1976).

The Sagnac – Von Laue Effect in Vacuum

The FOSREM is based on Sagnac-Von Laue effect

- Light beams propagating in oposite directions in a rotating frame experience a different optical path length



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- **At rest, the time of flight through the loop is**

$$T_0 = \frac{Circumference}{Speed\ of\ light} = \frac{2\,\pi\,R}{c}$$

- **When rotated at rate Ω**

- Cw beam travels father to catch up with the moving beam spliter, and its time of flight becomes:

$$T_{cw} = \frac{2\pi R + \Delta L}{c} = \frac{2\pi R + R\Omega T_0}{c}$$

- Ccw beam travels a shorter distance:

$$T_{cw} = \frac{2\pi R - \Delta L}{c} = \frac{2\pi R - R\Omega T_0}{c}$$

- **Difference in times of flight:**

$$\delta T \quad = |T_{cw} - T_{ccw}| = 2\frac{R\Omega T_0}{c}$$

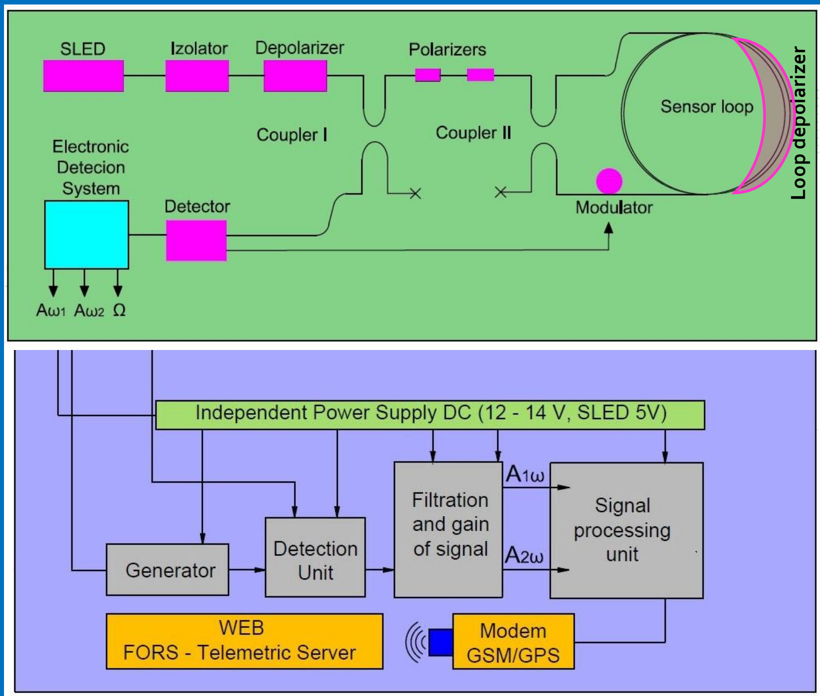
- **Phase difference (Sagnac-Von Laue phase shift):**

$$\varphi_s = 2\frac{R\Omega T_0}{c} = \frac{8\pi^2 R^2 \Omega}{c\lambda} = Scale\ factor\ x\ \Omega$$

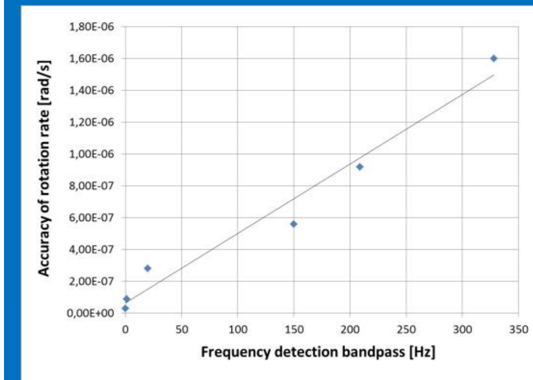
The two beams experience a Sagnac-Von Laue phase shift proportional to the rotation rate and the coil area

$$\varphi_s = \frac{4\pi RL}{c\lambda}\Omega = \frac{1}{S_o}\ x\ \Omega$$

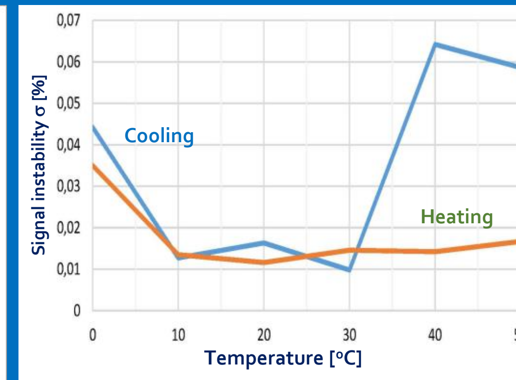
The FOSREM contra FOG



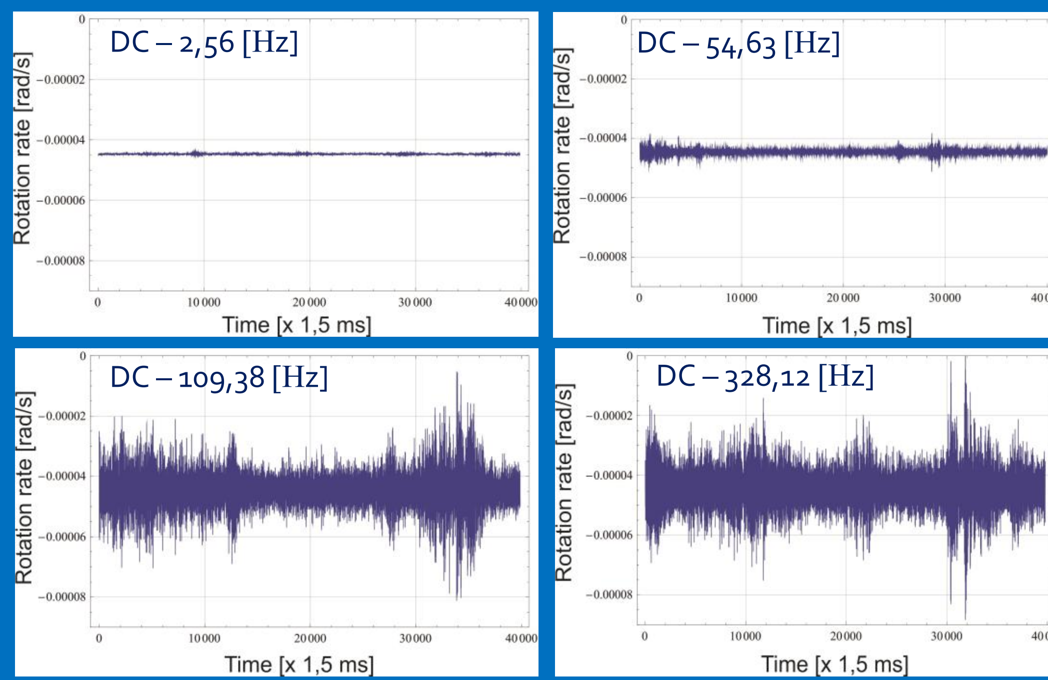
FOSREM accuracy



FOSREM thermal instability



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



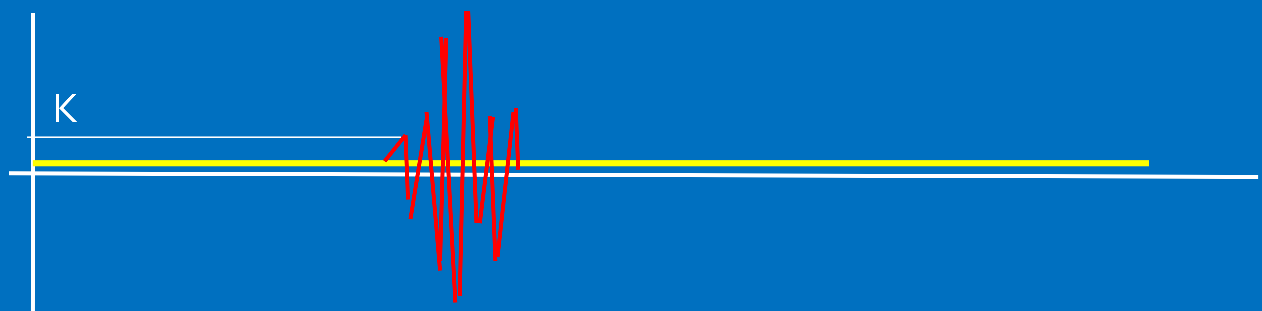
- # applied depolarized light for cost minimisation,
- # ESPU optimised for detection rotation rate instead of angle (FOG) up to 10 [rad/s]

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

- # S_o, S_e – optical and electronic constant determines during scalling on Earth rotation,
- # detection Ω on „drifting signal" by special numerical procedure

Measurement with bias phenomena

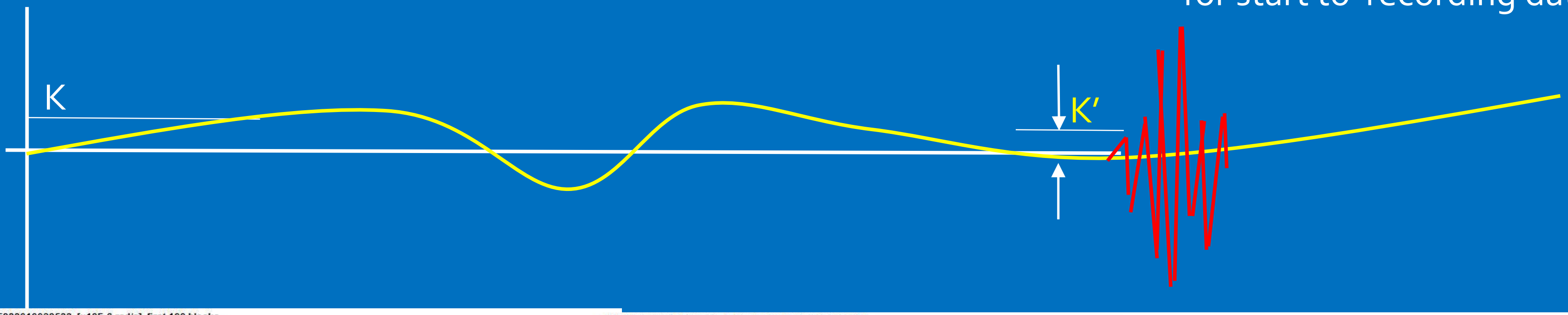
Ideal approach (without drift connected with bias phenomena)

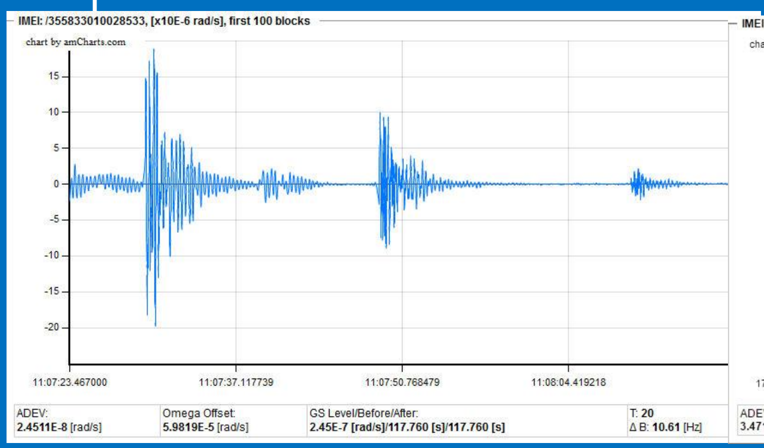


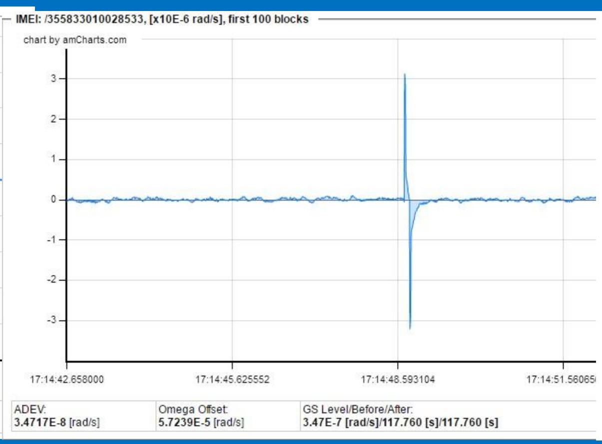
K – definied Ω level for start to recording data

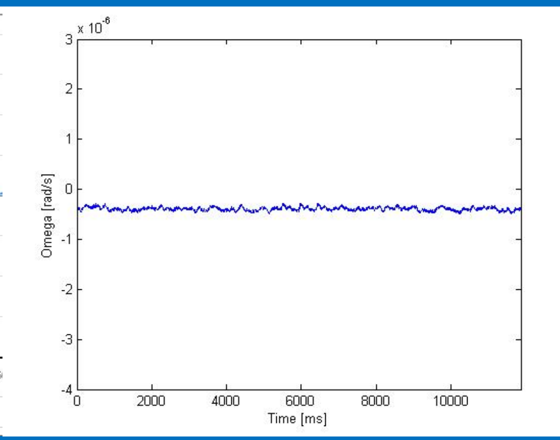
Real situation `drifting signal` (bias connected with enviroment)

K' – definied local Ω level for start to recording data

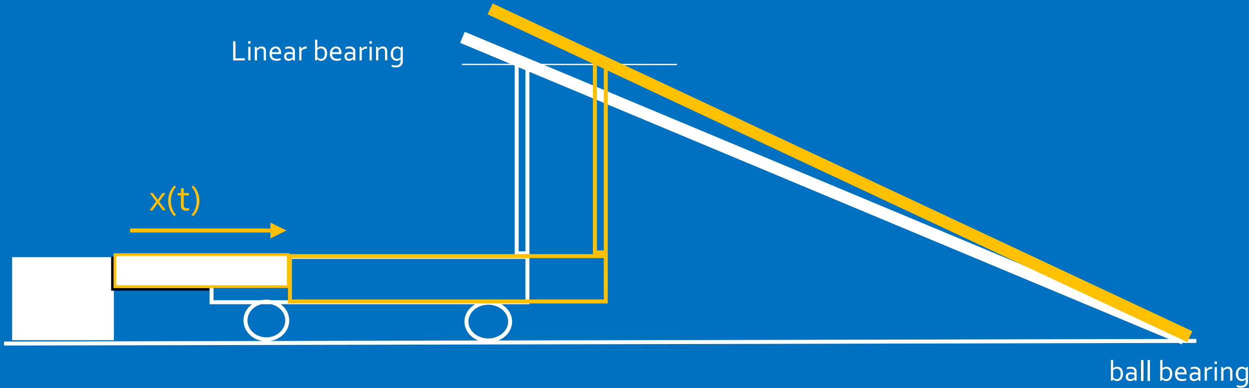


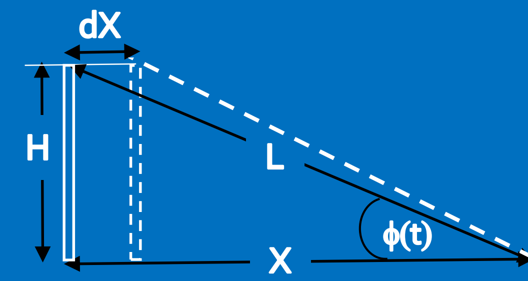






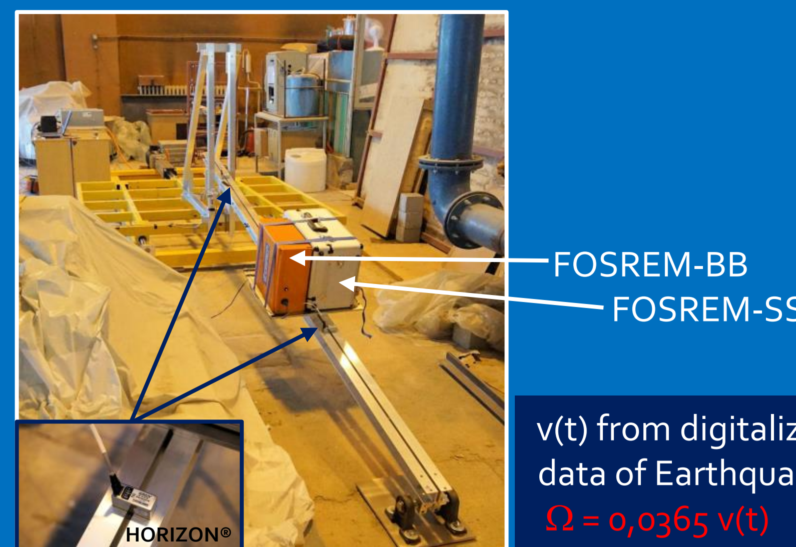
Set-up for `Earthquakes Simulation`





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

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

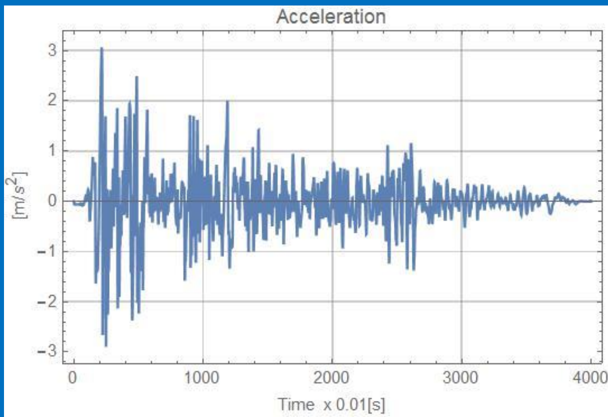


v(t) from digitalized data of Earthquakes

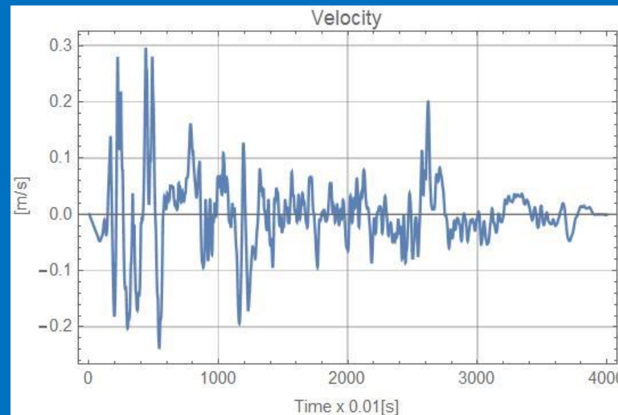
$\Omega = 0{,}0365\ \mathrm{v(t)}$ (1)

El Centro Earthquake

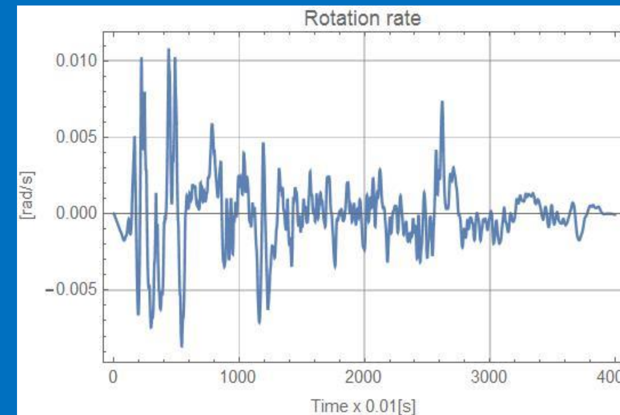
Digitalized data



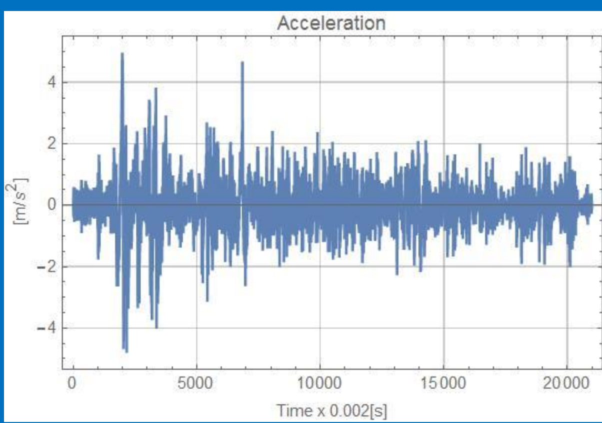
Simpson method



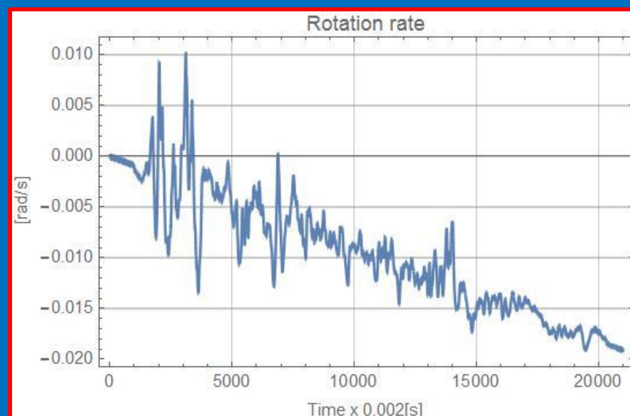
used formule (1)



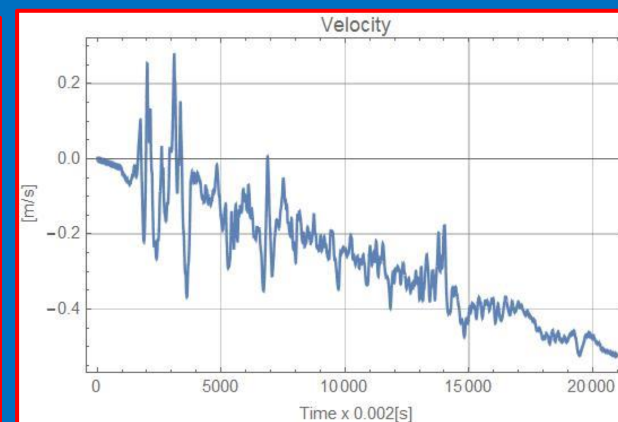
Accelerometer mounted on frame



calculation



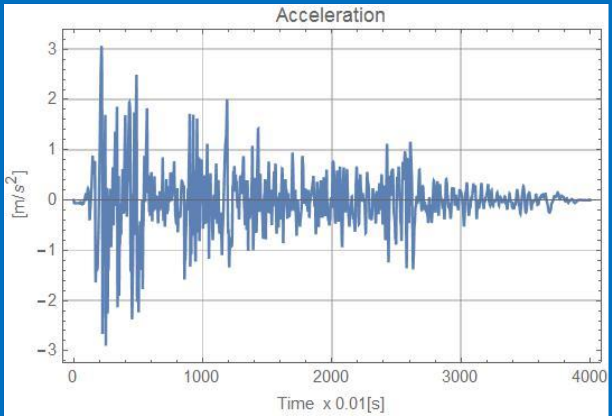
from formule (1)



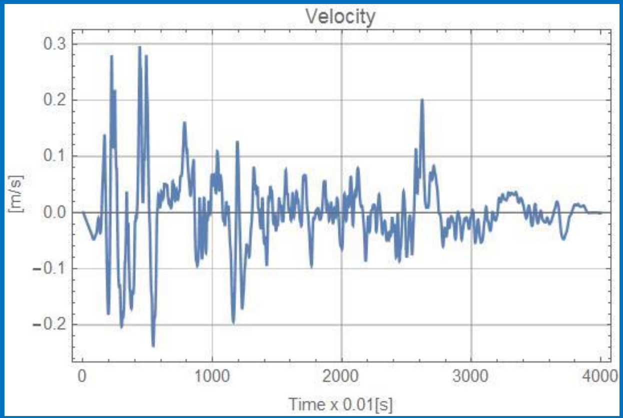
#1 -Error connected mainly with frame end positioning in different position

El Centro Earthquake

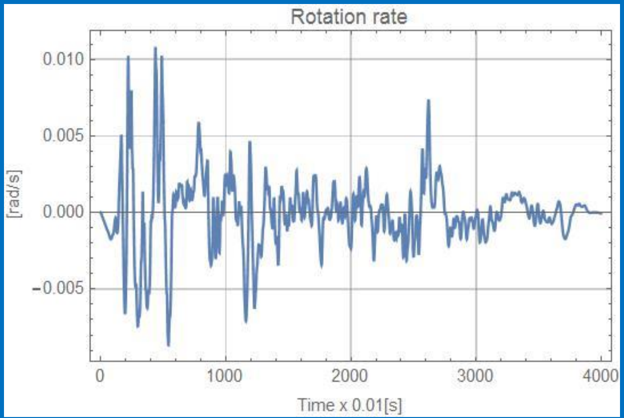
Digitalized data



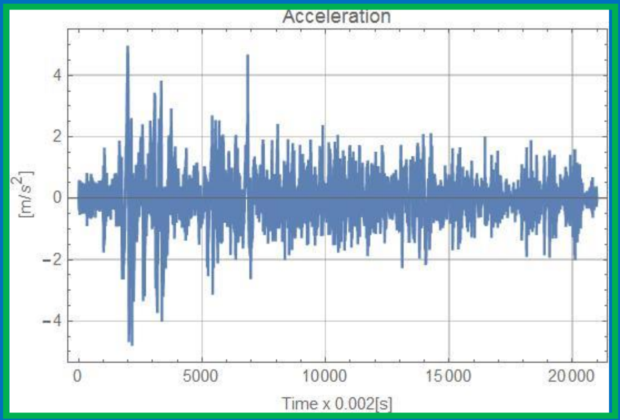
Simpson method



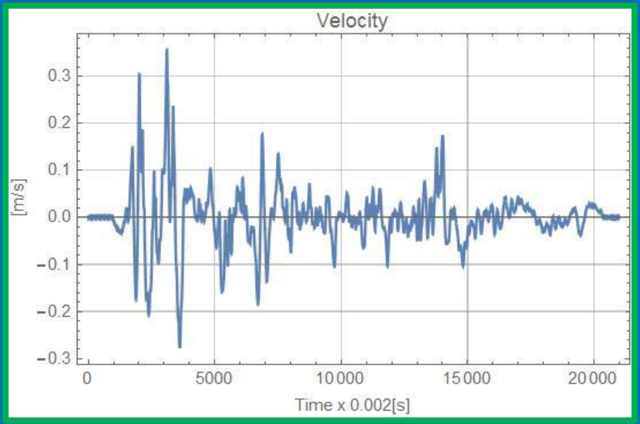
used formule (1)



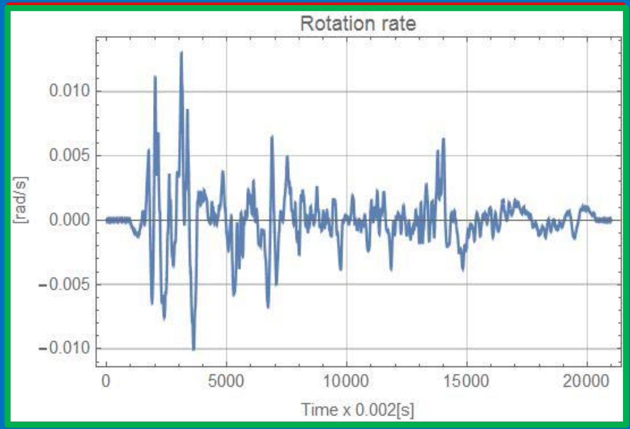
Accelerometer mounted on frame



calculation with correction

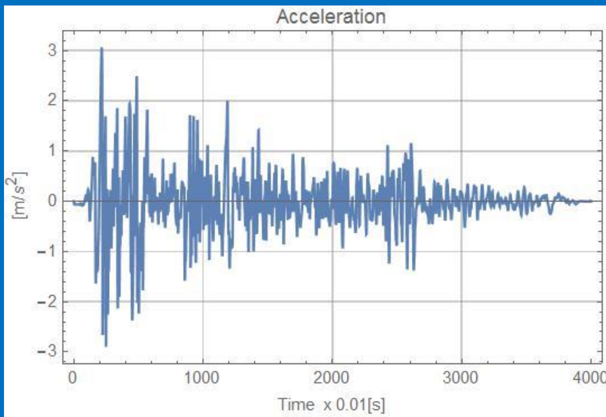


from formule (1) with correction

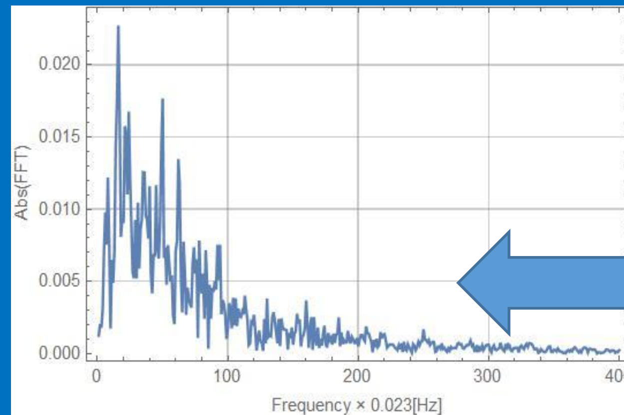


El Centro Earthquake

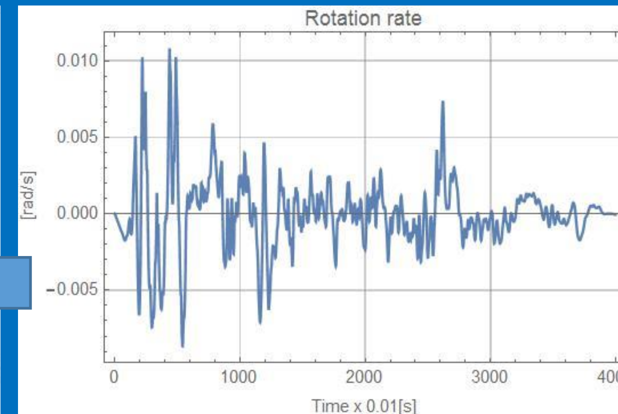
Digitalized data



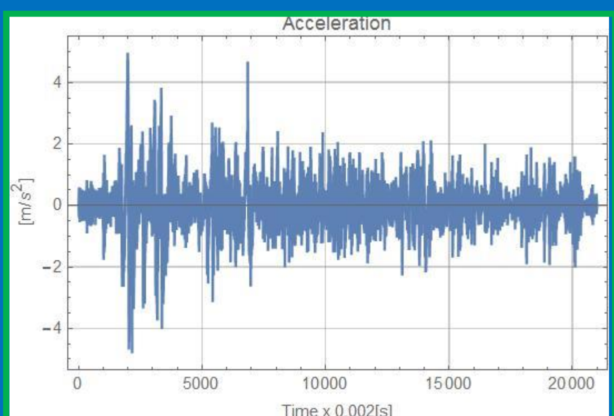
FT(Rotation Rate)



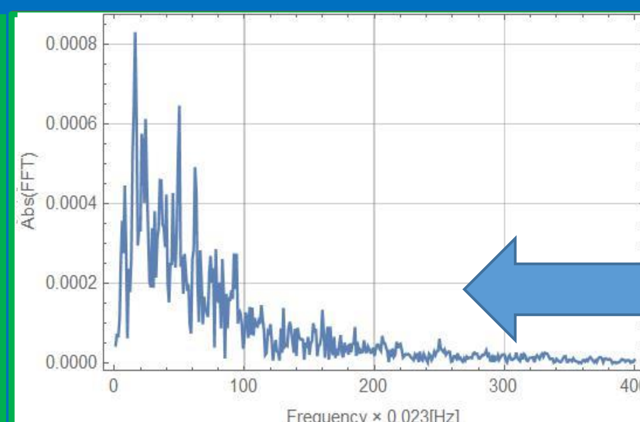
used formule (1)



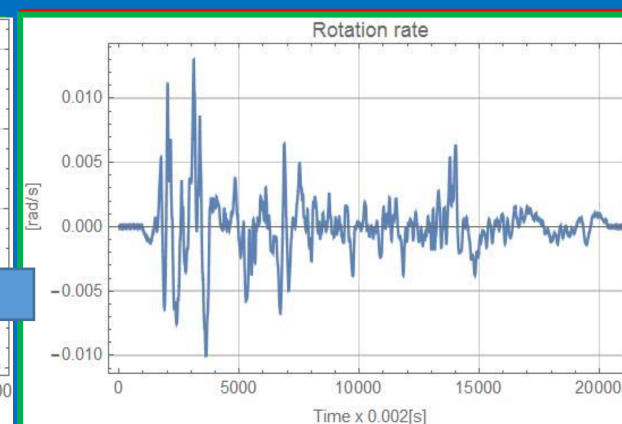
Accelerometer mounted on frame



FT(Rotation Rate)



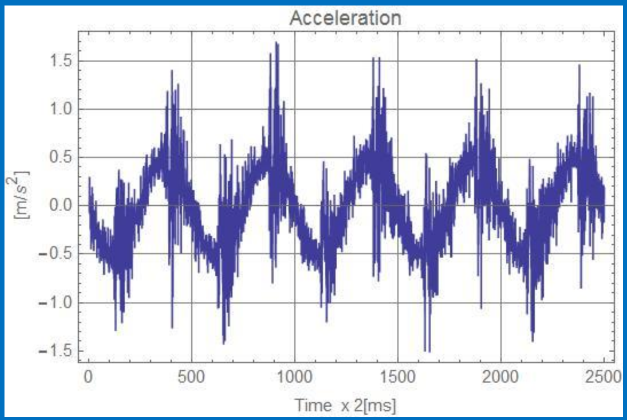
from formule (1) with correction



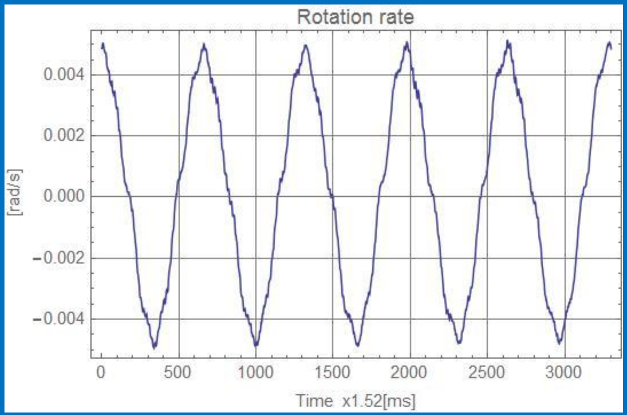
#2 – Measured values have different amplitude (acceleromeer data will be used in future investgations)

Sine 1 Hz (50% of amplitude)

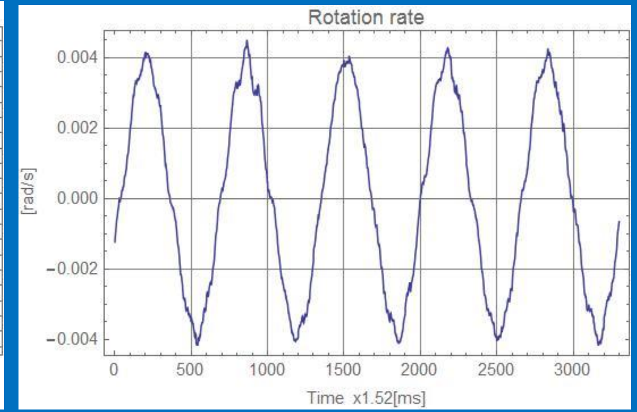
Accelerometer



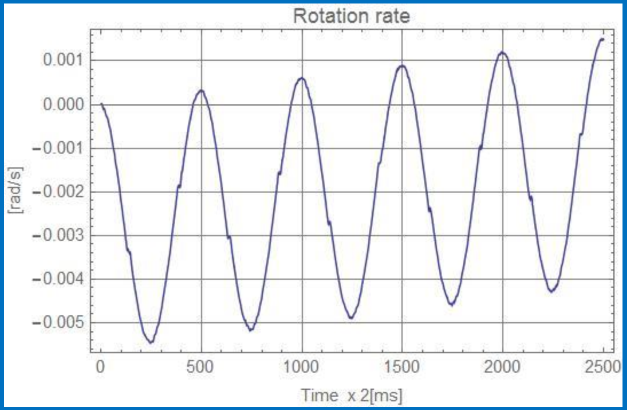
FOSREM-SS (DC- 10 Hz)



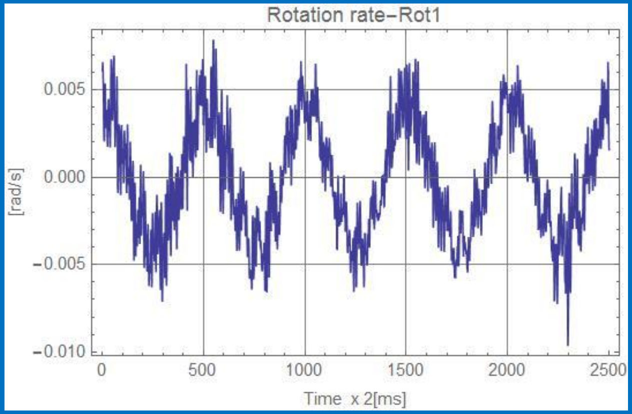
FOSERM-BB



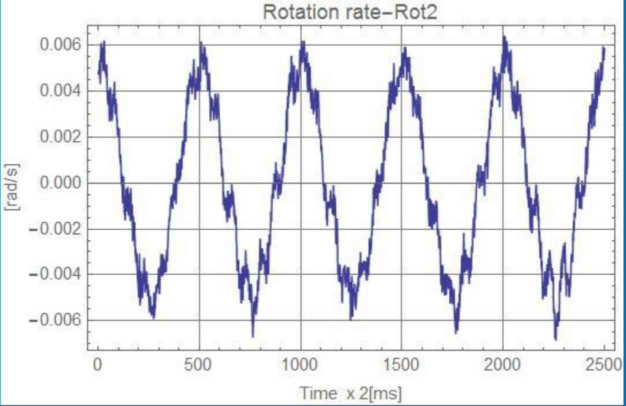
Rotation from accelerometer



HORIZON® „before”



HORIZON® „after”



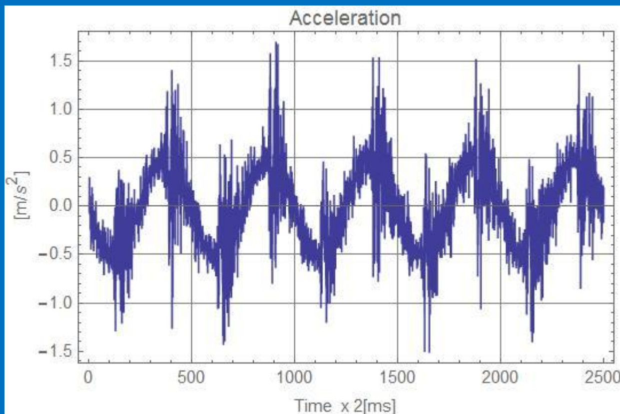
#1 HORIZON – Before shows noise connected with linear bearing
#2 All seismometers are same different calibrated

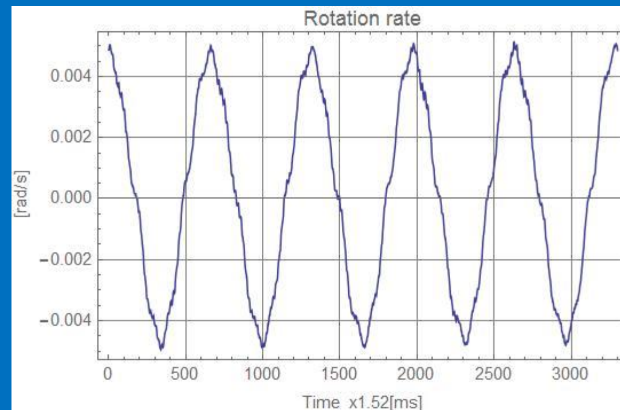
Sine 1 Hz (50% of amplitude)

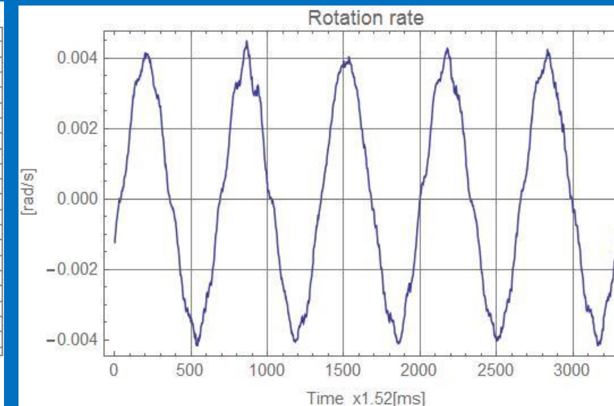
Accelerometer

FOSREM-SS (DC- 10 Hz)

FOSERM-BB



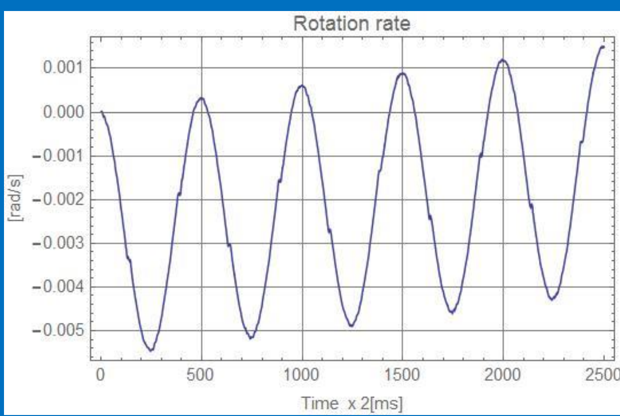


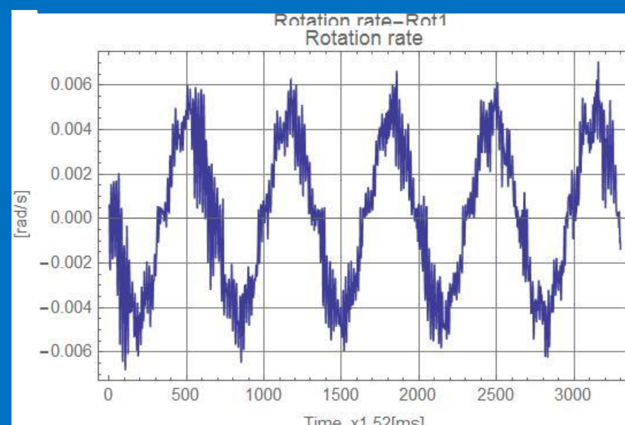


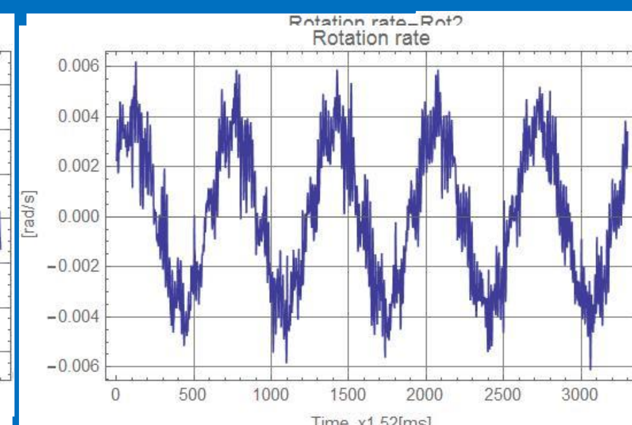
Rotation from accelerometer

FOSREM-SS (DC- 100 Hz)

FOSERM-BB



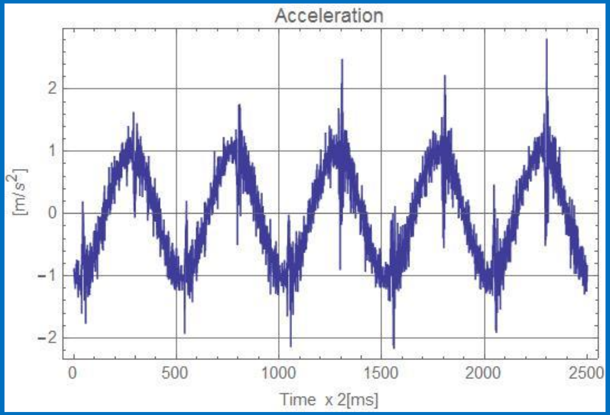




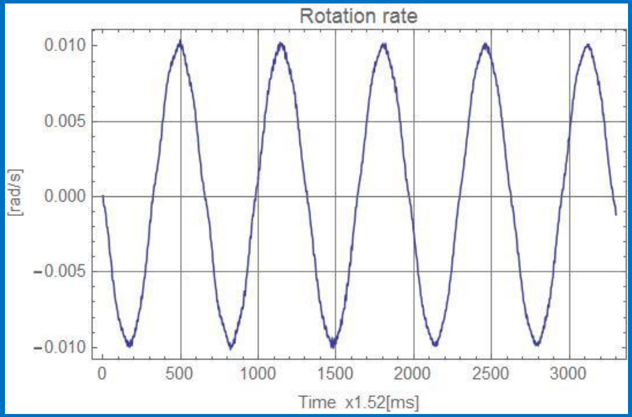
#3 FOSREM with passband to 100 HZ is to noisy but lower cutting amplitude (HORIZON probably has 500 Hz)

Sine 1 Hz (100% of amplitude)

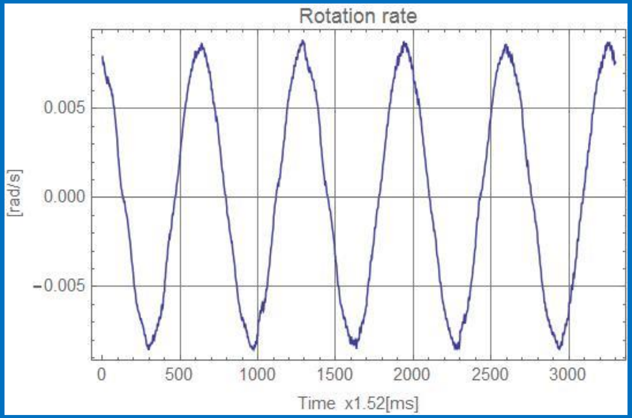
Accelerometer



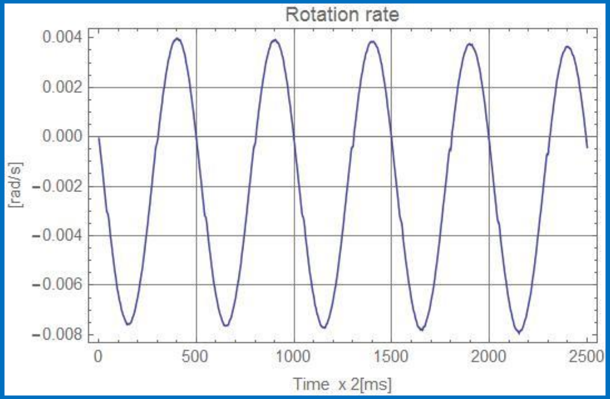
FOSREM-SS (DC- 10 Hz)



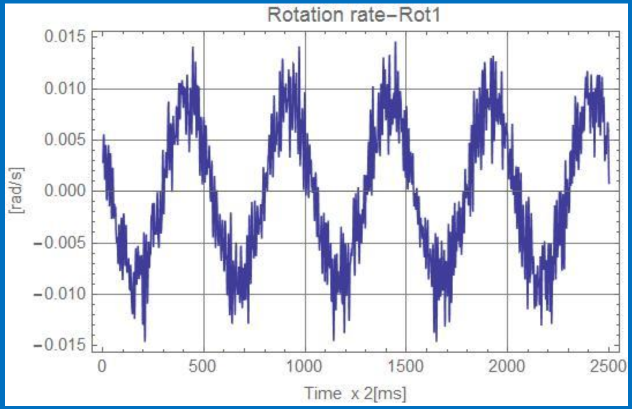
FOSERM-BB



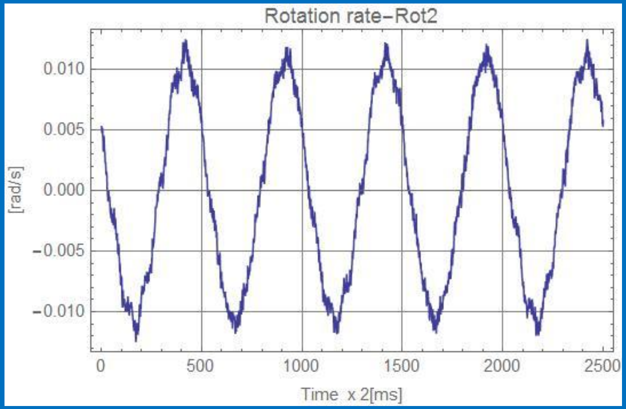
Rotation from accelerometer



HORIZON® „before”



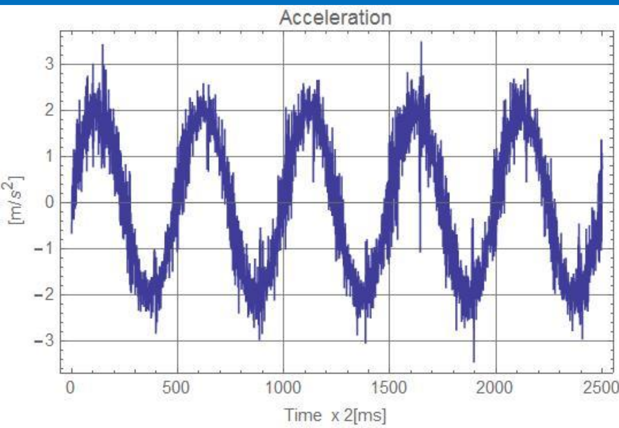
HORIZON® „after”



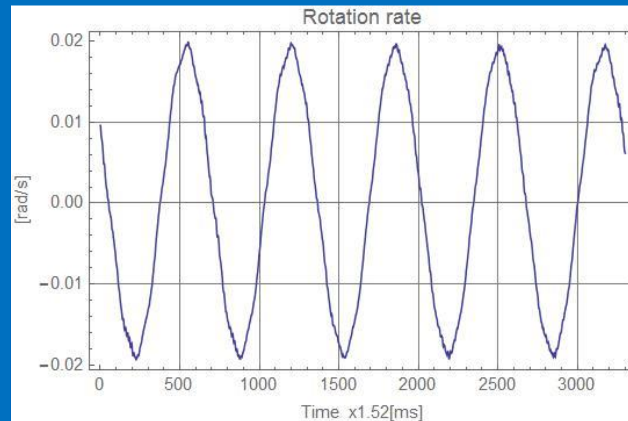
#1 HORIZON – Before shows nise connected with linear bearing
#2 all seismometers are some different calibrated

Sine 1 Hz (200% of amplitude)

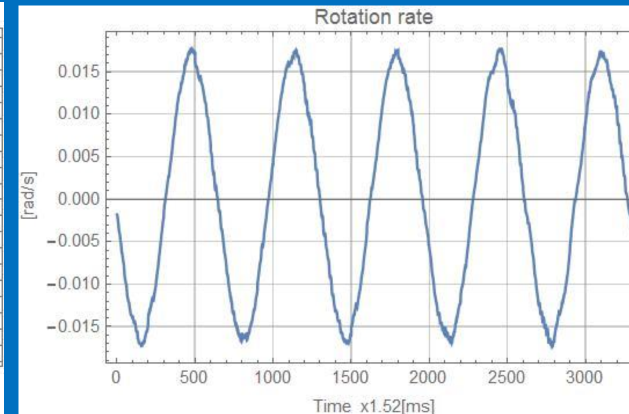
Accelerometer



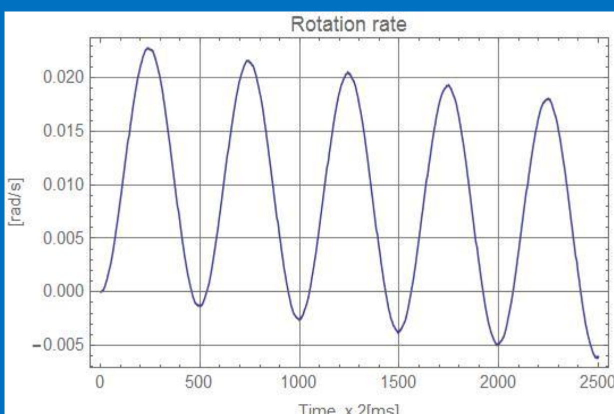
FOSREM-SS (DC- 10 Hz)



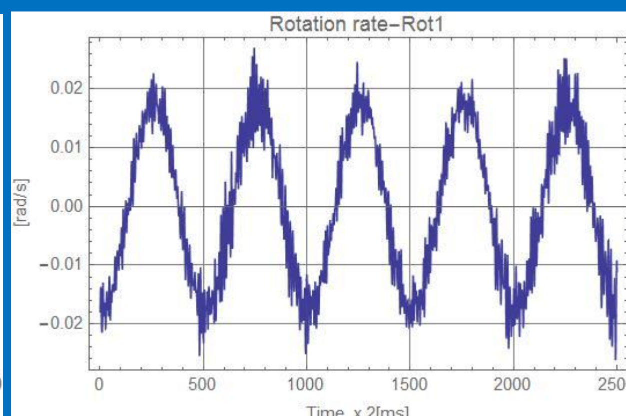
FOSERM-BB



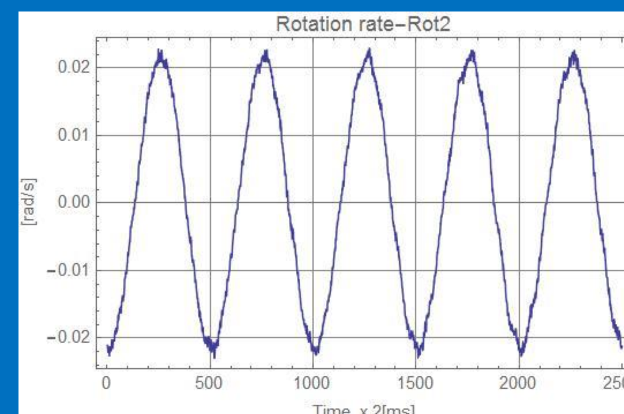
Rotation from accelerometer



HORIZON® „before”



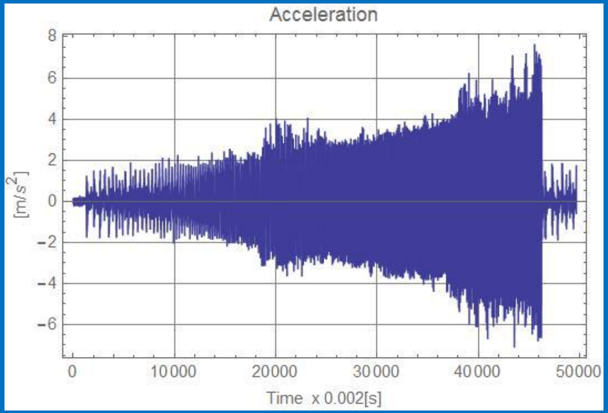
HORIZON® „after”



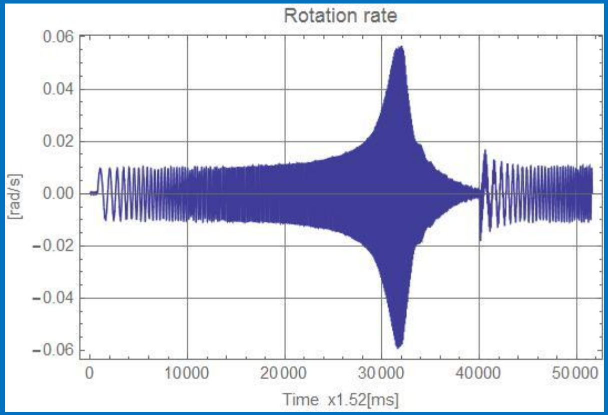
#1 HORIZONs have limited amplitude below above)

Sweep sine: 0,25 – 10 Hz

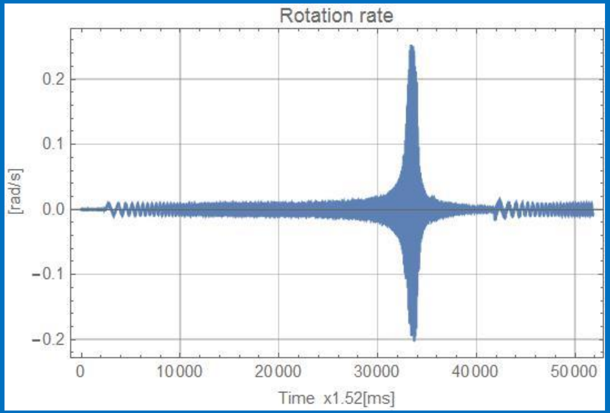
Accelerometer



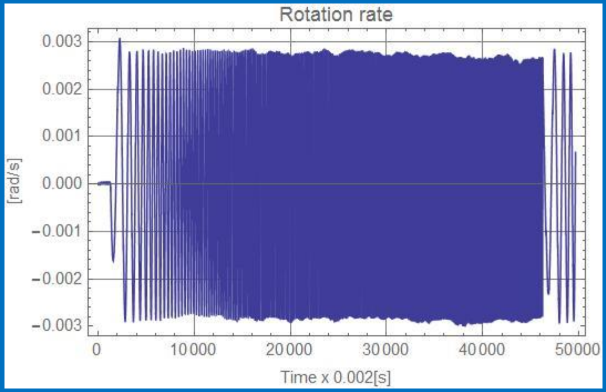
FOSREM-SS (DC- 10 Hz)



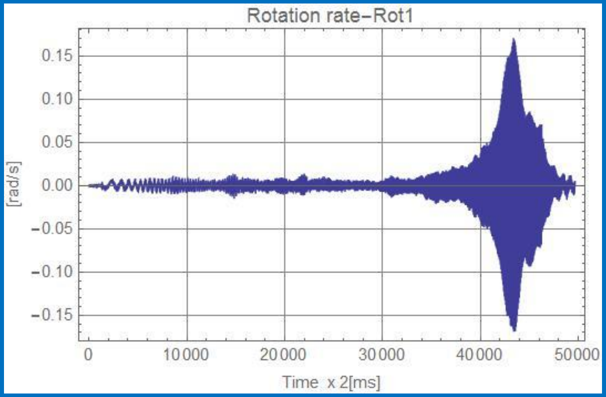
FOSERM-BB



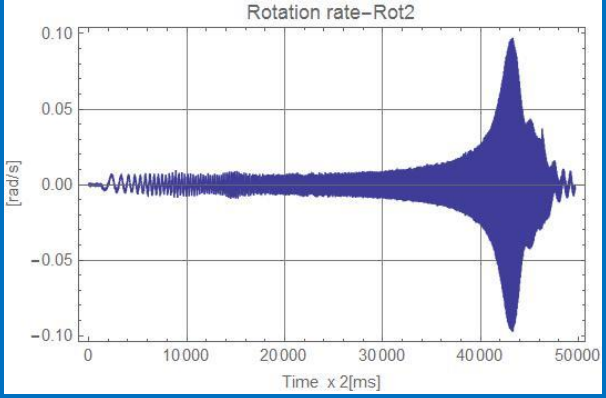
Rotation from accelerometer



HORIZON® „before"



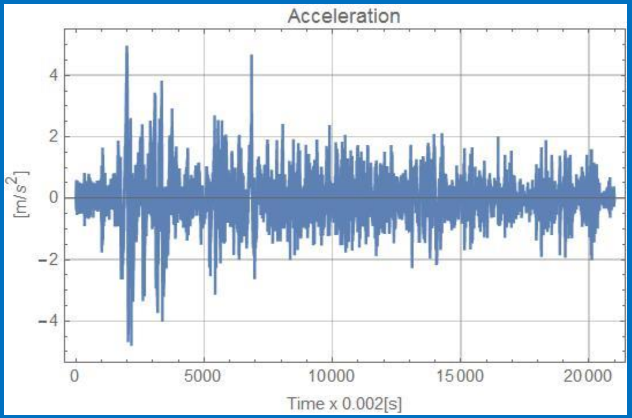
HORIZON® „after"



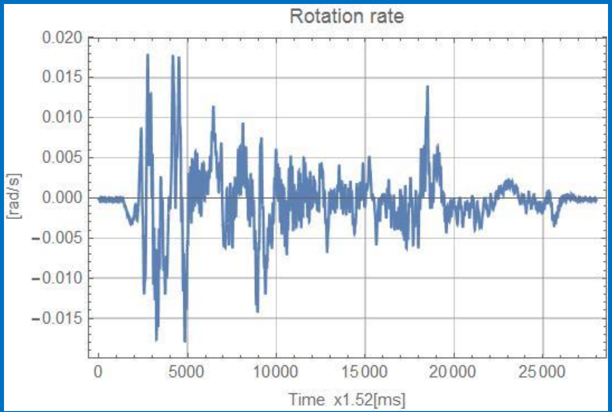
#1 The existence of resonanse characteristics of beam for about 8 Hz is well observed

El Centro Earthquake

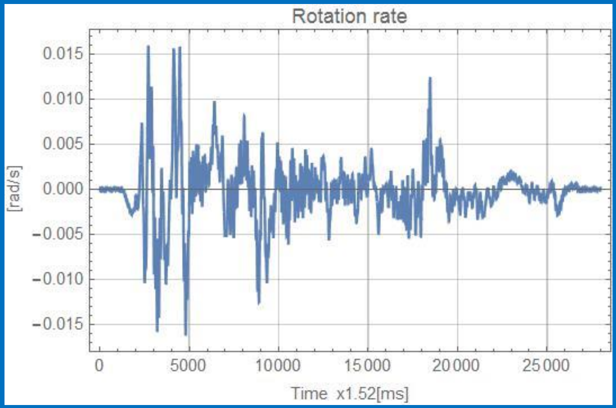
Accelerometer



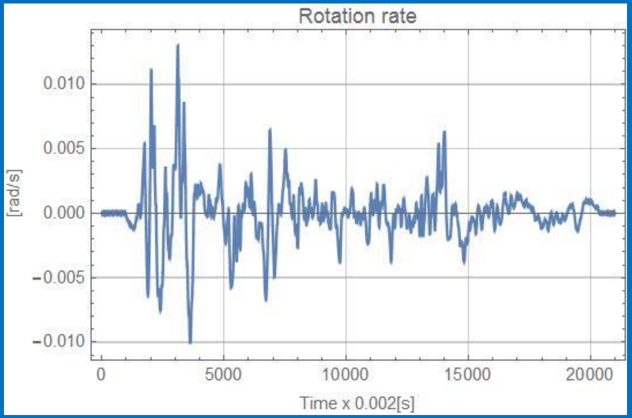
FOSREM-SS (DC – 10 Hz)



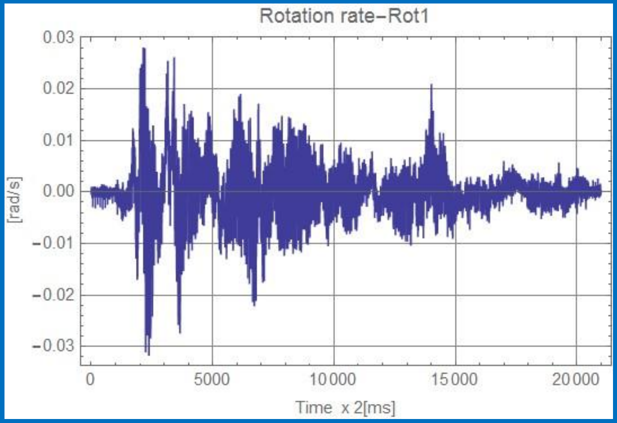
FOSERM-BB



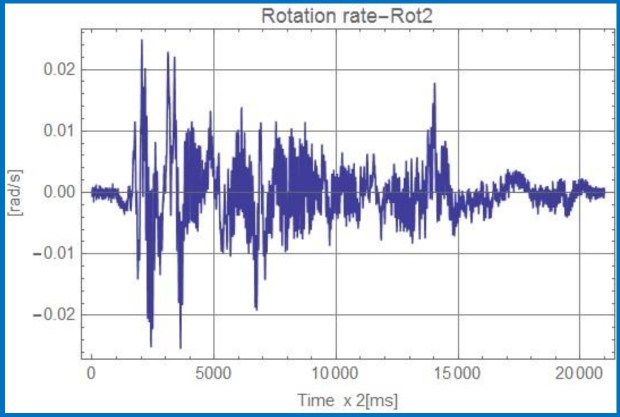
Rotation from accelerometer



HORIZON® „before”



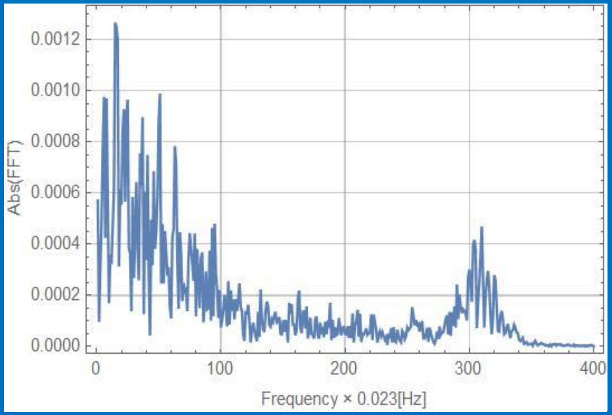
HORIZON® „after”



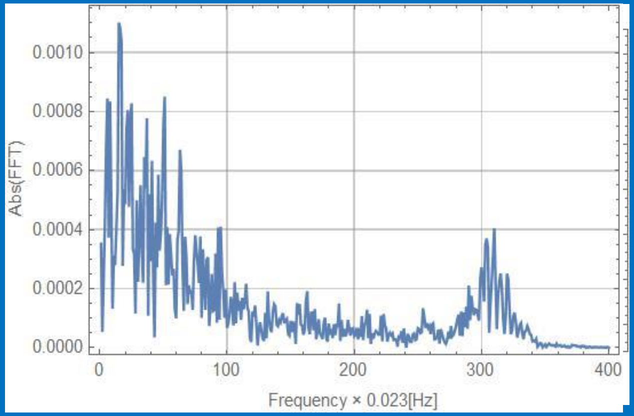
El Centro Earthquake

FT analyse

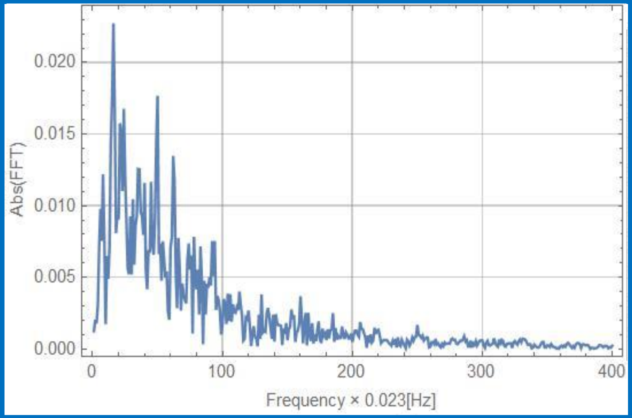
FOSREM-SS (DC – 10 Hz)



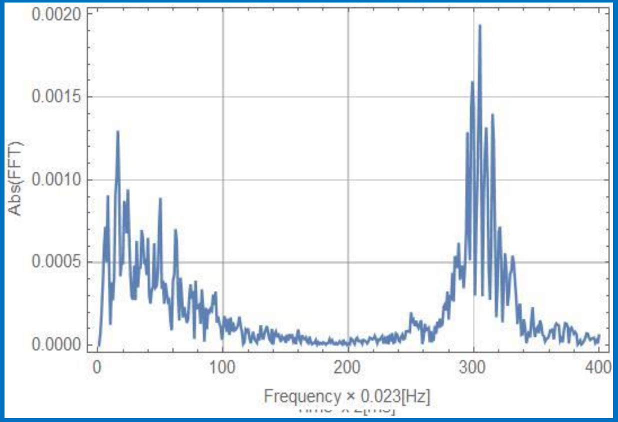
FOSERM-BB



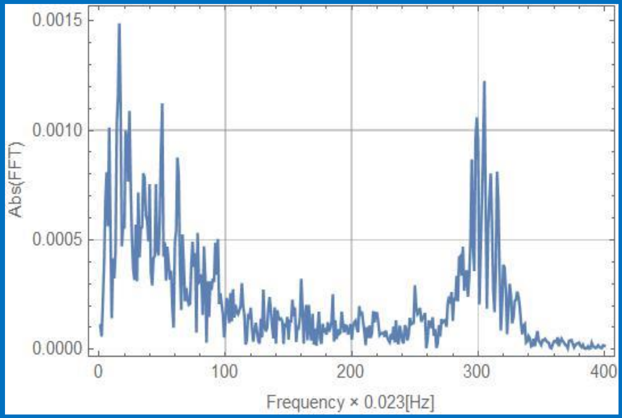
Rotation from accelerometer



HORIZON® „before"



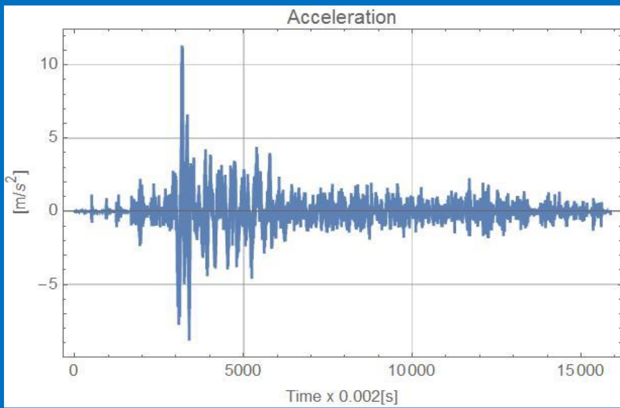
HORIZON® „after"



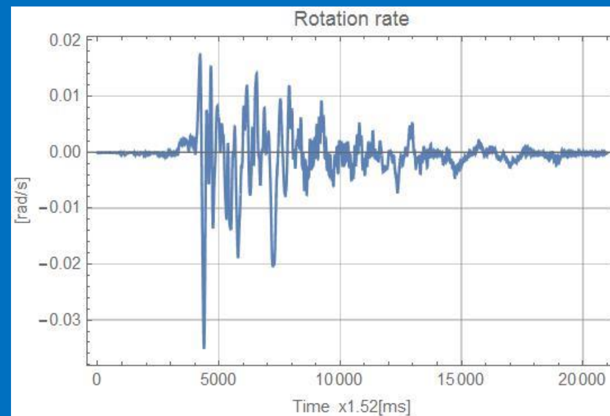
The spectrum are the same with additional component in range of 7 Hz (300 x 0,023= 6,9 Hz) connected with linear bearing works

Loma Prieta Earthquake with 100% amplitude

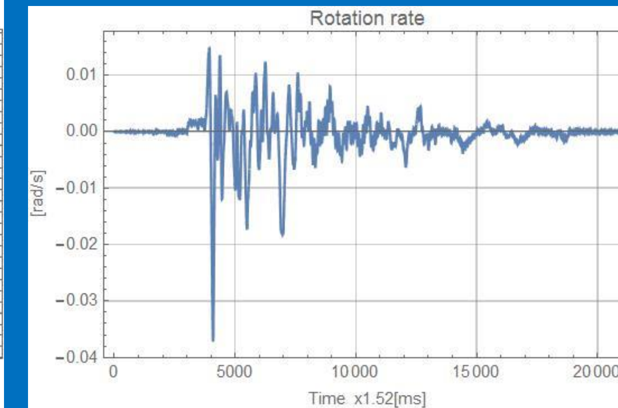
Accelerometer



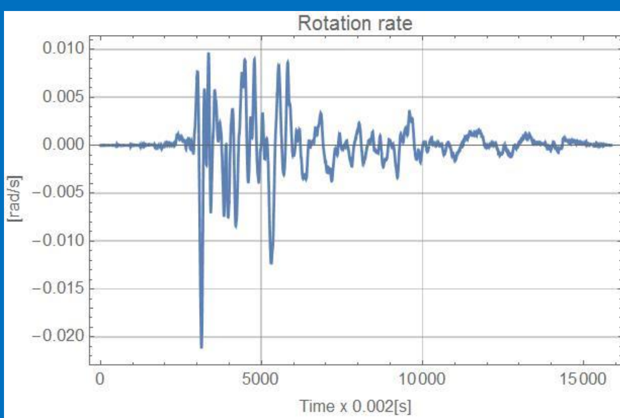
FOSREM-SS (DC – 10 Hz)



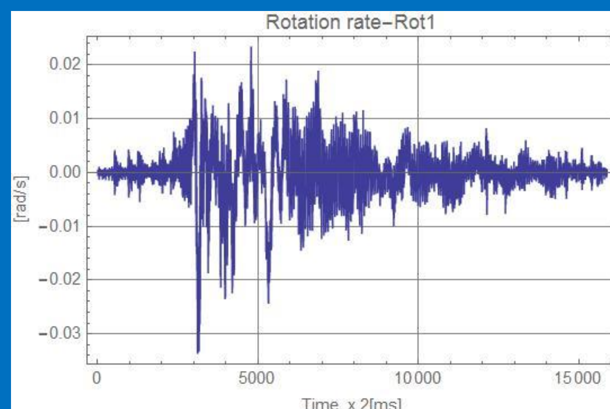
FOSERM-BB



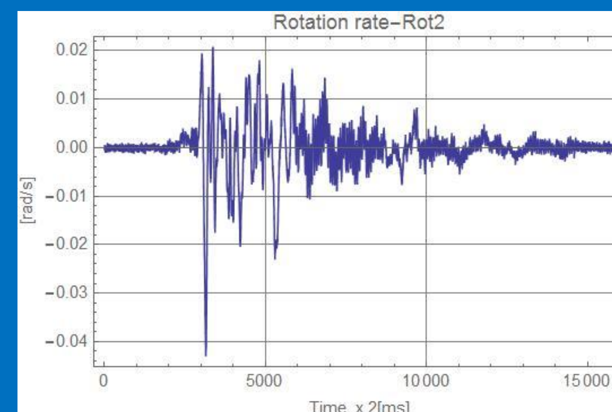
Rotation from accelerometer



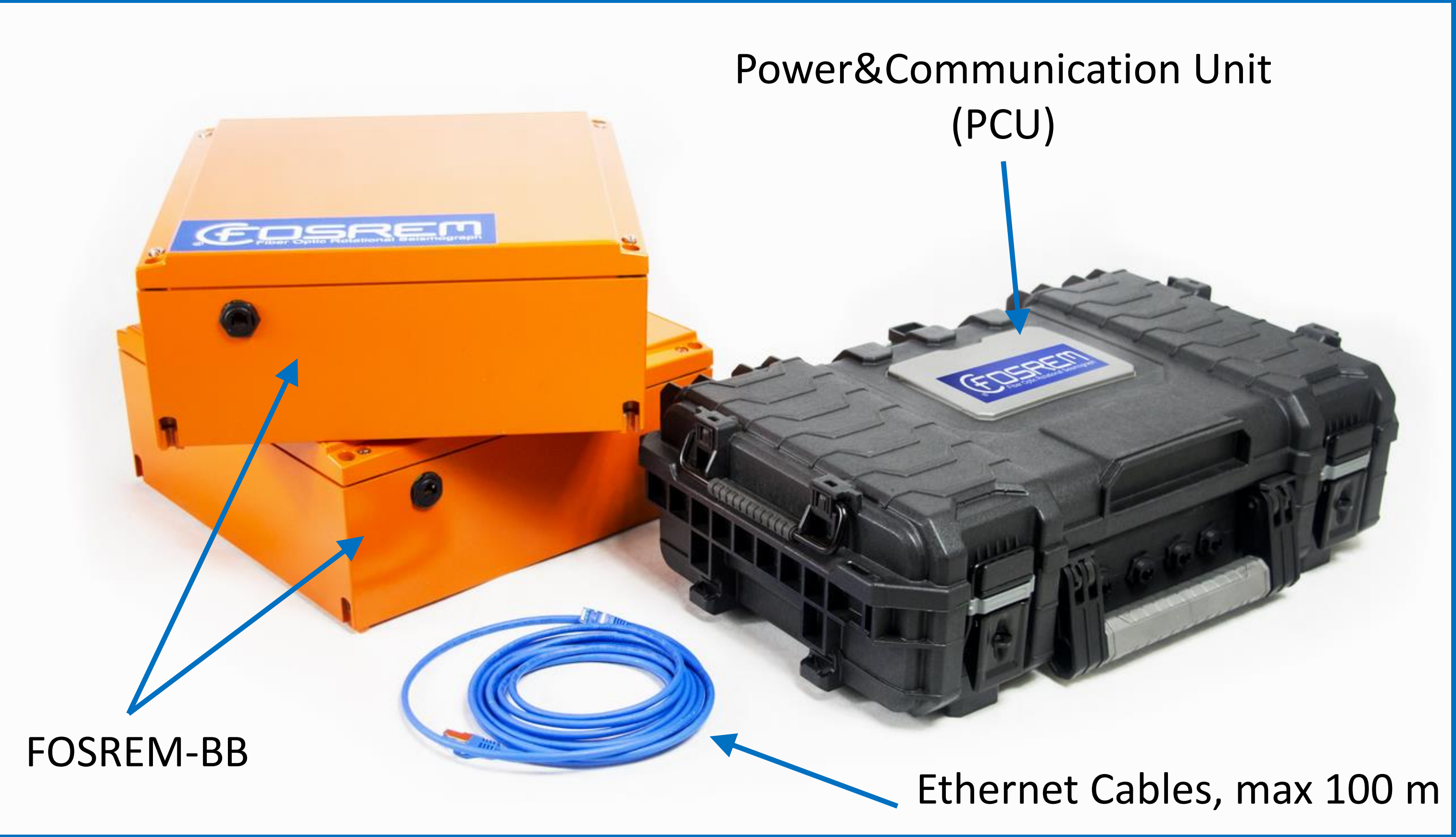
HORIZON® „before"



HORIZON® „after"

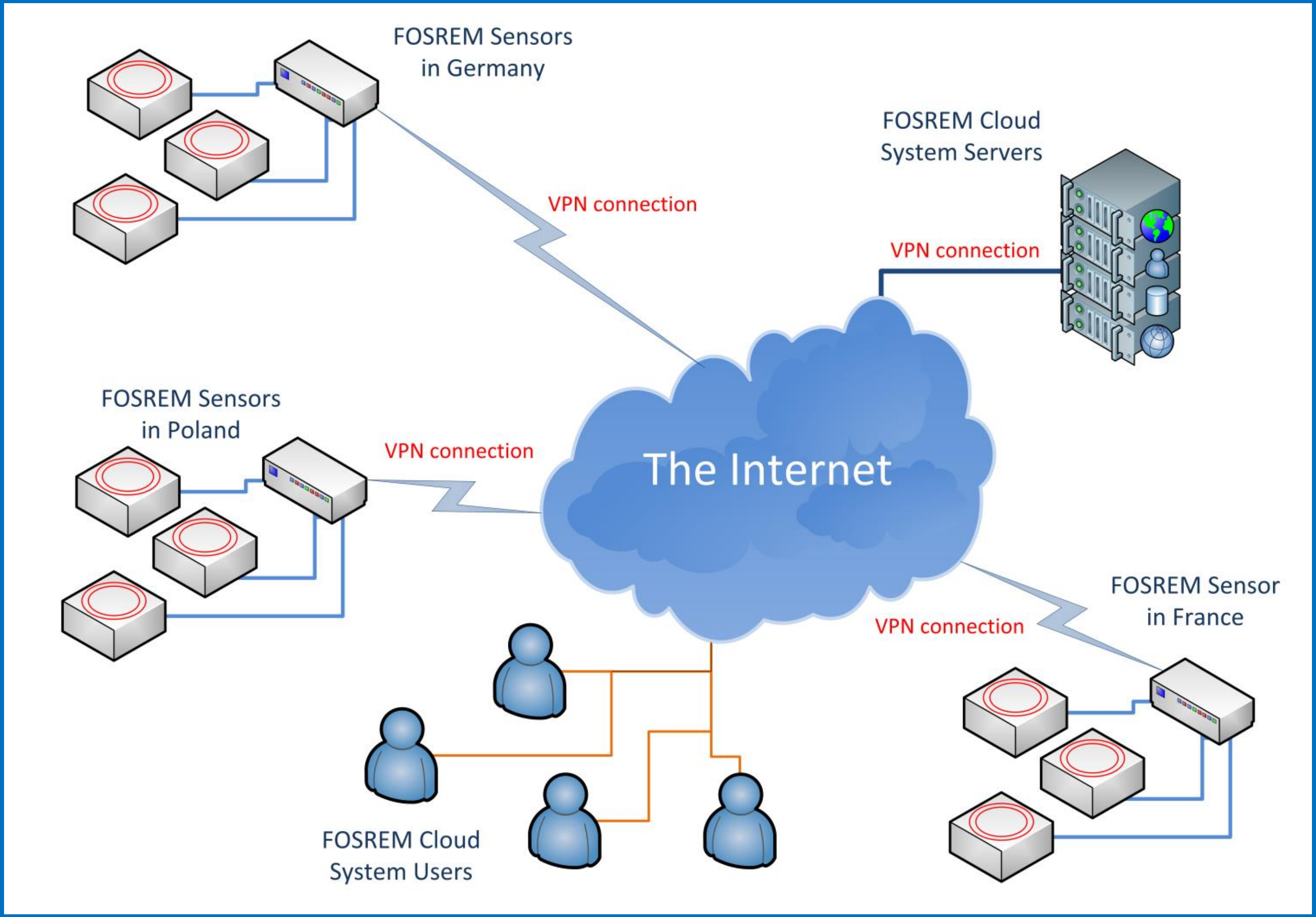


Multi-sensor synchronous measuring system



The FOSREM System includes two parts: FOSREM-BB sensor(s) (FOS-3) and Power & Communiation Unit (PCU). The connection provides data transmission and power supply over only one, standard STP cable within the distance of 100 meters.

FOSREM Cloud System



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.