RESIF, 12-14 NovembRE 2019
Biarritz, France

Some examples of measurements of the seismic rotation motion by the Ixblue fiber optic gyroscope sensor: the Blueseis 3A
The pylo Station and LSBB Experiments

Olivier Sèbe, Hélène Pauchet, Matthieu Sylvander (OMP), and Raphael Garcia (ISAE)

But also for LSBB experiement

Frédéric Guattari, Jean-Baptiste Decitre, Sébastien Judenherc, Charly Lallemand, Stéphane Gaffet, Daniel Boyer, Alain Cavaillou, François Schindelé

OUTLINES

- Rotation motion in seismology
  - Definition and interest
- The current different ways to estimate seismic rotation motion
- The Amatrice and Norcia records at LSBB (ixblue prototype)
- The PYLO Station Experiment: The Jonsac event (Bluseis 3A)
- Conclusions

ROTATION MOTION IN SEISMOLOGY

- Displacement vector field in elastic solid

Translation -> seismometer

$$\mathbf{u}(\boldsymbol{x}) = \begin{vmatrix} u_1 \\ u_2 \\ u_3 \end{vmatrix}$$

Deformation: ε

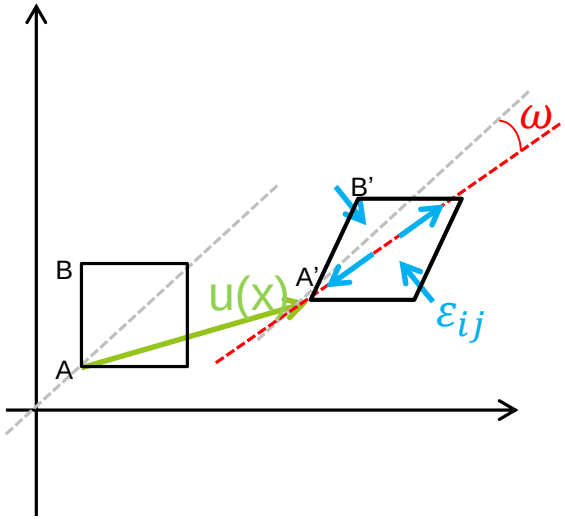
$$\varepsilon_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)$$

$$\mathbf{u}(\mathbf{x}+\delta\mathbf{x}) = \mathbf{u}(\mathbf{x}) + \boldsymbol{\varepsilon}\,\delta\mathbf{x} + \boldsymbol{\omega}\times\delta\mathbf{x}$$

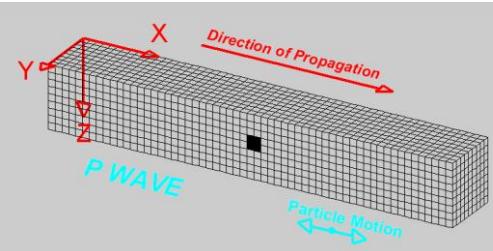
Displacement vector field

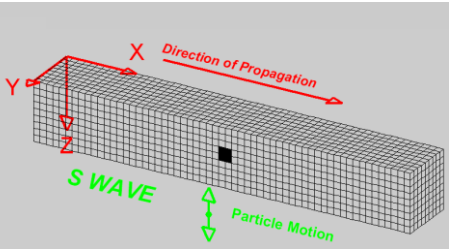
Rotation: $\boldsymbol{\omega} = {}^1/_2\,\boldsymbol{\nabla}\times\boldsymbol{u}(\boldsymbol{x})$

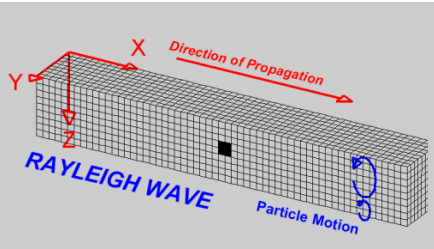
$$\boldsymbol{\omega} = \frac{1}{2}\begin{vmatrix} \partial_2 u_3 - \partial_3 u_2 \\ \partial_3 u_1 - \partial_1 u_3 \\ \partial_1 u_2 - \partial_2 u_1 \end{vmatrix}$$

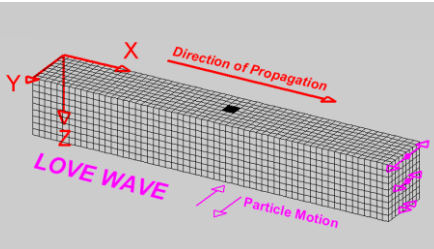


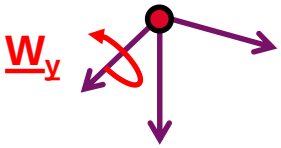
- Rotation motion of seismic waves
  - Helmotz formulation: $u = \underbrace{grad\,(\phi)}_{P\ waves} + \underbrace{Curl(\psi)}_{S\ waves}$ $curl\big(grad(\phi)\big)$=0 -> No rotation of P waves

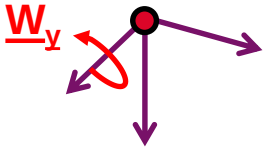


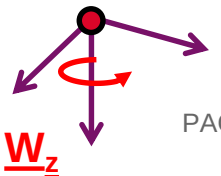








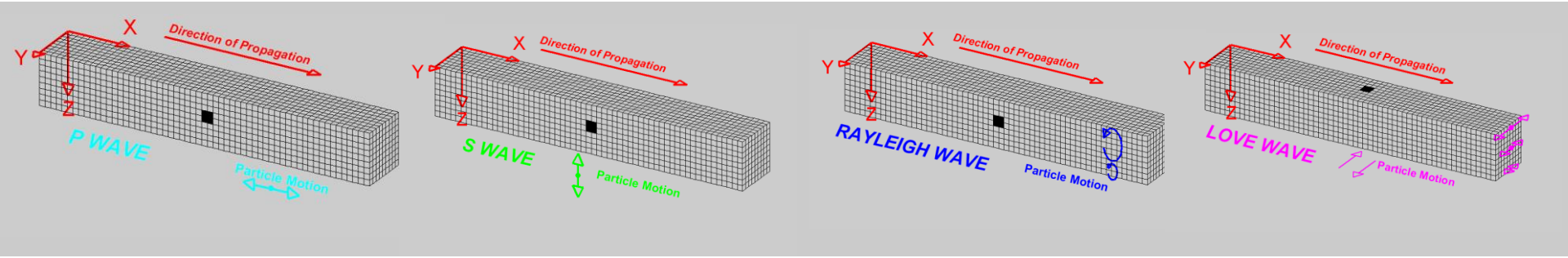


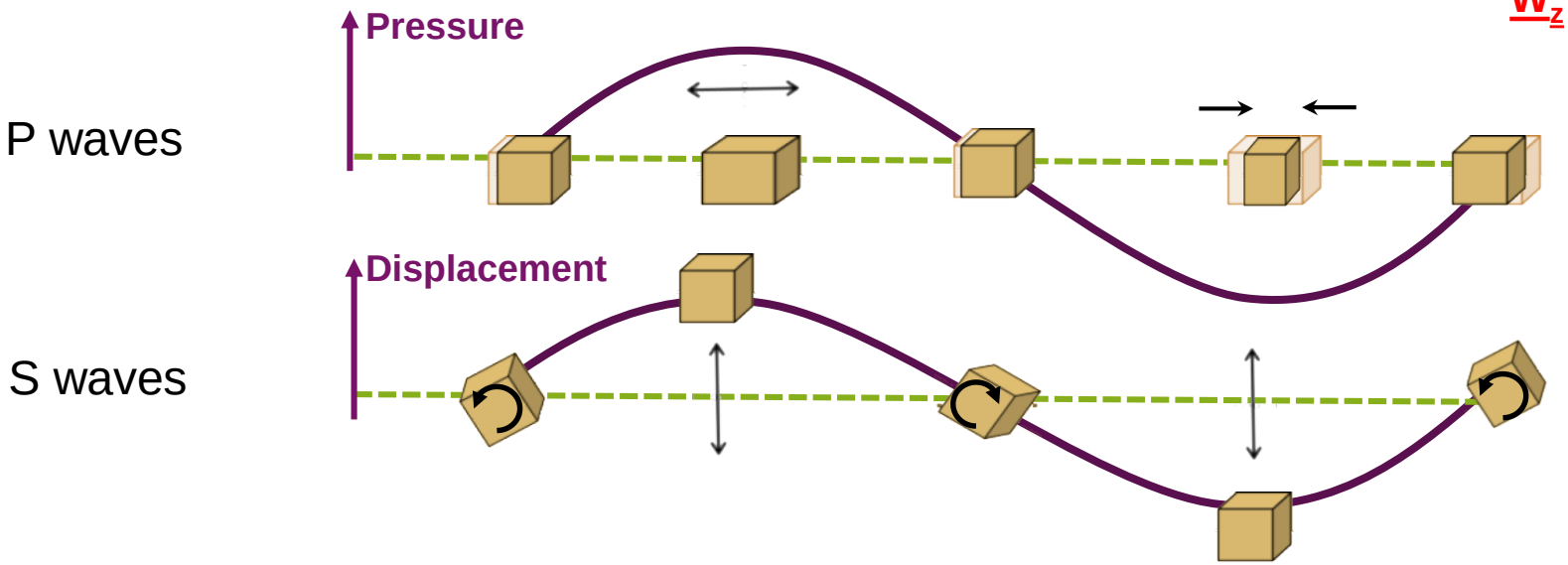


ROTATION MOTION IN SEISMOLOGY

- Rotation motion of seismic waves
  - Helmotz formulation: $u = \underbrace{grad\ (\phi)}_{P\ waves} + \underbrace{rot(\psi)}_{S\ waves}$

$curl\big(grad(\phi)\big)$=0 -> No rotation of P waves



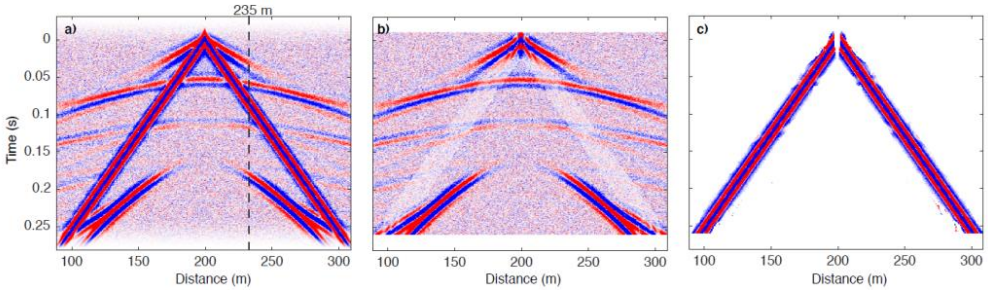


ROTATION MOTION IN SEISMOLOGY

- Interest:
  - **Wave field separation** from single 6C station (Sollberger 2018, Nakata 2016)

Helmotz formulation:
$u = \underbrace{grad\ (\phi)}_{P\ waves} + \underbrace{rot(\psi)}_{S\ waves}$ $curl\big(grad(\phi)\big)$=0 -> No rotation of P waves

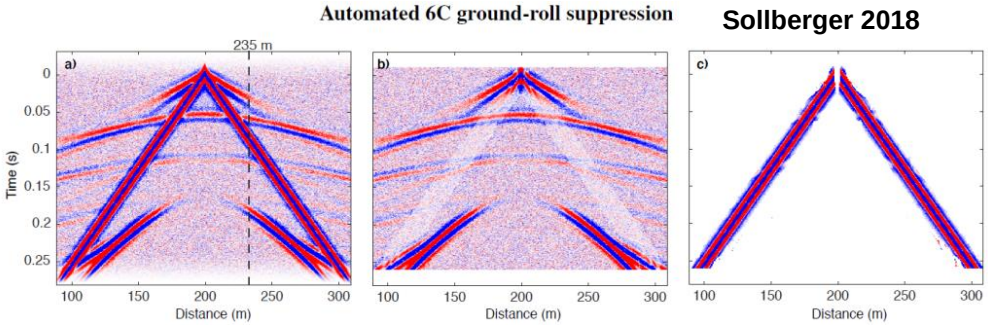
Automated 6C ground-roll suppression **Sollberger 2018**

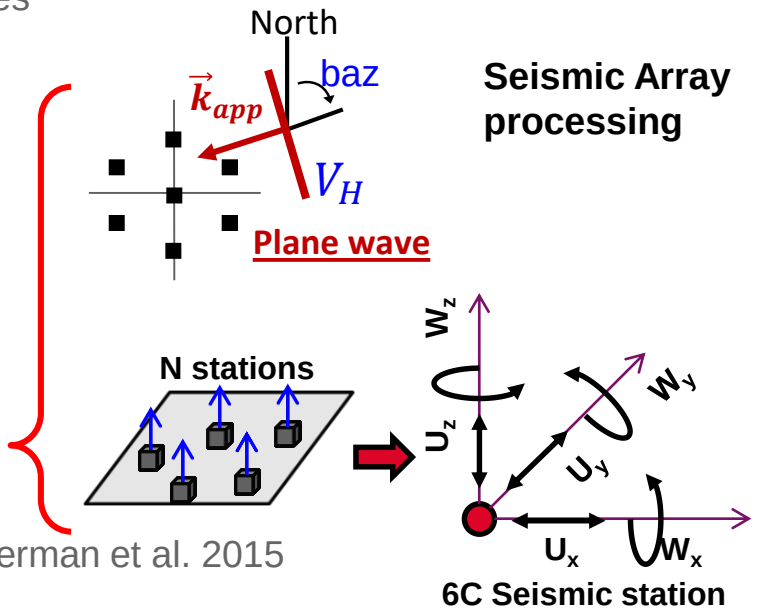


ROTATION MOTION IN SEISMOLOGY

- Interest:
  - **Wave field separation** from single 6C station (Sollberger 2018, Nakata 2016)

Helmotz formulation:
$u = \underbrace{grad\ (\phi)}_{P\ waves} + \underbrace{rot(\psi)}_{S\ waves}$ $curl\big(grad(\phi)\big)$=0 -> No rotation of P waves

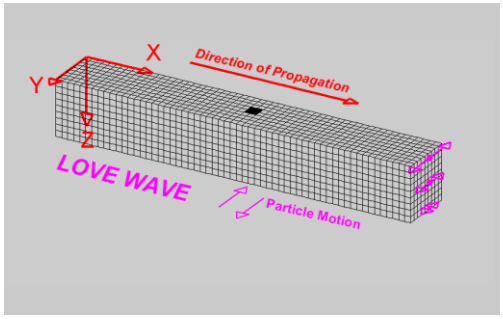


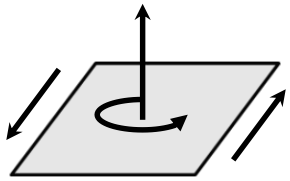


  - **Phase velocity** and **Direction finding** from single 6C station (translations and rotations)

Igel et al. 2007, Kurrle et al. 2010 Hadziioannou et al 2012, Wasserman et al. 2015

  - ➢ **Transverse acceleration and rotation are in phase**





$$\omega = \frac{1}{2}\begin{bmatrix}\partial_y u_z - \partial_z u_y \\ \partial_z u_x - \partial_x u_z \\ \partial_x u_y - \partial_y u_x\end{bmatrix}$$

$$u = u_y\left(t - \frac{x}{c}\right)$$

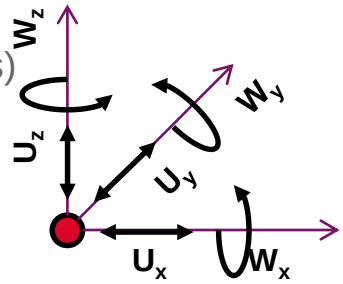
$$\dot{\omega}_z(\omega) = -\frac{\ddot{u}_y(\omega)}{2c(\omega)}$$

ROTATION MOTION IN SEISMOLOGY

- Interest:
  - **Phase velocity** and **Direction finding** from single 6C station (translations and rotations)

Igel et al. 2007, Kurrle et al. 2010 Hadziioannou et al 2012, Wasserman et al. 2015

  - ➢ **Transverse acceleration and rotation are in phase**



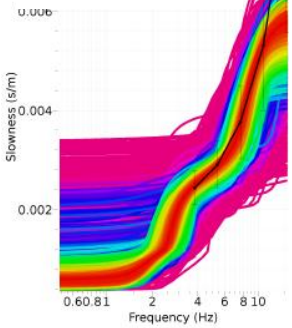
6C Seismic station

Local phase velocity

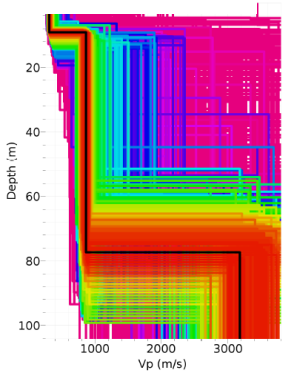
$$c(\omega) = -\frac{\ddot{u}_y(\omega)}{2\dot{\omega}_z(\omega)}$$

$$\dot{\omega}_z(\omega) = -\frac{\ddot{u}_y(\omega)}{2c(\omega)}$$

Love wave dispersion



Vs Profile

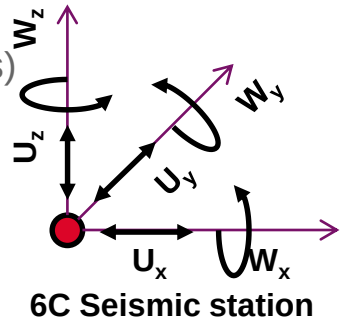


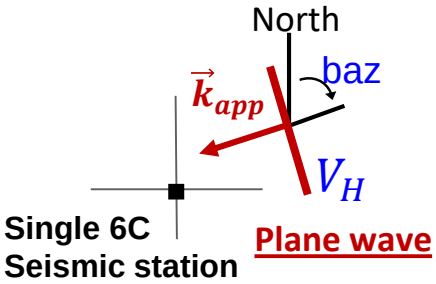
ROTATION MOTION IN SEISMOLOGY

- Interest:
  - **Phase velocity** and **Direction finding** from single 6C station (translations and rotations)

Igel et al. 2007, Kurrle et al. 2010 Hadziioannou et al 2012, Wasserman et al. 2015

  - ➢ **Transverse acceleration and rotation are in phase**



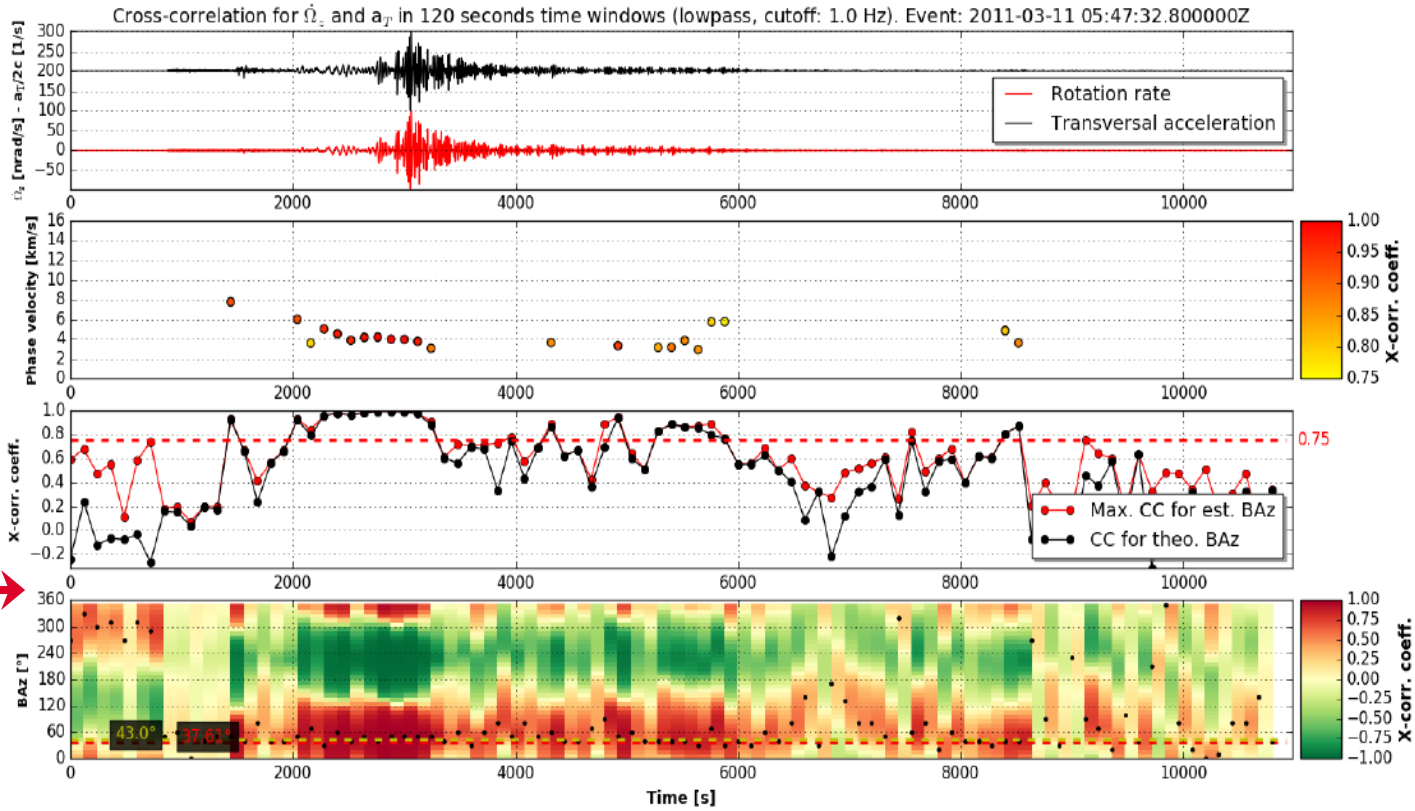


$$\dot{\omega}_z(\omega) = -\frac{\ddot{u}_y(\omega)}{2c(\omega)}$$

Direction finding

$$Max\left[Corr\left(\dot{\omega}_z, \ddot{u}_T(\theta)\right)\right]$$

Tohoku-Oki earthquake 2011 (Ring-Laser)

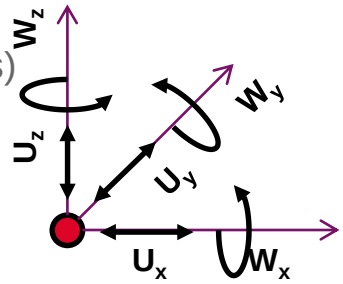


ROTATION MOTION IN SEISMOLOGY

- Interest:
  - **Phase velocity** and **Direction finding** from single 6C station (translations and rotations)

Igel et al. 2007, Kurrle et al. 2010 Hadziioannou et al 2012, Wasserman et al. 2015

  - ➢ **Transverse acceleration and rotation are in phase**



6C Seismic station

Local phase velocity

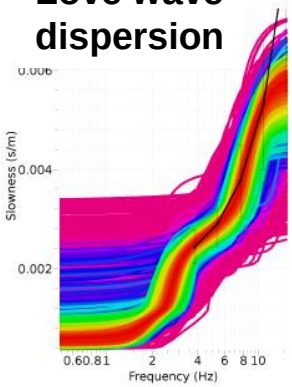
$$c(\omega) = -\frac{\ddot{u}_y(\omega)}{2\dot{\omega}_z(\omega)}$$

$$\dot{\omega}_z(\omega) = -\frac{\ddot{u}_y(\omega)}{2c(\omega)}$$

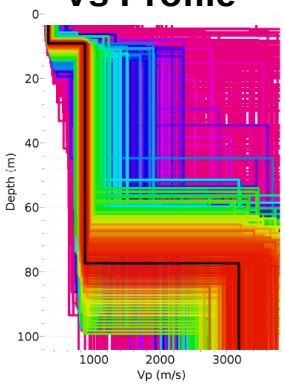
Direction finding

$$Max\left[Corr\left(\dot{\omega}_z, \ddot{u}_T(\theta)\right)\right]$$

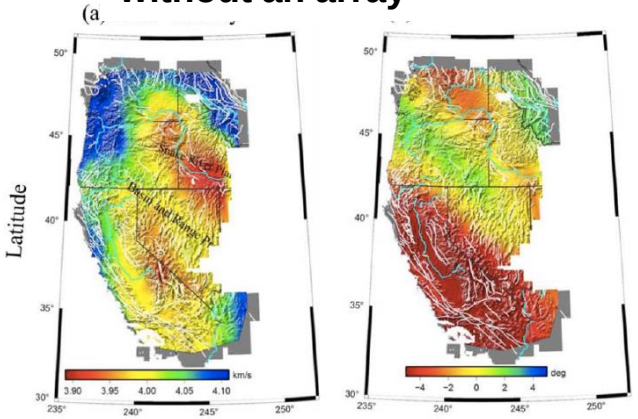
Love wave dispersion



Vs Profile

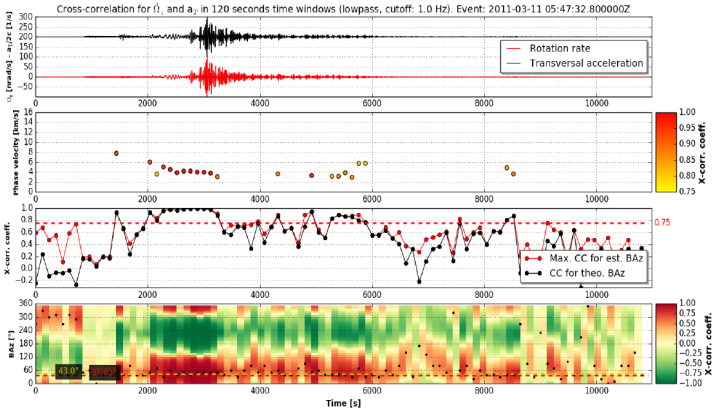


Wavefield gradiometry without an array



Liang &Langston 2009

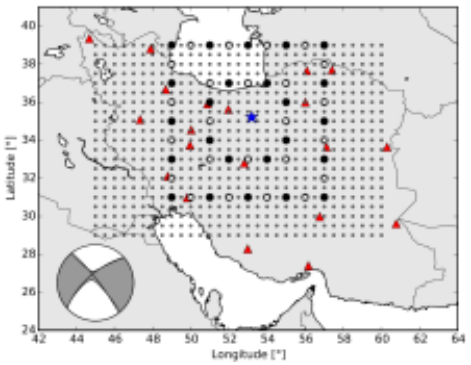
Tohoku-Oki earthquake 2011 (Ring-Laser)



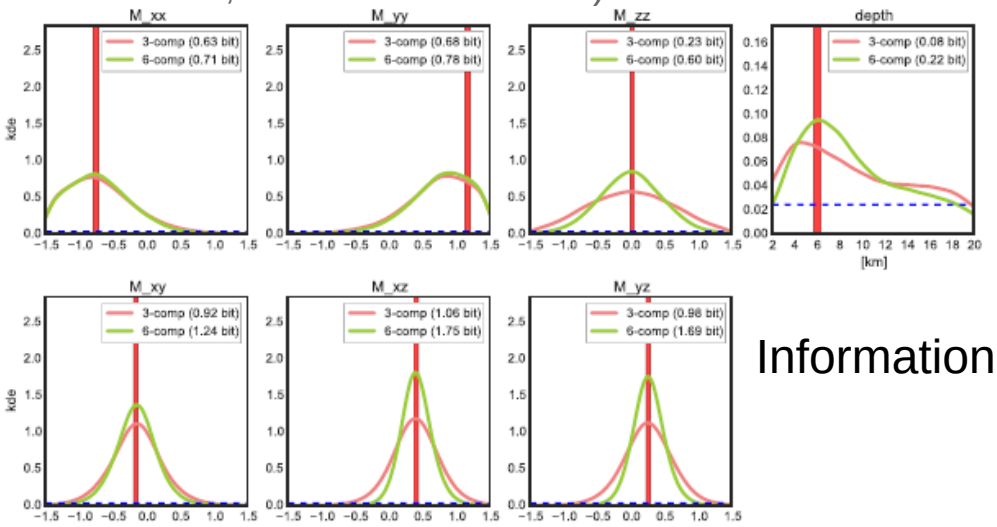
ROTATION MOTION IN SEISMOLOGY

- Interest:
  - Improved source characterization (Donner et al. 2018, Reinwald et al. 2016)

Focal mechanism inversion:



Donner 2016

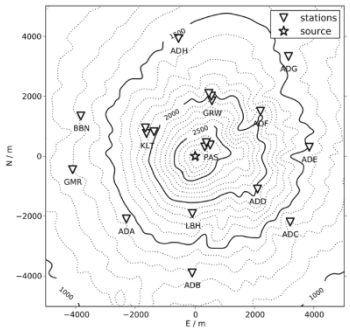


Information gain

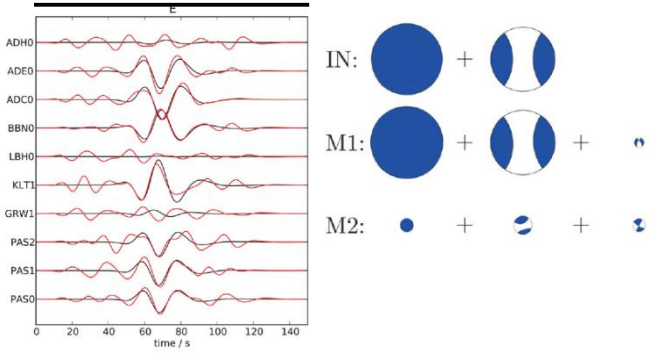
The resolution power of N/2 6C stations is greater than N 3C Stations

  - Remove tilt effects on moment tensor inversion (Van Driel et al. 2015)

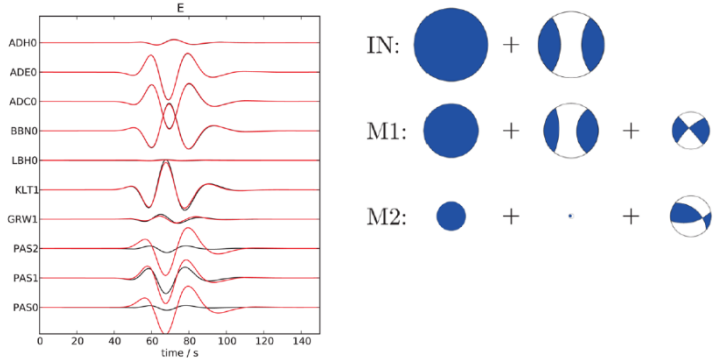
Small number of station and heterogeneous media



Gaussian noise

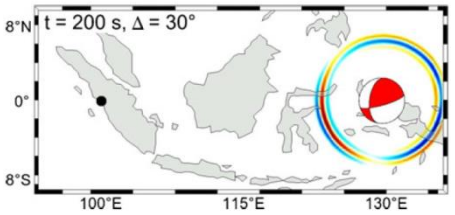


Tilt-contamined seismograms



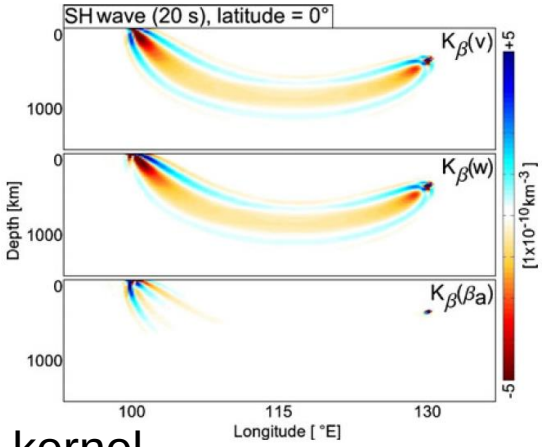
ROTATION MOTION IN SEISMOLOGY

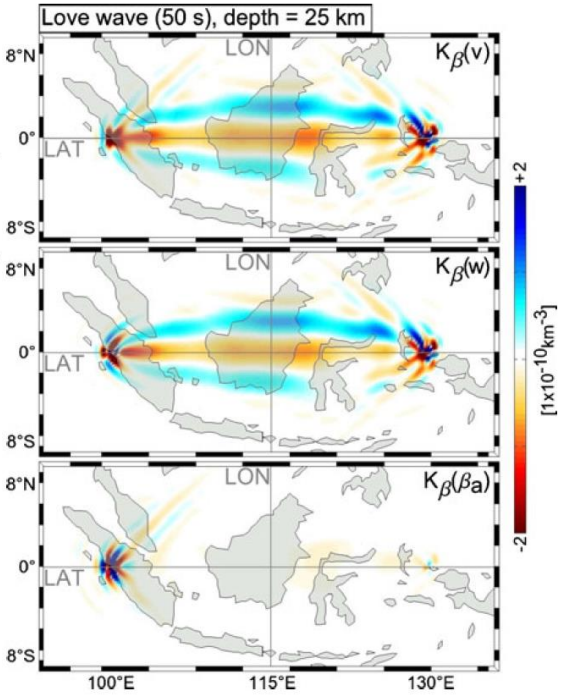
- Interest:
  - Seismic tomography improvement (Fichtner 2008, Bernauer et al. 2009, 2012)
    - **Observable: Amplitude ratio of velocity and rotation**
    - **Tomography without travel time!**
    - **Constraint on local structure without knowledge in the deeper Earth**

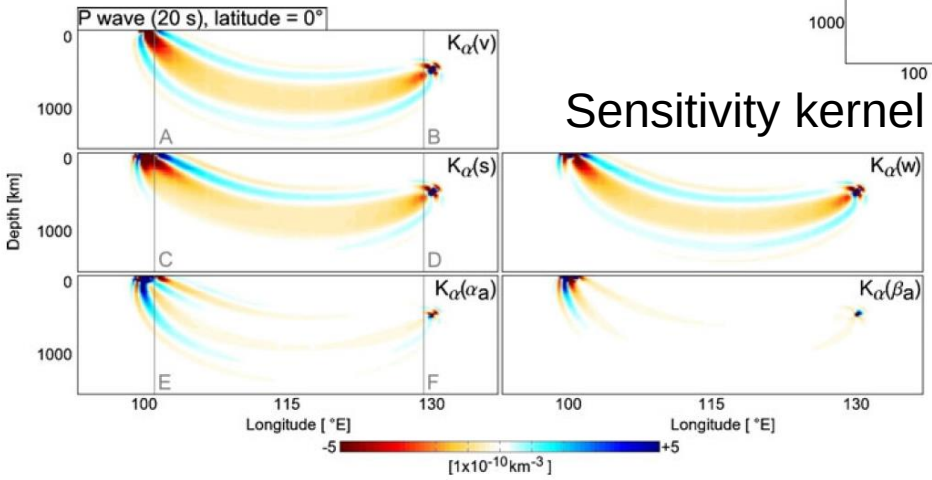


Apparent S velocity: $\beta_a(X_r) = \frac{1}{2}\frac{\dot{u}(X_r)}{\omega(R_r)}$

Apparent Pvelocity: $\alpha_a(X_r) = \frac{\dot{u}(X_r)}{s(X_r)}$







Sensitivity kernel

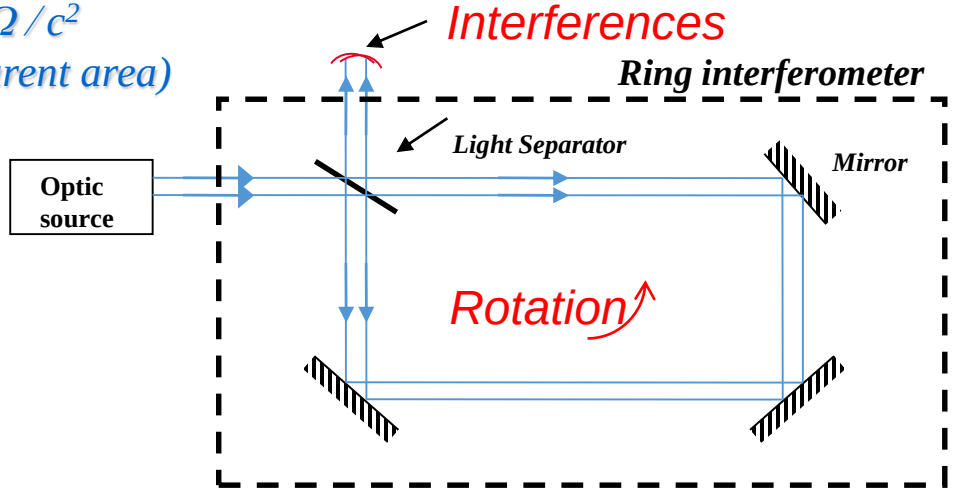
- Seismic risk and strong motion: rotation effect on building

ROTATIONAL MEASUREMENT: THE OPTIC SENSORS

- The Optic Gyroscope “seismometers” are based on the Relativistic **Sagnac Effet**:
  - Interfering 2 counter–propagating beams and measuring phase shift of the light propagating in “moving” ring cavity :

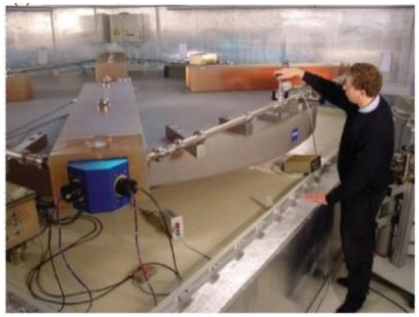
$$\Delta T = 4.S.\ \Omega / c^2$$

(where S is apparent area)

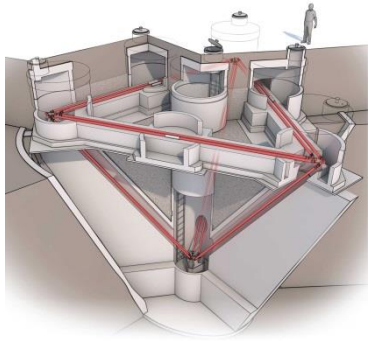


  - the co-rotating path is longer than one turn, the counter-rotating one is shorter

- the Ring Laser Gyroscope (RLG).

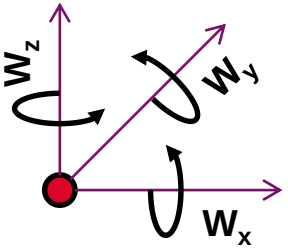


ROMY
Target sensitivity: 10^{-12}rad/s

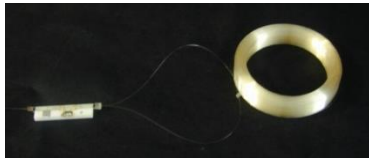


Wettzell Geodetic Observatory
10^{-10}rad.s^{-1}/√Hz before 2009
10^{-11}rad.s^{-1}/√Hz after 2009

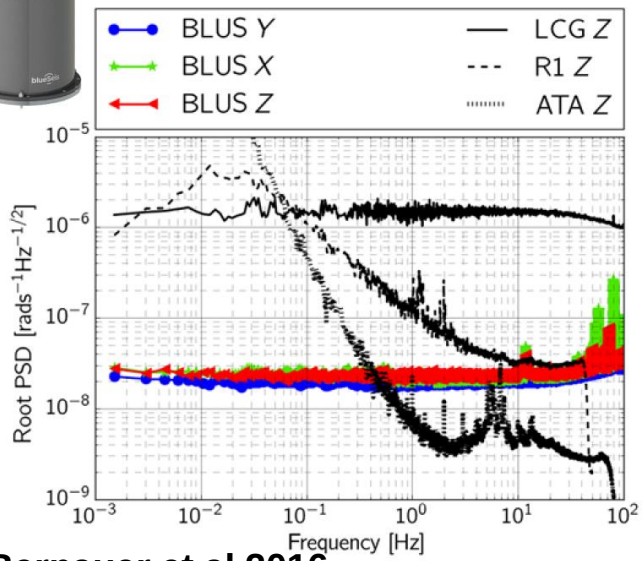
- Ring cavity = **fiber-optic gyroscope (FOG) ~4-6km**
  - BlueSeis 3A: first portable “3 axes” instrument with such low noise of 20 nrad/s/√Hz



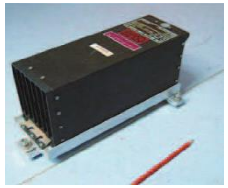
3C Rotational Seismometer



OTHER SENSORS AND PERFORMANCE

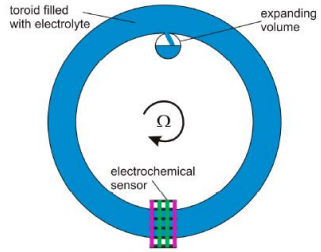


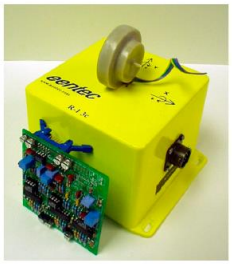
Bernauer et al 2016



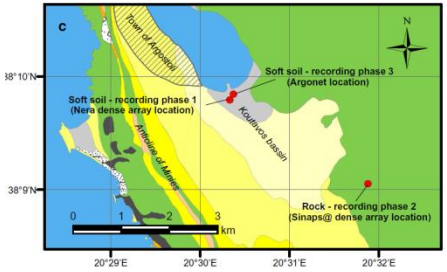
LCG demonstrator, FOG

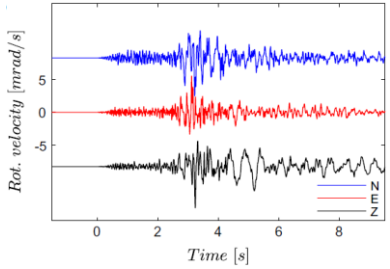
R1: Electrochemical rotational sensor



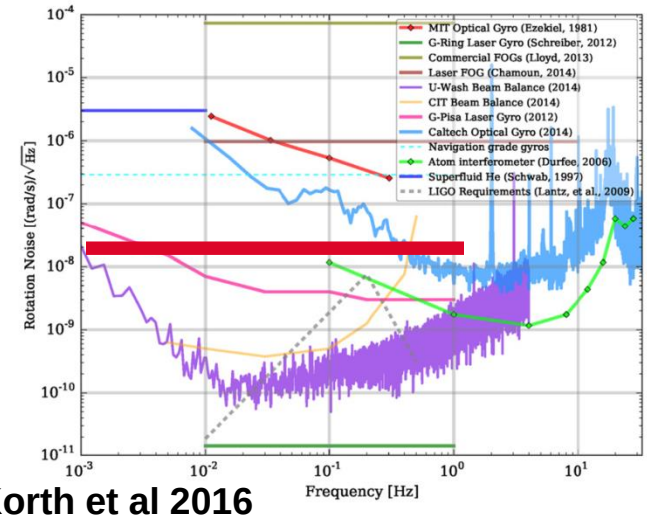


R1: SINAP@ Kefalonia post seismic experiment





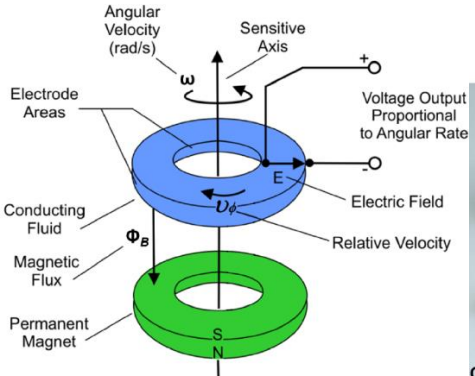
Sbaa et al 2016

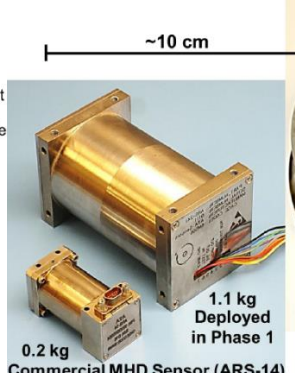


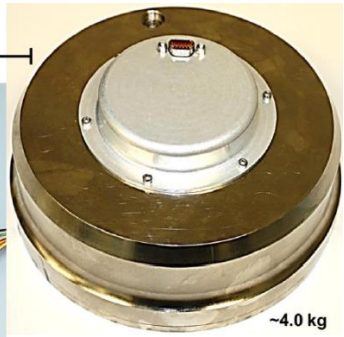
Korth et al 2016

ATA: Magneto-hydrodynamic sensor

Pierson et al 2016

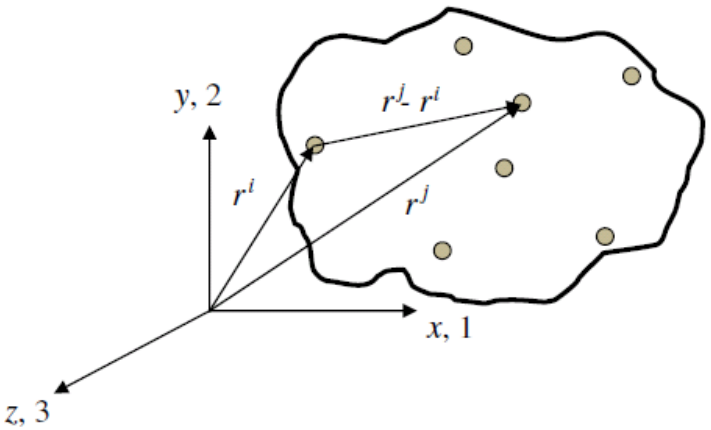






ROTATION MEASUREMENT: INDIRECT ESTIMATIONS

- Array-Derived Rotation (ADR)



$$\mathbf{u}(\mathbf{x}+\delta\mathbf{x}) = \mathbf{u}(\mathbf{x}) + \mathbf{G}\delta\mathbf{x}$$

- Finite difference approximation of the Gradient tensor **G**

Data | **G** unknown | $\boldsymbol{\delta x}$ Array geometry

$$\begin{Bmatrix} u_1^j - u_1^i \\ u_2^j - u_2^i \\ u_3^j - u_3^i \end{Bmatrix} = \begin{bmatrix} u_{1,1} & u_{1,2} & u_{1,3} \\ u_{2,1} & u_{2,2} & u_{2,3} \\ u_{3,1} & u_{3,2} & u_{3,3} \end{bmatrix} \begin{Bmatrix} r_1^j - r_1^i \\ r_2^j - r_2^i \\ r_3^j - r_3^i \end{Bmatrix}$$

where $u_{i,j} = \frac{\partial u_i}{\partial x_j}$

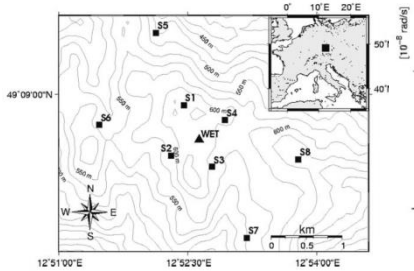
Gradient along the vertical direction!

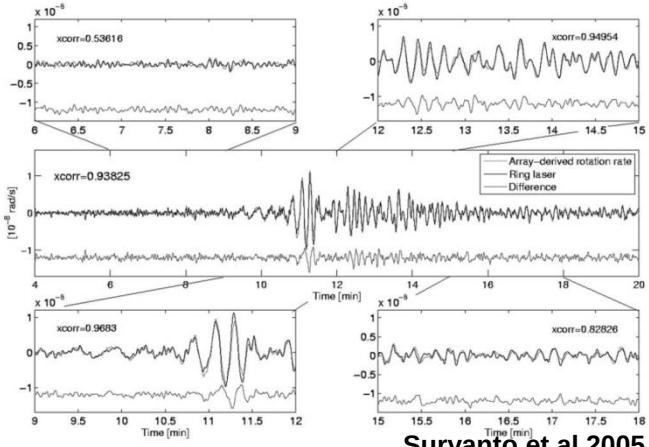
- Free surface condition:

$$\begin{cases} u_{1,3} = -u_{3,1} \\ u_{2,3} = u_{3,2} \\ u_{3,3} = -\dfrac{\lambda}{\lambda + 2\mu}\left(u_{1,1} + u_{2,2}\right) \end{cases}$$

- **Mean square inversion** of the Gradient tensor G, 6 unknowns :
(Spudich et al 1995, Spudich & Fletcher 2008, 2009)

Estimation of $\varepsilon_{i,j}$ and ω

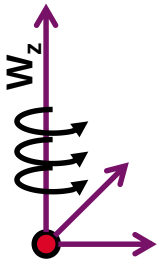


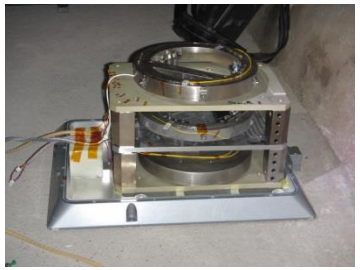


Suryanto et al 2005

IXBLUE ROTATIONAL SENSORS AT LSBB

- iXblue experiment: toward giant-FOG (Guattari et al 2017 & 2018)

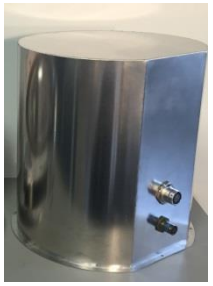


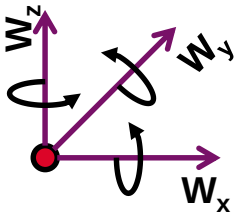


3x1C Rotation

R=9cm

Scorsese 1

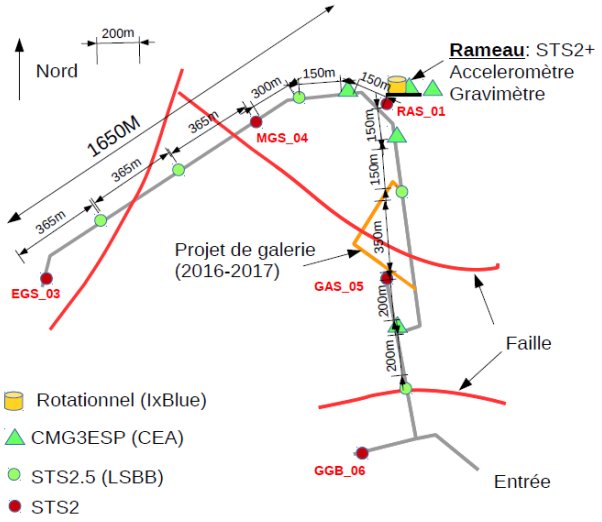


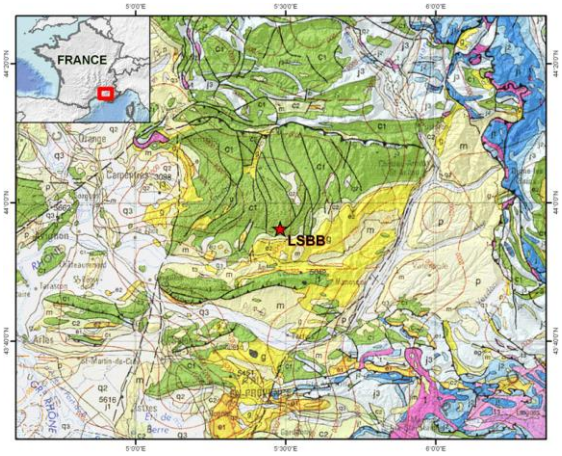


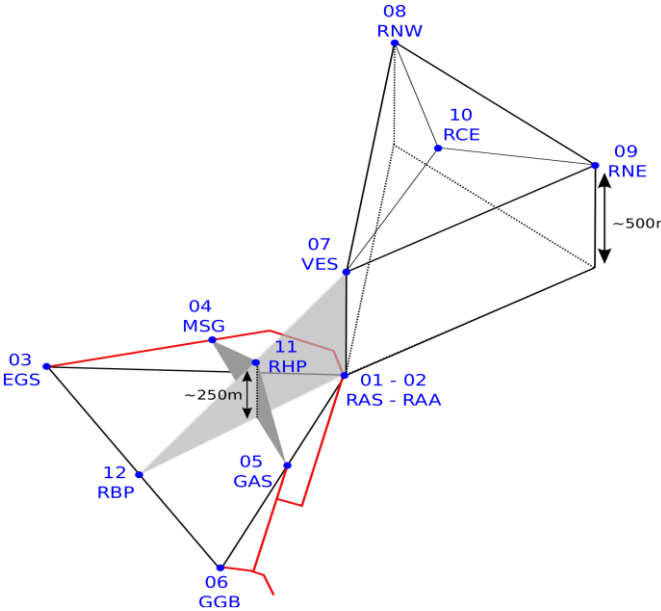
3x1C Rotation

R=9cm

Scorsese 2

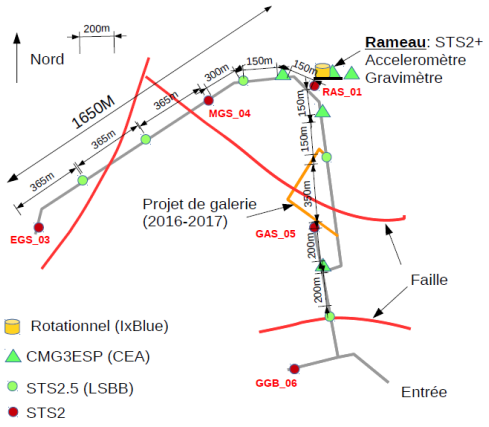


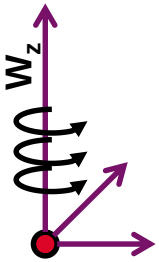


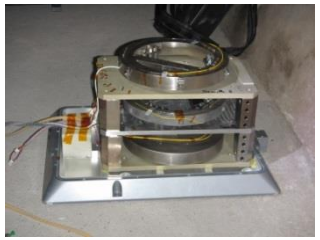


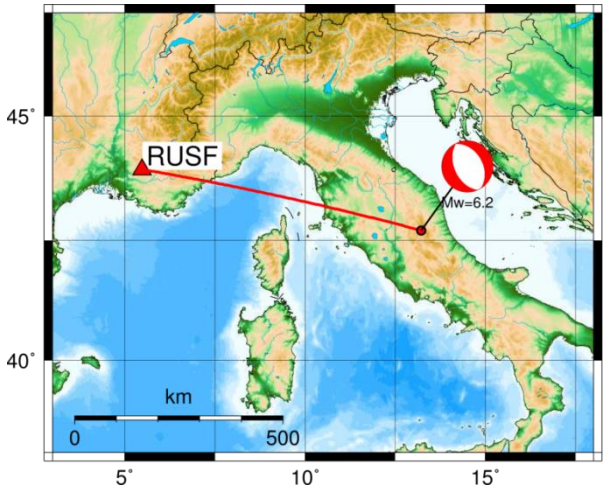
BROAD-BAND SEISMIC RECORDS OF THE AMATRICE EARTHQUAKE

- The broad-band seismic records of the Amatrice earthquake:
  - Origin time: 2016-08-24 at 3h36 local time
  - Magnitude: 6.2
  - Epicentral distance: 650km

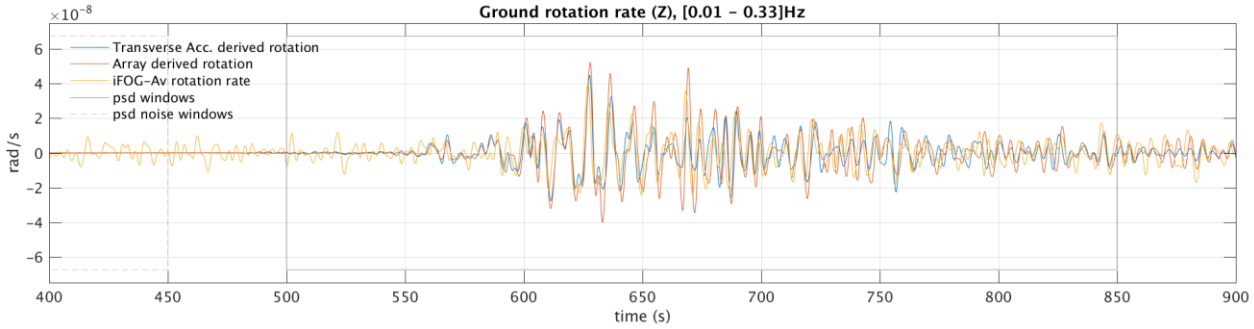


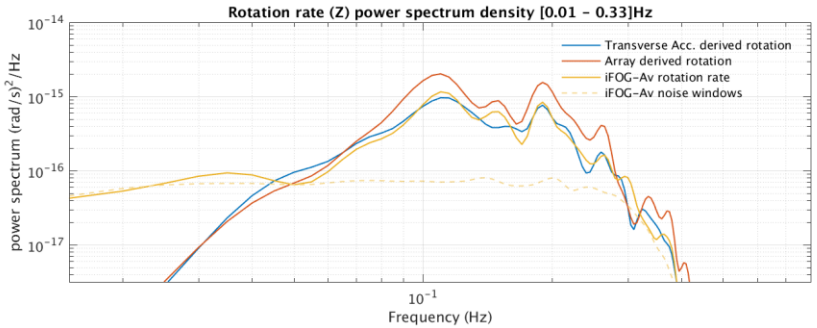


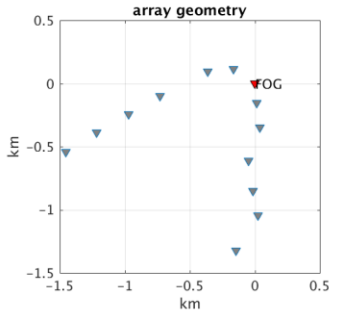




- Time & frequency (psd) comparison



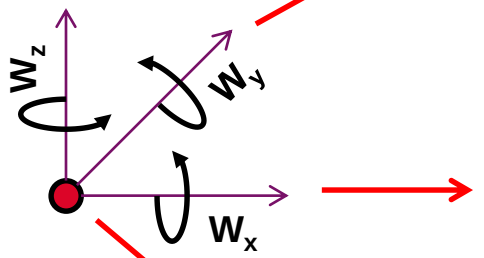




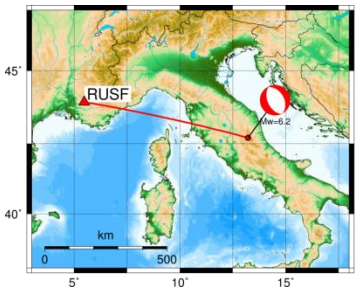
- Vertical rotation motion: about **5x10-8 rad/s**.
- The iXblue instrument noise level: < **20nrad/s/√Hz**

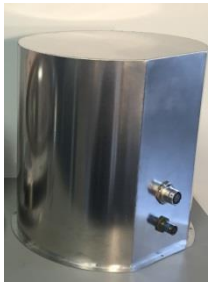
SCORSESE 2:

- Comparison:
  - Array derived rotation
  - Transverse acceleration



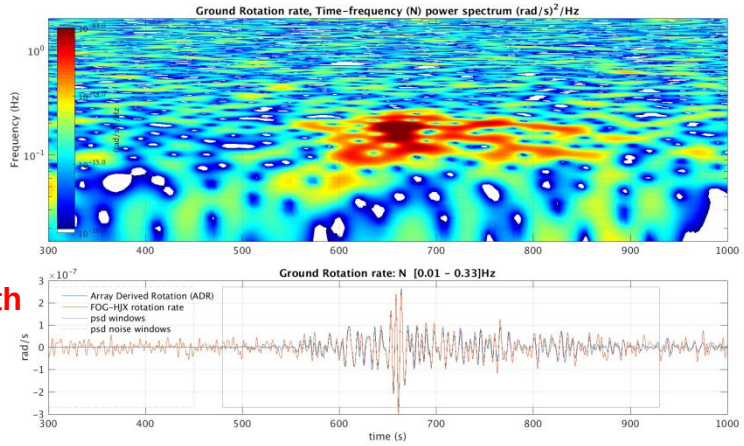
3C Rotational Seismometer

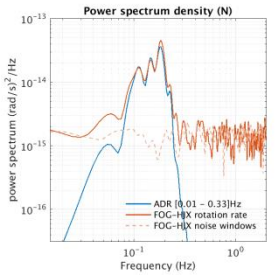


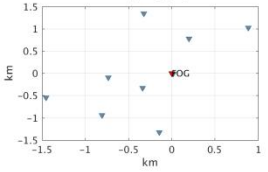


- R_Z: 10^{-7} rad/s
- R_N: $3x10^{-7}$ rad/s
- R_E: 10^{-7} rad/s

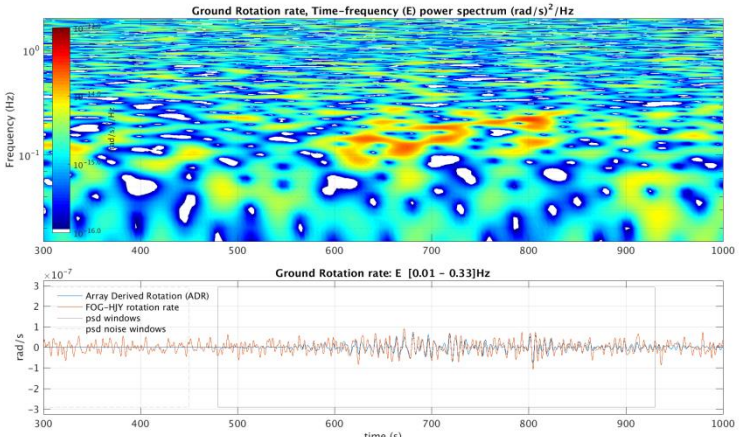
R_{North}

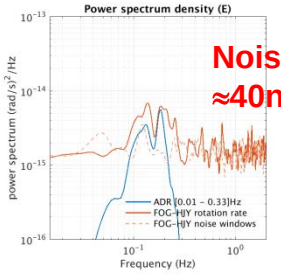


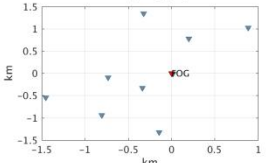




R_{East}

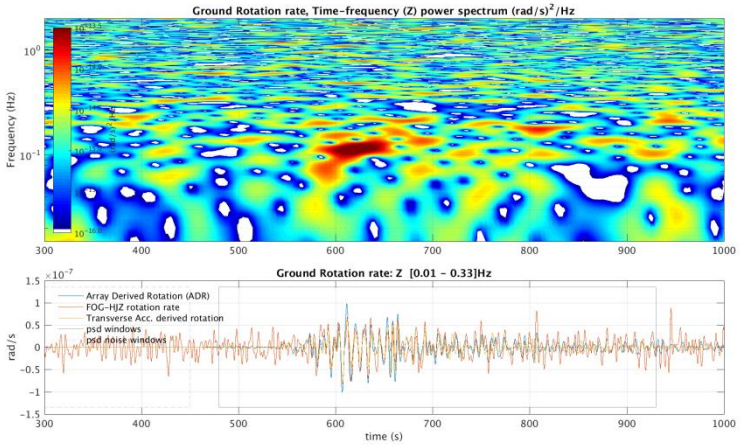


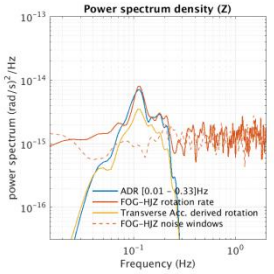


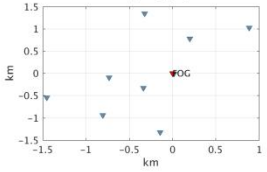


Noise level ≈40nrad/s/Hz$^{0.5}$

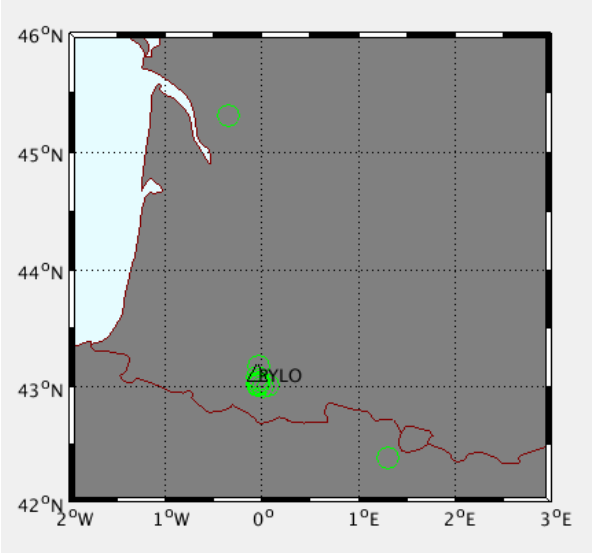
R_Z





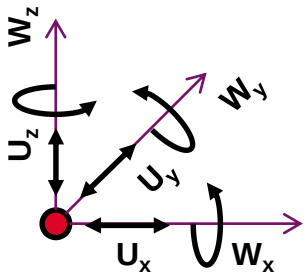


INSTALLATION OF A 6C STATION AT PYLO, LOURDES



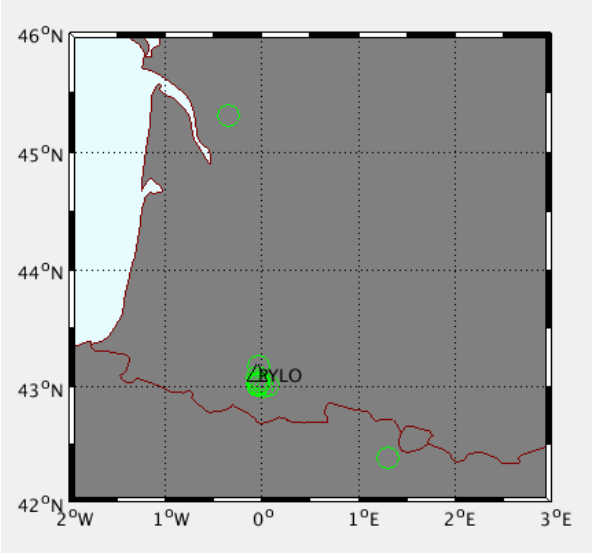
Direct Rotation measurment: blueseis 3A at **PYLO**

From February to September: continuous recordings

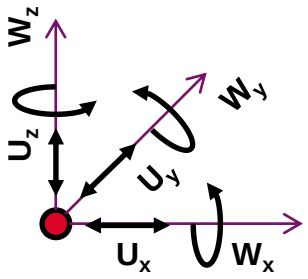


1 x 6C Seismic station

INSTALLATION OF A 6C STATION AT PYLO, LONG TERM NOISE RECORDINGS



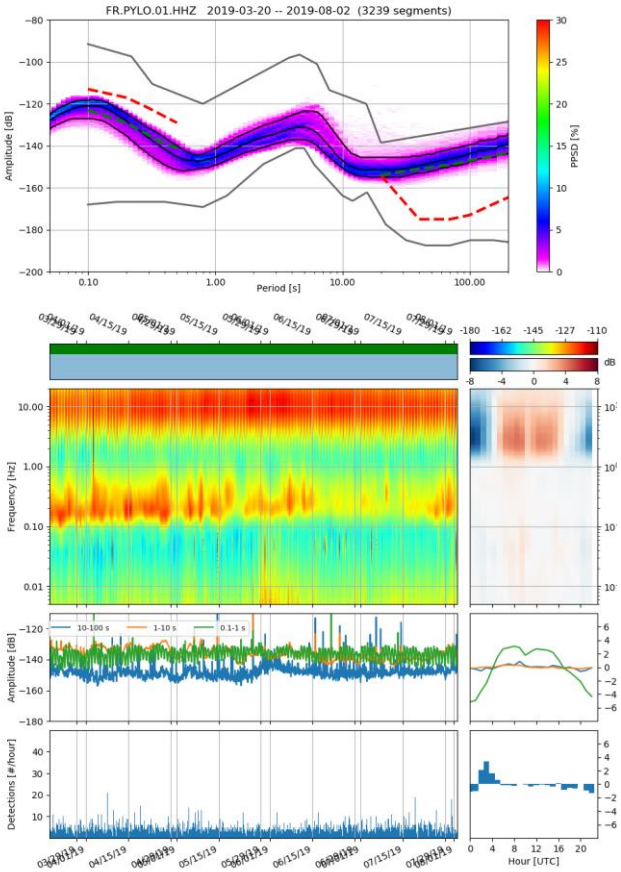
Direct Rotation measurment: blueseis 3A at **PYLO**



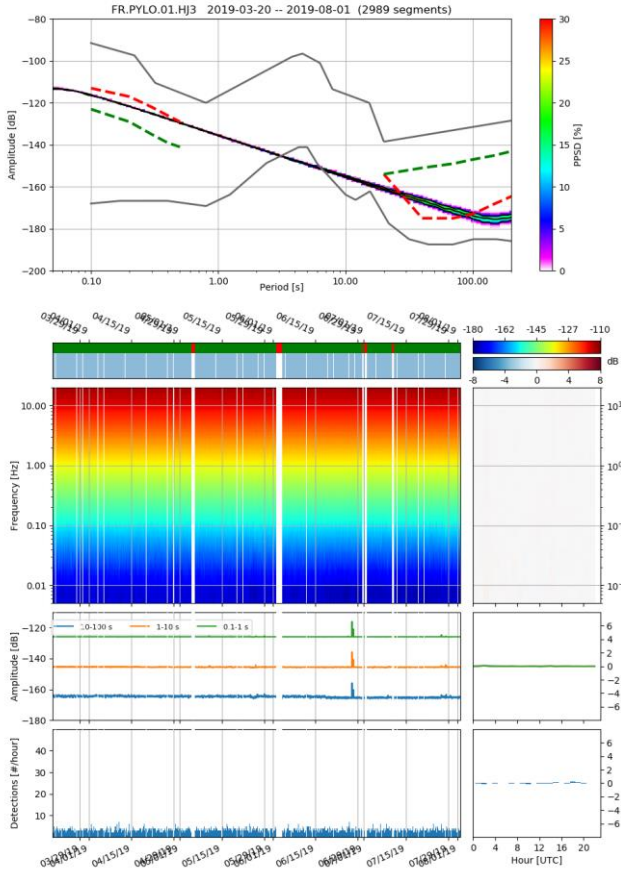
1 x 6C Seismic station

From February to September: continuous recordings

Trillium



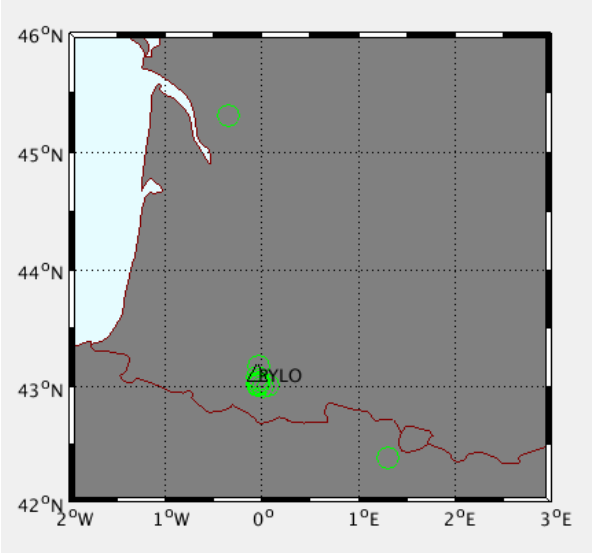
BlueSeis 3A



Seismic rotation noise not reached

Need care for installation…reboot before to leave…

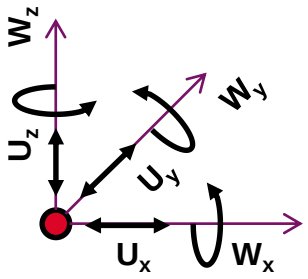
INSTALLATION OF A 6C STATION AT PYLO, EVENT RECORDS…



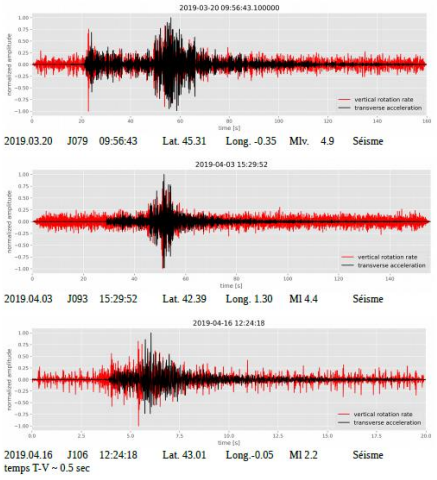
From February to September:
about 12 events has been detected :

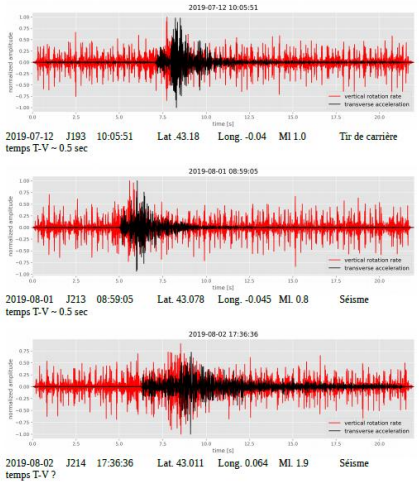
nÂ°	time	lat	lon	magtype	mag
1	2019/03/20 09:56:43.000	45.31000	-0.35000	Mlv	4.90000
2	2019/04/03 15:29:52.000	42.39000	1.30000	Ml	4.40000
3	2019/04/16 12:24:18.000	43.01000	-0.05000	Ml	2.20000
4	2019/05/03 10:16:05.000	43.06000	-0.03000	Ml	1.20000
5	2019/05/03 22:11:19.000	43.00000	0.01000	Ml	1.80000
6	2019/05/06 20:44:27.000	43.03000	-0.04000	Ml	1.90000
7	2019/05/28 22:57:55.000	43.01000	-0.04000	Ml	1.80000
8	2019/05/28 22:58:15.000	43.02000	-0.05000	Ml	1.80000
9	2019/05/29 02:30:49.000	43.01000	-0.05000	Ml	2.00000
10	2019/07/12 10:05:51.000	43.18000	-0.04000	Ml	1.00000
11	2019/08/01 08:59:05.000	43.07800	-0.04500	Ml	0.80000
12	2019/08/02 17:36:36.000	43.01100	0.06400	Ml	1.90000

Direct Rotation measurment:
blueseis 3A at **PYLO**

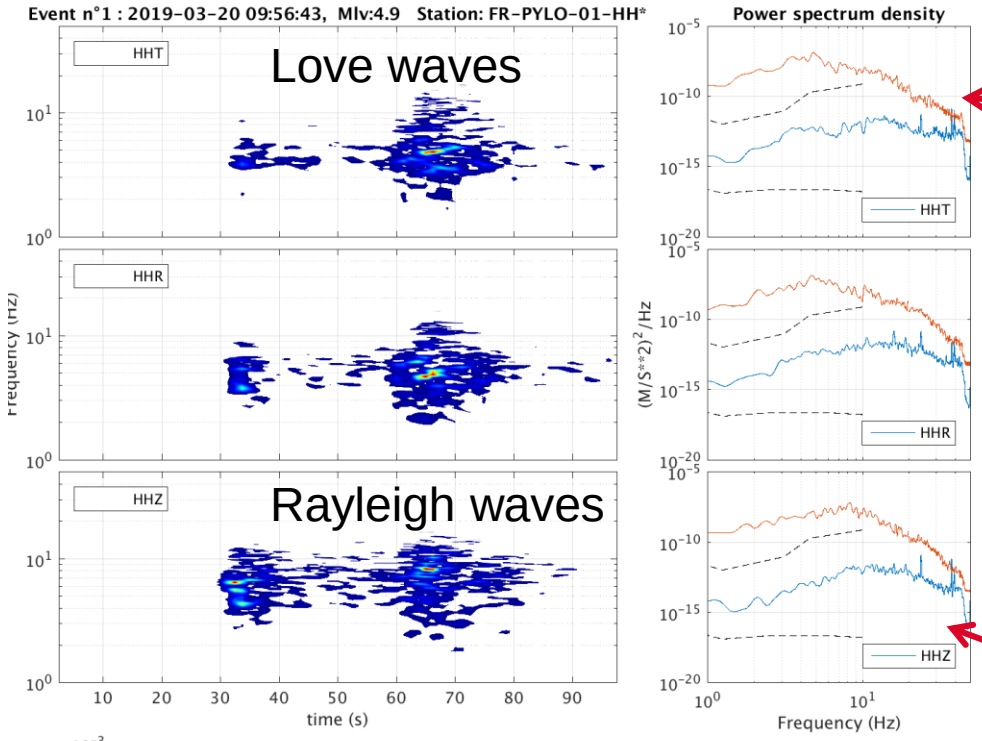


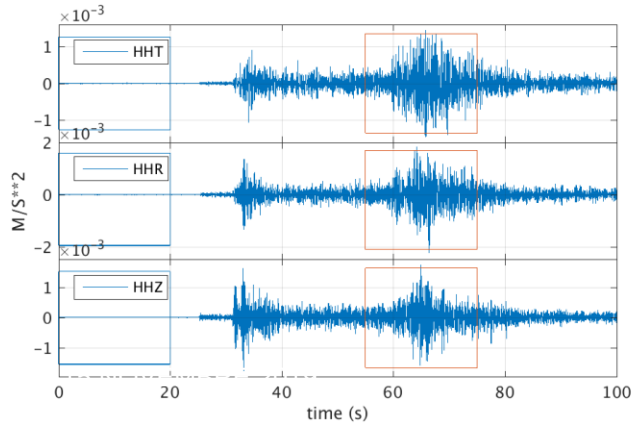
1 x 6C Seismic station

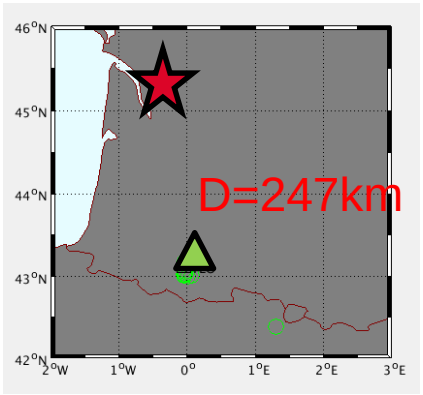


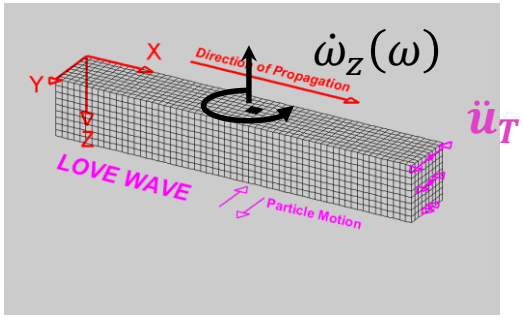


6C EVENT RECORDS: JONZAC, ML=4.9



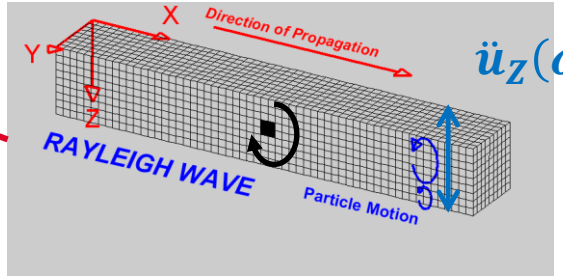






$$\dot{\omega}_z(\omega) \quad \ddot{u}_T(\omega)$$

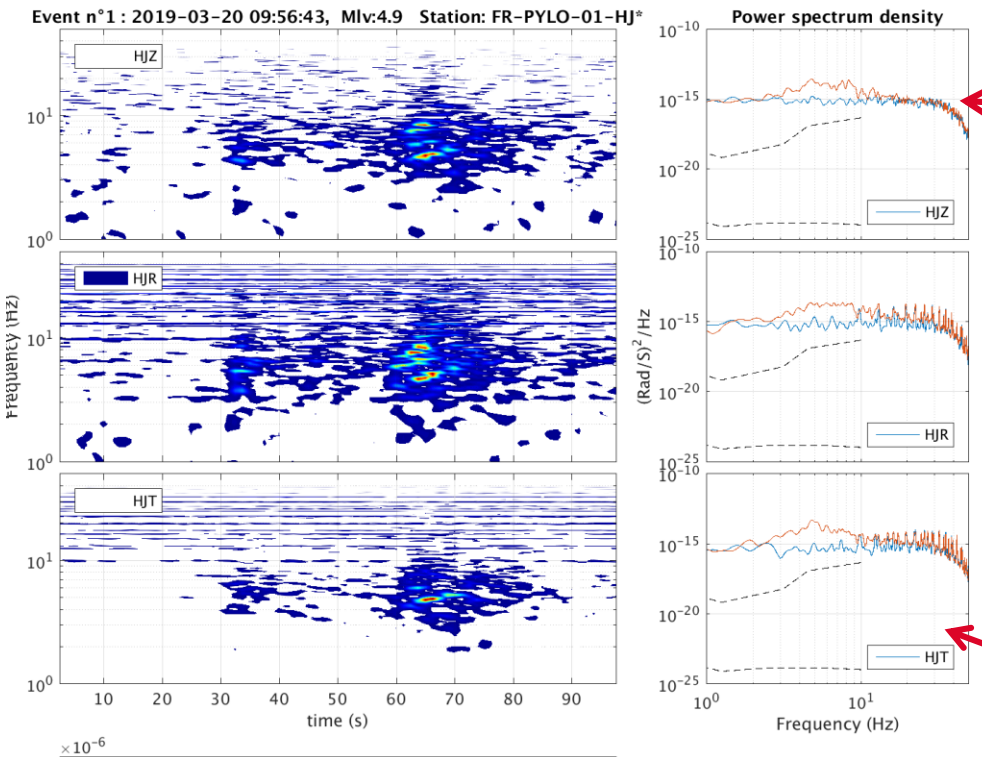
$$\dot{\omega}_z(\omega) = -\frac{\ddot{u}_T(\omega)}{2c(\omega)}$$

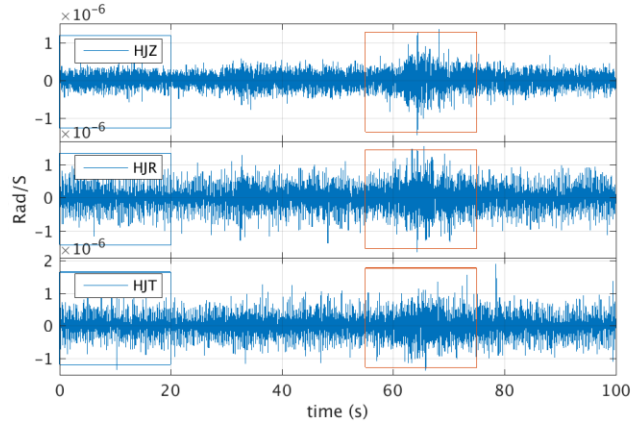


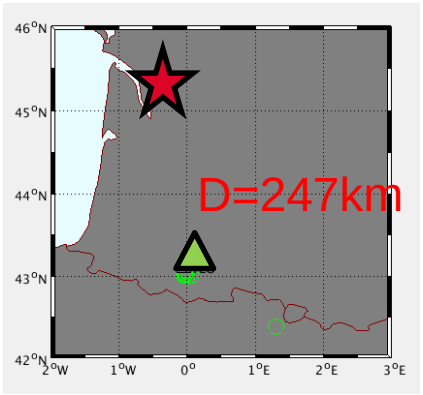
$$\ddot{u}_Z(\omega)$$

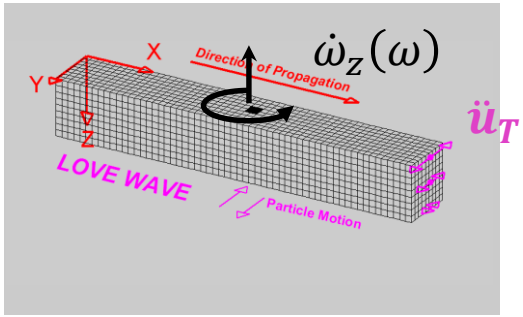
$$\dot{\omega}_T(\omega) = -\frac{\ddot{u}_Z(\omega)}{c(\omega)}$$

6C EVENT RECORDS : JONZAC, ML=4.9



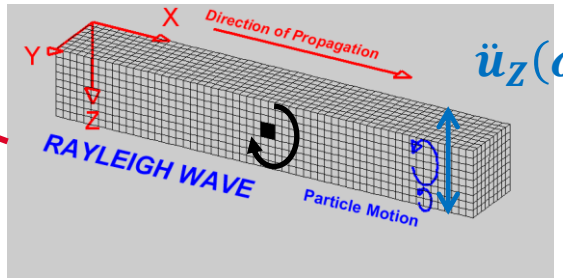






$$\dot{\omega}_Z(\omega) \quad \ddot{u}_T(\omega)$$

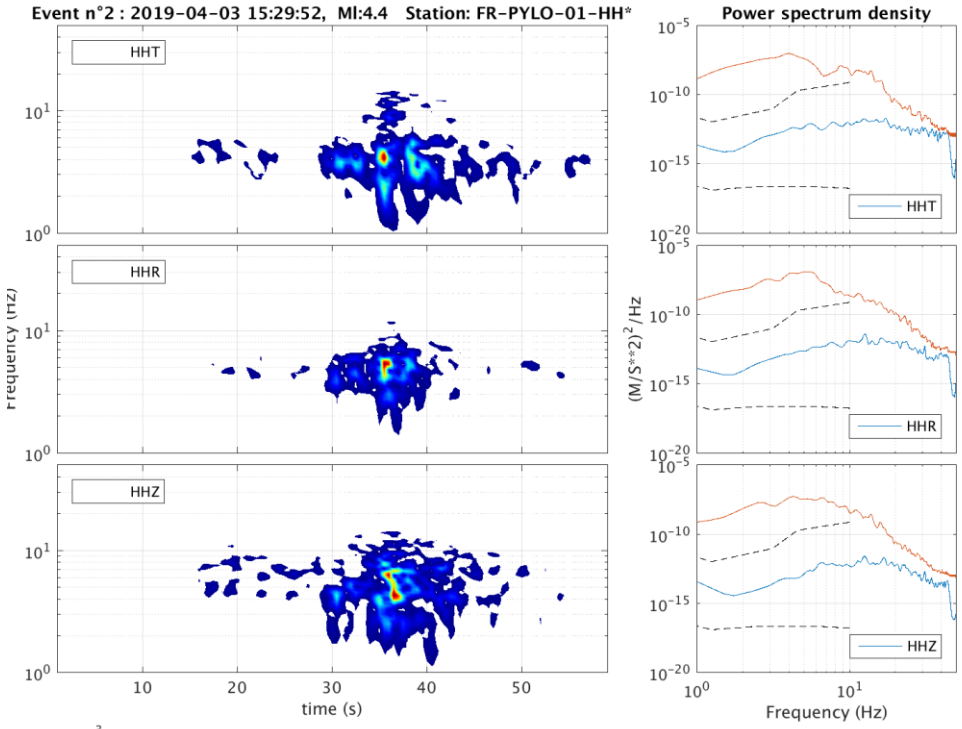
$$\dot{\omega}_Z(\omega) = -\frac{\ddot{u}_T(\omega)}{2c(\omega)}$$

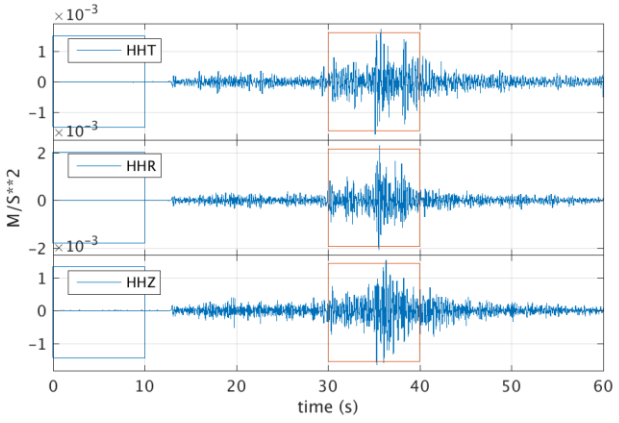


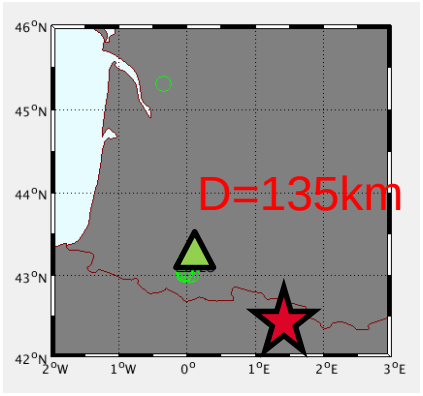
$$\ddot{u}_Z(\omega)$$

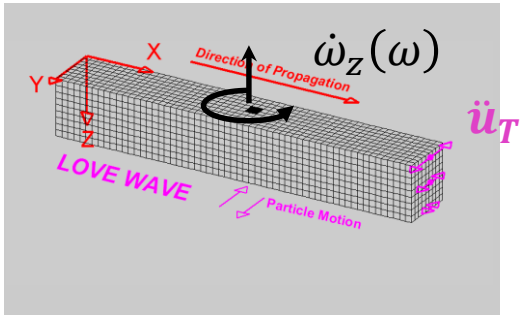
$$\dot{\omega}_T(\omega) = -\frac{\ddot{u}_Z(\omega)}{c(\omega)}$$

6C EVENT RECORDS : ANDORE, ML=4.4

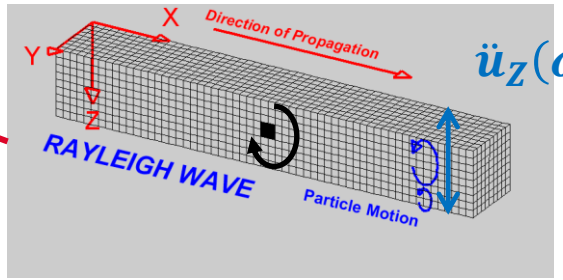






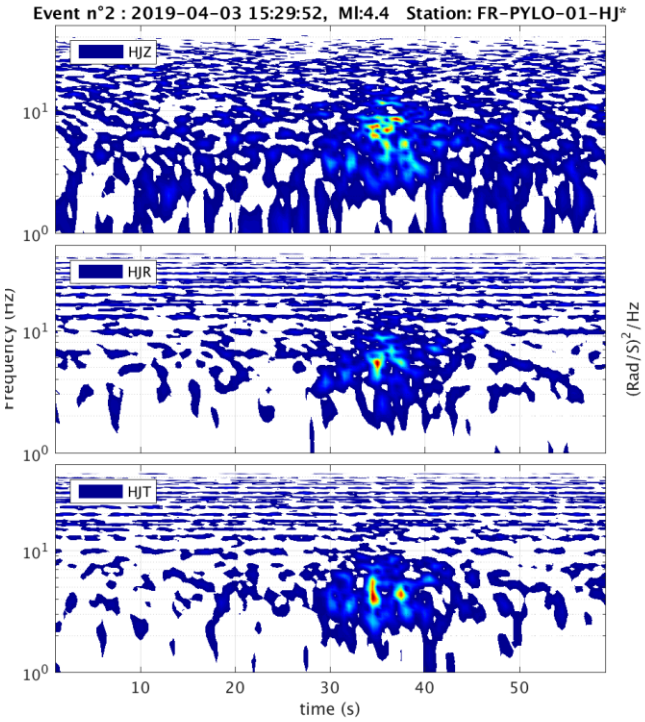


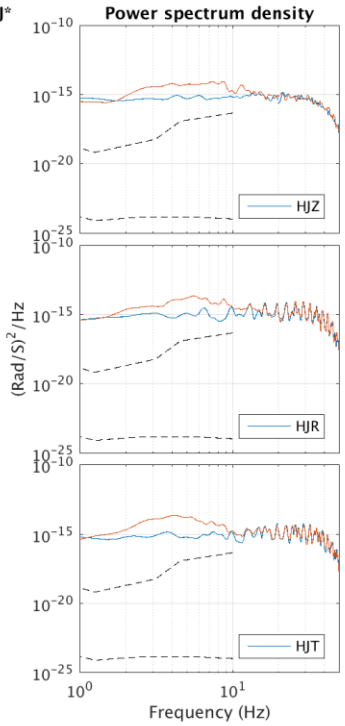
$$\dot{\omega}_Z(\omega) = -\frac{\ddot{u}_T(\omega)}{2c(\omega)}$$

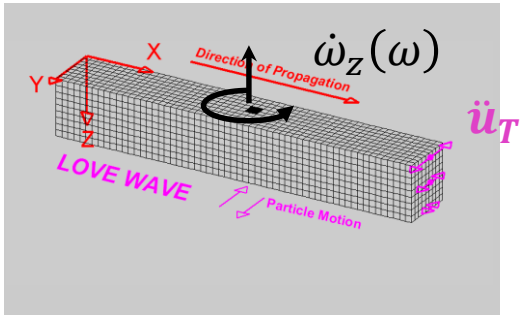


$$\dot{\omega}_T(\omega) = -\frac{\ddot{u}_Z(\omega)}{c(\omega)}$$

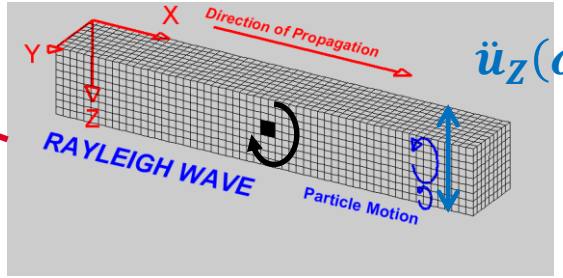
6C EVENT RECORDS : ANDORE, ML=4.4



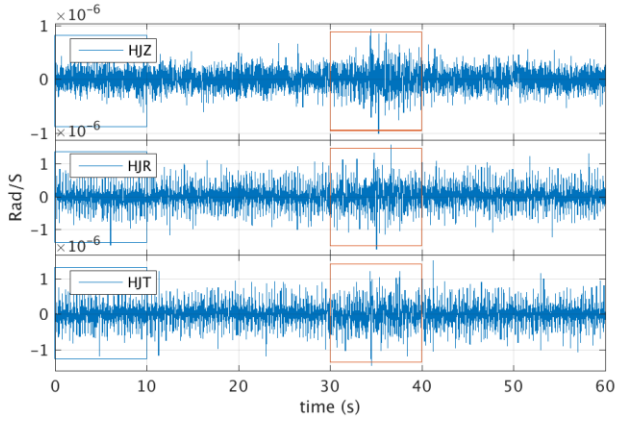


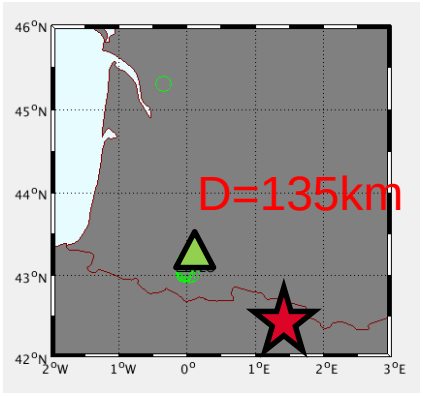


$$\dot{\omega}_Z(\omega) = -\frac{\ddot{u}_T(\omega)}{2c(\omega)}$$

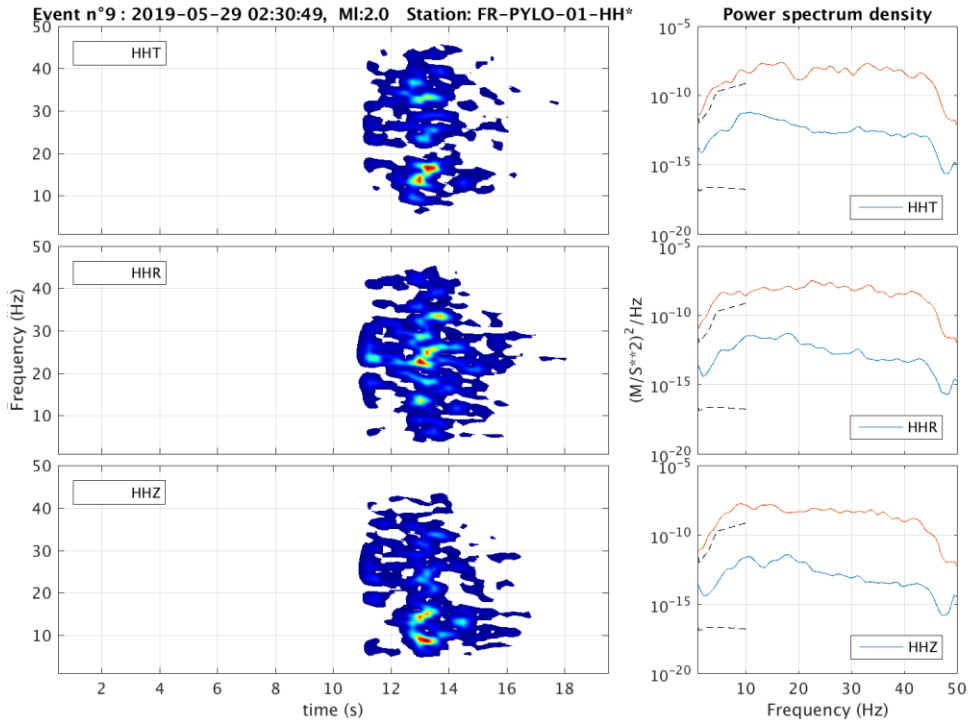


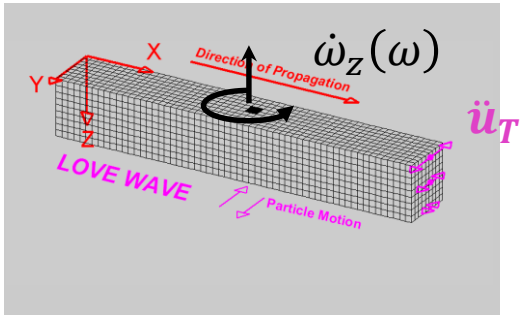
$$\dot{\omega}_T(\omega) = -\frac{\ddot{u}_Z(\omega)}{c(\omega)}$$



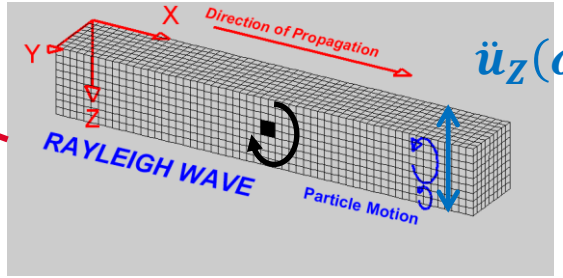


6C EVENT RECORDS : LOCAL EVENT, ML=2.0

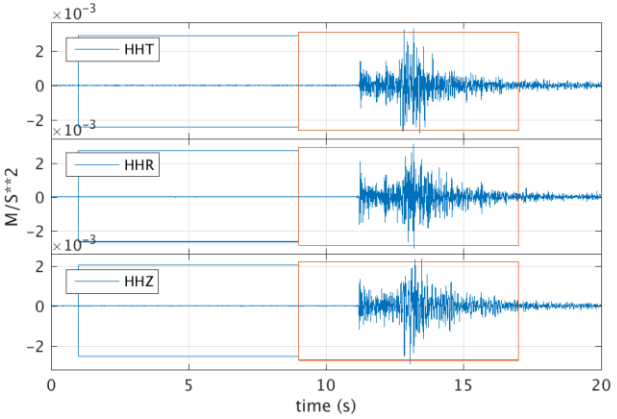


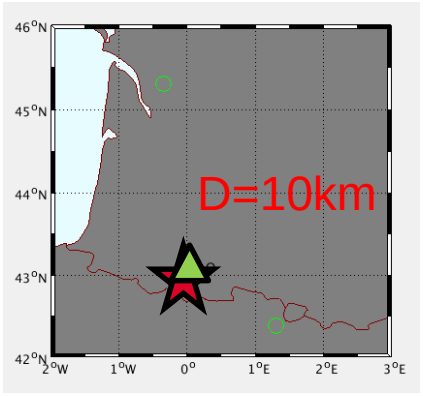


$$\dot{\omega}_z(\omega) = -\frac{\ddot{u}_T(\omega)}{2c(\omega)}$$

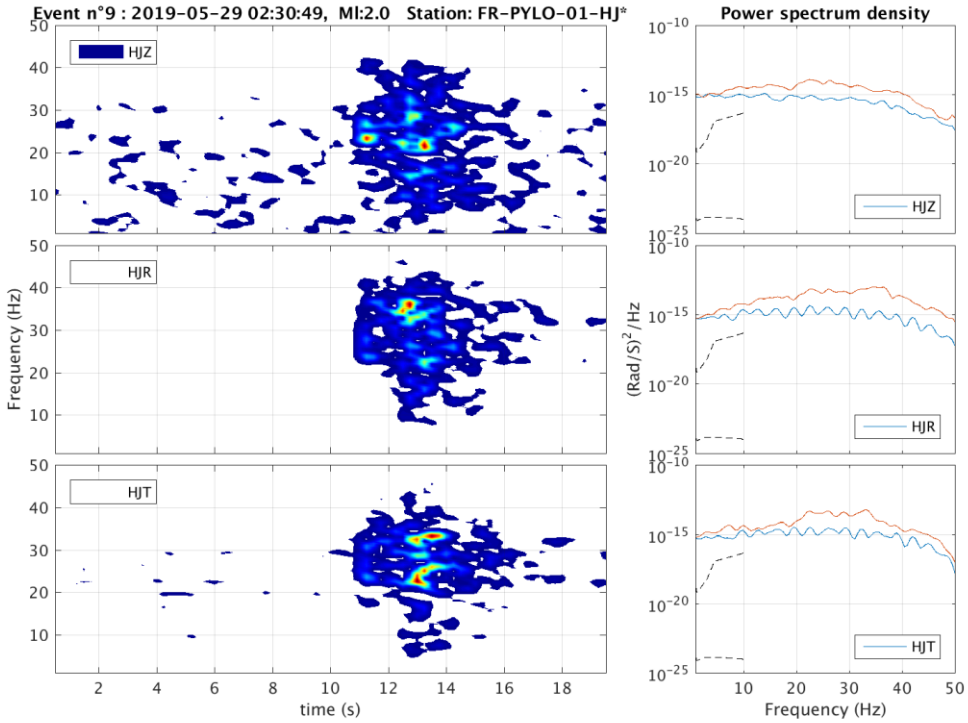


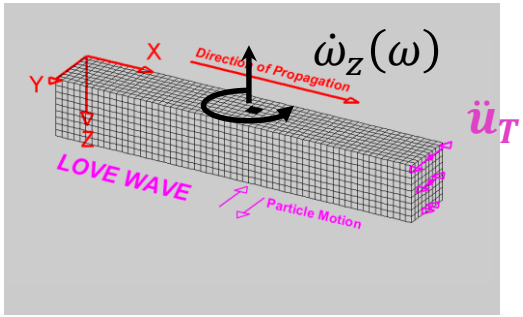
$$\dot{\omega}_T(\omega) = -\frac{\ddot{u}_Z(\omega)}{c(\omega)}$$



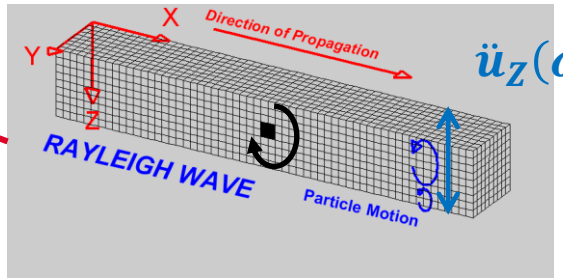


6C EVENT RECORDS : LOCAL EVENT, ML=2.0

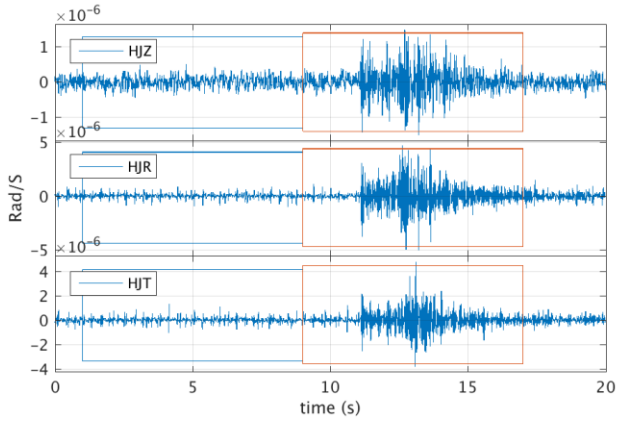


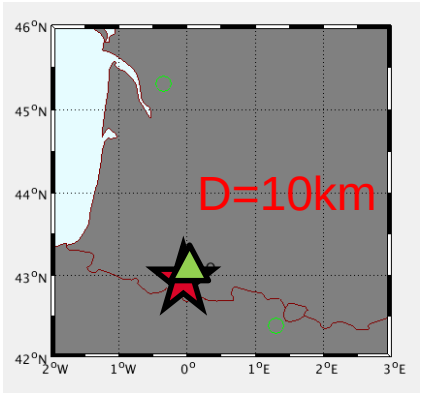


$$\dot{\omega}_z(\omega) = -\frac{\ddot{u}_T(\omega)}{2c(\omega)}$$

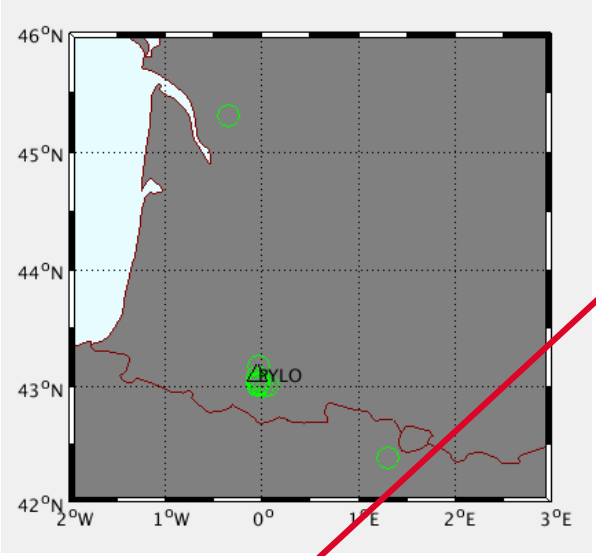


$$\dot{\omega}_T(\omega) = -\frac{\ddot{u}_Z(\omega)}{c(\omega)}$$

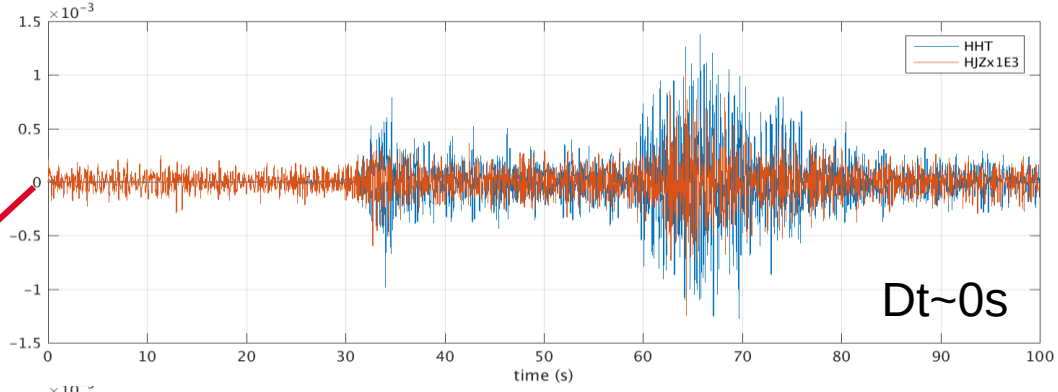


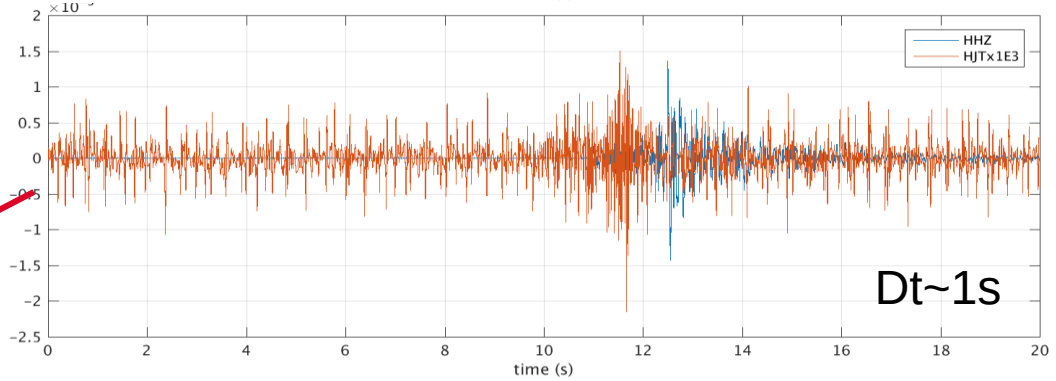


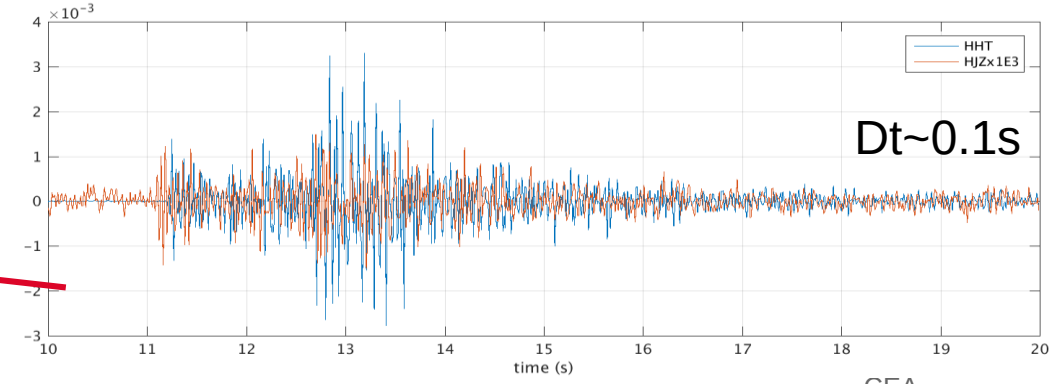
CLOCK DRIFT…



nÂ°	time	ɛ	mag
1	2019/03/20 09:56:43.000		4.90000
2	2019/04/03 15:29:52.000		4.40000
3	2019/04/16 12:24:18.000		2.20000
4	2019/05/02 10:16:05.000		1.20000
5	2019/05/03 22:11:19.000		1.80000
6	2019/05/06 20:44:27.000		1.90000
7	2019/05/28 22:57:55.000		1.80000
8	2019/05/28 22:58:15.000		1.80000
9	2019/05/29 02:30:49.000		2.00000
10	2019/07/12 10:05:51.000		1.00000
11	2019/08/01 08:59:05.000		0.80000
12	2019/08/02 17:36:36.000		1.90000

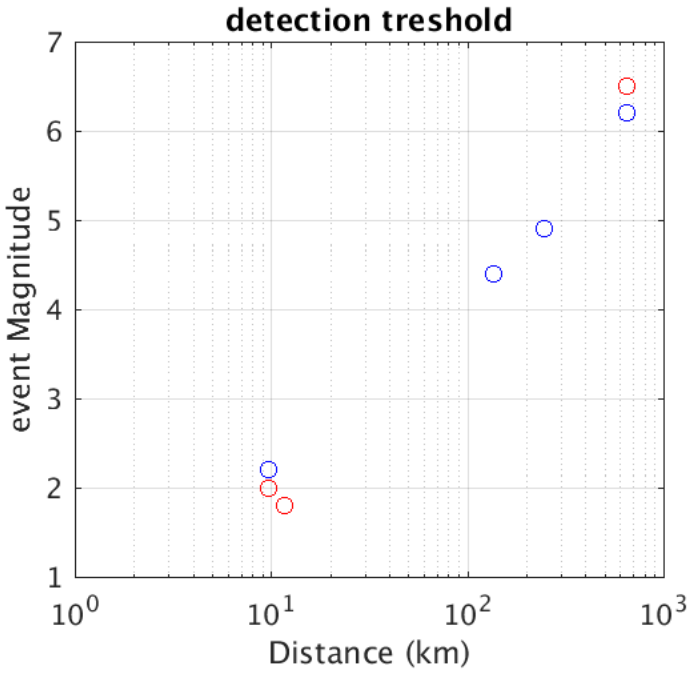




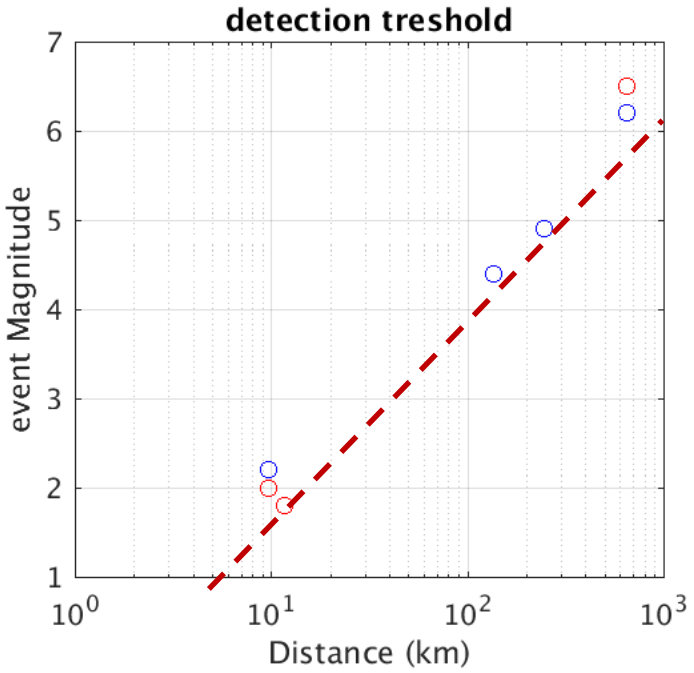


SAV -> Quartz problem!

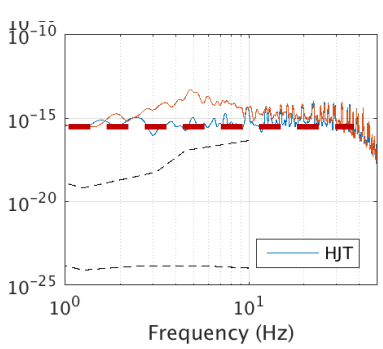
ROTATION MOTION AMPLITUDE MEASURED: PRELIMINARY RESULTS…

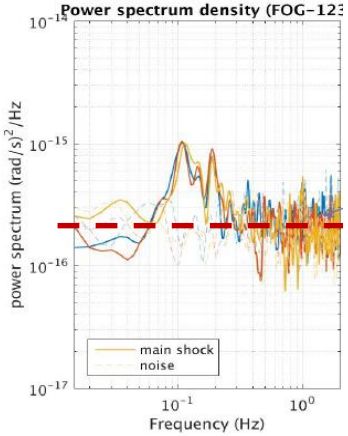


ROTATION MOTION AMPLITUDE MEASURED: PRELIMINARY RESULTS…

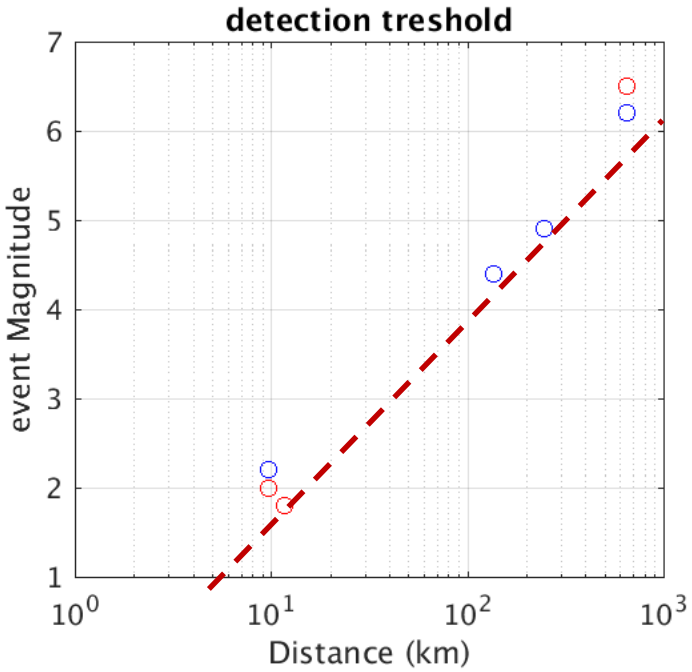


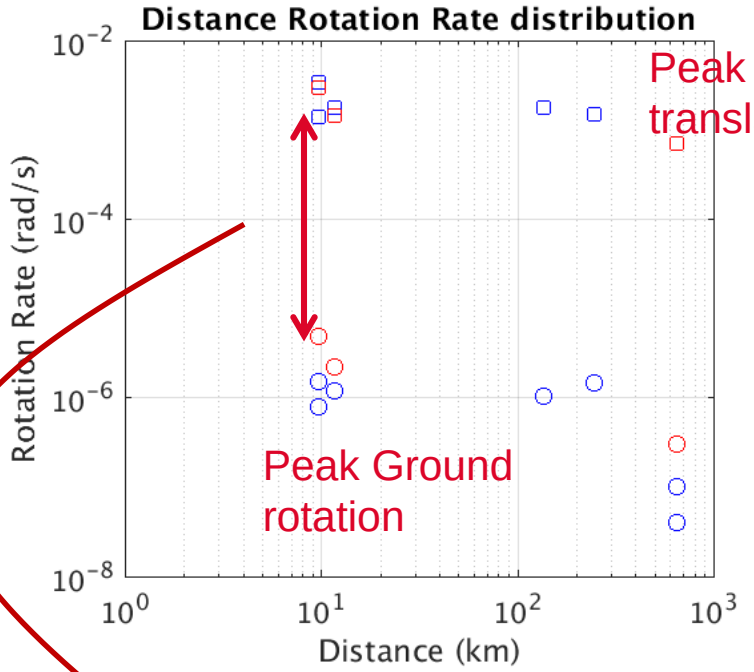
Noise level limit: 20nrad/s/sqrt(Hz)



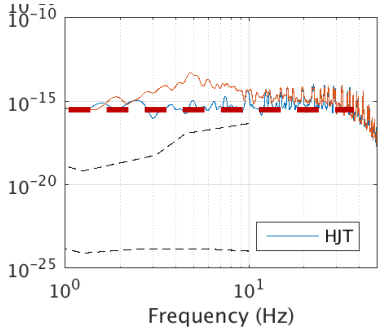


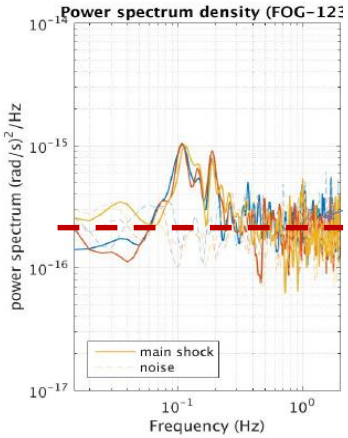
ROTATION MOTION AMPLITUDE MEASURED: PRELIMINARY RESULTS…





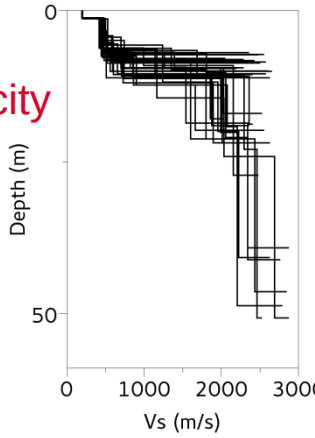
Noise level limit: 20nrad/s/sqrt(Hz)

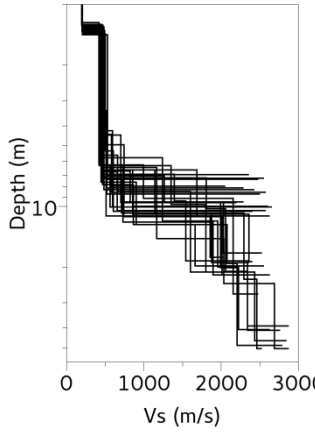




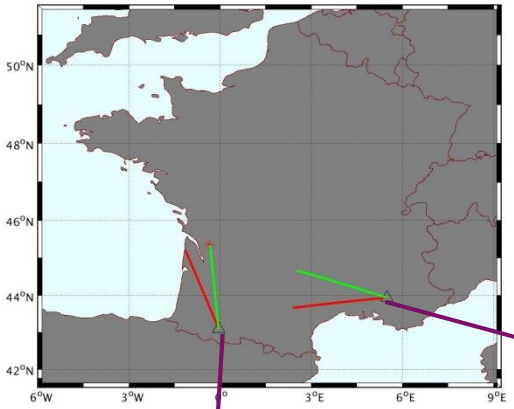
Local Wave Velocity estimation:
500 – 2000 m/s

$$Vs(\omega) = -\frac{\ddot{u}_T(\omega)}{2R(\omega)}$$





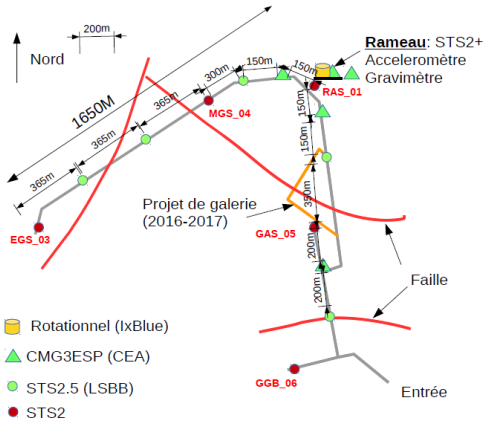
JONZAC EARTHQUAKE: A FIRST 6C RECORD!



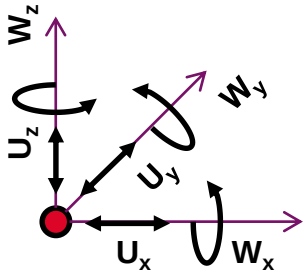
Direction Finding:

$$\dot{\omega}_z(\omega) = -\frac{\ddot{u}_T(\omega)}{2c(\omega)}$$

$$\boldsymbol{Max}\left[\boldsymbol{Corr}\left(\dot{\omega}_z, \ddot{u}_T(\theta)\right)\right]$$



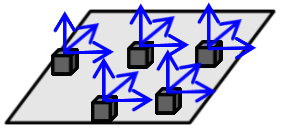
Direct Rotation measurment: blueseis 3A at **PYLO**

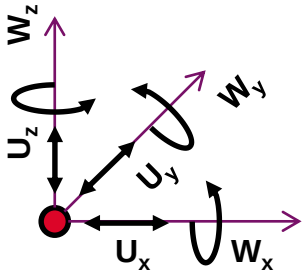


1 x 6C Seismic station

Rotation derived from array analysis at **LSBB**

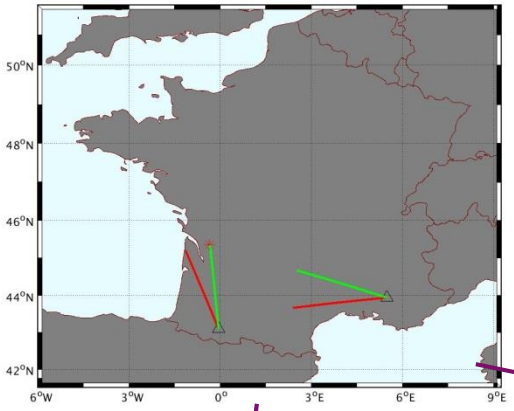
N x 3C Stations





6C Seismic station

JONZAC EARTHQUAKE: DIRECTION FINDING

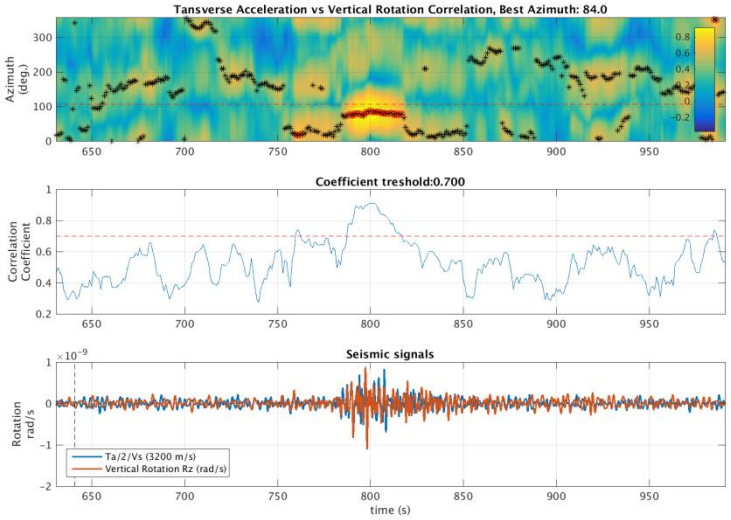


Direction Finding:

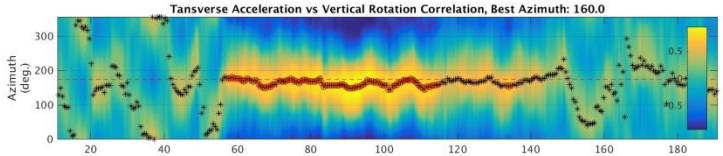
$$\dot{\omega}_z(\omega) = -\frac{\ddot{u}_T(\omega)}{2c(\omega)}$$

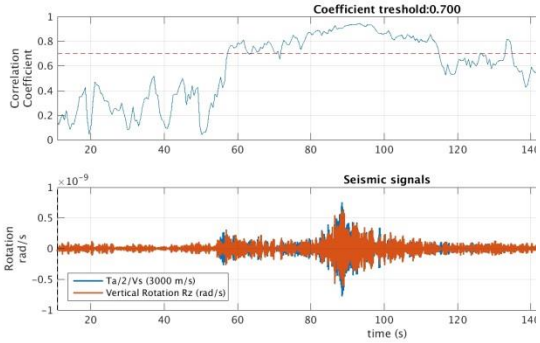
$$\boldsymbol{Max}\left[\boldsymbol{Corr}\left(\dot{\boldsymbol{\omega}}_{\boldsymbol{z}}, \ddot{\boldsymbol{u}}_{\boldsymbol{T}}(\boldsymbol{\theta})\right)\right]$$

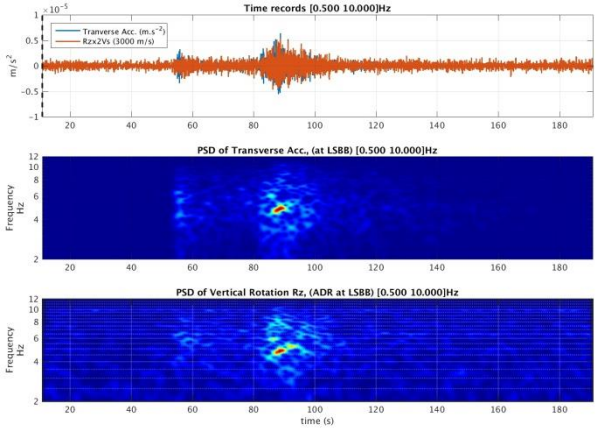
Rotation derived from array analysis at **LSBB**

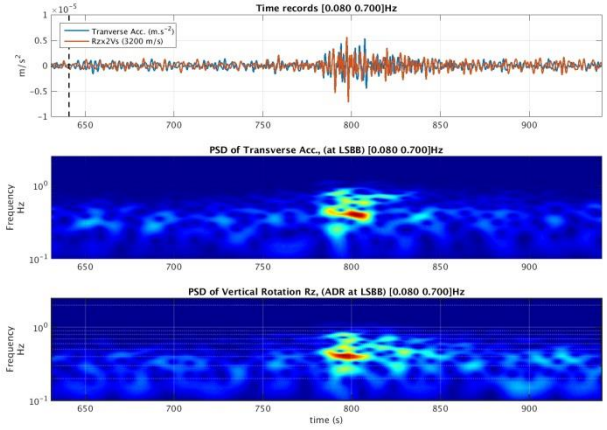


Direct Rotation measurment: blueseis 3A at **PYLO**





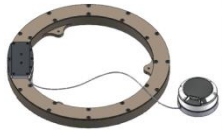




CONCLUSION

- BlueSeis 3A: New instrument
  - Very good job but be carrefull
    - Soft improvement
    - Clock Quartz changed
  - New version of the BlueSeis 3A: improved processing

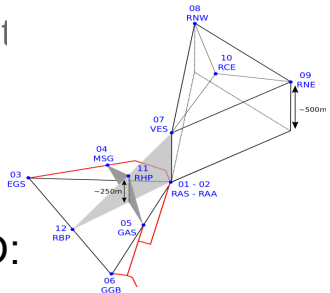
- Give the possibility to record seismic rotation in Moderated active region as France:
  - frequency range [0.01 100]Hz
  - Noise level: 20 nrad/s/sqrt(Hz)

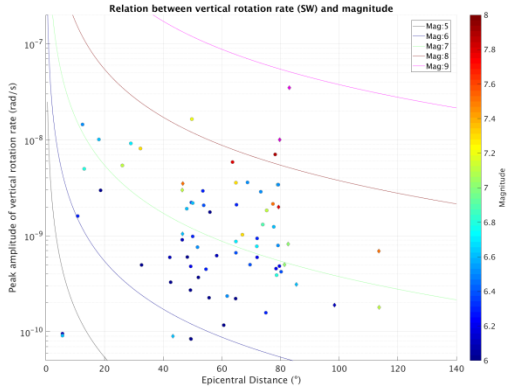


- Next generation: BlueSeis 1C
  - 5 nrad/s/sqrt(Hz)

- Toward a systematic 6C seismic measurment : **Need more recordings to evaluate performance and Interest**:
  - Re-install the BlueSeis3A
  - Compare with other sensor and array derived rot (LSBB)
  - Test the new BlueSeis 1C

Array Derived rotation @LSBB





R.Rusch PhD: