Earthquake-induced rotational ground motions: instruments and measurements

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Summary

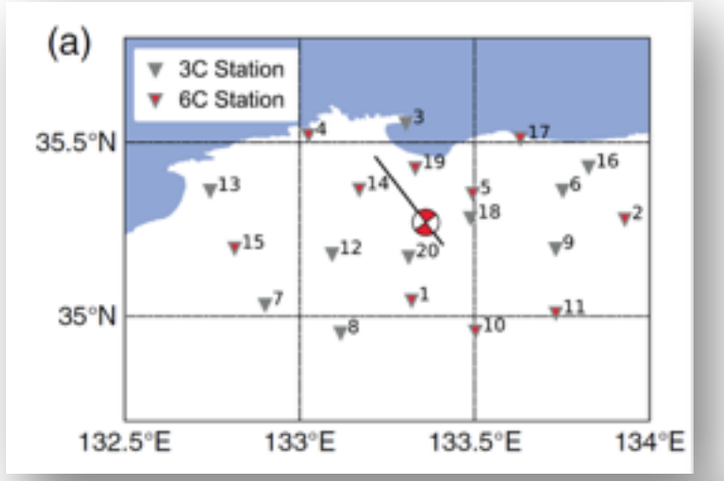
- What is rotations seismology ?
- The instruments
- Basic theory for data processing
- Open questions
- The first underground observations
- The 2016 central Italy sequence data
- The first 6C field campaign
- Conclusions and still open questions

What is Rotational seismology ?

Rotational seismology is the field of study devoted to the investigation of all aspects of rotational motions induced by natural or artificial seismic sources

The impact on seismology itself is expected to be large:

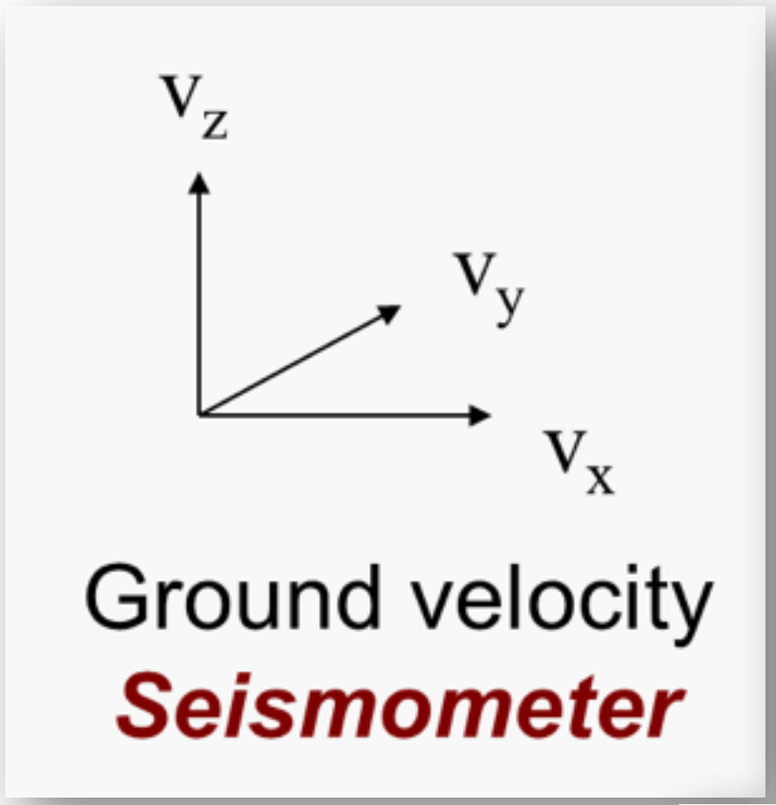
- Seismic tomography [Bernauer et al., 2012, Wassermann et al., 2016];
- Point and finite source inversion [Donner et al., 2016, Donner et al., 2017]
- Volcano source inversion [van Driel et al., 2015]
- Scattering phenomena constraints
- Wavefield reconstruction
- tilt-translation coupling (long period observations and in ocean bottom seismometry)



Ground motion in linear elasticity

The theory of linear elasticity predicts 6 D.O.F of rigid body ground motion

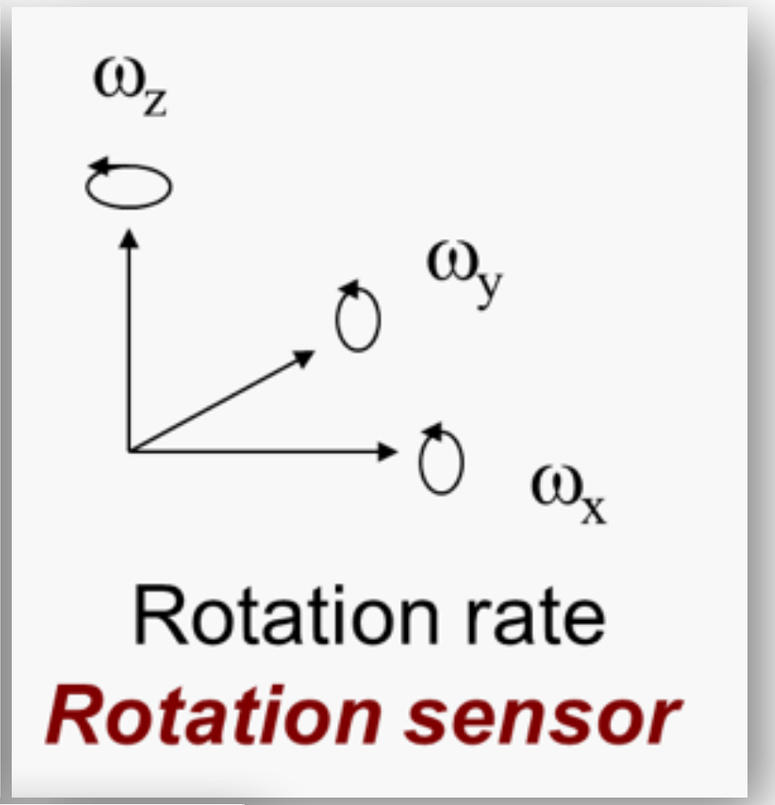
3 D.O.F.



Ground velocity

Seismometer

3 D.O.F.

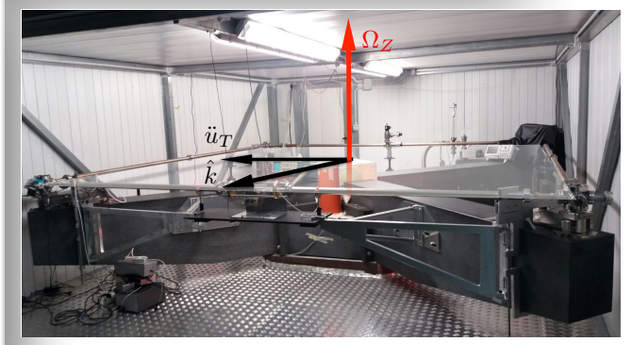


Rotation rate

Rotation sensor

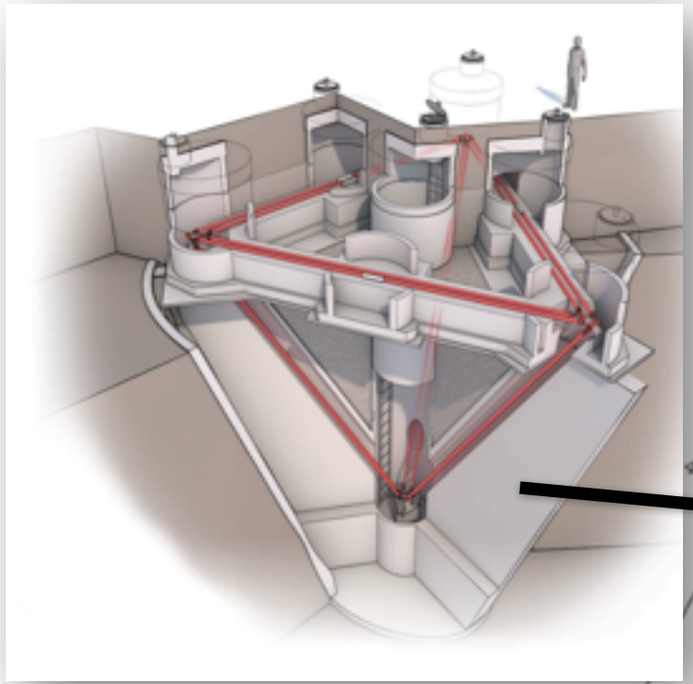
Rotations can be derived as the curl operator applied to the wavefield

$$\boldsymbol{\theta} = \frac{1}{2}\nabla \times \mathbf{u}(\mathbf{x}) = \frac{1}{2}\begin{pmatrix} \frac{\partial u_z}{\partial y} - \frac{\partial u_y}{\partial z} \\ \frac{\partial u_x}{\partial z} - \frac{\partial u_z}{\partial x} \\ \frac{\partial u_y}{\partial x} - \frac{\partial u_x}{\partial y} \end{pmatrix}.$$

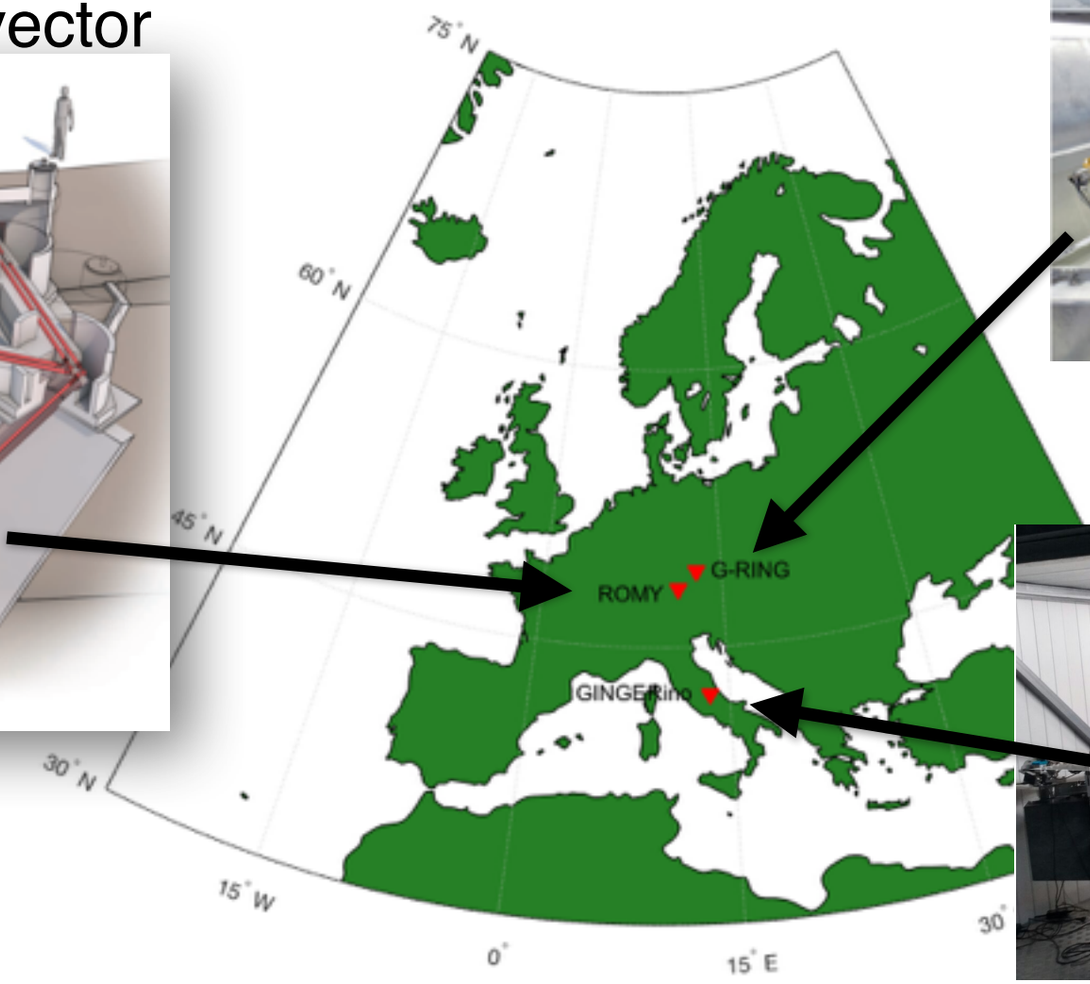


RING LASER IN THE WORLD

3+1 components
Full rotation vector

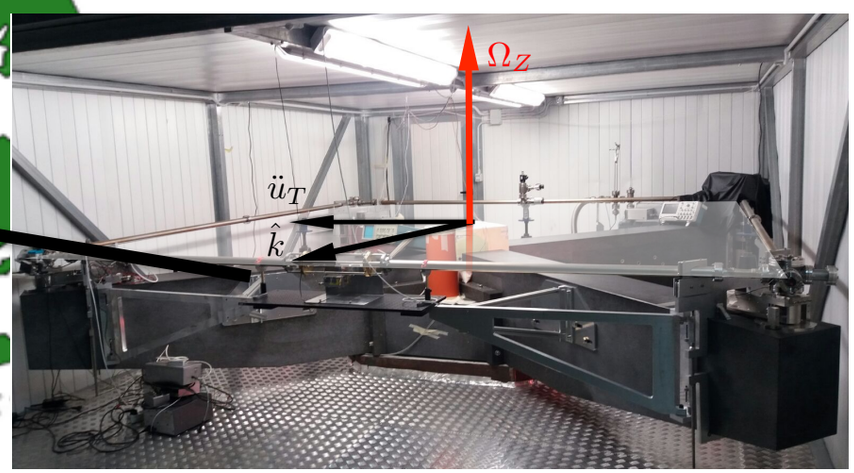


ROMY_ERC
Munich Germany



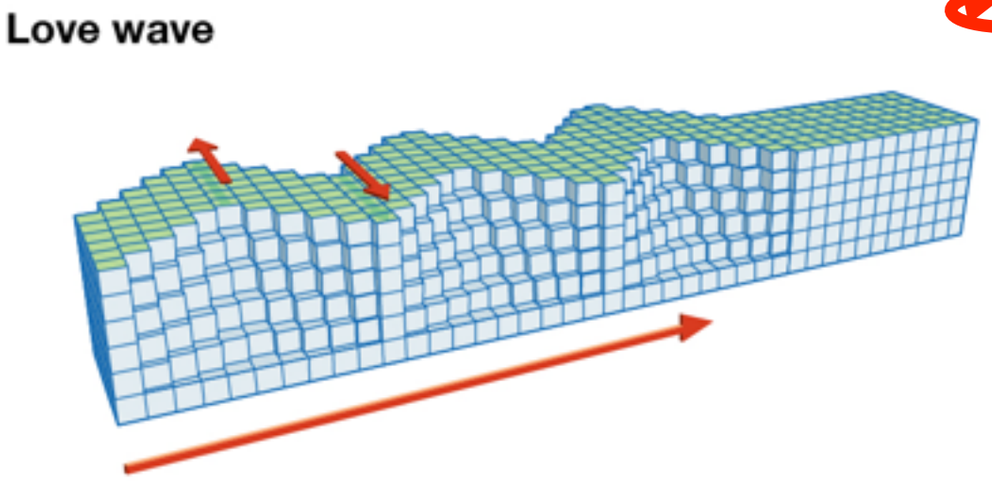
Z-component of rotation

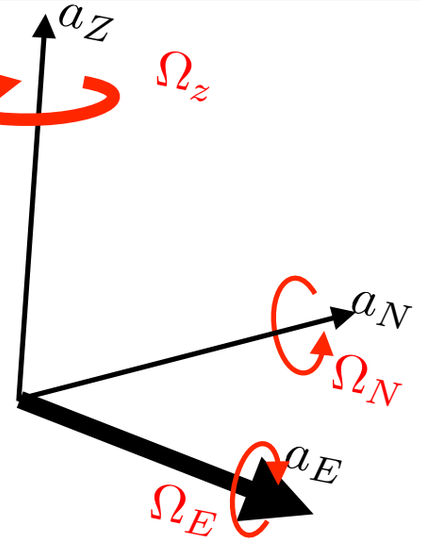
G-Wettzell Germany



Gingerino
Gran Sasso- Italy

What can we learn from colocated 6C observations about the local structure ?

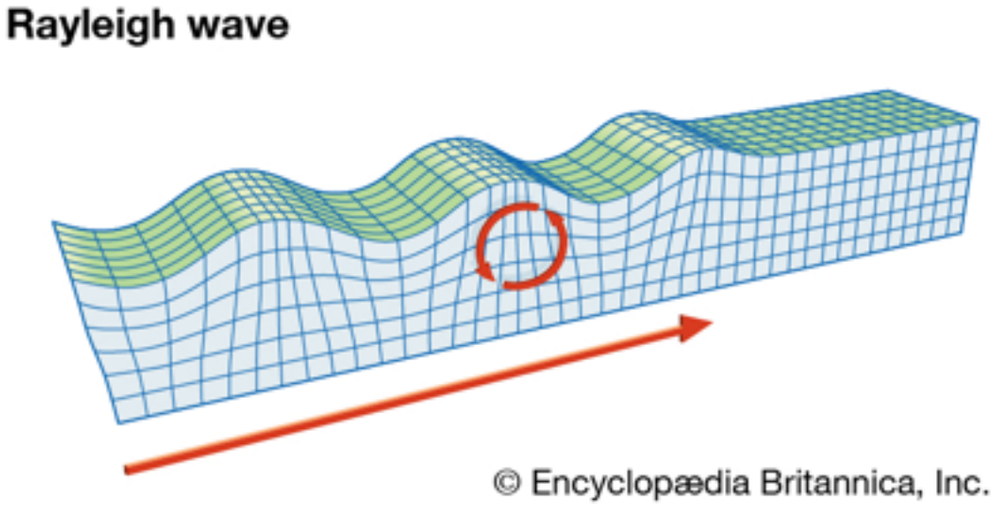


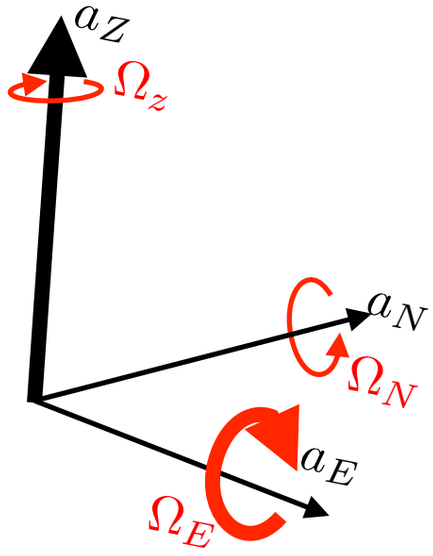


$$\Omega_z = -\frac{a_E}{2C_L}$$

Igel et al. 2004

From a single colocated measure we can measure both Love and Rayleigh waves phase velocities



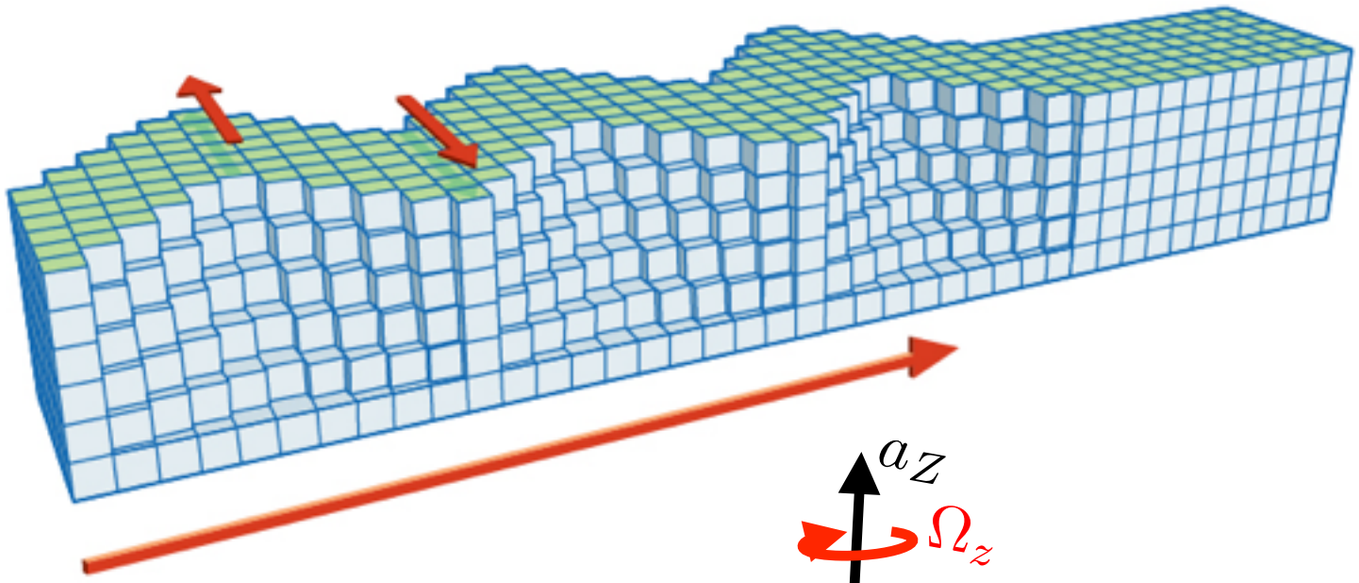


$$\Omega_E = \frac{a_Z}{C_R}$$

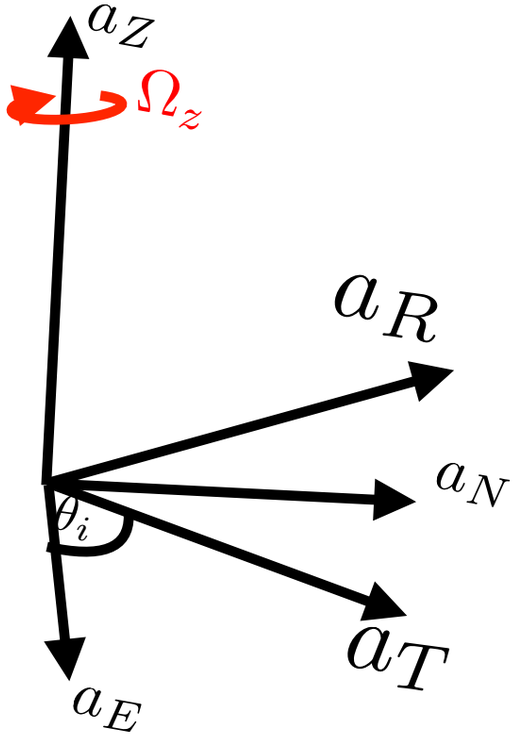
Lin et al. 2011

What can we learn about the Wavefield propagation?

Love wave



$$\Omega_z = -\frac{a_E}{2C_L}$$

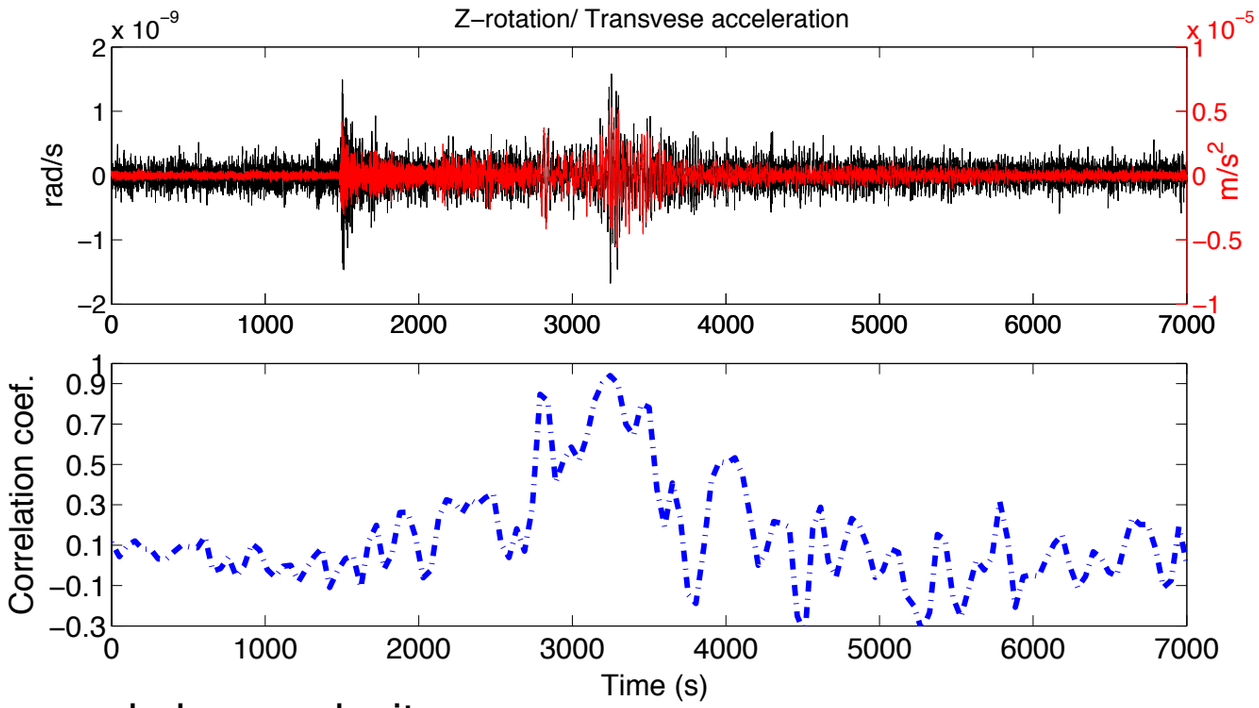


From a single colocated measure we can identify the direction of the incoming wavefield (BAZ) both for Rayleigh and Love Waves.

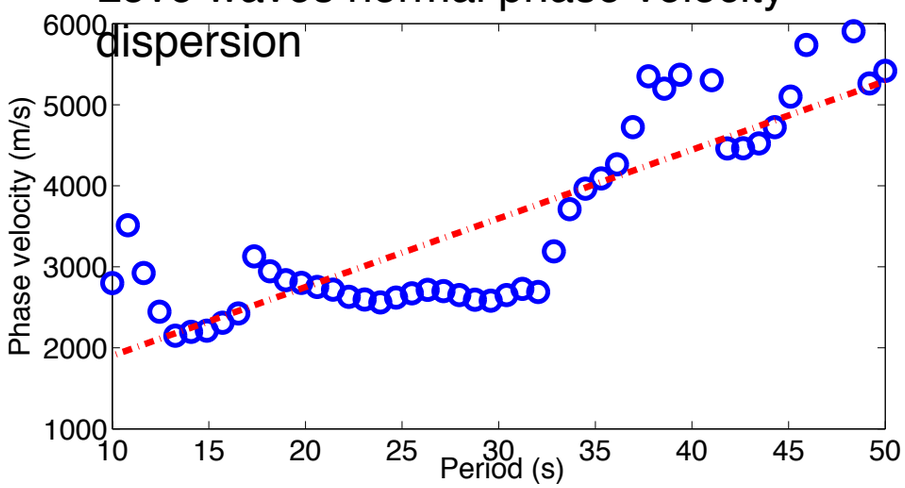
Method

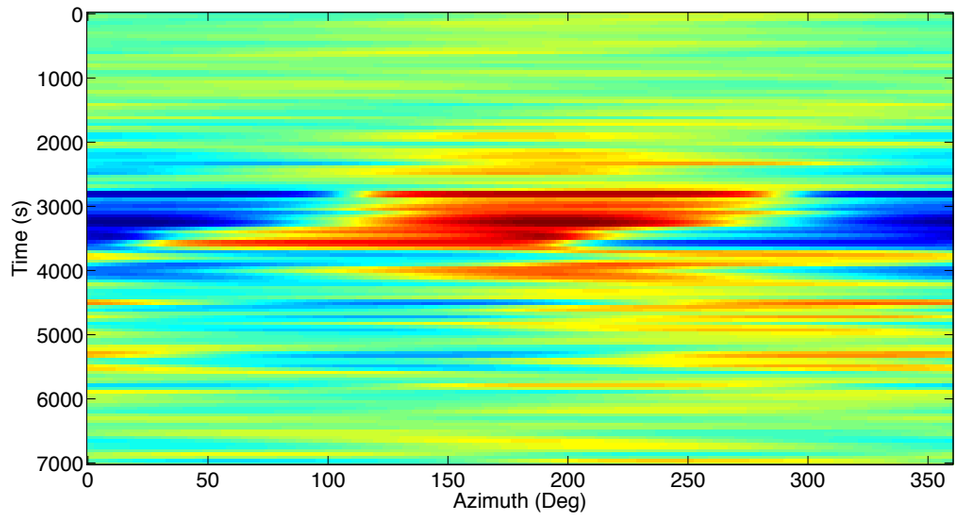
In the case of Love waves or SH waves we rotate the horizontal components of the seismometer until we find a direction of maximum correlation

[Simonelli et al., 2016] First deep underground observation of rotational signals from an earthquake at teleseismic distance using a large ring laser gyroscope . Annals of Geophysics



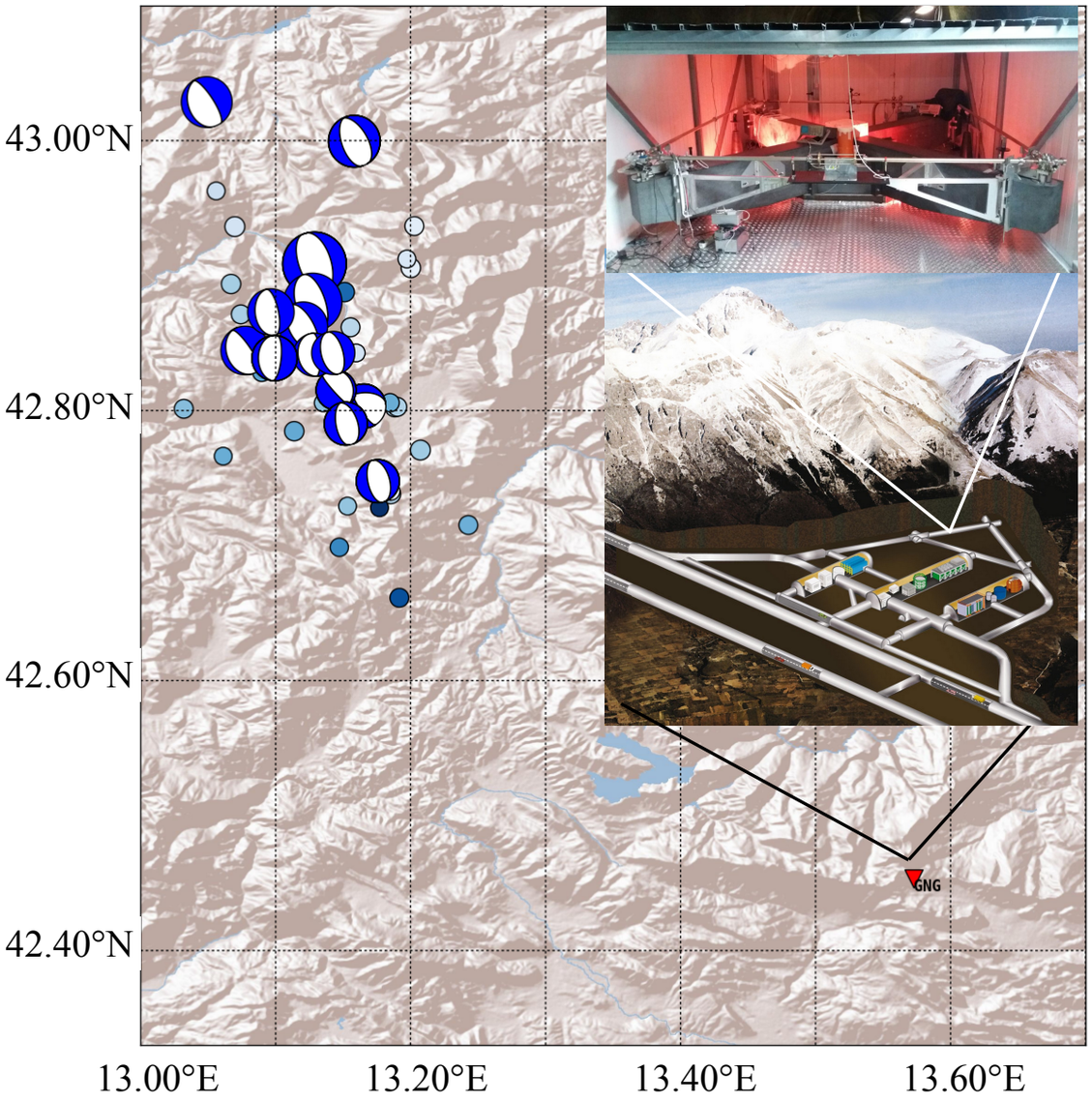
The first underground rotational signal !



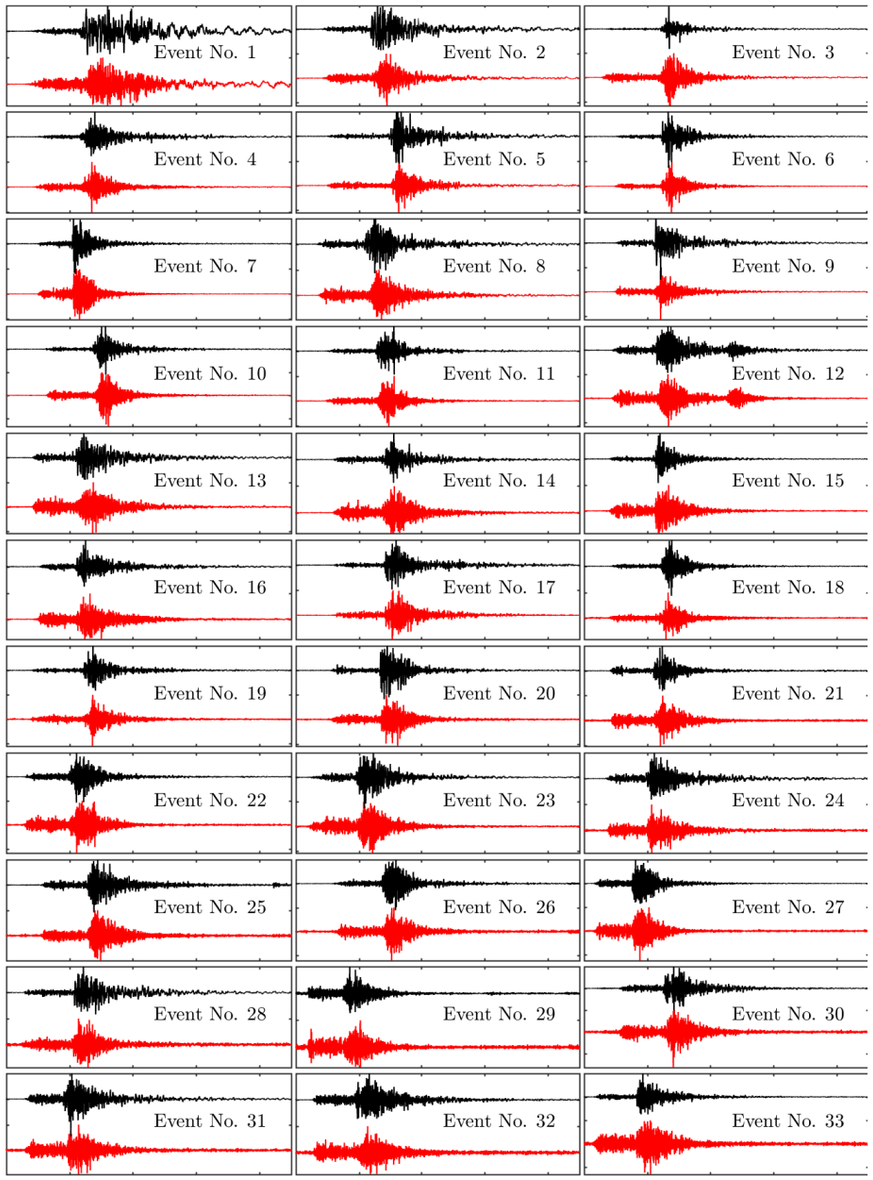


The 2016 central Italy seismic sequence

[Simonelli et al., 2017] Rotational motions from the 2016, central Italy seismic sequence, as observed by an underground ring laser gyroscope. GJI. submitted.



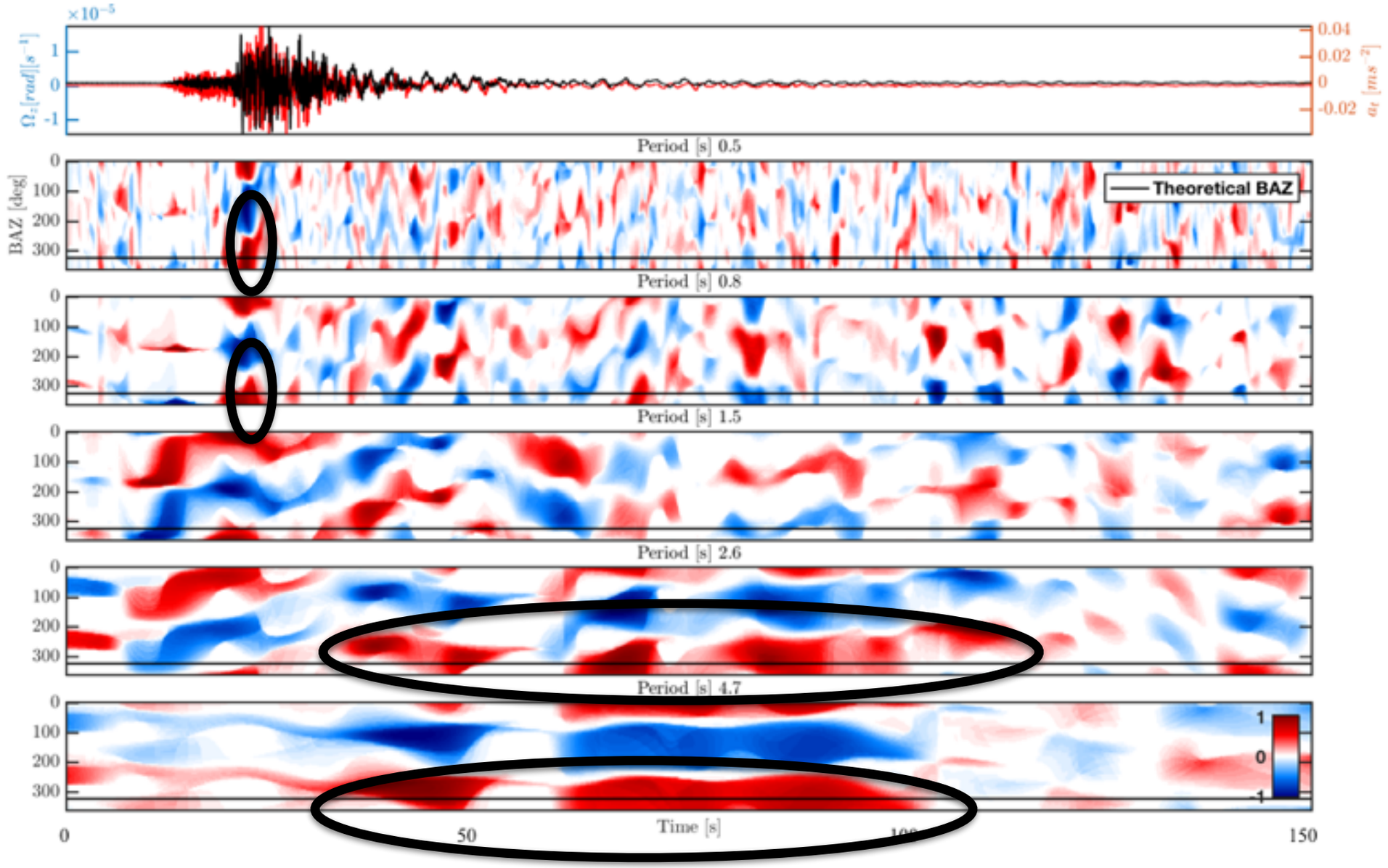
The selected events:
Red: Rot. rate
Black: Transverse acc.



[Simonelli et al., 2017] Rotational motions from the 2016, central Italy seismic sequence, as observed by an underground ring laser gyroscope. GJI. submitted.

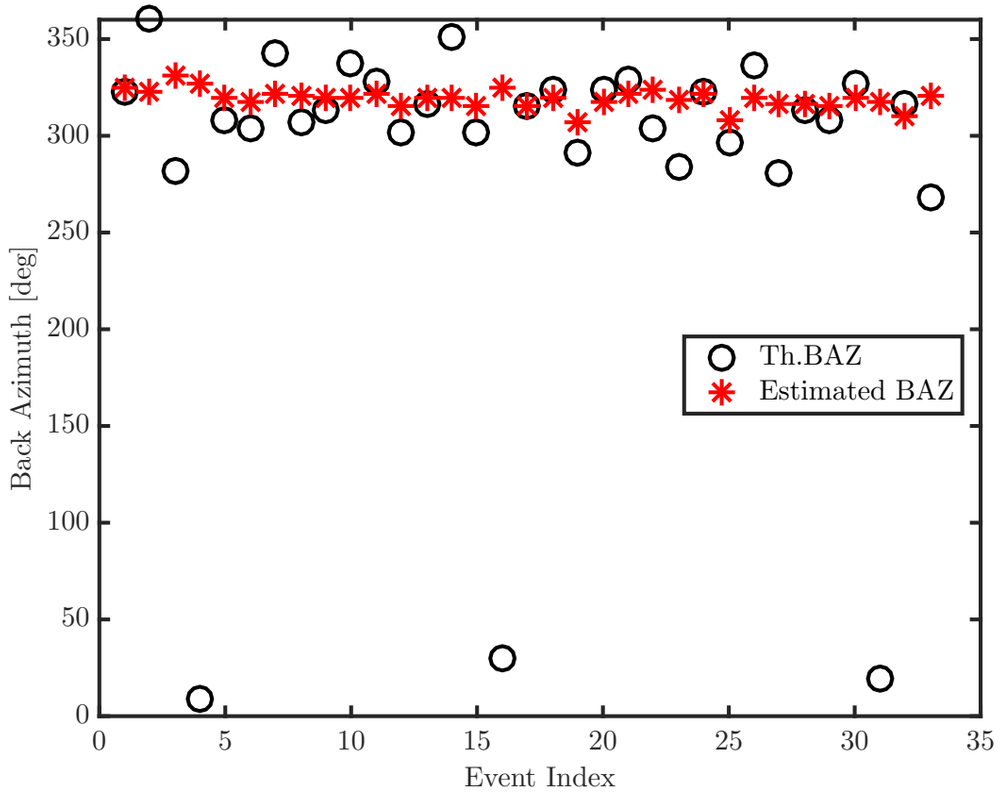
The Wavelet Transform technique is particularly suitable for non-stationary signals like Earthquakes. In contrast to the Fourier Transform, the wavelet transform allows exceptional localization, both in the time domain via translation t of the wavelet, and in the frequency domain via dilations scales b, which can be changed from minimum to maximum, chosen by the user. An example from the Visso Mw 5.9 event

S wave Horizontally polarized (SH onset)

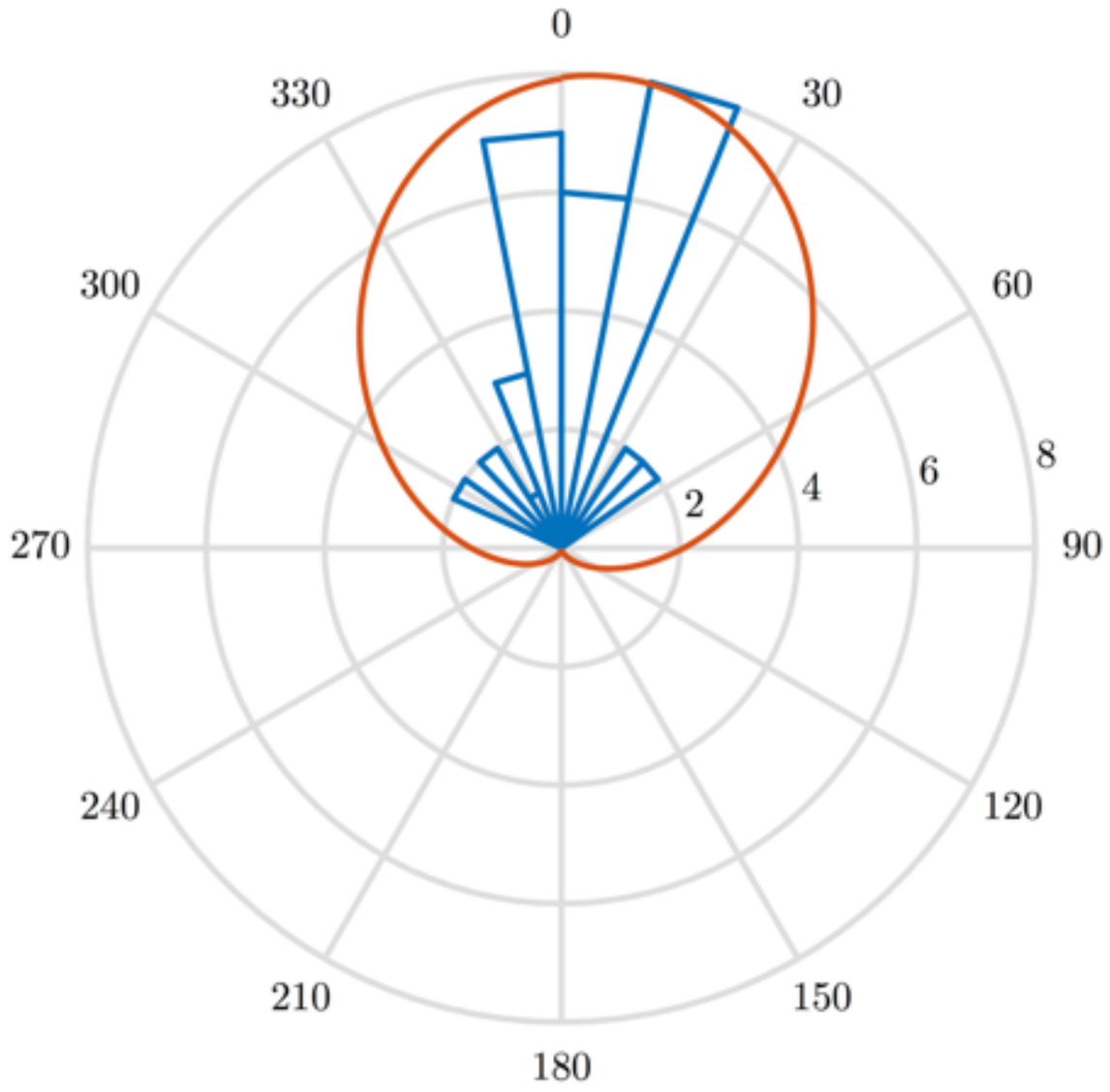


Love waves

[Simonelli et al., 2017] Rotational motions from the 2016, central Italy seismic sequence, as observed by an underground ring laser gyroscope. GJI. submitted.



Wave-field propagation direction measurements: source Back-azimuth (BAZ), Theoretical vs Estimated

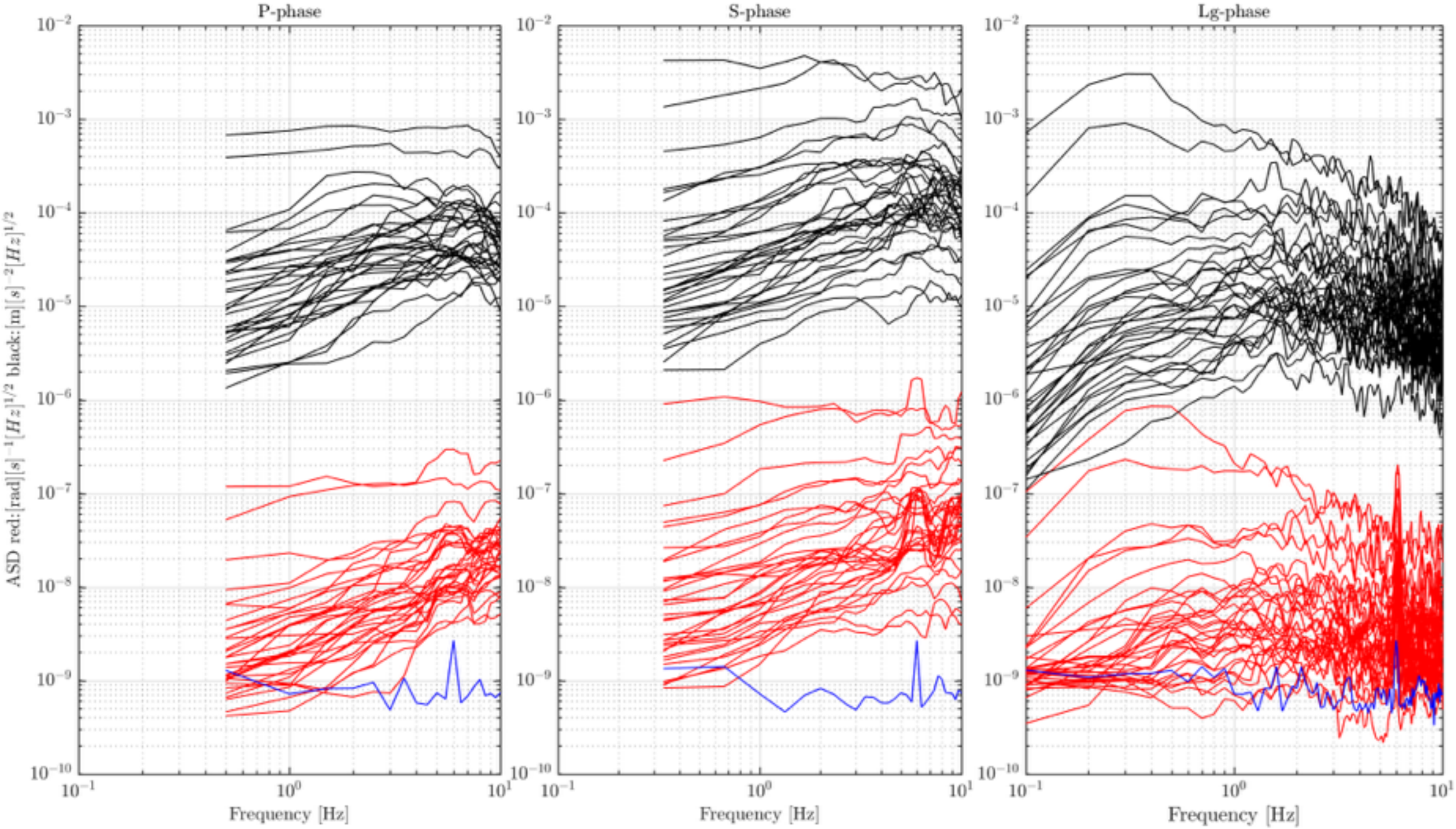


Statistical analysis of the misfit: Polar distribution of the misfit and Gaussian modeling

Phase velocity estimation

[Simonelli et al., 2017] Rotational motions from the 2016, central Italy seismic sequence, as observed by an underground ring laser gyroscope. GJI. submitted.

Event ASD estimations for P-coda S-coda and Lg phase



Phase velocity estimation

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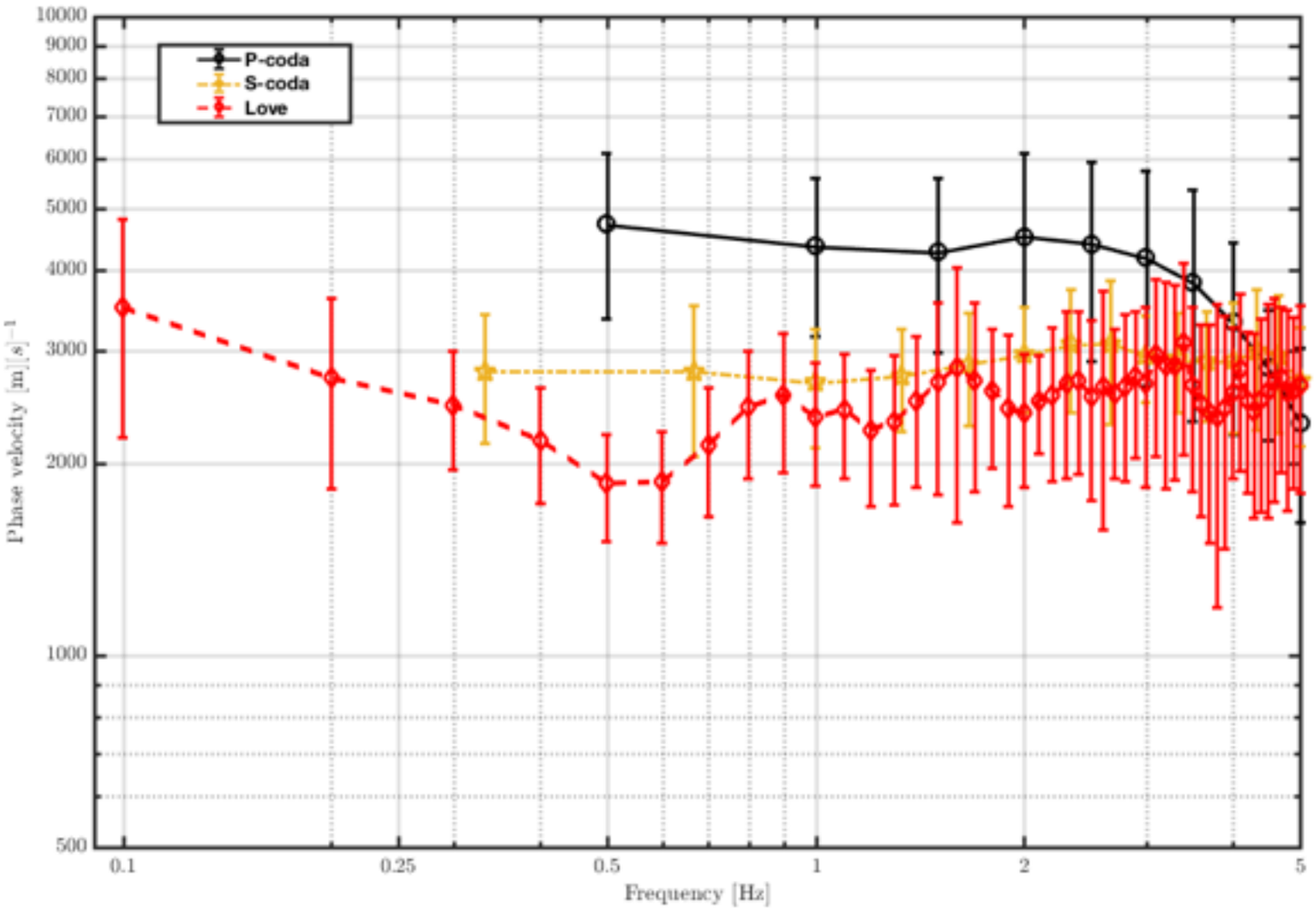
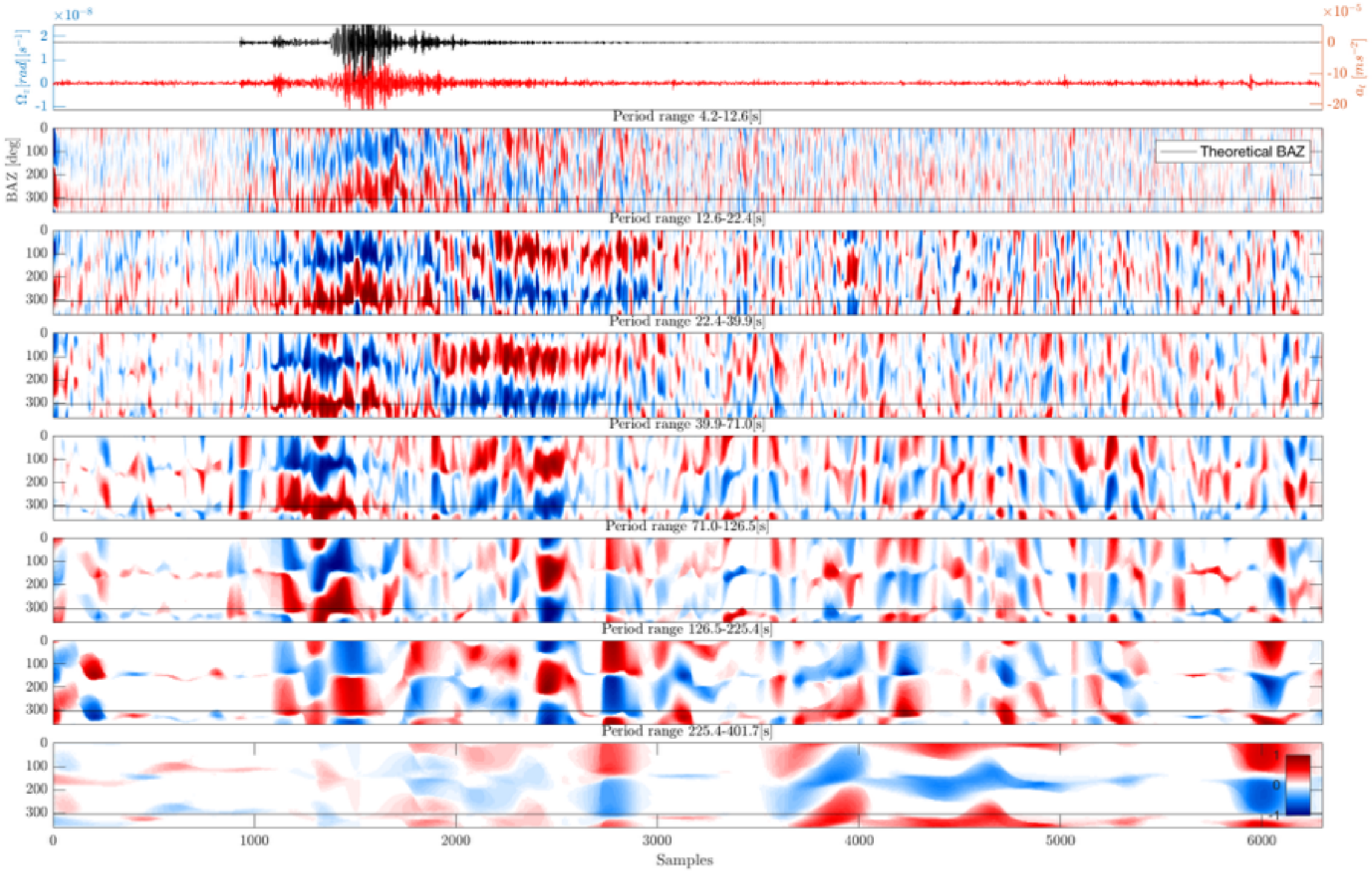


After processing the entire sequence dataset we could obtain the phase-velocities dispersion curves for:

- Rotational signals in the P-coda (3D effects, local scattering)
- S coda
- Lg , Love waves

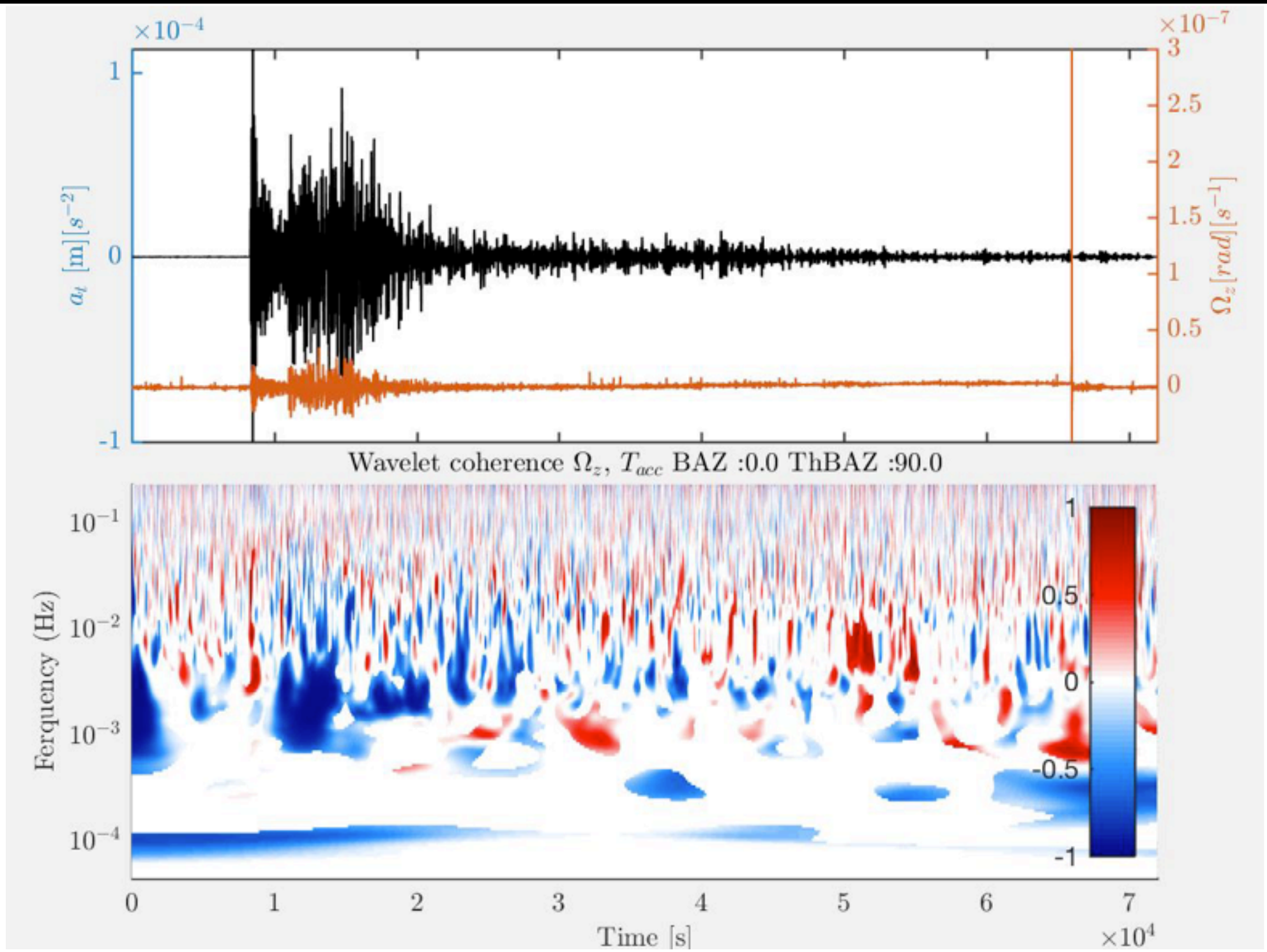
Breaking News

[Simonelli et al., 2017c] Love waves trains observed after the MW 8.1 Tehuantepec earthquake @ AGU2017



Breaking News

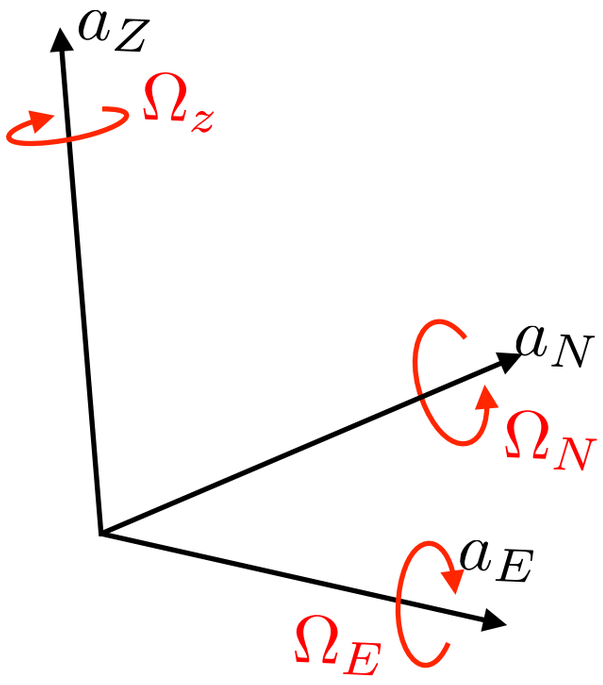
Earthquake magnitude of Mw 7.2 on date 12-11-2017 and time 19:18:17 (Italy) in region Iran [Land]



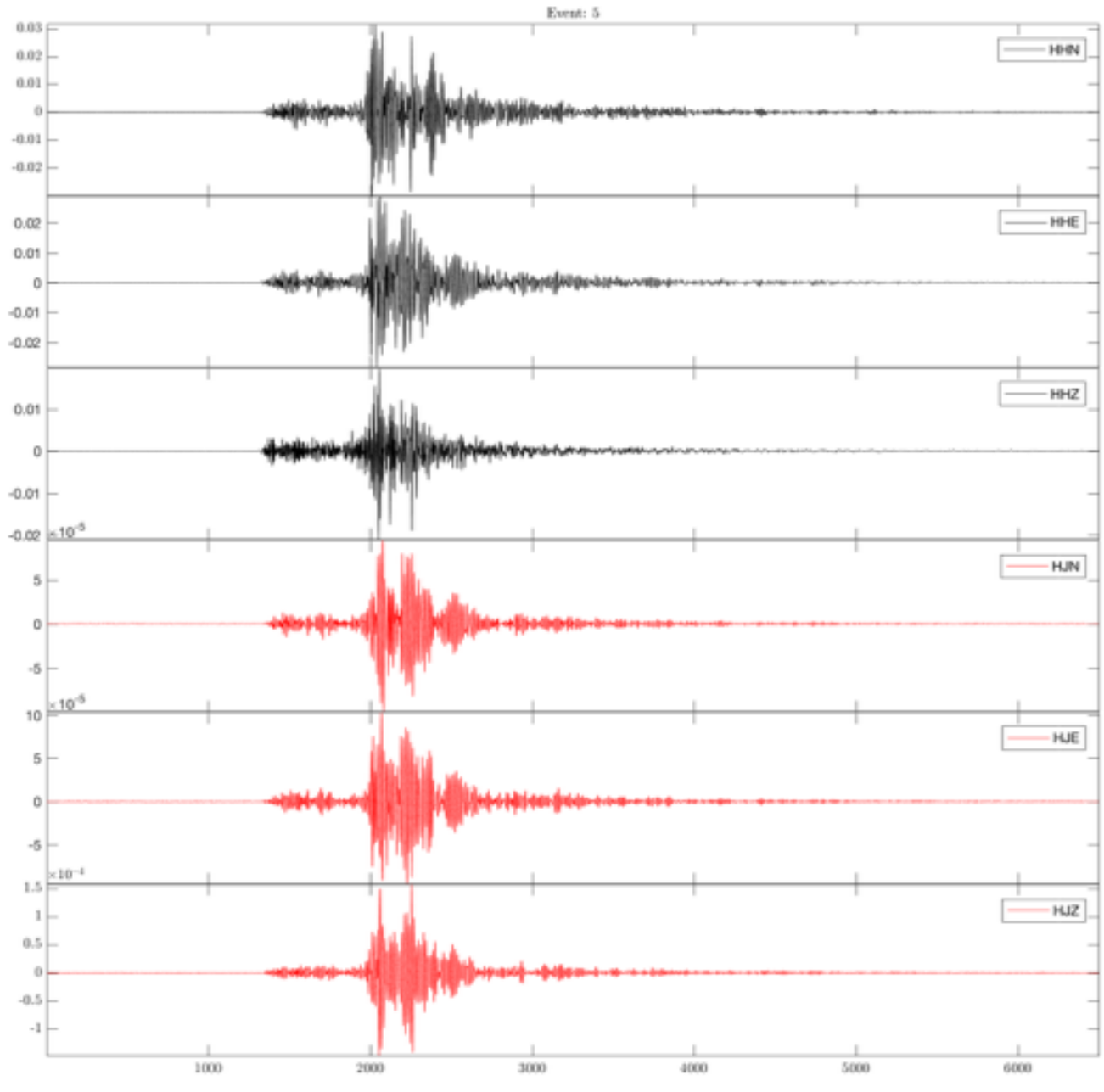
Rotate and wavelet-correlate

Blueseis – First 6C Observations

Oral contribution accepted for: AGU 2017 in December
Paper in submission [Simonelli et al. 2017b]



For the first time we could record broadband data from local events and analyze the 6-components of the local ground motion



Blueseis – First 6C Observations

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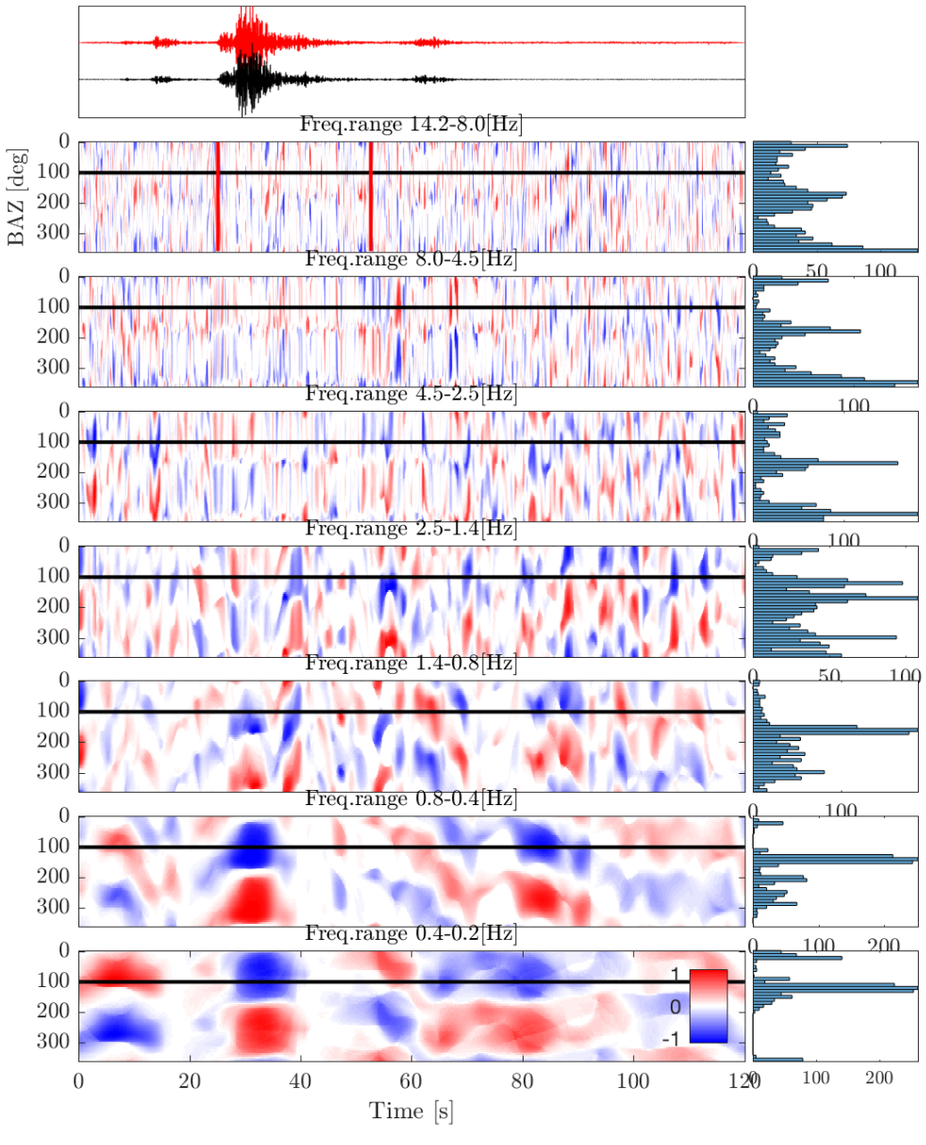
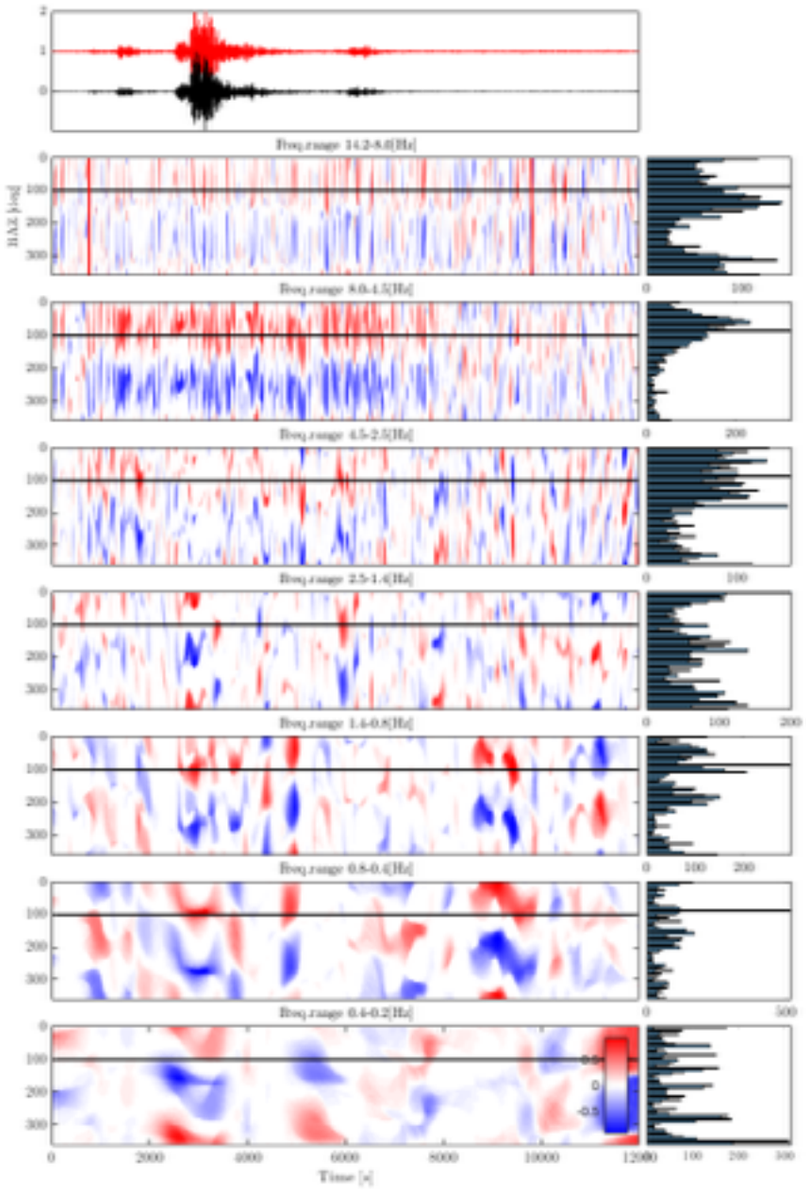
BAZ estimation for R-waves



BAZ estimation for L-waves



Conclusions

1) **After G-Wettzell another large ring laser, with an area larger than 10m^{2} was built in Gran Sasso underground laboratory, it has a sensitivity of the order of 10^{-10} rad/s, in the frequency band of interest for seismology. This enlarge the possibility to observe earthquakes from teleseismic distance to very local, given the geographical location of the instrument. [Belfi et al. 2017, RSI]**

2) **Underground rotations has been observed a first observation of a teleseismic event is reported in chapter 2 and its relative analysis. This confirms in another structural context the possibility of BAZ estimation for tele seismic events. The phase velocity analysis for Love waves show a normal dispersion in agreement with the PREM model of the Earth for periods longer than 10 seconds [Simonelli et al., 2016, Annals of Geophysics]**

3) **A large dataset of local and regional events occurred during the 2016 seismic sequence of central Italy is recorded. The quantity of data collected permitted a statistical study on the BAZ estimation at shorter distances and in different frequency bands. The phase velocity for different seismic phases is estimated by mean of spectral ratios far all the events and the results are stacked in order to obtain a dispersion curve for three time intervals: the P-coda, S-coda and Lg phase. [Simonelli et al., 2017a, *submitted*]**

4) **A first campaign is performed using the state of the art of portable 3C rotational sensors in Colfiorito. For the first time the six components observations of earthquakes at local distances are reported. The data are processed in order to estimate the BAZ of the incoming wave field using the Love waves and for the first time (given the availability of the horizontal rotation rates) using Rayleigh waves. An estimation of the local phase velocity is given in the 5-10 Hz range for Love and Rayleigh waves. [Simonelli et al., 2017b, in prep.]**

Open questions, next challenges

- ➢ Stable observations with the 4C -> 3C ROMY ring laser
- ➢ Comparison of ROMY with G-Ring and Gingerino (vertical component, amplitudes, waveforms)
- ➢ Field observations with blueSeis, demonstrate impact on source inversion
- ➢ Finite source tracking with 6C measurements, nuclear explosions monitoring
- ➢ Scattering in crust and mantle from BAZ dependence
- ➢ How to make use of the gradient of 6C measurements?
- ➢ How to use 6C for earthquake physics? Dynamic rupture?
- ➢ A theory of rotational motions in anisotropic media -> inverse problem
- ➢ Static rotations from large events
- ➢ Ocean Bottom 6C experiment
- ➢ Planetary mission with 6C (Moon, Mars)

Thanks for the attention