Rotational seismic detection through G-Pisa ring laser gyroscope

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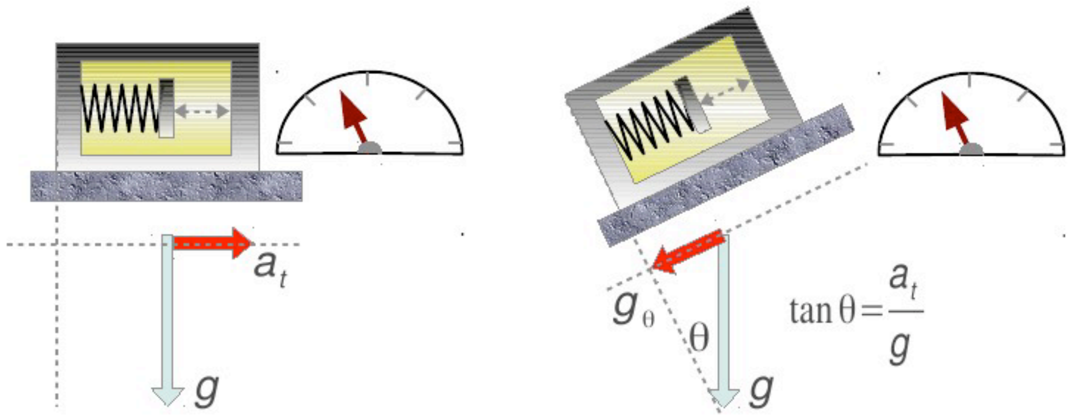
Rotational Seismology

- The ground motion is fully described by 12 parameters:
  - 3 translations (3-D vector)
  - 6 strains (3×3 symmetric tensor)
  - 3 rotations (3-D pseudo-vector)

The reading of a conventional seismometer can be misleading!



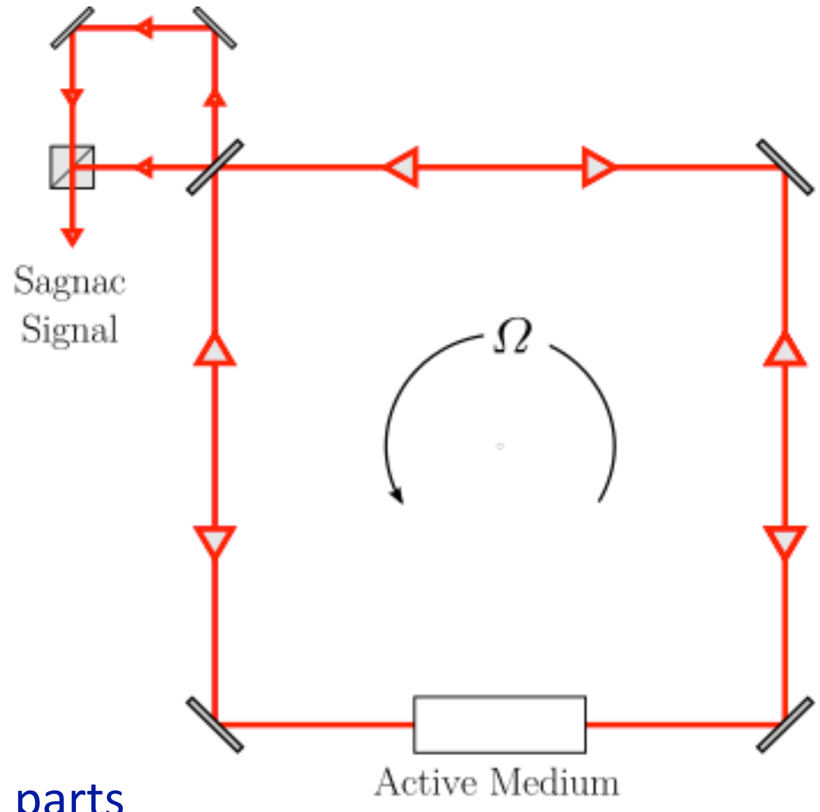
For surface plane waves, rotation rate relates to ground acceleration via the phase velocity: $\ddot{u}_T = 2c_L\Omega_z$ $\ddot{u}_z = c_R\Omega_T$

A linear acceleration of 1 mm/s^2 produces a rotational signal of the order of a few 10^{-7} rad/s

⇨ Rotational seismology requires very high sensitivity gyroscopes

Ring laser gyroscopes

In a ring laser rotating with respect to an inertial frame, the cavity optical lengths for the two counter-propagating laser beams becomes different.



Sagnac interferometric signal:

$$\Delta f = \frac{4A}{\lambda p}\vec{n}\cdot\vec{\Omega}$$

- Entirely insensitive to translations
- Generated from light - no mechanical parts
- Extremely high linearity
- Very large dynamical range

Large-frame laser gyroscopes

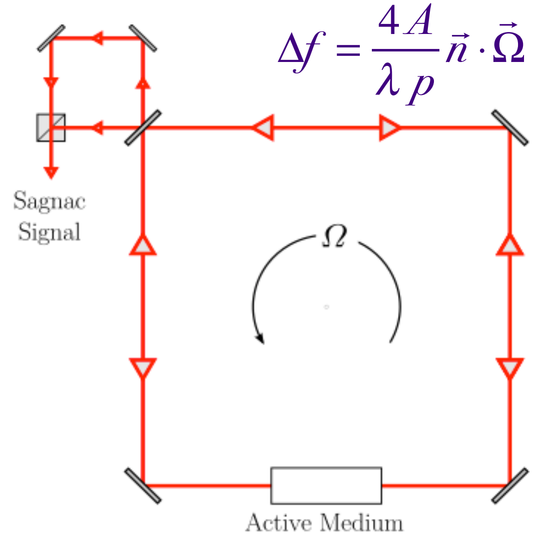
Cross-talking between the two beams produces self-locking of the two frequency, when $\Delta f \lesssim \Delta \nu$

($\Delta \nu$: laser linewidth)

This limits the sensitivity to small rotation rate

Bias is given by the Earth rotation ($\Omega = 7.27 \times 10^{-5}$ rad/s).

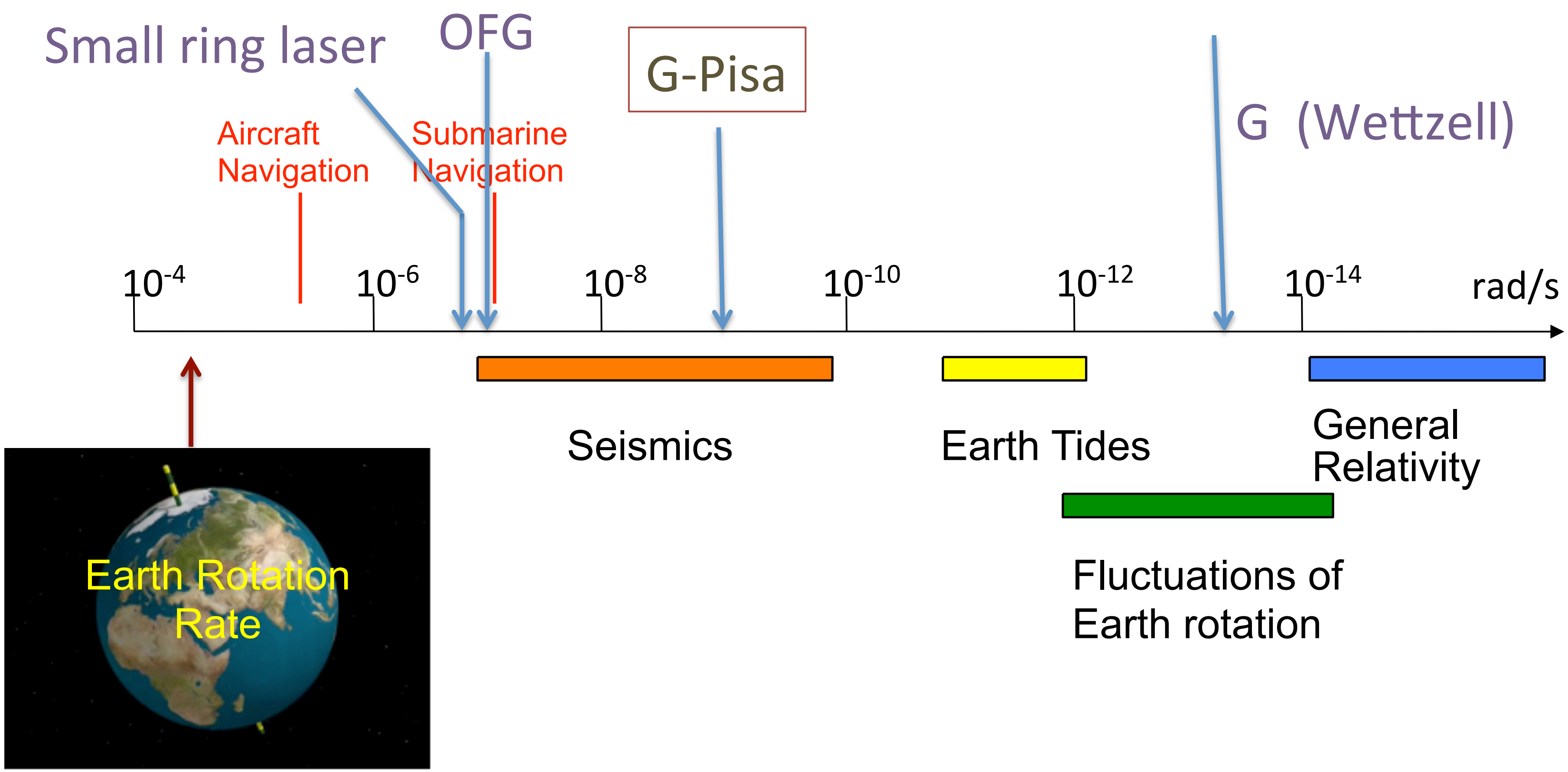
$$\Delta f = \frac{4A}{\lambda p} \vec{n} \cdot \vec{\Omega}$$



To satisfy the condition $\Delta f \lesssim \Delta \nu$, it needs:

- A/p > 1 m
- Very high quality optical cavity
  "supermirrors" with R > 99.999%

Measuring rotations



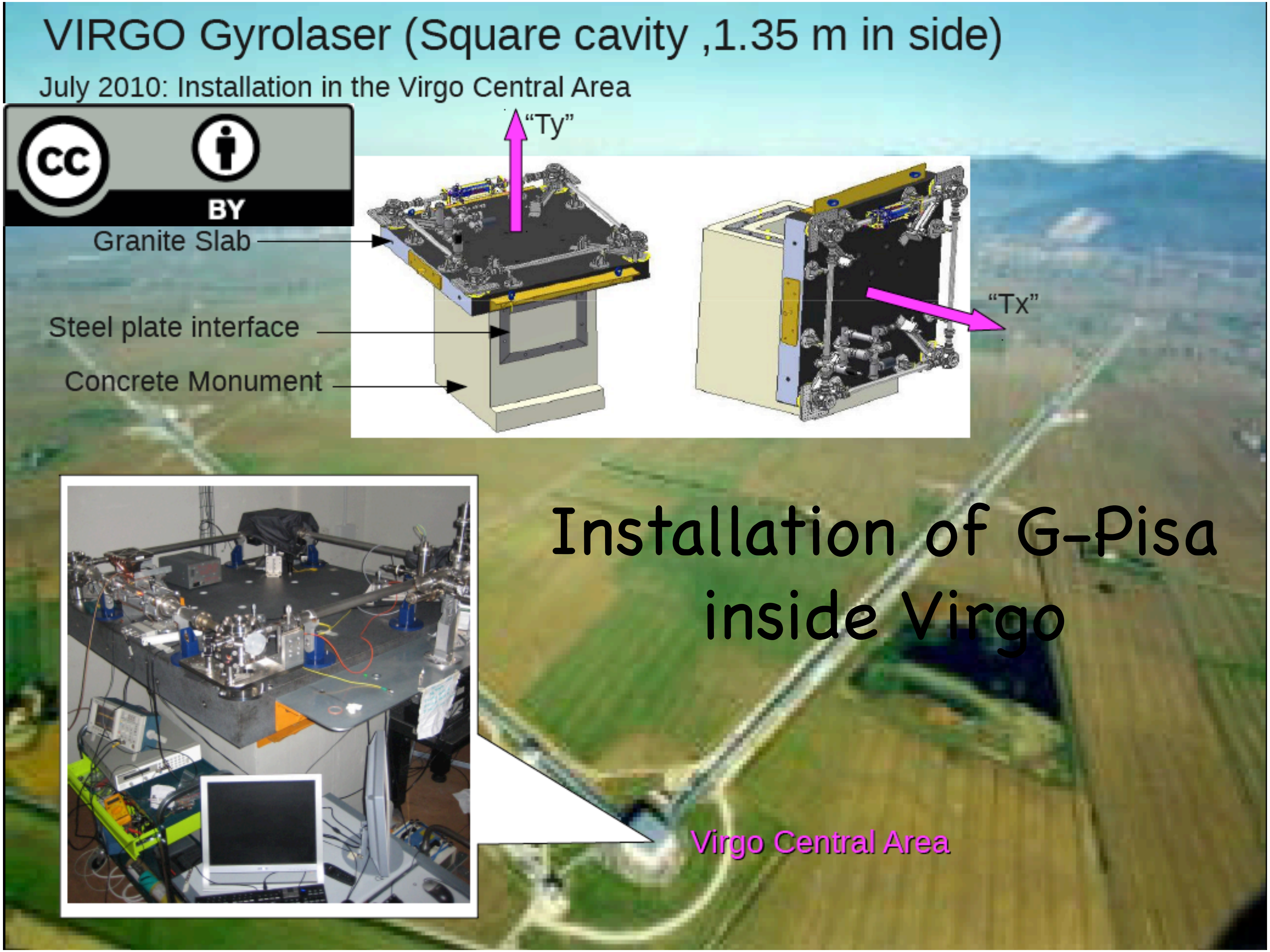
G-Pisa project

- G - Pisa project was born from the requirement for the control of the mirrors in VIRGO gravitational interferometric antenna.
  - Monitor of seismic rotational noise
  - Direct sensing of the suspension tilts
  - Enhance the performances of VIRGO suspensions, extending the control from the present 4 degrees of freedom to 6 degrees of freedom

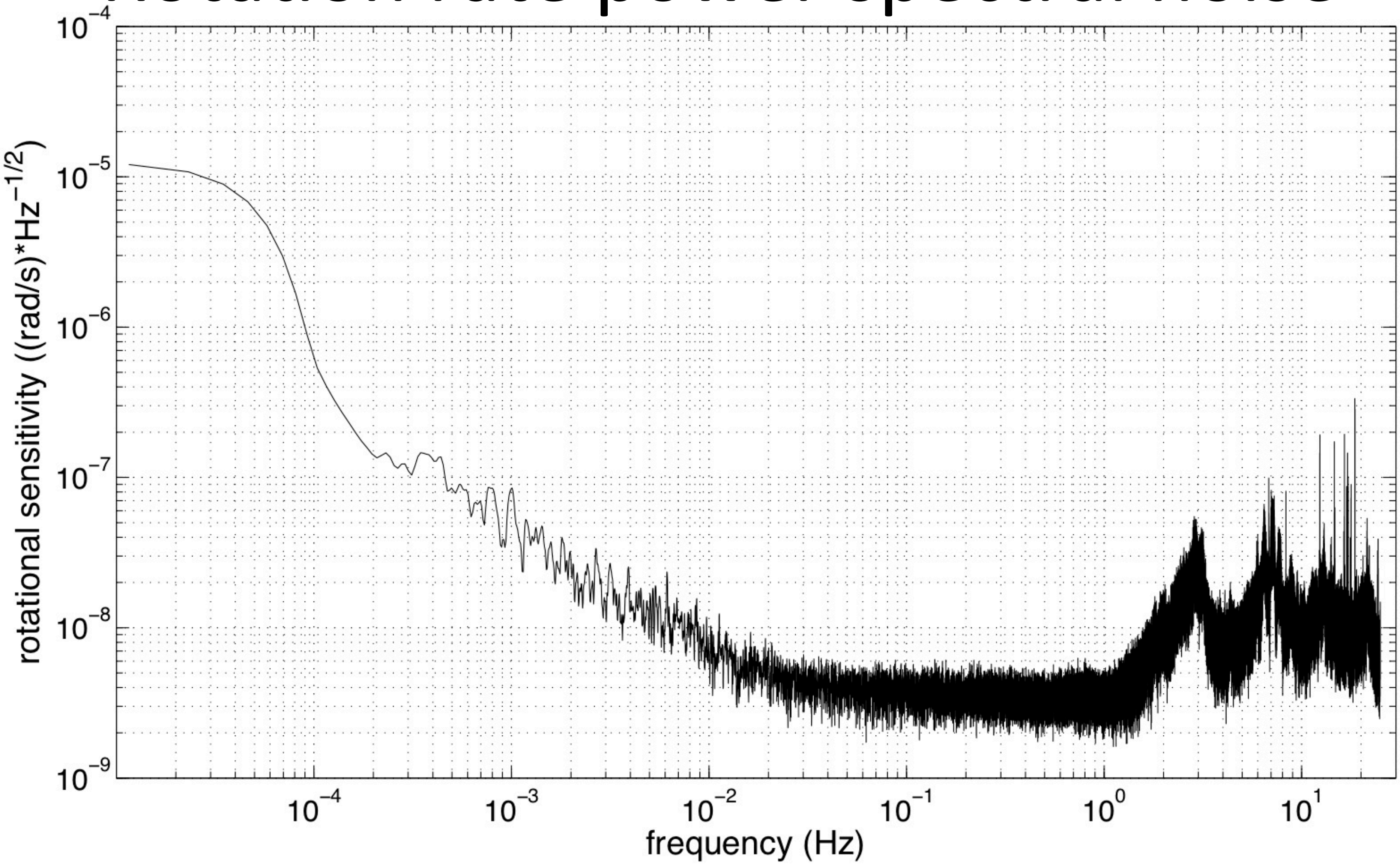
- ***Requirements:***
  - Angular resolution: better thana few 10^{-9} rad /√Hz at 10 - 100 mHz
  - Linear dimensions ≈ 1 m × 1 m

G-Pisa

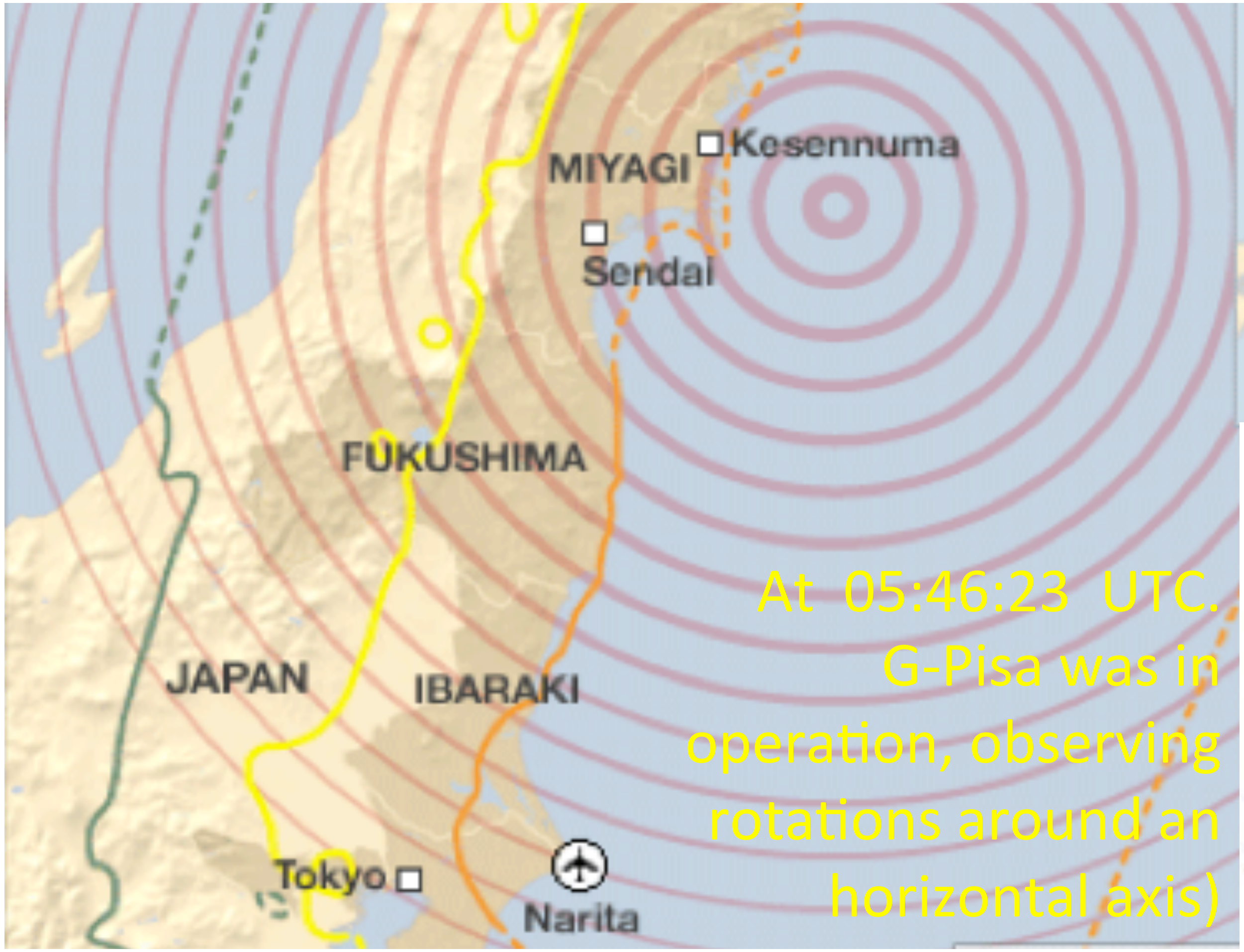
- Location coordinates: 43°37’53”N, 10°30’16” E
- He-Ne laser in square cavity with side 1.35 m
- Stainless steel vacuum cavity mounted on a granite slab 1.5×1.5×0.18 m^3 (≈1 ton)
- The granite is screwed to a 2 ton concrete monument in horizontal/vertical orientation


VIRGO Gyrolaser (Square cavity ,1.35 m in side)
July 2010: Installation in the Virgo Central Area
BY
"Ty"
Granite Slab
Steel plate interface
Concrete Monument
"Tx"
Installation of G-Pisa
inside Virgo
Virgo Central Area

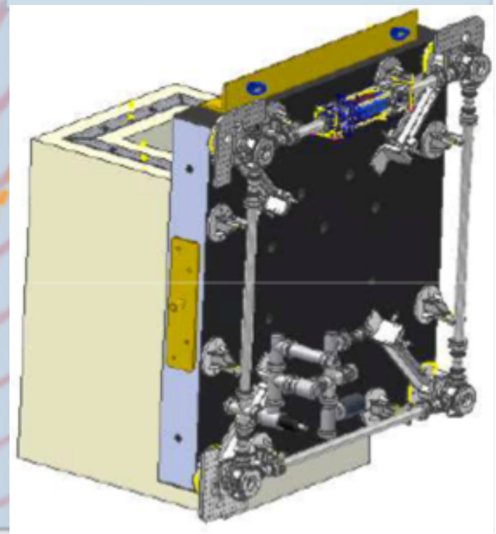
Rotation rate power spectral noise



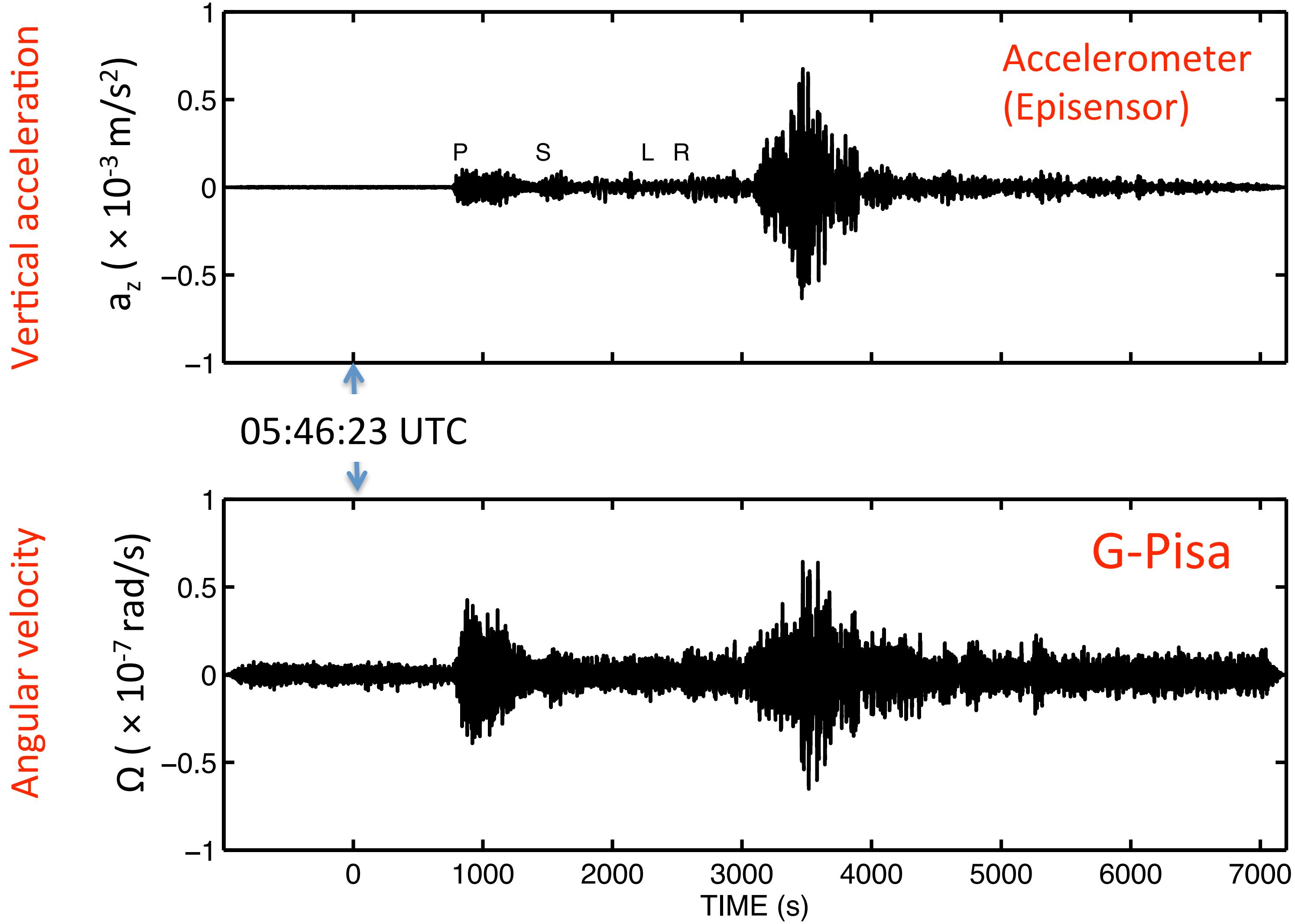
March 11, 2011



At 05:46:23 UTC.
G-Pisa was in
operation, observing
rotations around an
horizontal axis)



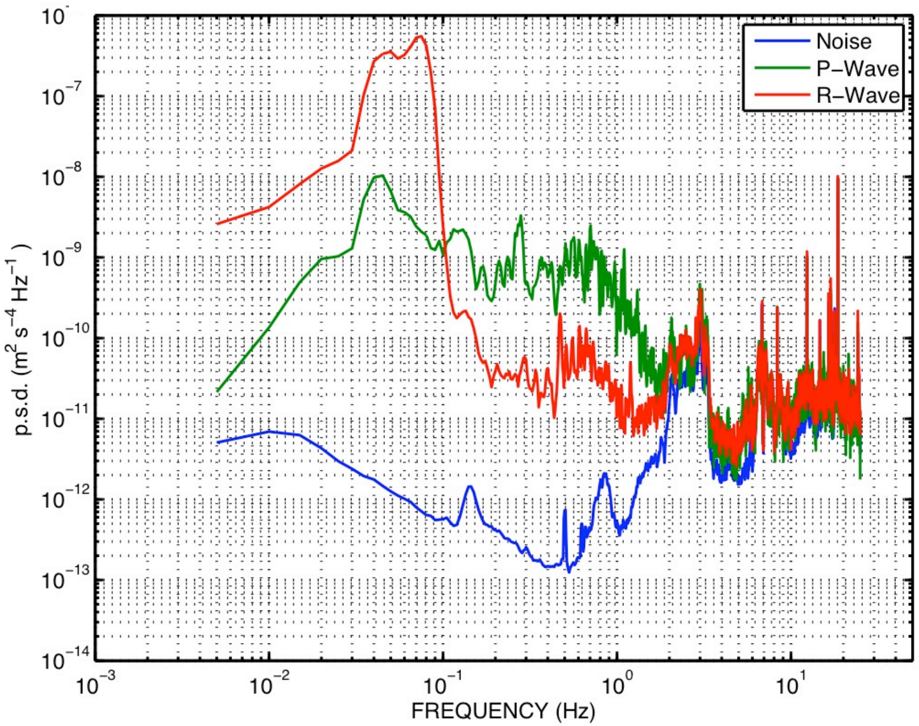
March 11, 2011, M_w=9 Sendai-Honshu earthquake



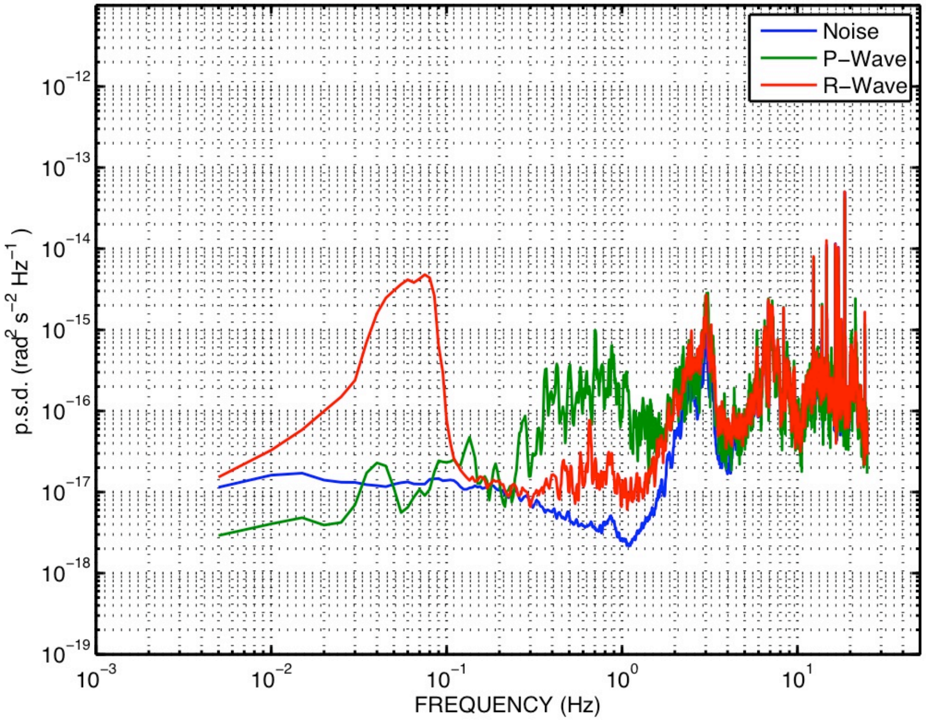
Traces have been band-pass filtered over the 100 s – 1 s period range using a 2-pole, 2-passes Butterworth filter. Time 0 corresponds to the origin time of the earthquake (05:46:23 UTC)

Sendai-Honshu Earthquake, March 11th 2011

Linear vertical acceleration (*Episensor*)



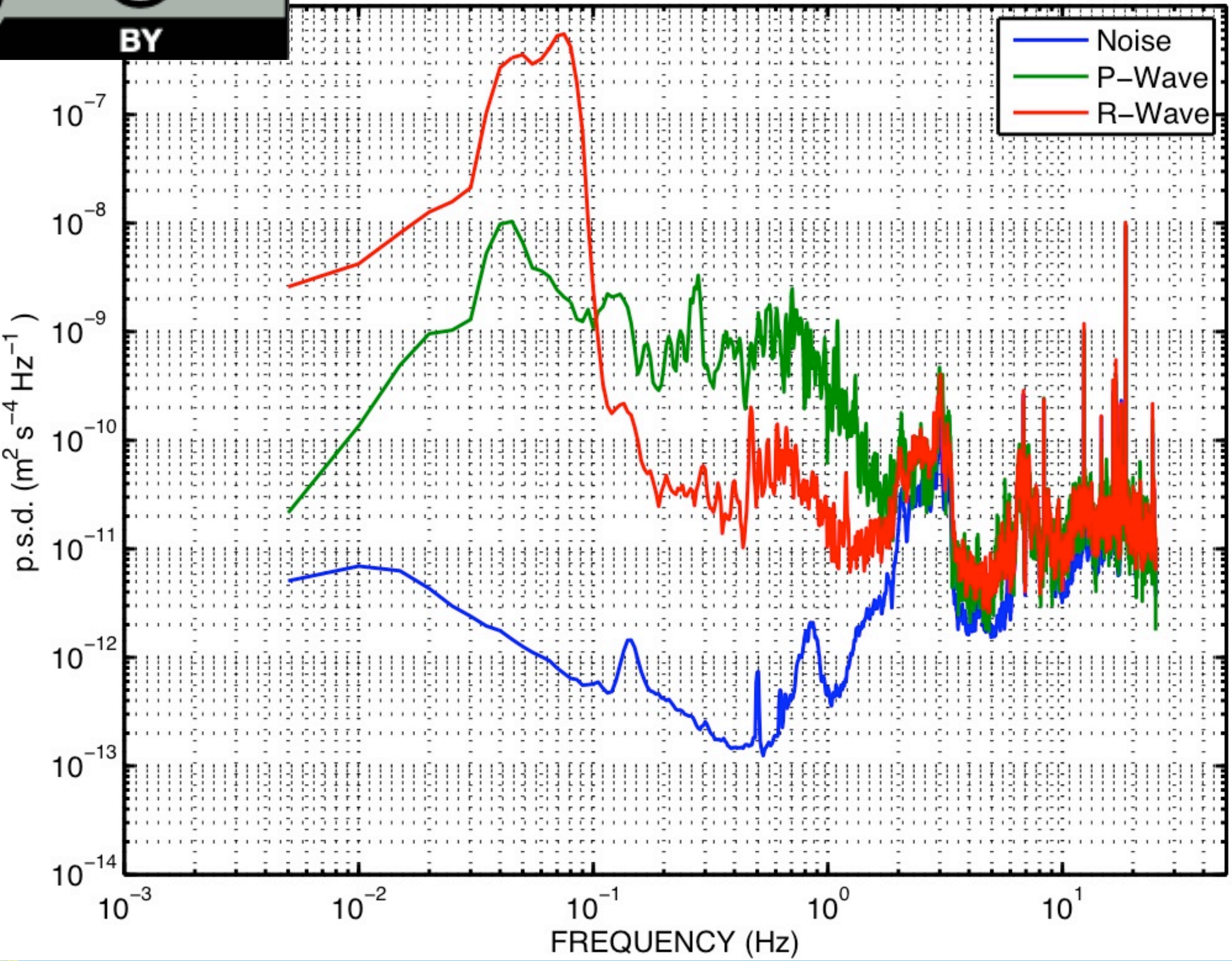
Rotation rate (*gyro*)



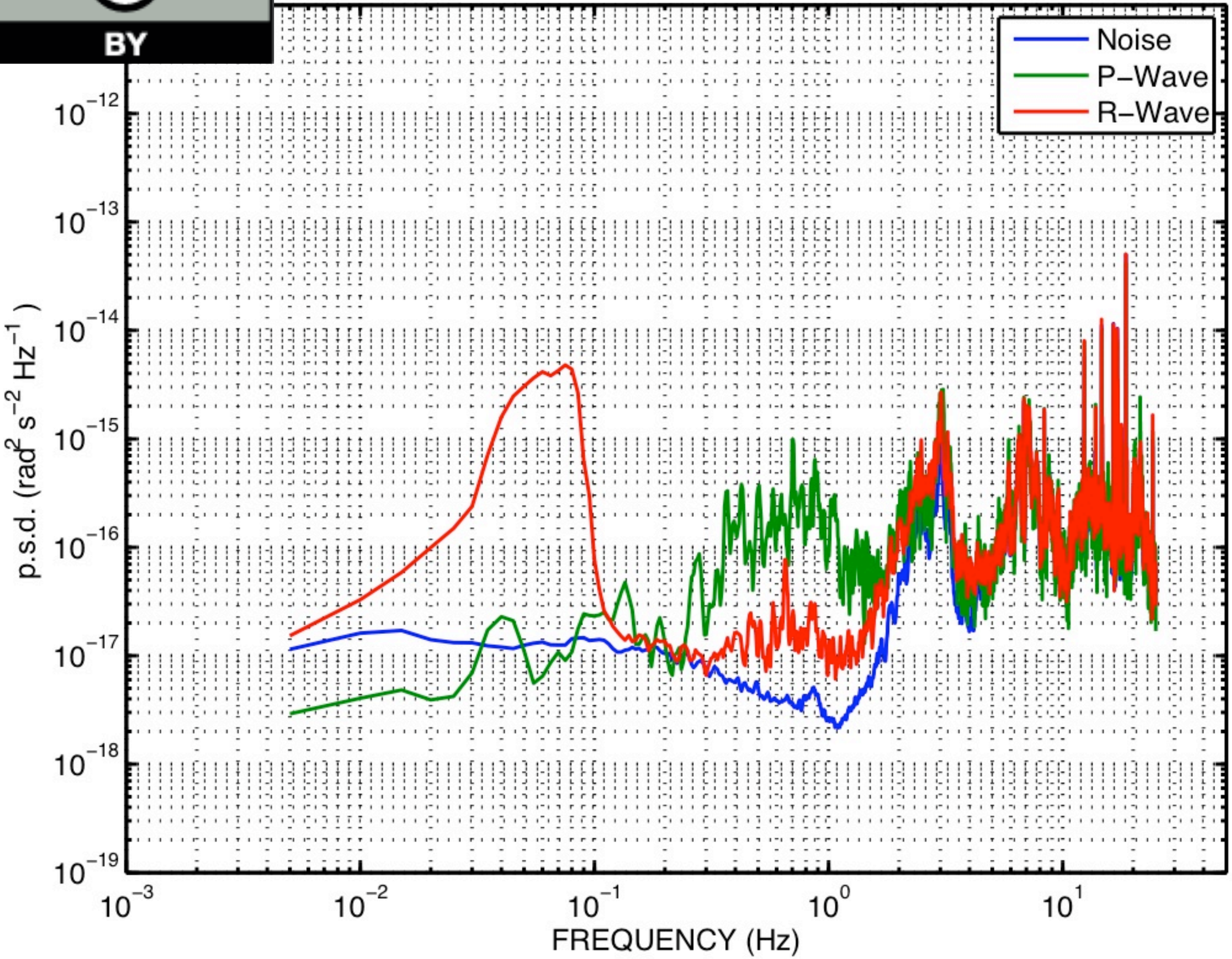
Power spectral estimates for the time series of a 5-h-long noise window preceding the earthquake, a 600-s-long window encompassing the P-wave arrivals and coda, and a 1,800-s-long window starting at the Rayleigh-wave arrival.

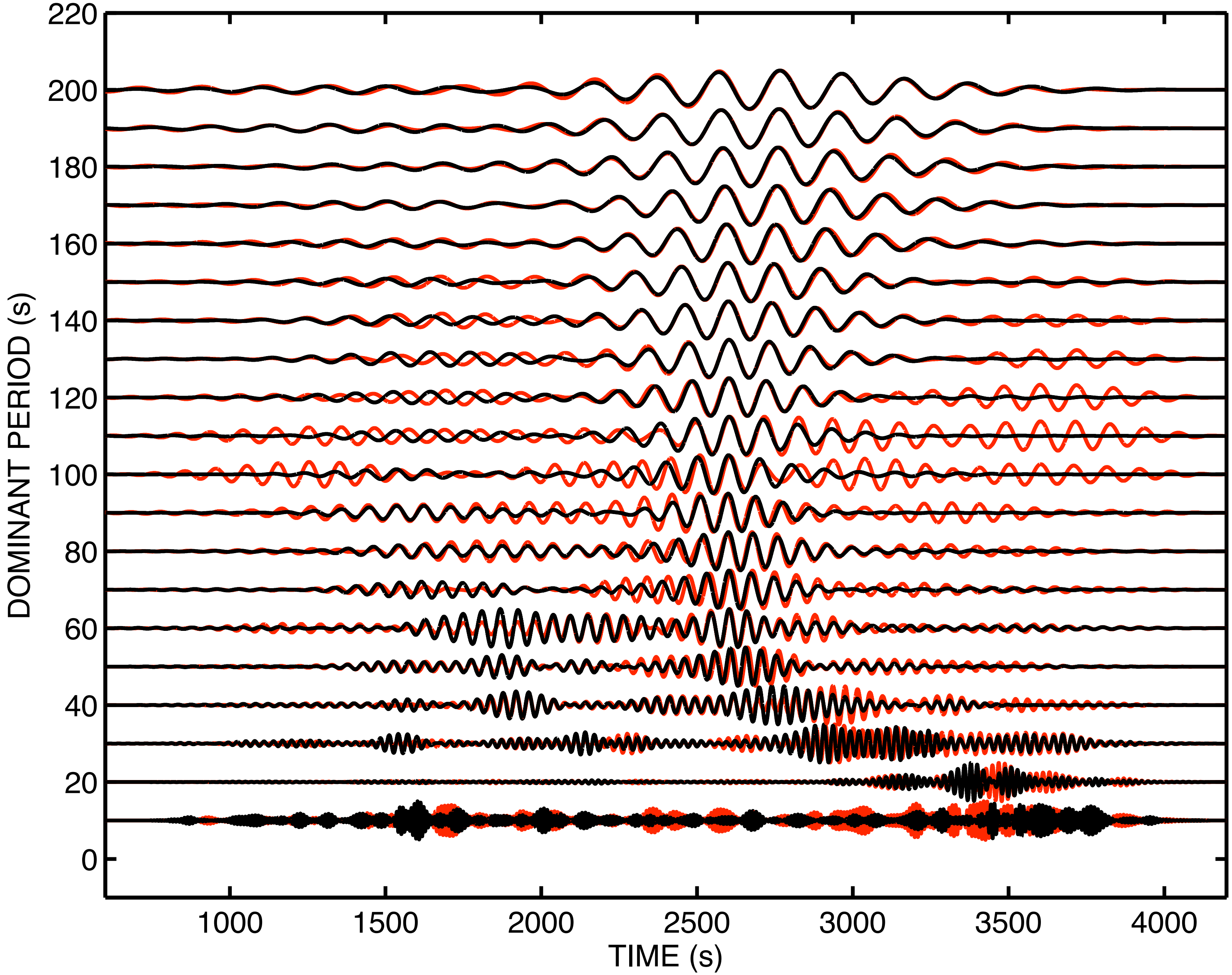
Power spectra are obtained by averaging and then squaring individual spectral estimates obtained over a 200-s-long window sliding by 50% of its length along the selected signal segments. Before transformation, individual signal slices were detrended, demeaned, and tapered by a 5% Tukey window

Linear vertical acceleration (*Episensor*)



Rotation rate (*gyro*)





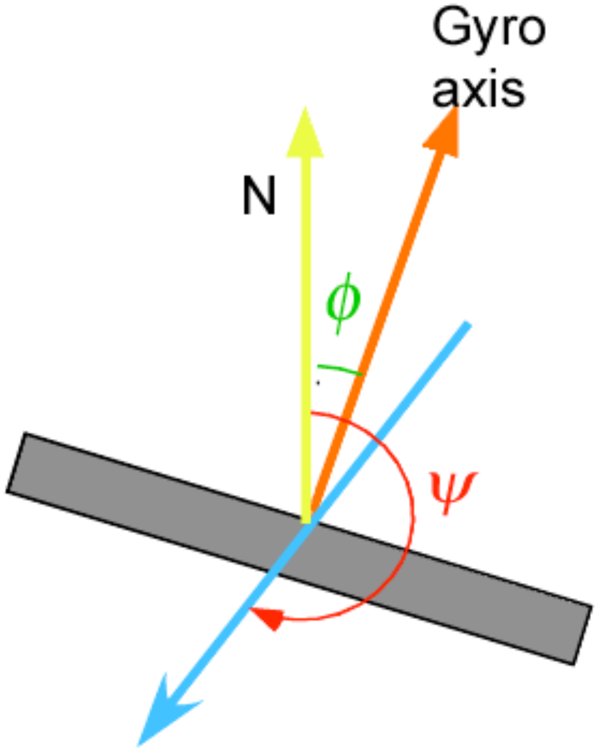
220
200
180
160
140
120
100
80
60
40
20
0
DOMINANT PERIOD (s)
1000
1500
2000
2500
3000
3500
4000
TIME (s)

Phase velocity evaluation

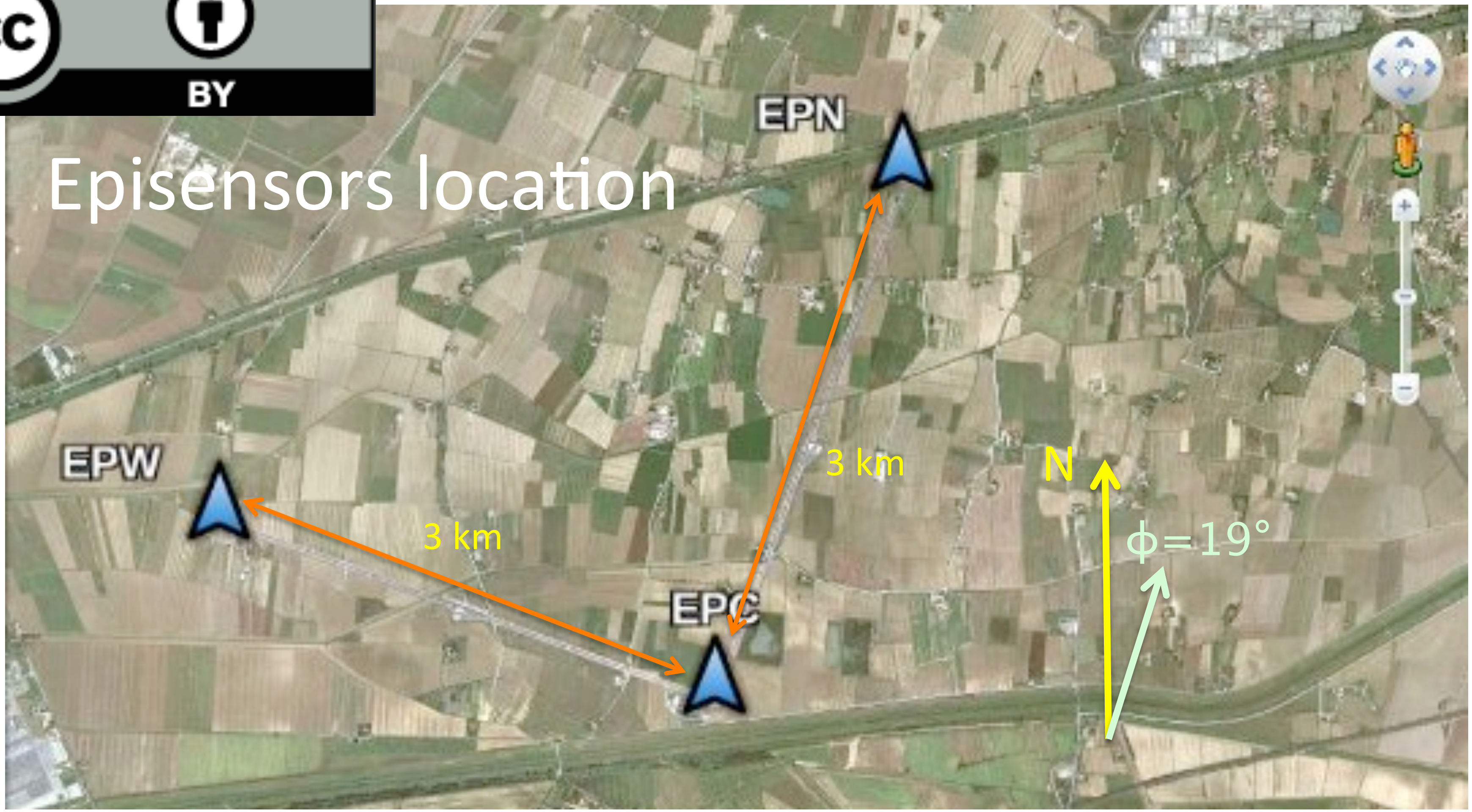
$$\ddot{u}_z = c_R \Omega_T \qquad c_R = \frac{\ddot{u}_z}{\Omega_T}$$

$$\Omega_T = \Omega_x \sin(\psi - \phi)$$

- An estimation of the local Rayleigh wave velocity requires the knowledge of the azimuthal angle ψ of the incoming seismic wave.
- We reconstructed ψ by using the records from the array of tri-axial Episensor's located at the extremity of the VIRGO apparatus



Episensors location

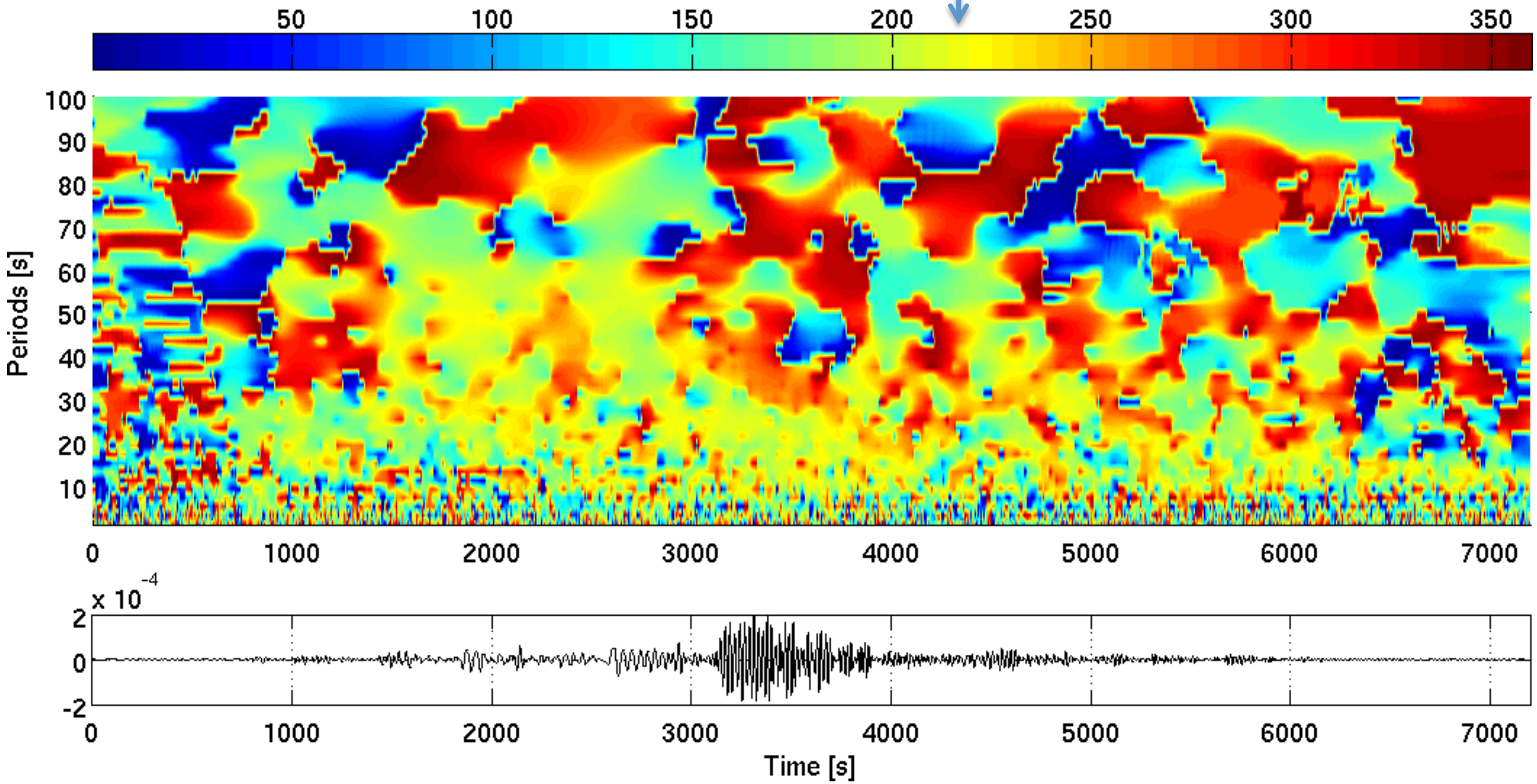


Data from the array can provide the surface waves VELOCITY (**V**) and AZIMUTH (ψ) estimation of the incoming wavefield

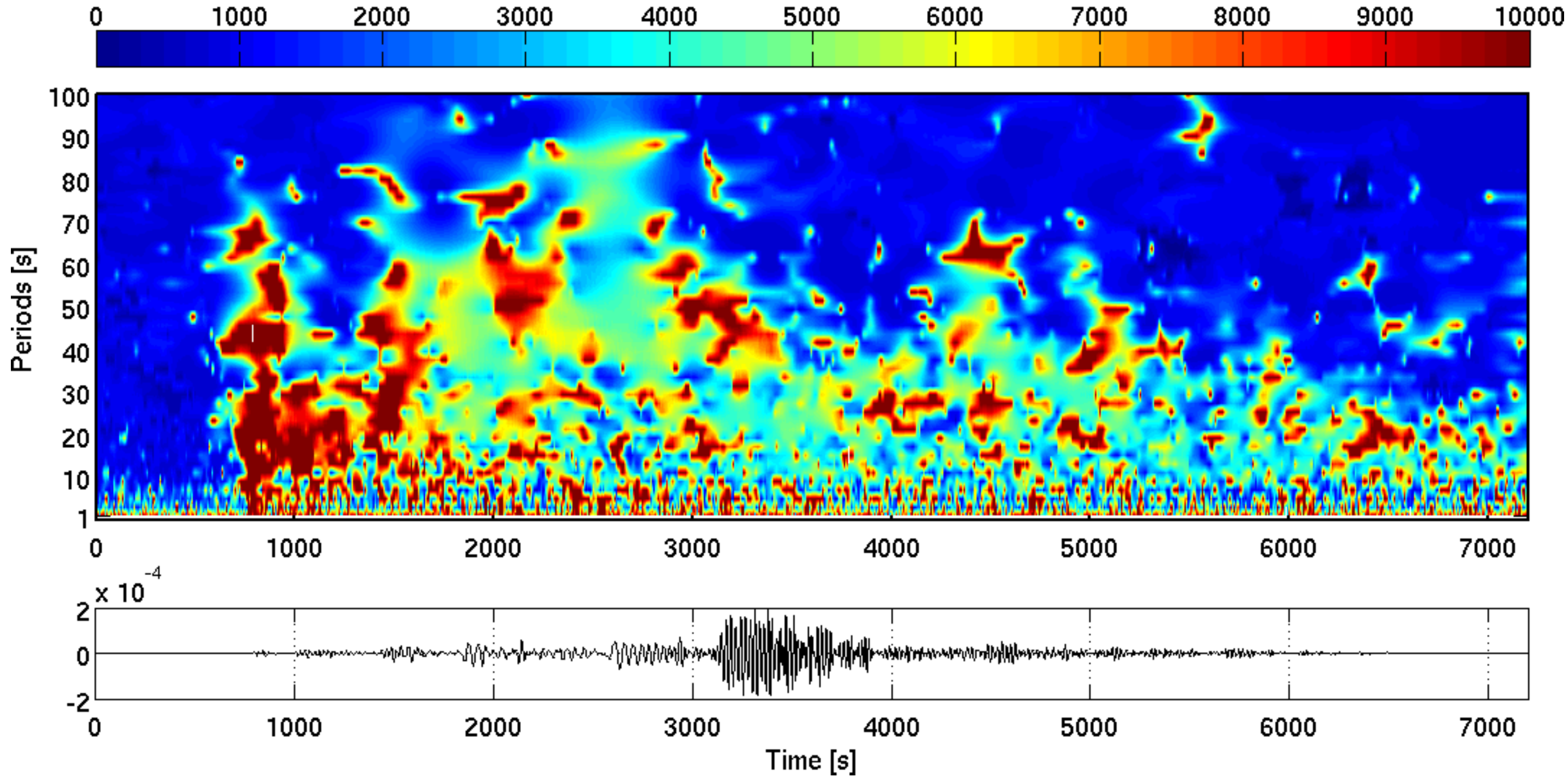
- ψ (t ; ω) will be used to correct Gyrolaser signal
- **V** (t; ω) will be used to investigate dispersion properties

Azimuth estimation from array

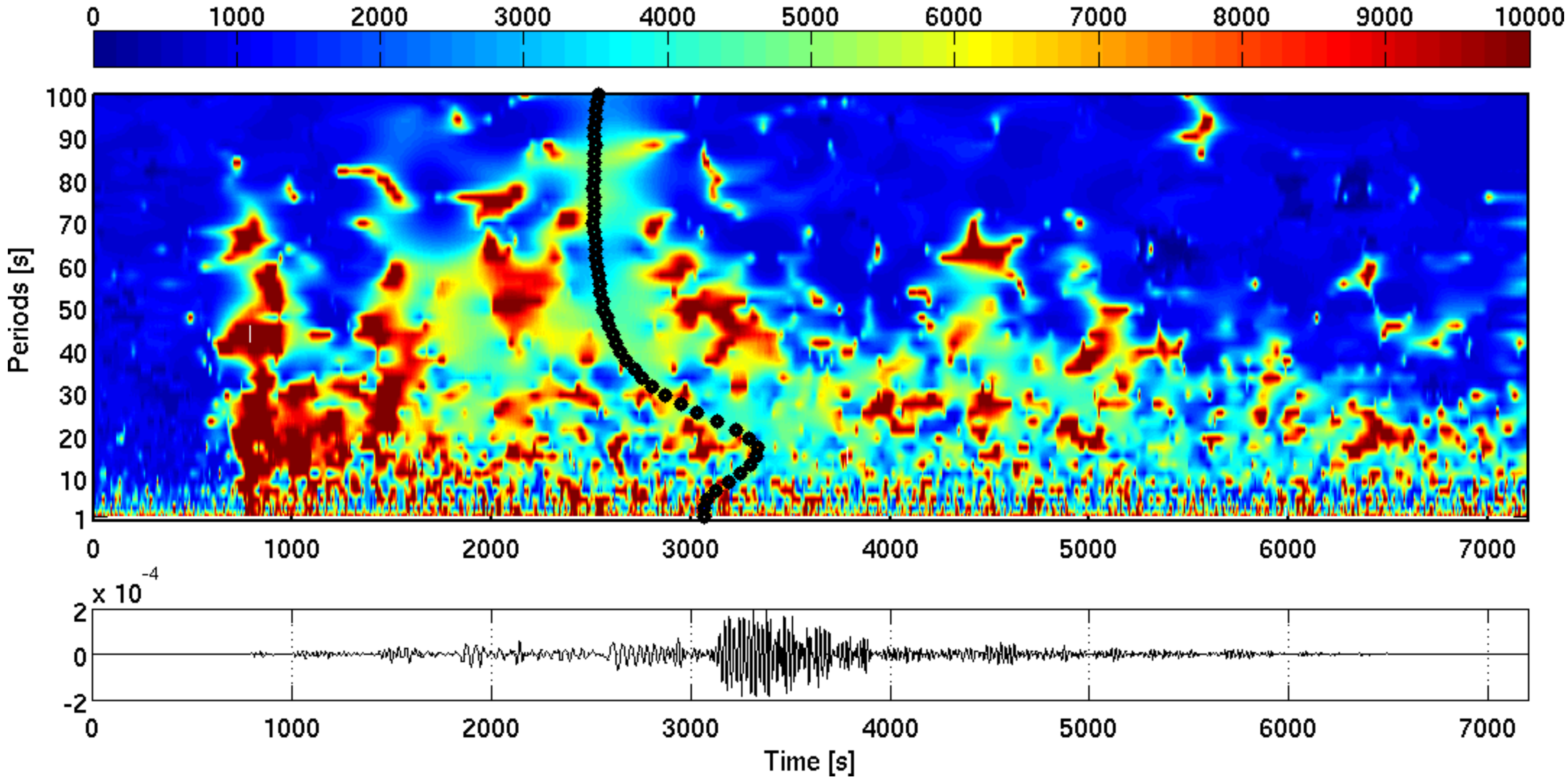
expected ≈ 216°



Surface wave velocity estimation from the array

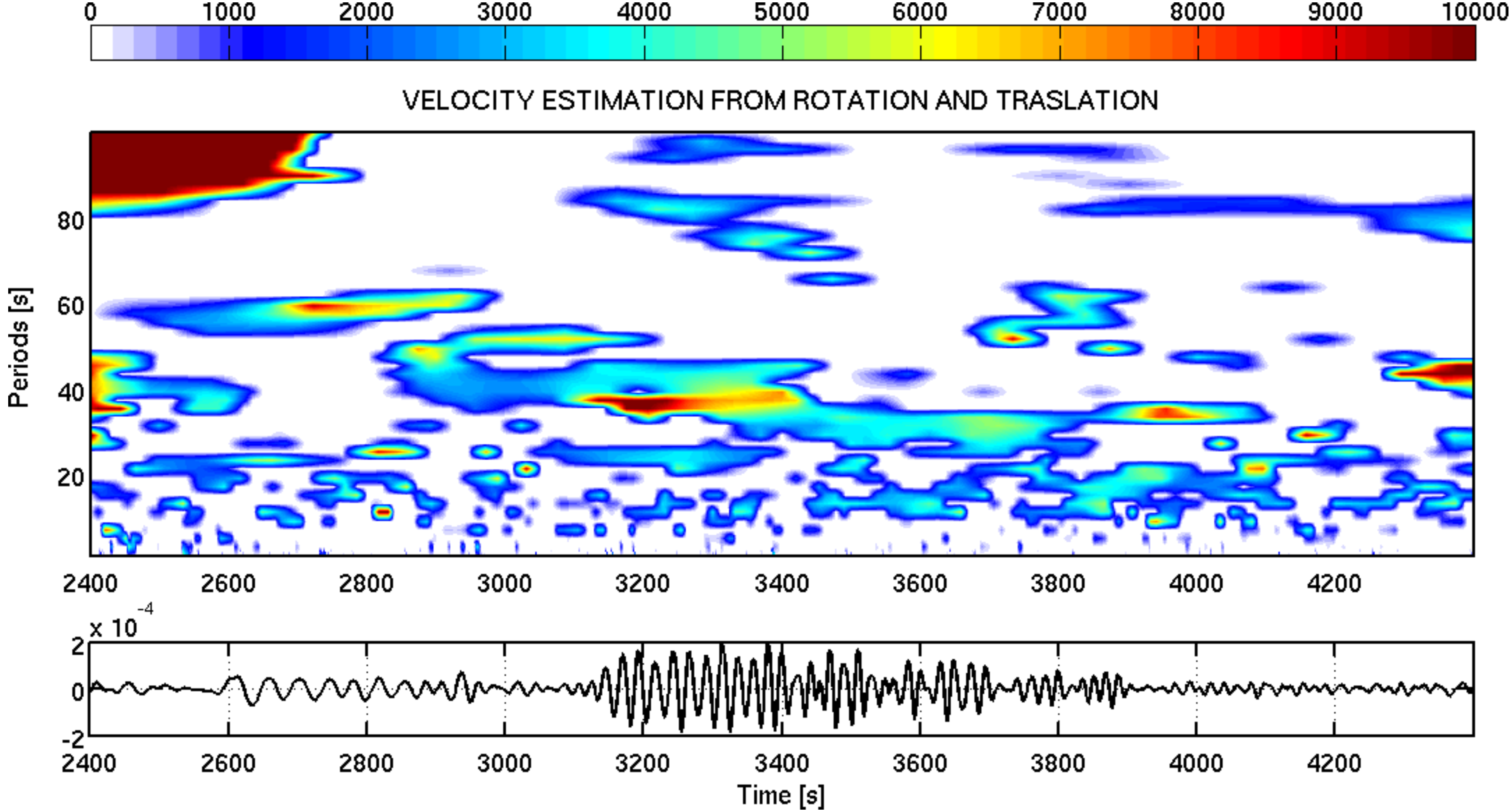


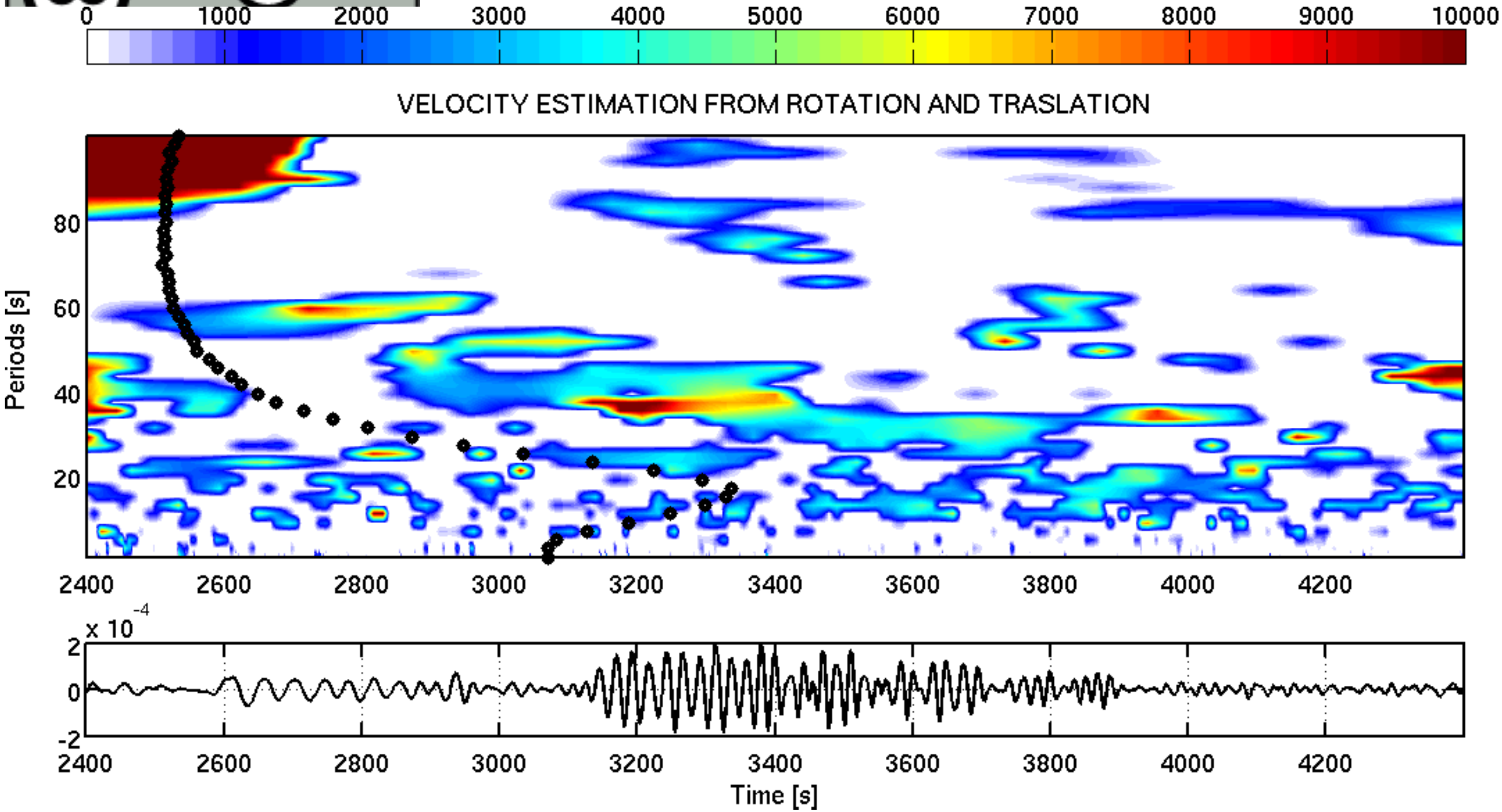
Surface wave velocity estimation from the array



Correlation between the gyro and a collocated linear accelerometer

- We select the time interval (Δ**t**) that includes Rayleigh-waves train (2400-4400 s) of the signal recorded by G-Pisa and of the array-based azimuth estimation
- For every frequency:
  - we correct G-Pisa signal with array-based azimuth estimation in sliding time windows of length twice the dominant period with 50% overlap
  - In the above windows we calculate Zero-lag correlation coefficient (ZLCC) between corrected rotation rate and vertical acceleration of the collocated accelerometer
  - When ZLCC > threshold (0.75), velocity is estimated trough a least squares method


0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
VELOCITY ESTIMATION FROM ROTATION AND TRASLATION
Periods [s]
80
60
40
20
2400
2600
2800
3000
3200
3400
3600
3800
4000
4200
x 10^-4
2
0
-2
Time [s]



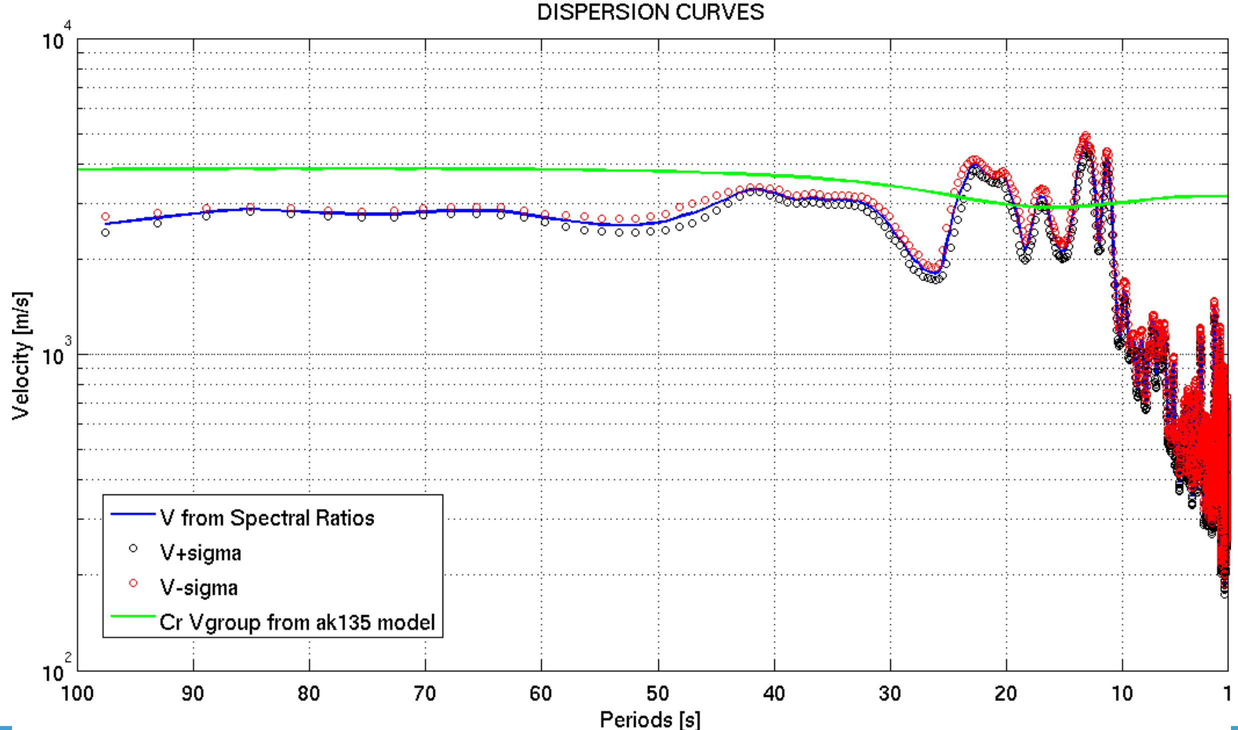
ZLCC is good with some delay with the R-waves expected arrival time.

Probably due to interference with the tail of S-waves

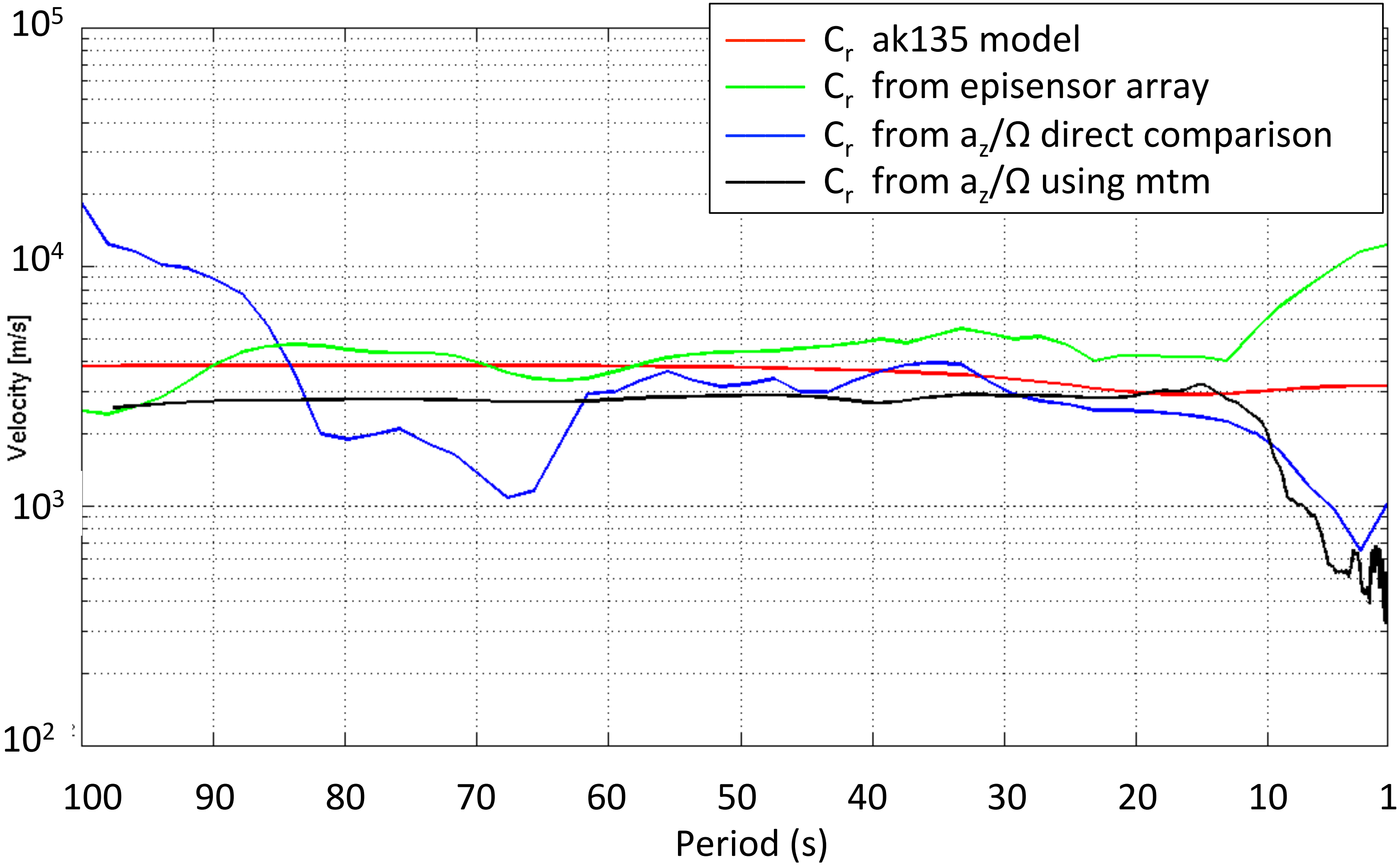
Spectral velocity through multitaper method

$$c_R(\omega) = a_z(\omega)/\Omega_T(\omega)$$

- Correct G-Pisa signal using the theoretical azimuth dependent factor for every frequency
- Calculate $a_z(\omega)$ and $\Omega(\omega)$ with multi-taper method
- Calculate $V_{Rayleigh}$ mediating the values of $a_z(\omega) / \Omega(\omega)$ within frequency windows of length 10 spectral coefficients with 90% overlap.



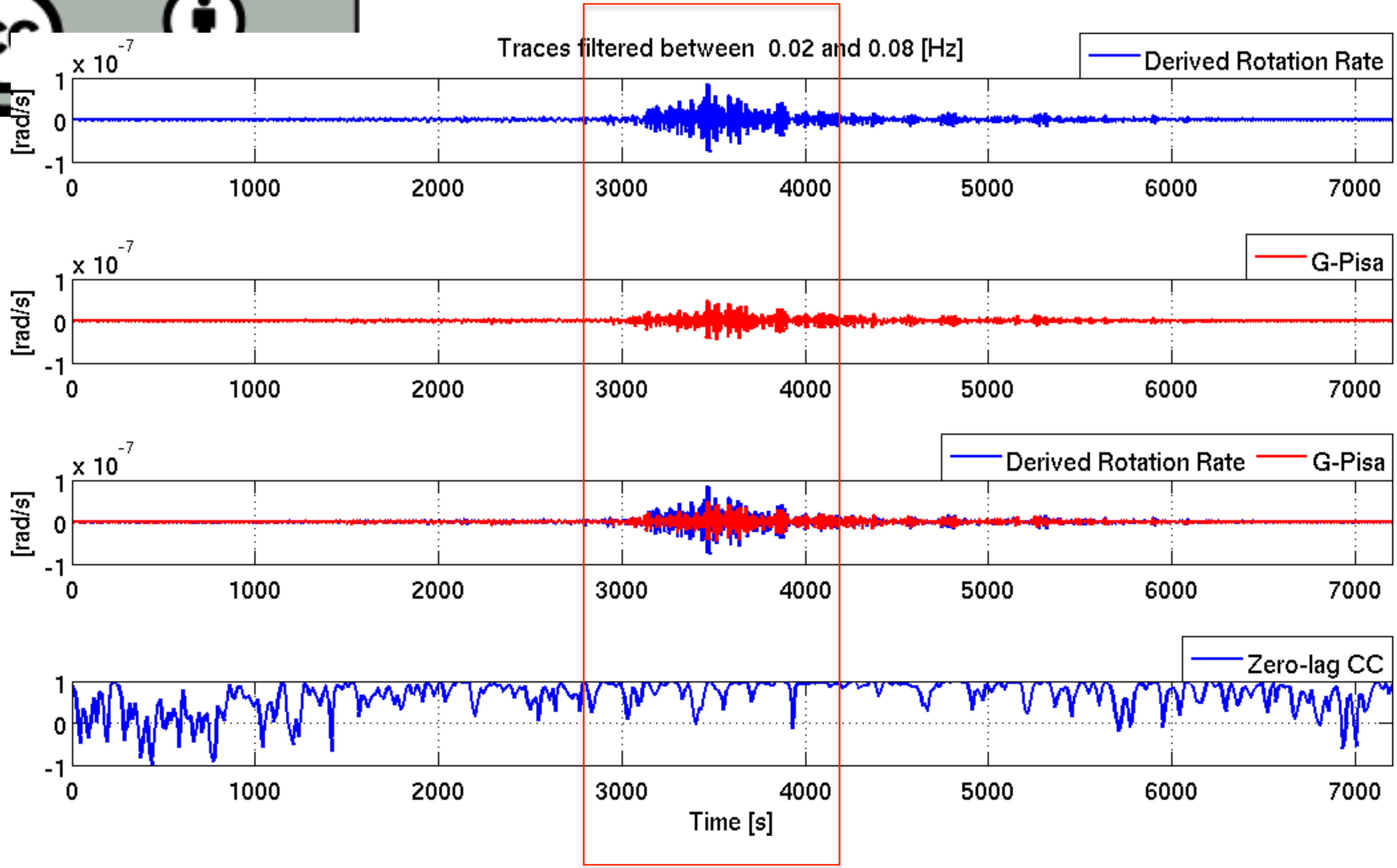
Dispersion curve



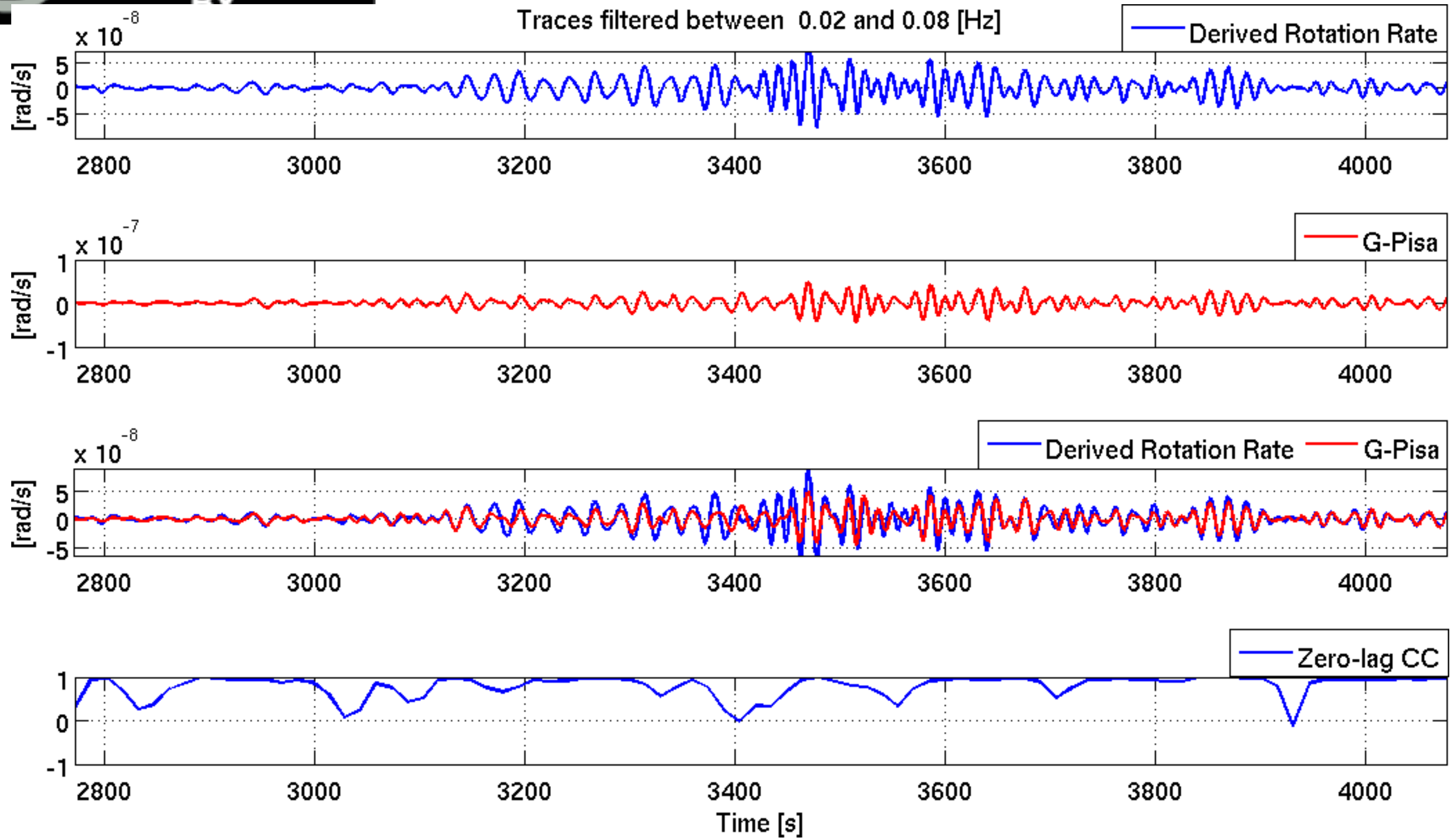
Correlation between the rotational signal of G-Pisa and the rotational signal reconstructed from the Episensor's array

- Using the geodetic method (Spudich et al. 1995), we can calculate the rotation rate from a seismic array.

- We assume free surface boundary condition, plane wave propagation, and spatially uniform displacement gradients



In order to quantify the similarity between array-derived rotation rate and G-Pisa recorded signal, the normalized zero-lag correlation coefficient has been calculated in a sliding time-window of length 30s with 50% overlap.



- A good match is observed especially between 2500-4000 s, where Rayleigh-waves are expected.

Conclusion

- For the first time, the rotational seismic signals induced by an earthquake around an horizontal axis has been quantitatively analysed.
- We observed a remarkable consistency of the rotational signal with the vertical acceleration detected by a collocated accelerometer, with good cross-correlation values.
- These results has been also validated against the rotational signal, calculated from an accelerometer array with 3 km of basis.
- Rayleigh wave velocity dispersion curve has been evaluated and compared both from gyroscope and from the array

- Good consistency has been found in 60 s – 10 s band
- Large discrepancy is present at the high frequencies (periods 10 s – 1 s), which can be explained by the local geology and the loss of signal coherency between array elements
- No reliable comparison is possible at very low frequencies due to the limits of the available seismic instrumentation

- A quite large number of local and regional seism has been also detected during the working period of the gyro in VIRGO site, and their analysis could improve our elaborations, in particular at the high frequencies
- The gyro is presently again operative in a new localization, and high-quality long-period seismometer will be collocated