Direct and array-derived rotations in the Gran Sasso underground laboratory: application to earthquakes and seismic noise

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Introduction: Motivations

- Local wavefield features: arrays or 6C-4C?

- Logistics
  - urban areas
  - mines
  - boreholes

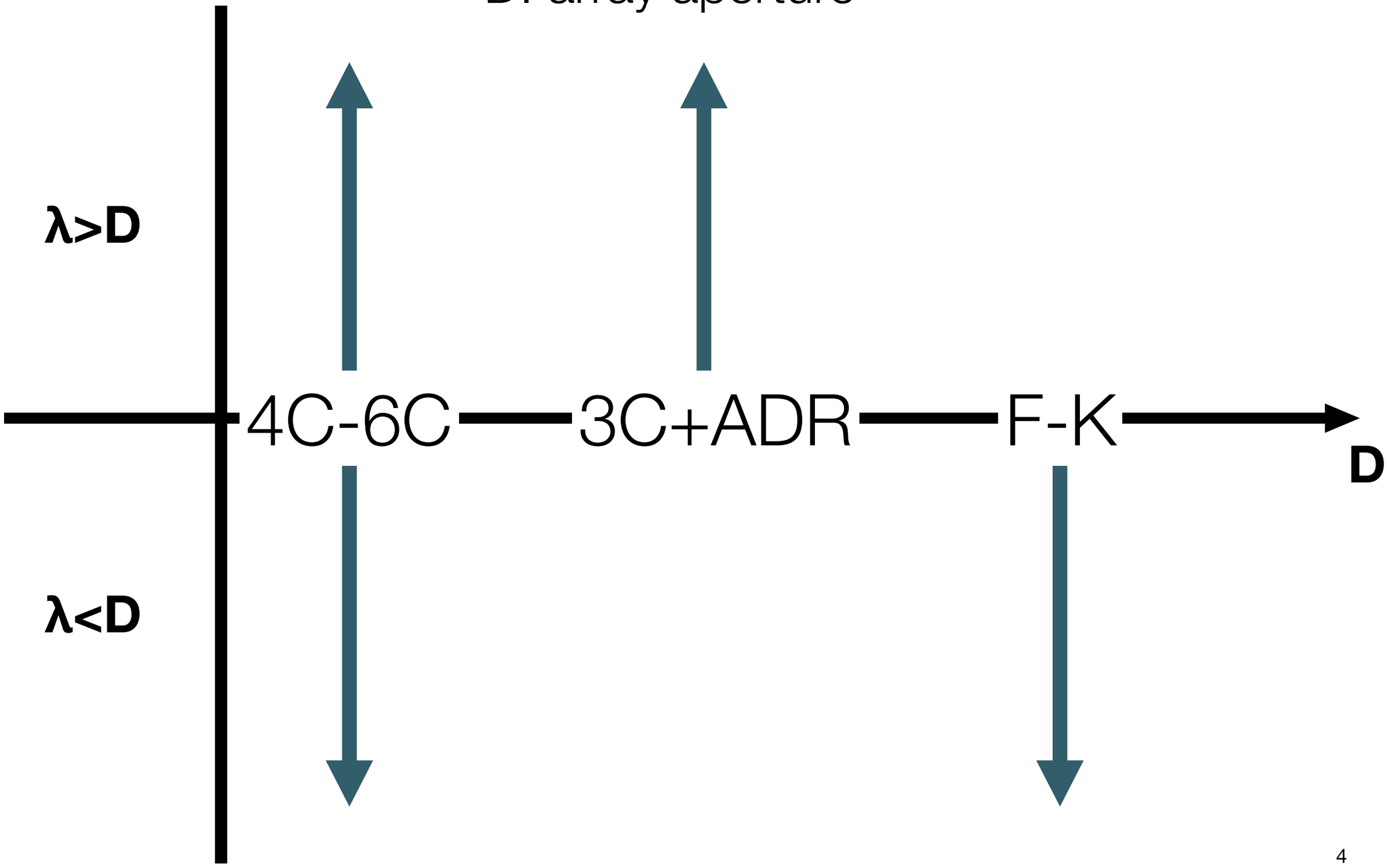
  Limited access

  - ocean bottom
  - other planets

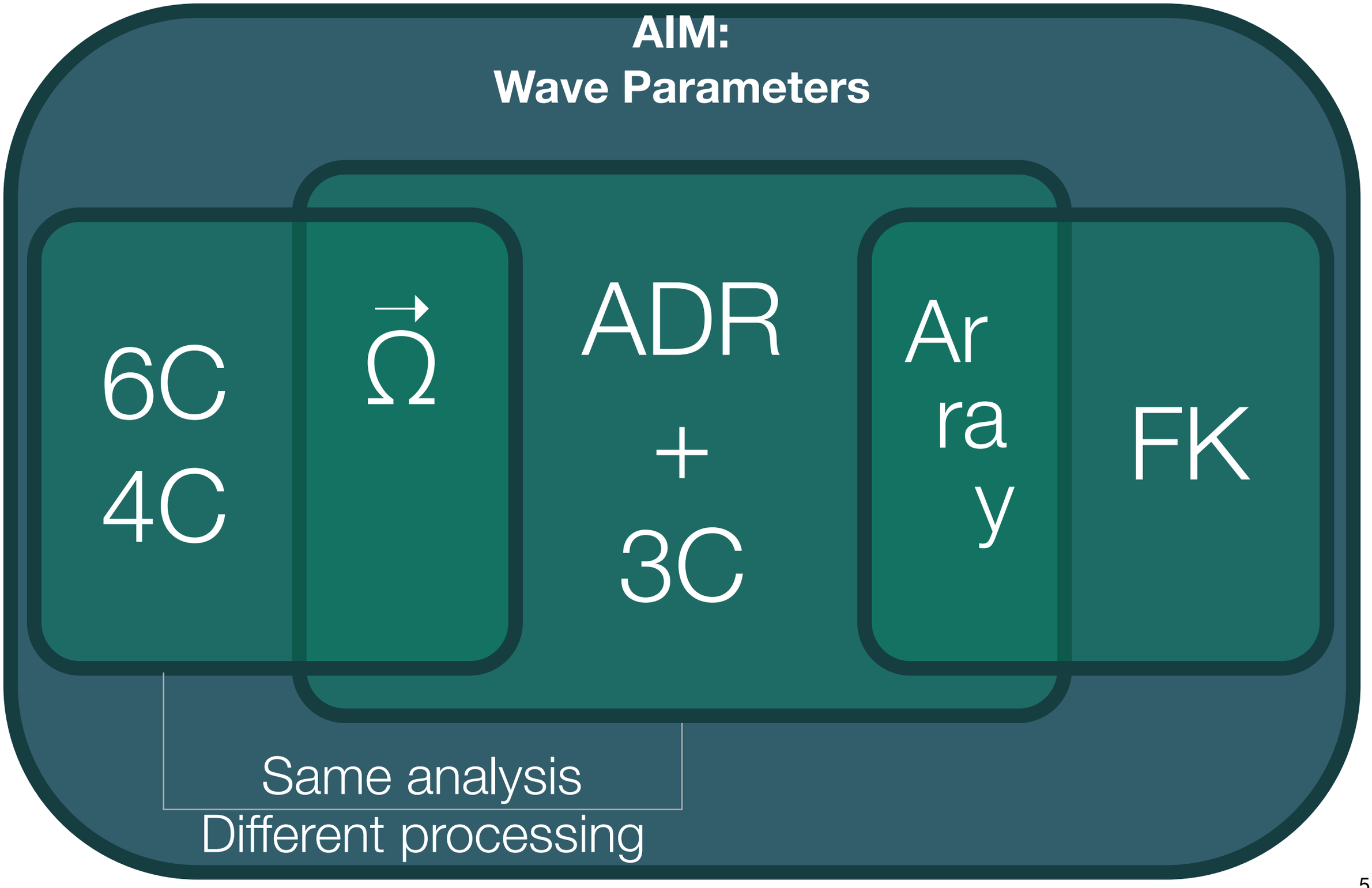
  too few instruments

- Information
  - 6C:
    - complete mode selectivity (Rayleigh, Love, P, SH, SV)
    - all of wave parameters (3D direction + V_p, V_s)
  - 4C:
    - SH separation from P, SV
    - BAZ and phase velocity

Introduction



Introduction

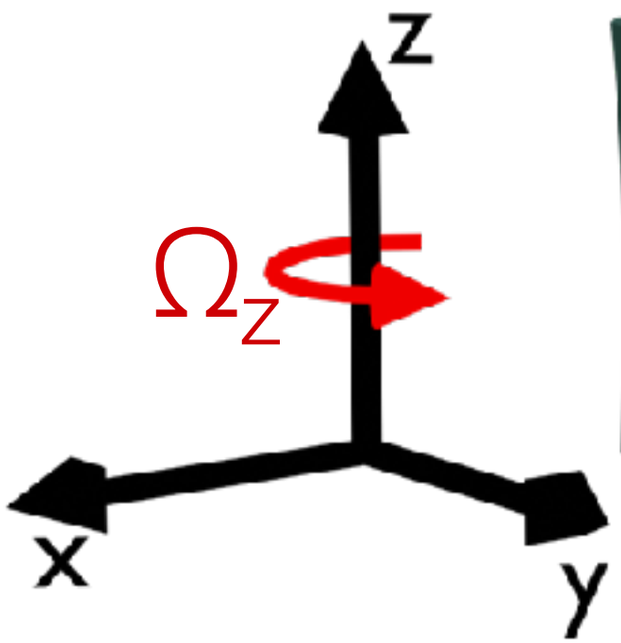


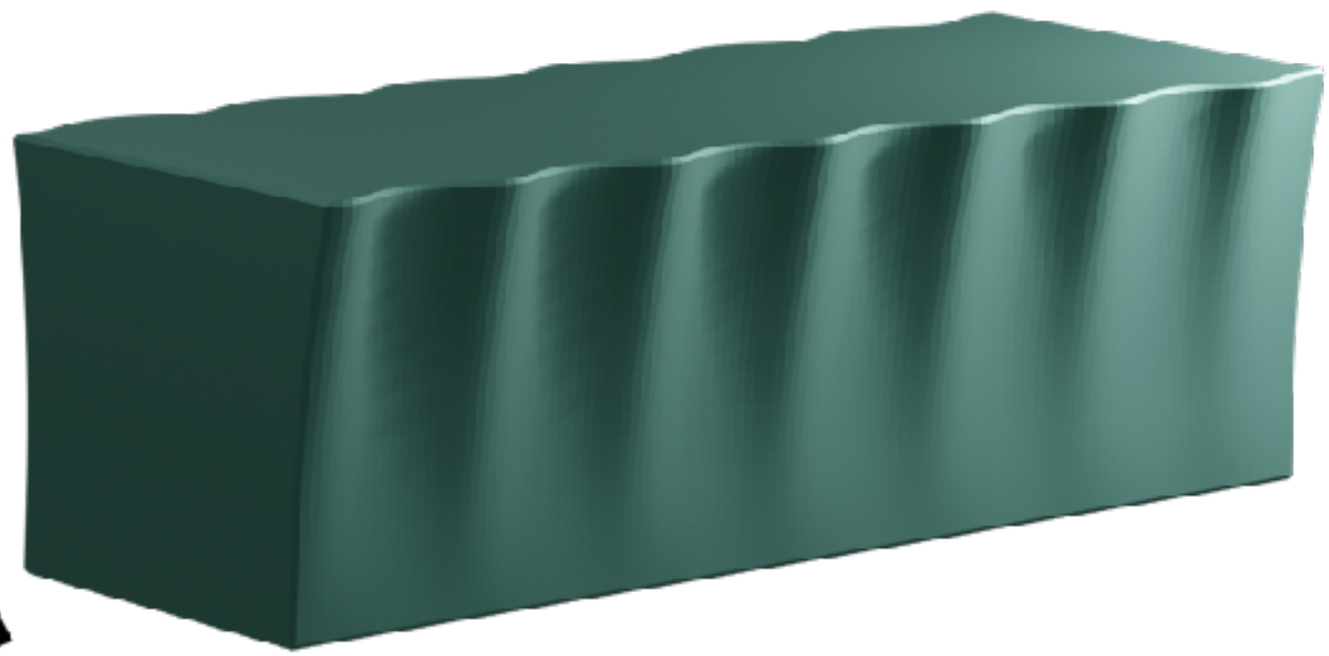
Physical Principles

$$\vec{\Omega} = \frac{1}{2}\nabla \times \vec{v}(\vec{r}) \qquad \text{e.g. } \Omega_z = \frac{1}{2}\left[\frac{\partial v_y}{\partial x} - \frac{\partial v_x}{\partial y}\right]$$

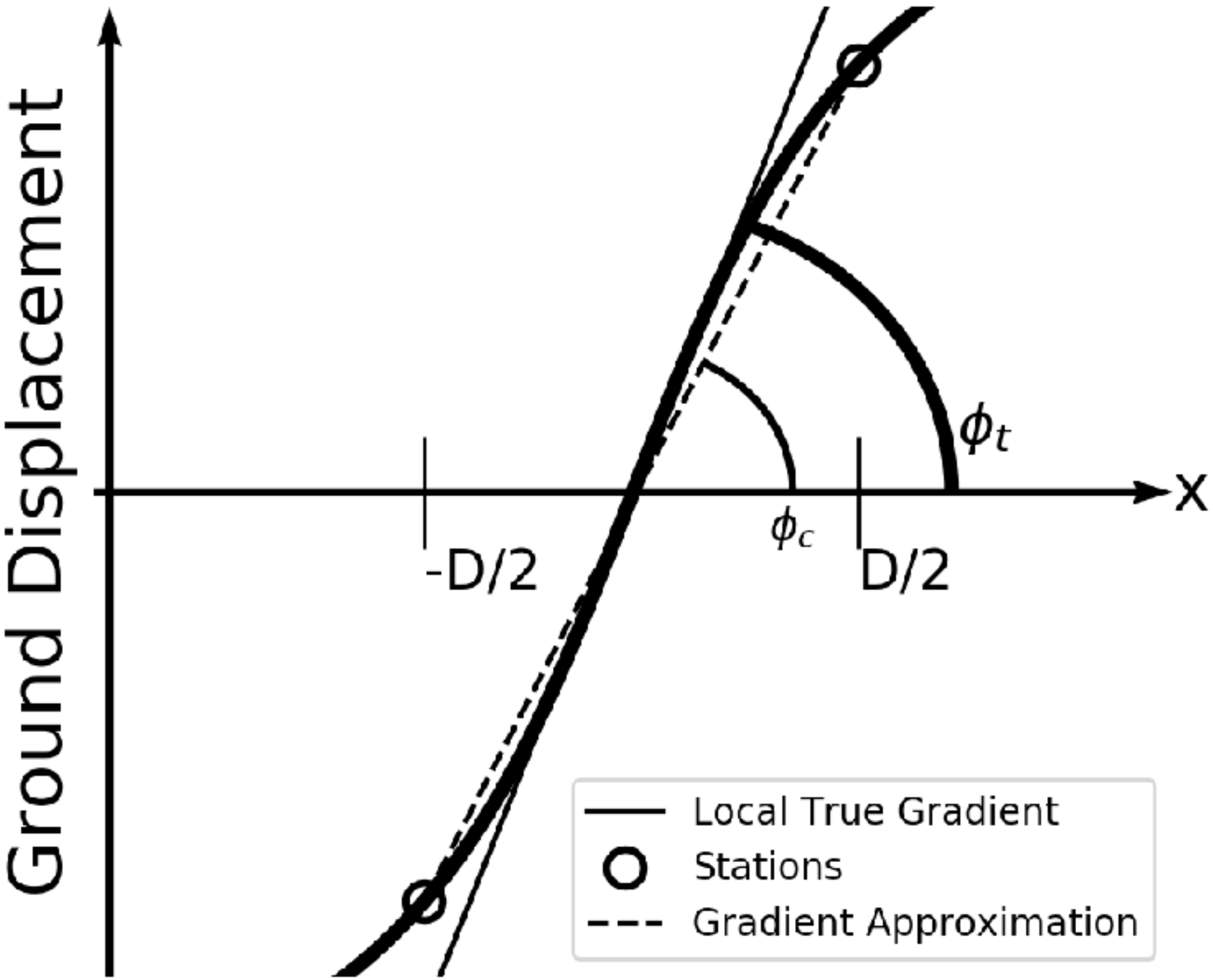
Love wave as a plane wave traveling at z = 0

$$v_T \sim Ae^{i\omega[x/c_L - t]} \longrightarrow \Omega_z = -\frac{1}{2c_L} a_T$$





Techniques: ADR



$$\frac{\partial v_i}{\partial x_j}$$

$$\frac{\Delta v_i}{\Delta x_j}$$

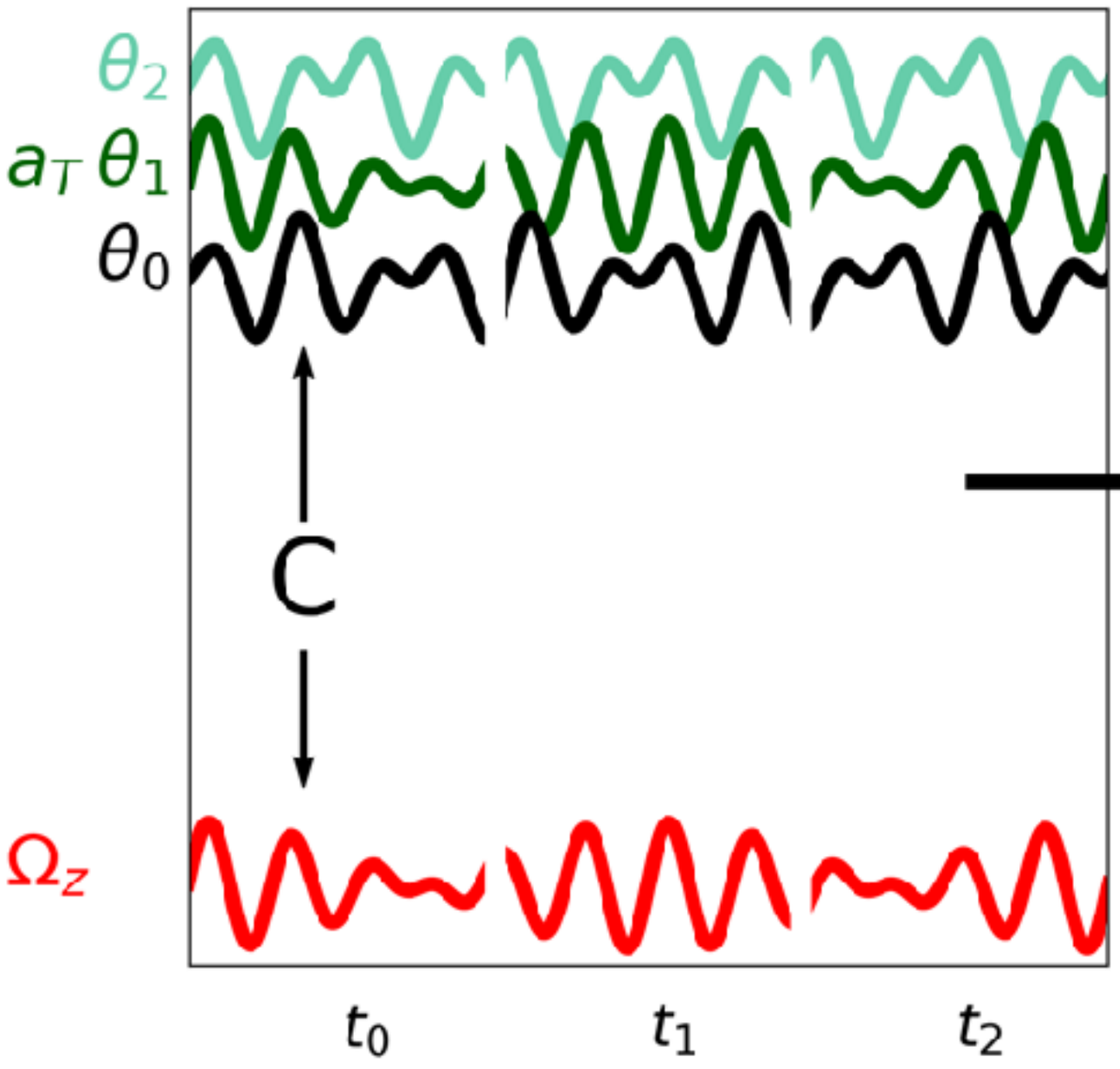
$(D < \lambda/4)$

$$\Omega_Z$$

Techniques: Zero Lag Correlation

$$\Omega_z = -\frac{1}{2c_L} a_T$$

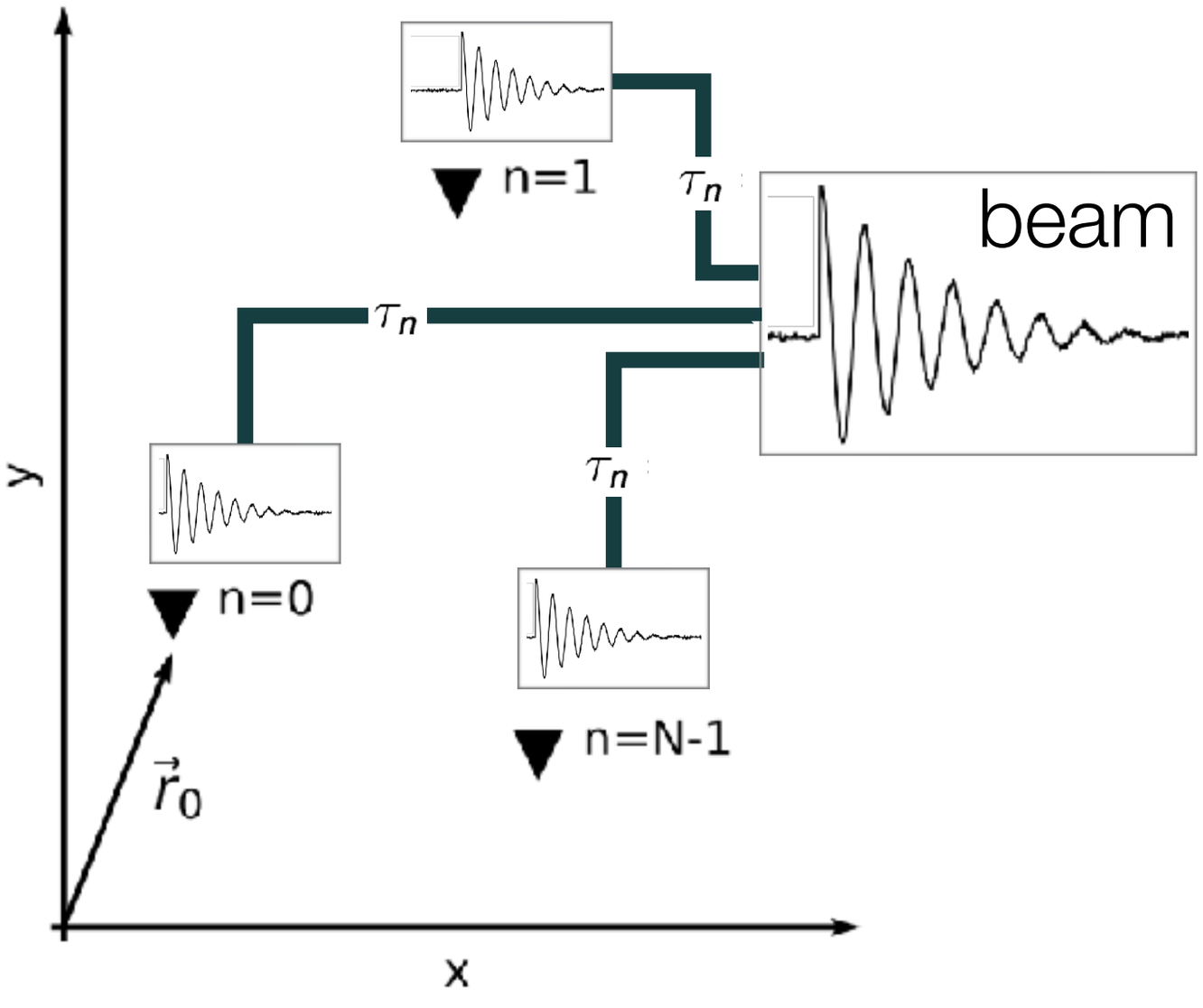
- Subdivision in time-slices
- Grid-search for θ ∈ [0, 2π)



Techniques: F-K

- Horizontal array, plane wave, select reference frame
- Area homogeneity: no scattering

→ **Delay and sum:** $\tau_n = \vec{s} \cdot \vec{r}_n$ (s: slowness)

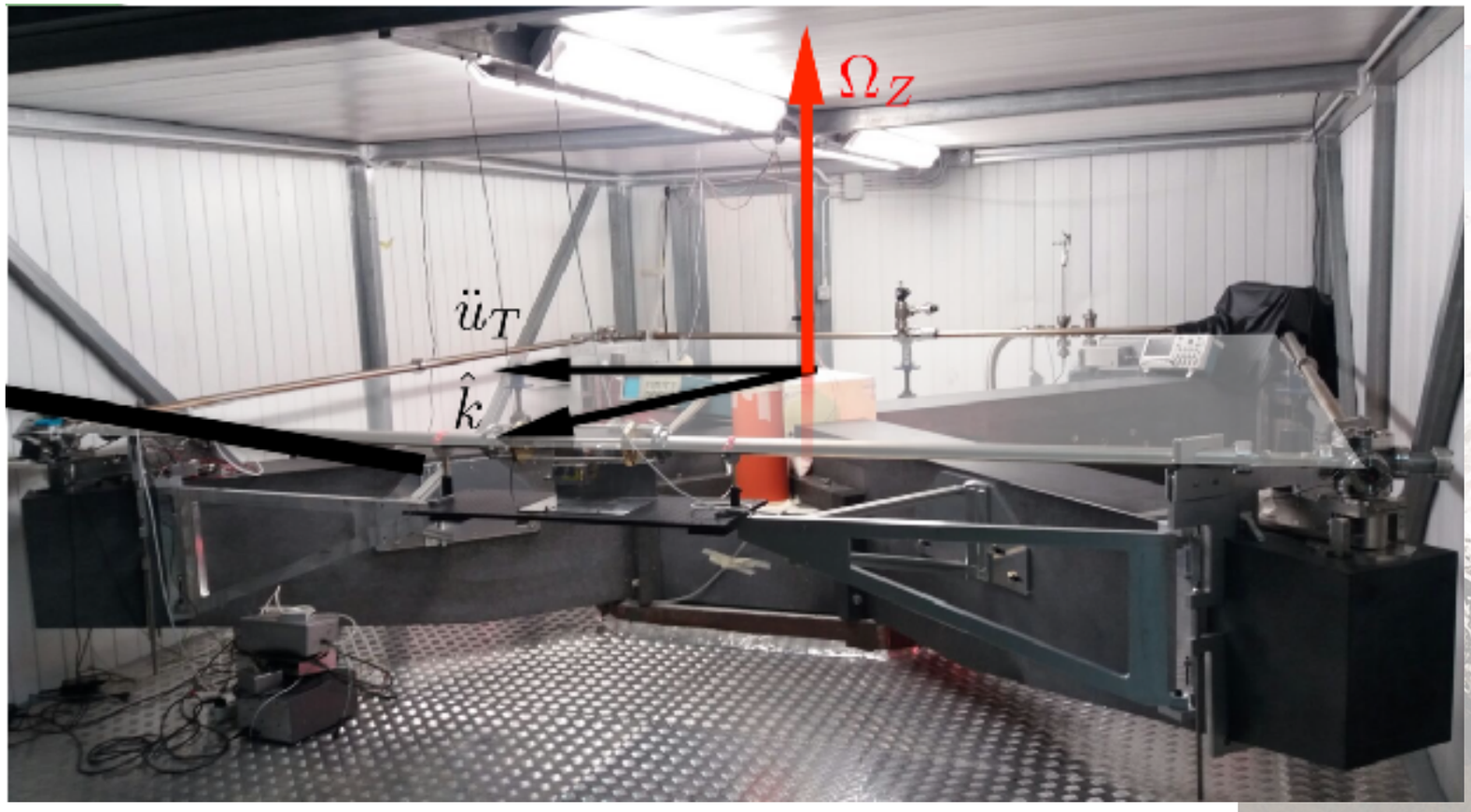


- $\vec{s}$ unknown
- grid search
- maximise beam power

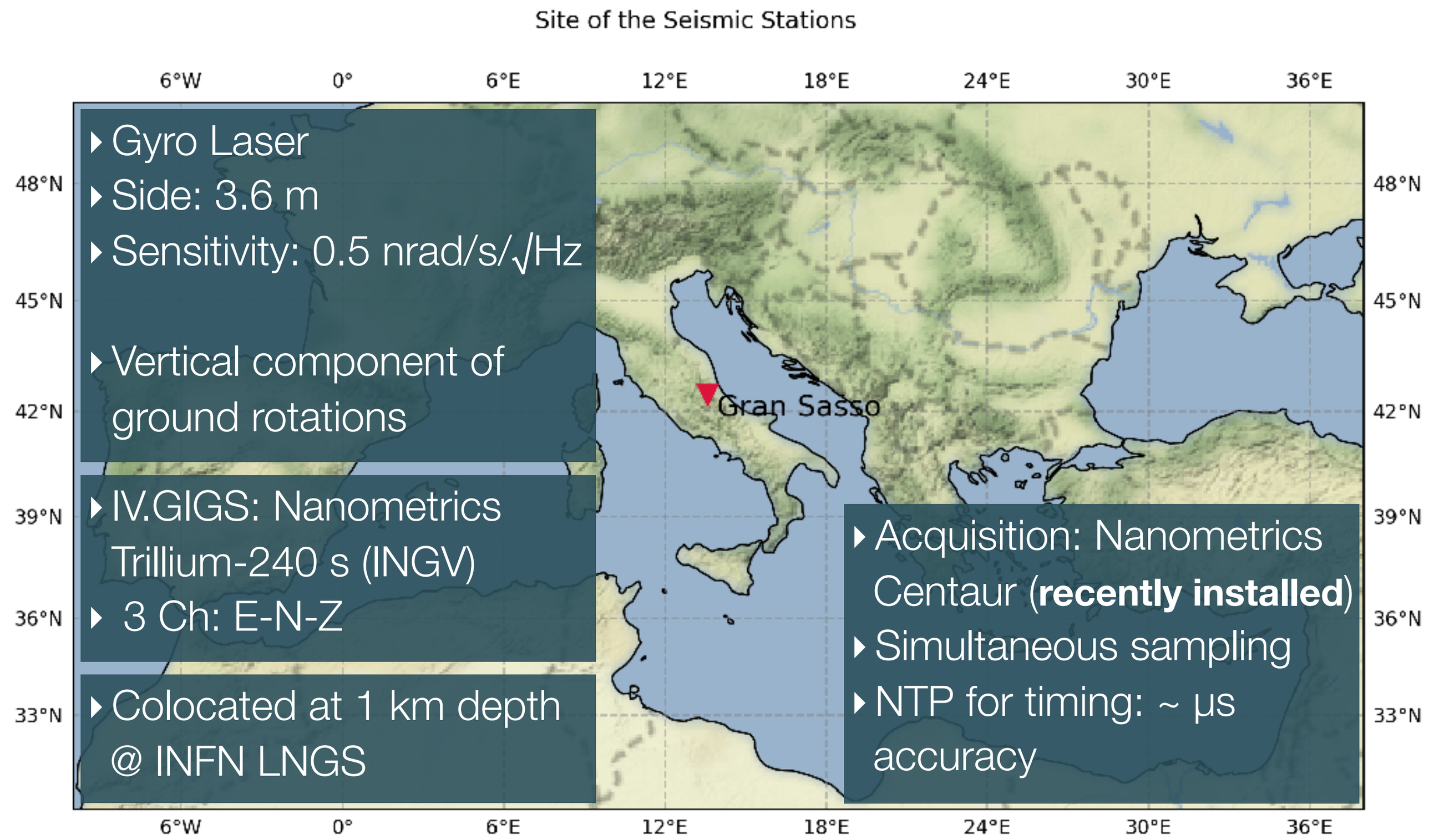
d: spatial sampling

- Nyquist: $2d < \lambda$
- Resolution: $\lambda < D$

Observations: 4C analysis



Experimental Setup:



- Gyro Laser
- Side: 3.6 m
- Sensitivity: 0.5 nrad/s/√Hz

- Vertical component of ground rotations

- IV.GIGS: Nanometrics Trillium-240 s (INGV)
- 3 Ch: E-N-Z

- Colocated at 1 km depth @ INFN LNGS

- Acquisition: Nanometrics Centaur (**recently installed**)
- Simultaneous sampling
- NTP for timing: ~ μs accuracy

Observations: Earthquake Data Analysis

List of analysed events

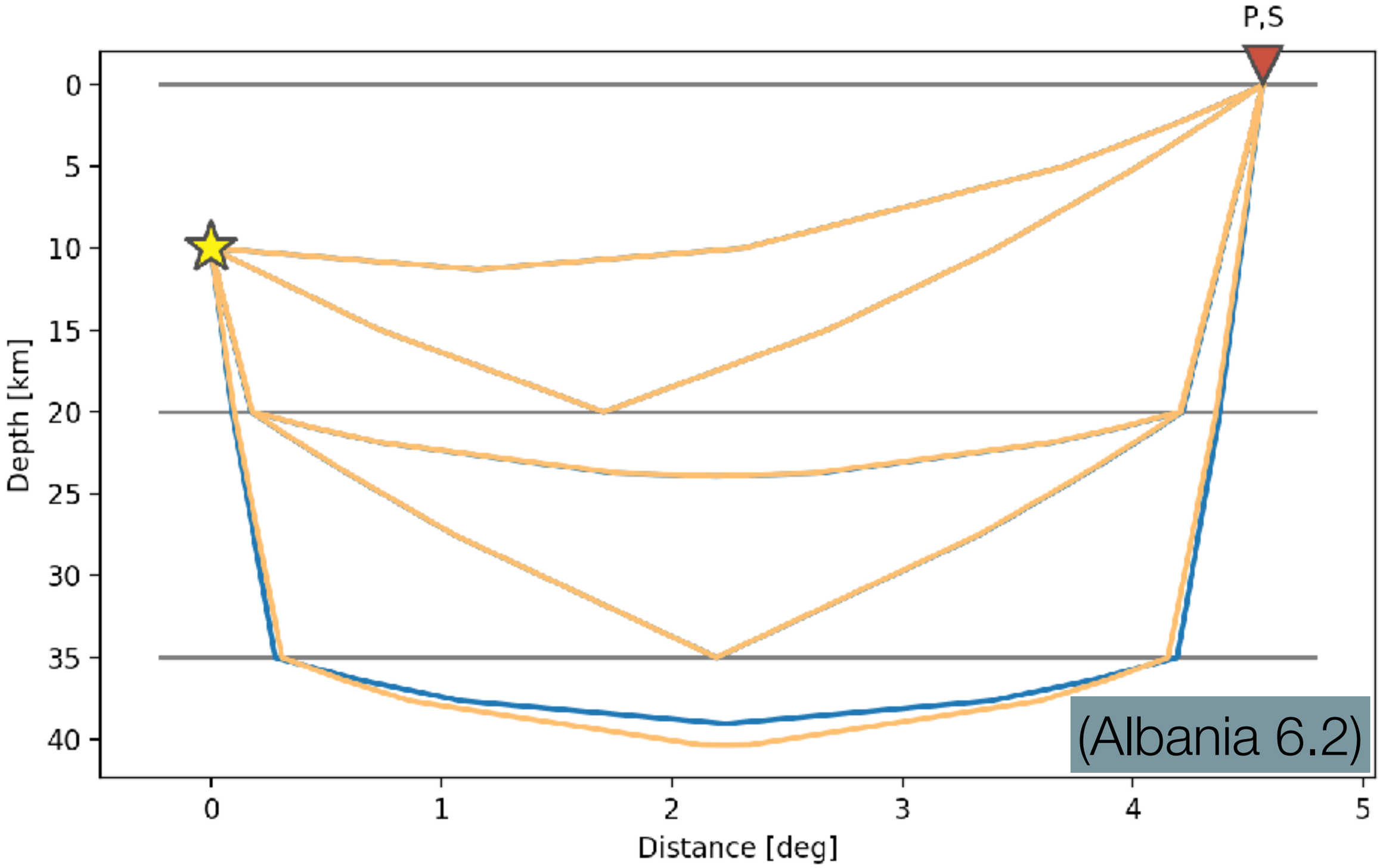
- Albania 6.2
- Albania 5.4
- Bosnia and Herzegovina 5.4
- Creta 6.0
- Mugello 4.5

As recent as early December

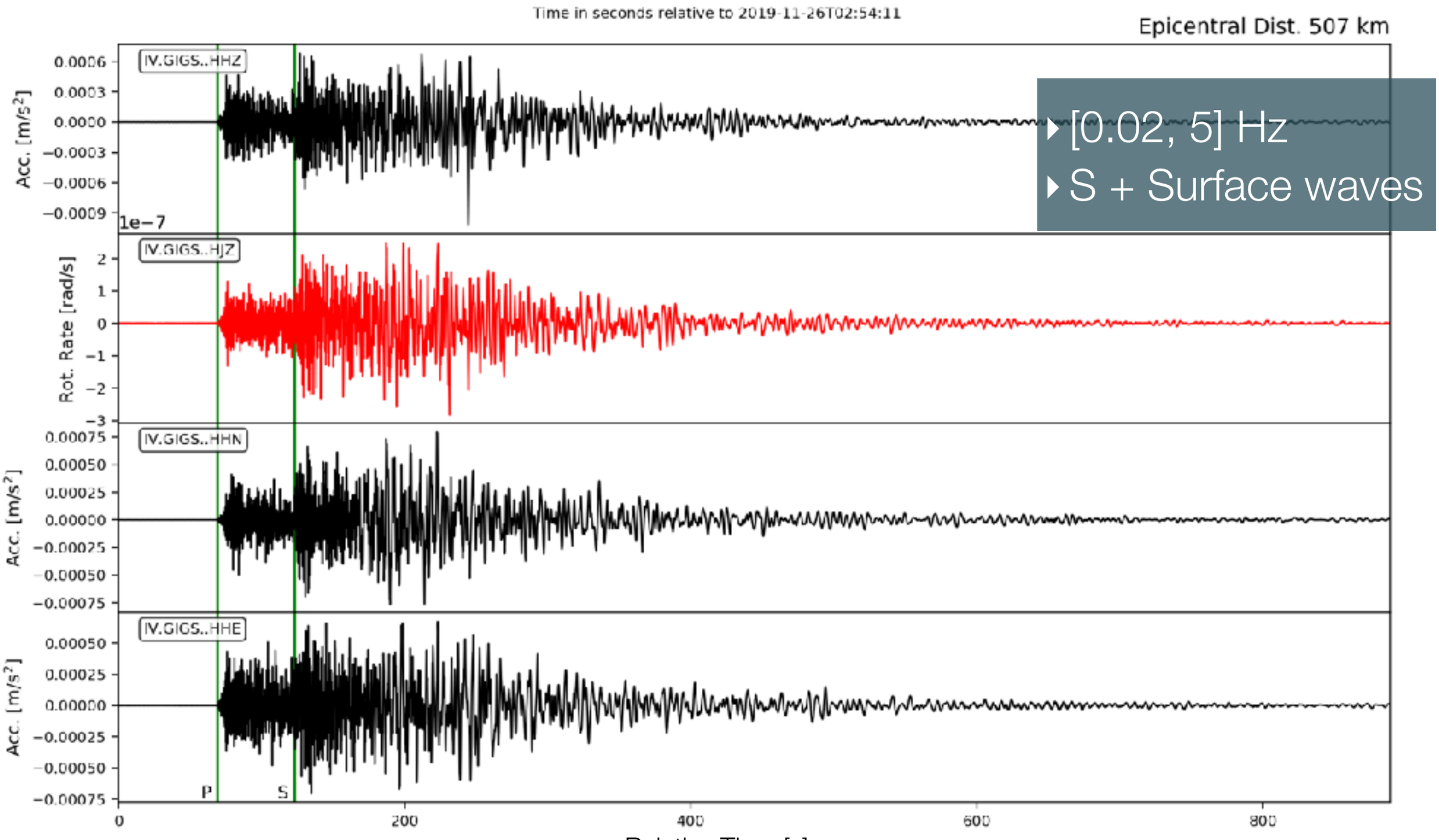
Approximation: measure @ surface
(Reasonable: depth < λ)

Observations: Earthquake Data Analysis

Obspy taup package: picking of P, S first arrivals

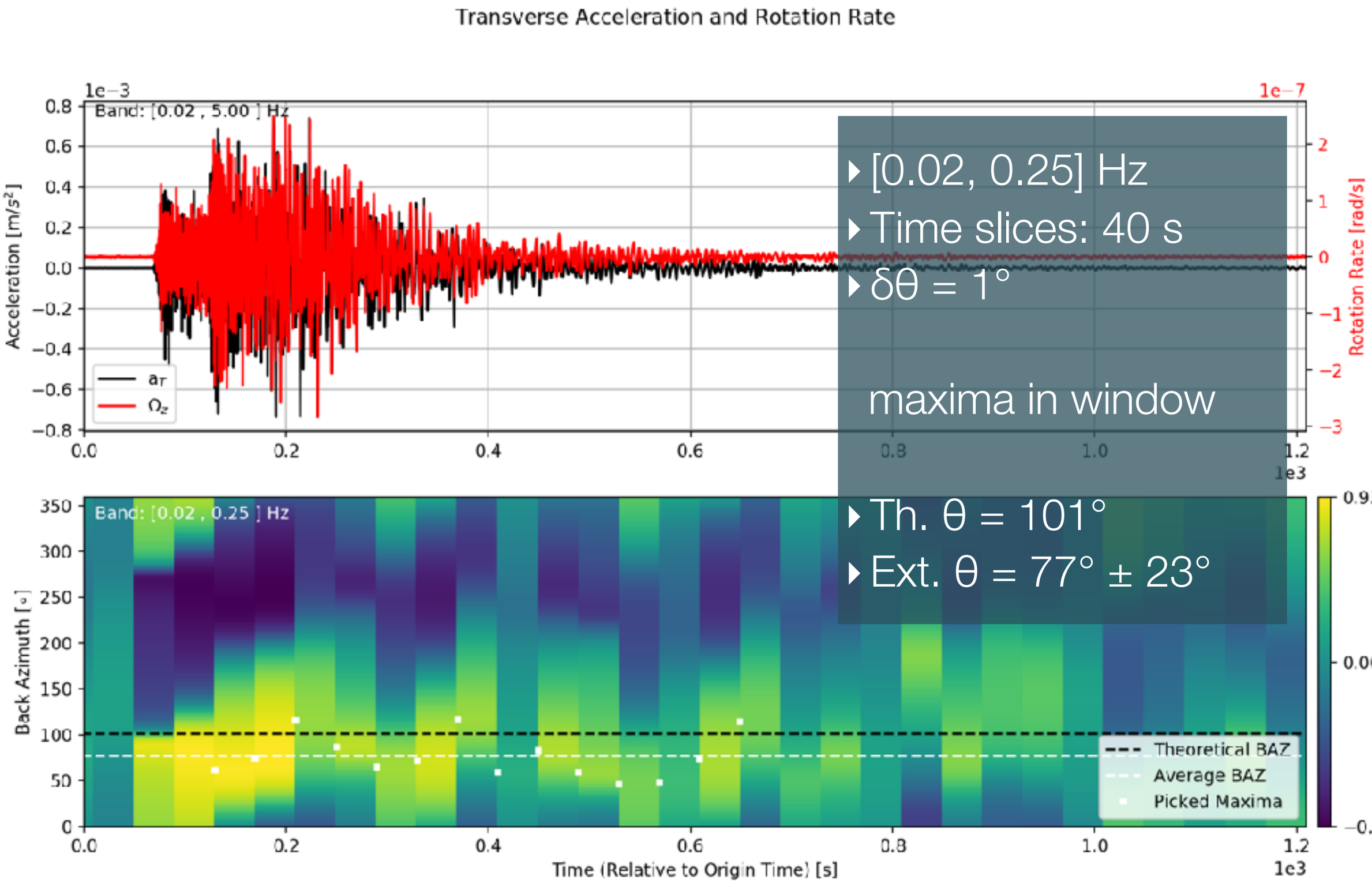


Northern coast of Albania, Mw 6.2



- [0.02, 5] Hz
- S + Surface waves

Northern coast of Albania, Mw 6.2

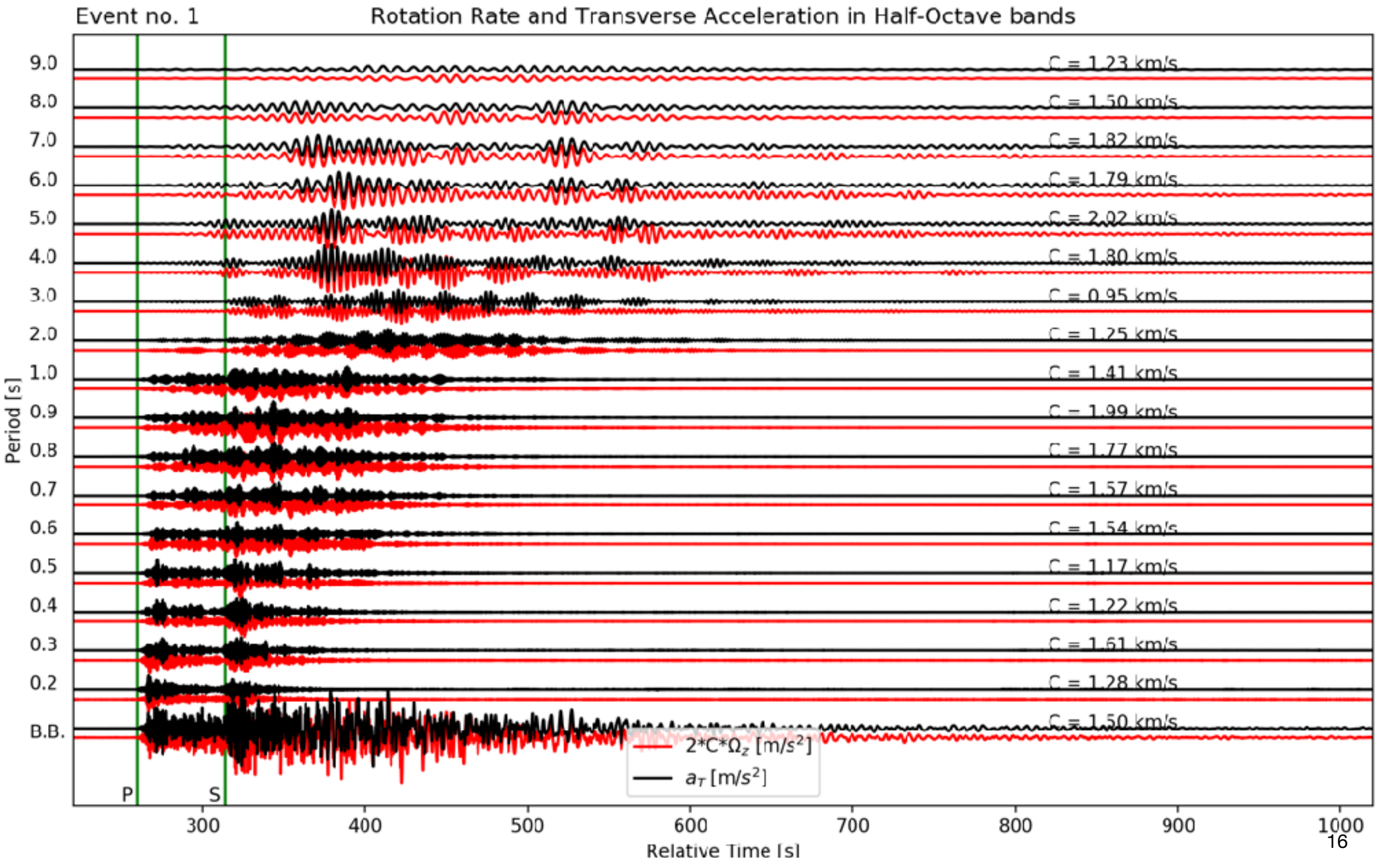


- [0.02, 0.25] Hz
- Time slices: 40 s
- $\delta\theta = 1°$

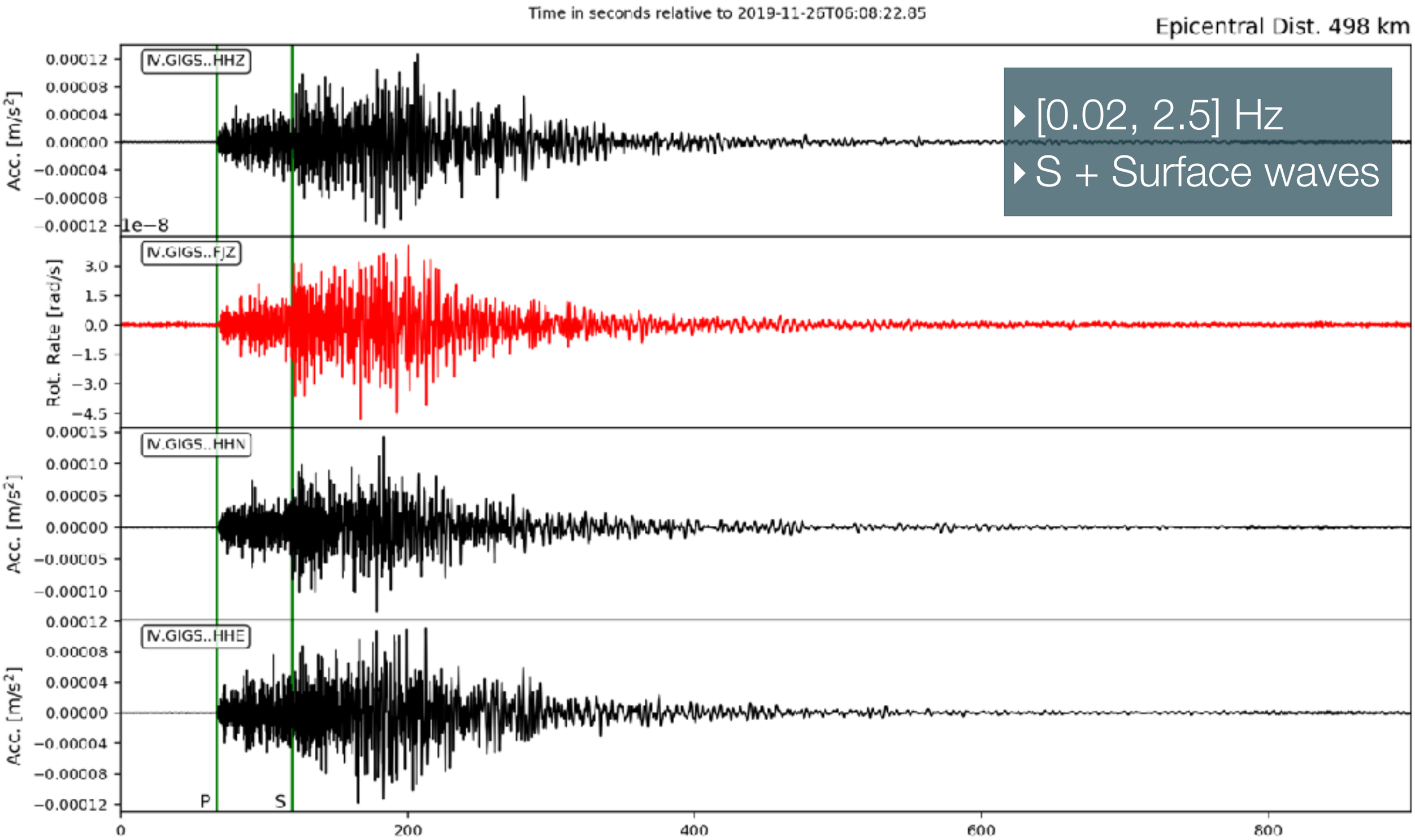
maxima in window

- Th. $\theta = 101°$
- Ext. $\theta = 77° \pm 23°$

Northern coast of Albania, Mw 6.2

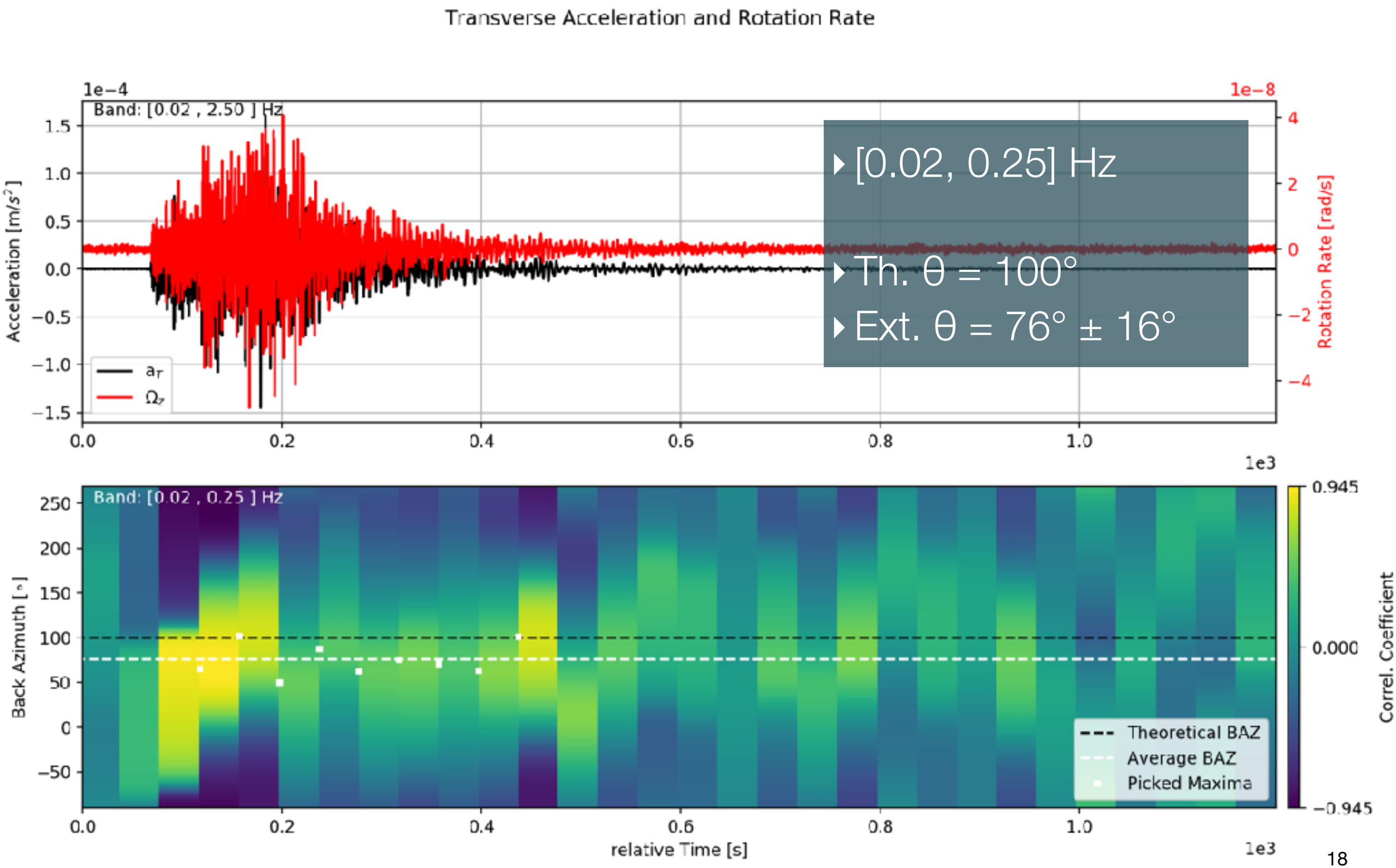


Northern coast of Albania, ML 5.4



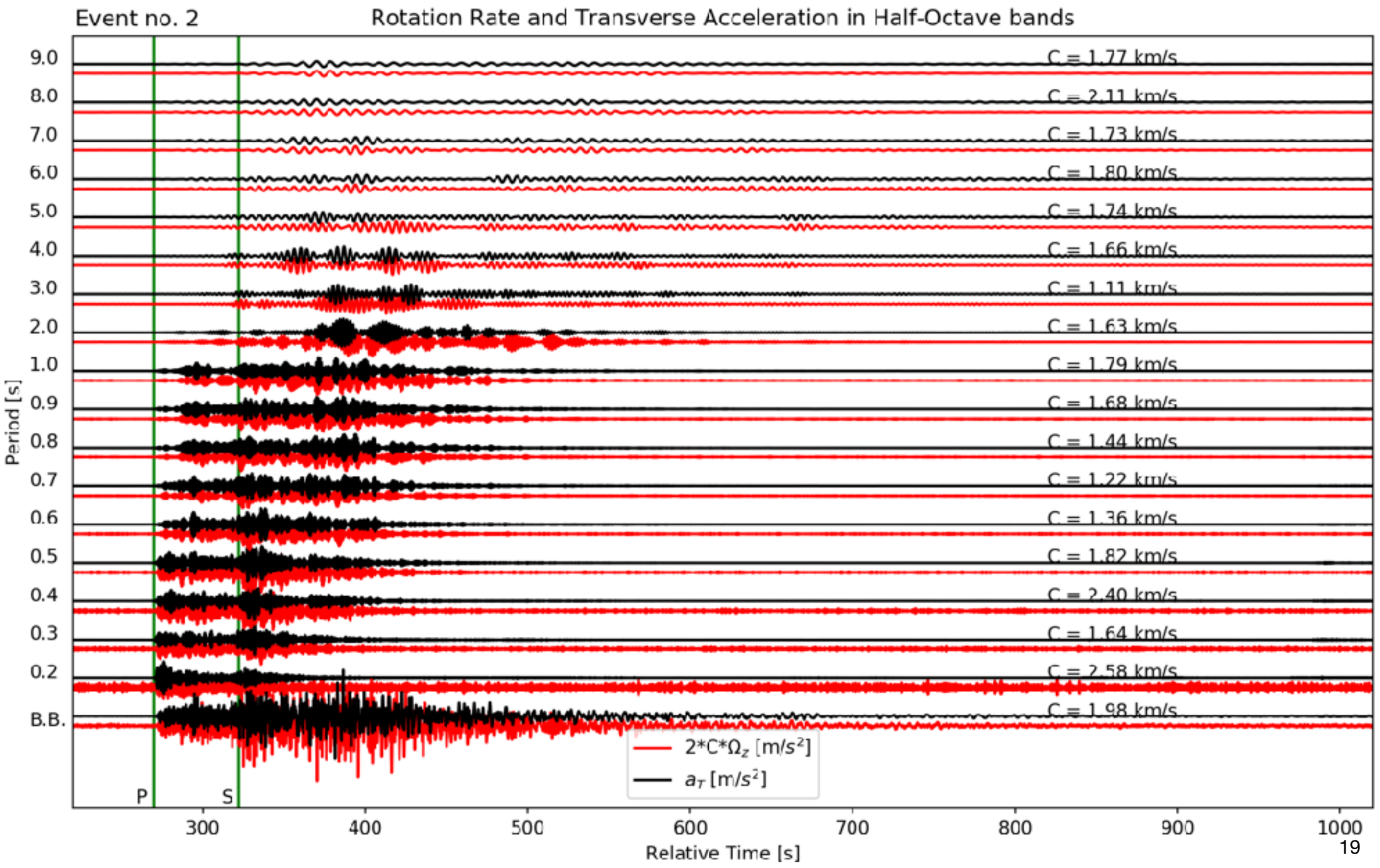
- [0.02, 2.5] Hz
- S + Surface waves

Northern coast of Albania, ML 5.4

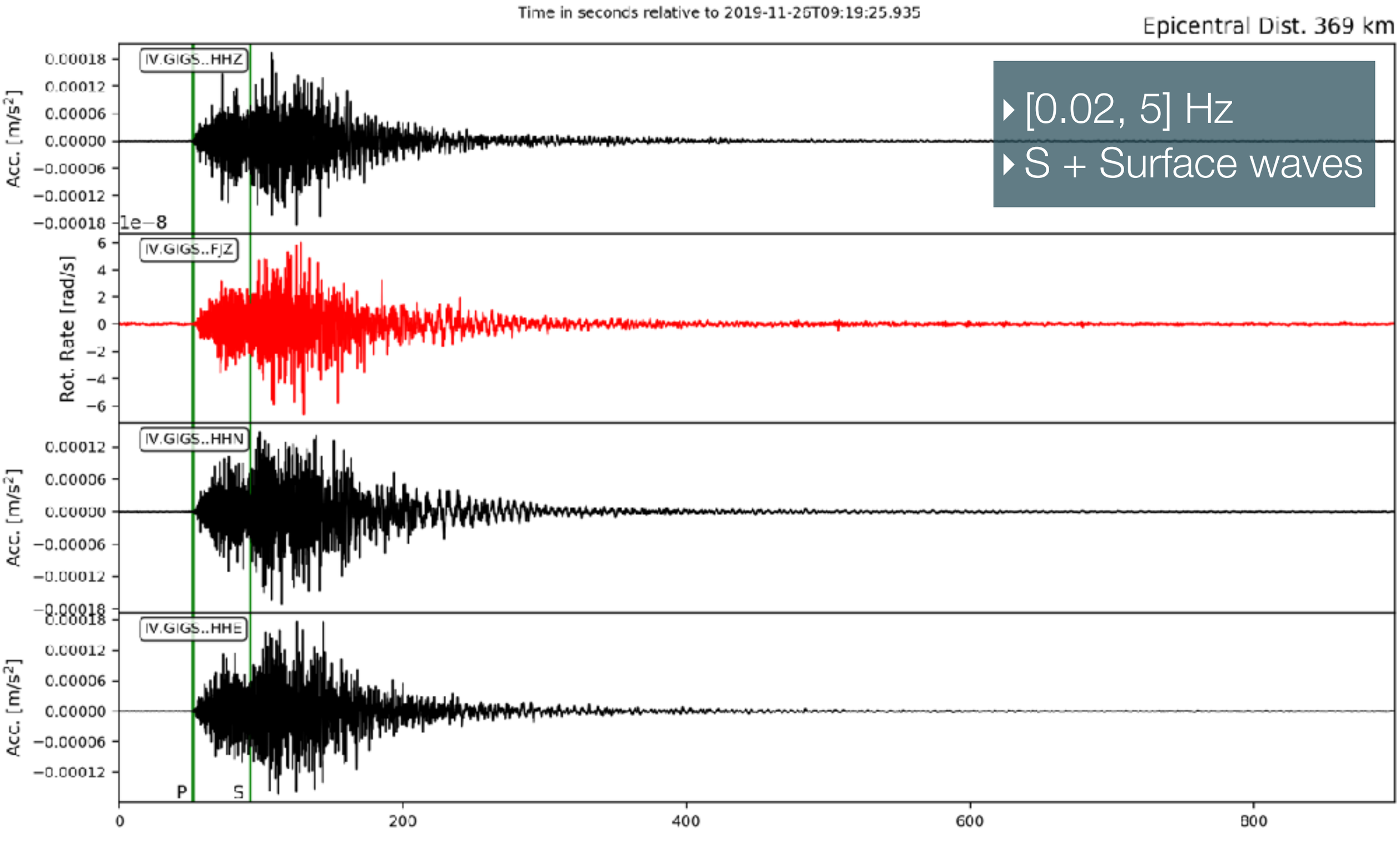


- [0.02, 0.25] Hz
- Th. θ = 100°
- Ext. θ = 76° ± 16°

Northern coast of Albania, ML 5.4

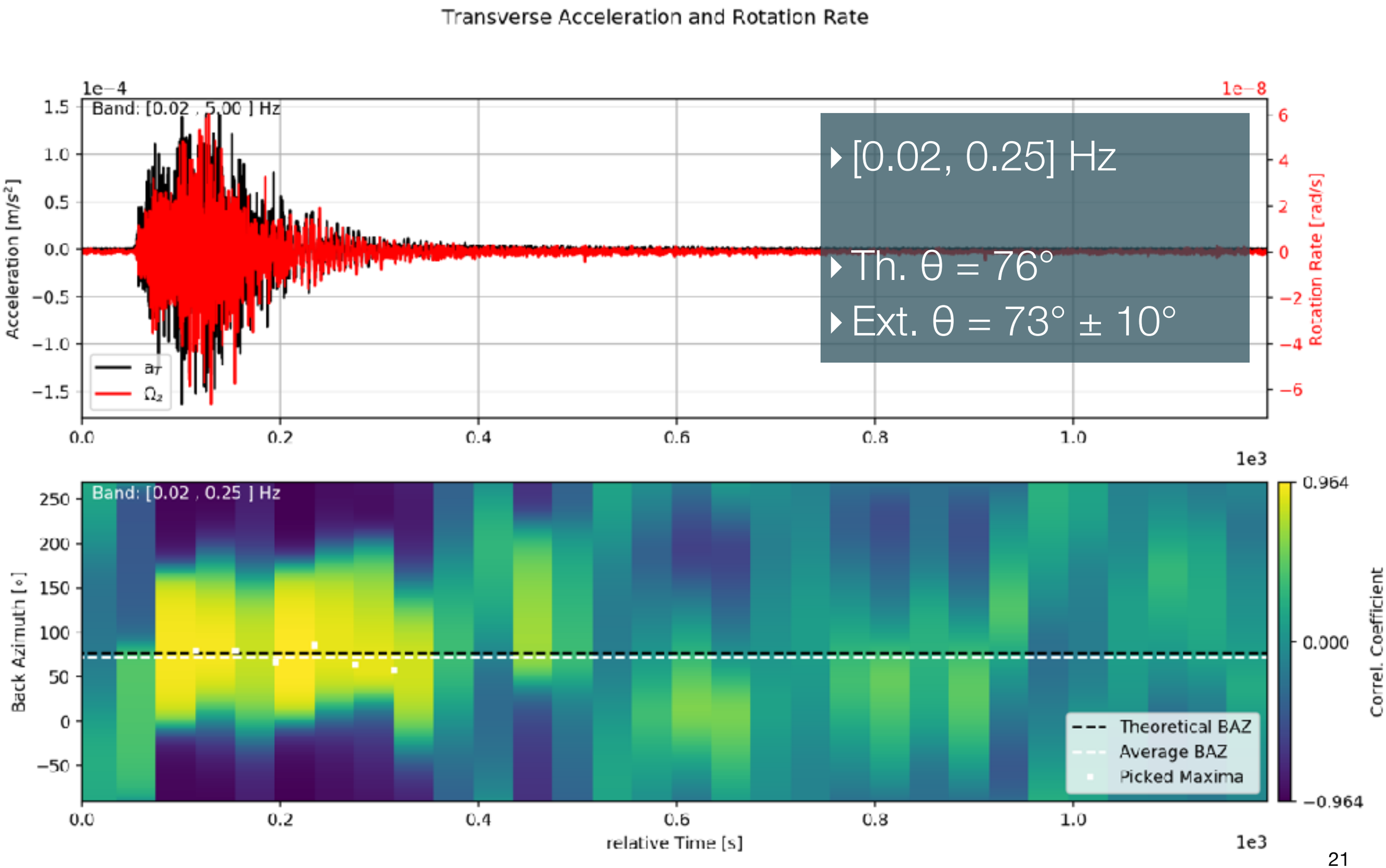


Bosnia and Herzegovina, mb 5.4



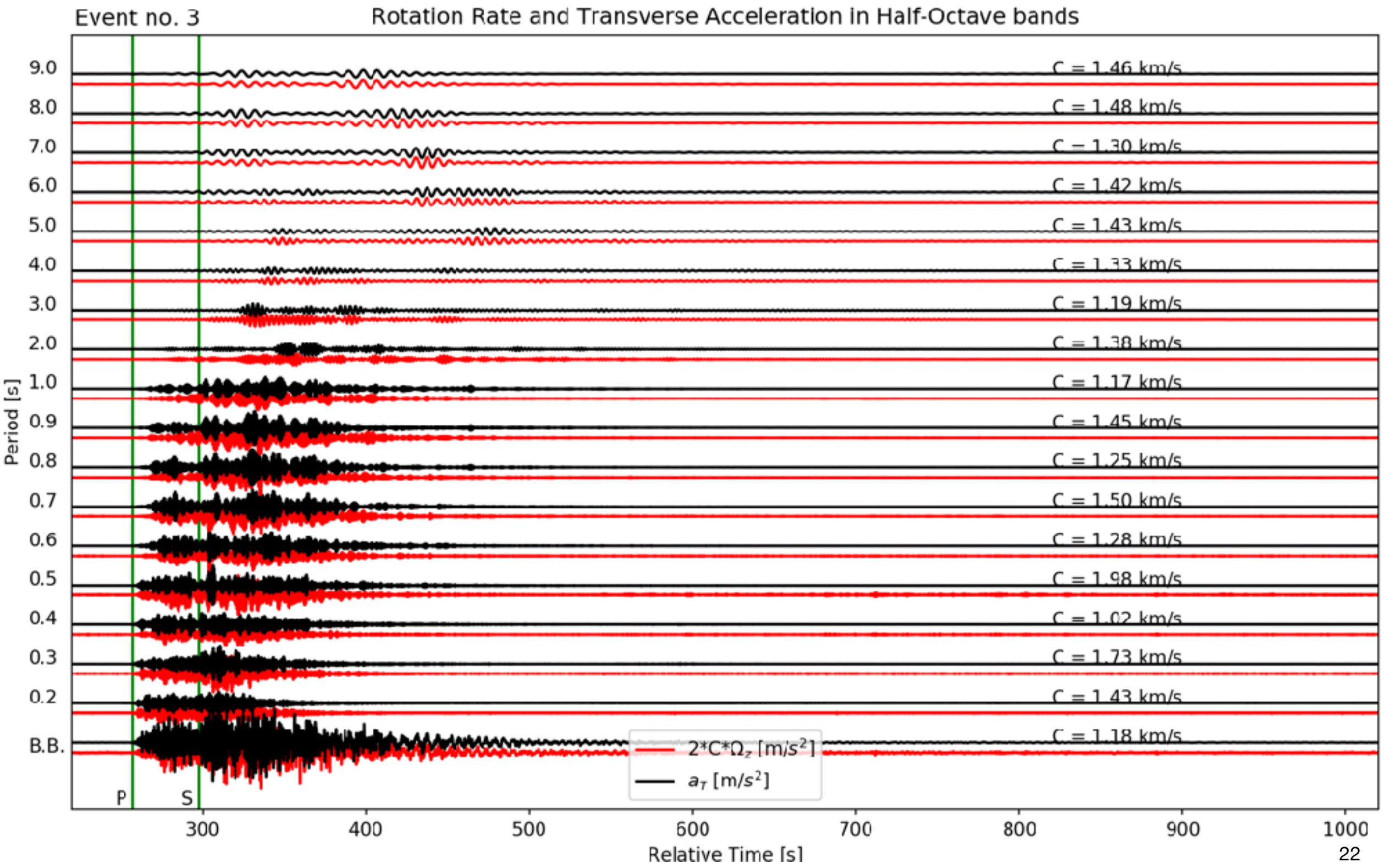
- [0.02, 5] Hz
- S + Surface waves

Bosnia and Herzegovina, mb 5.4

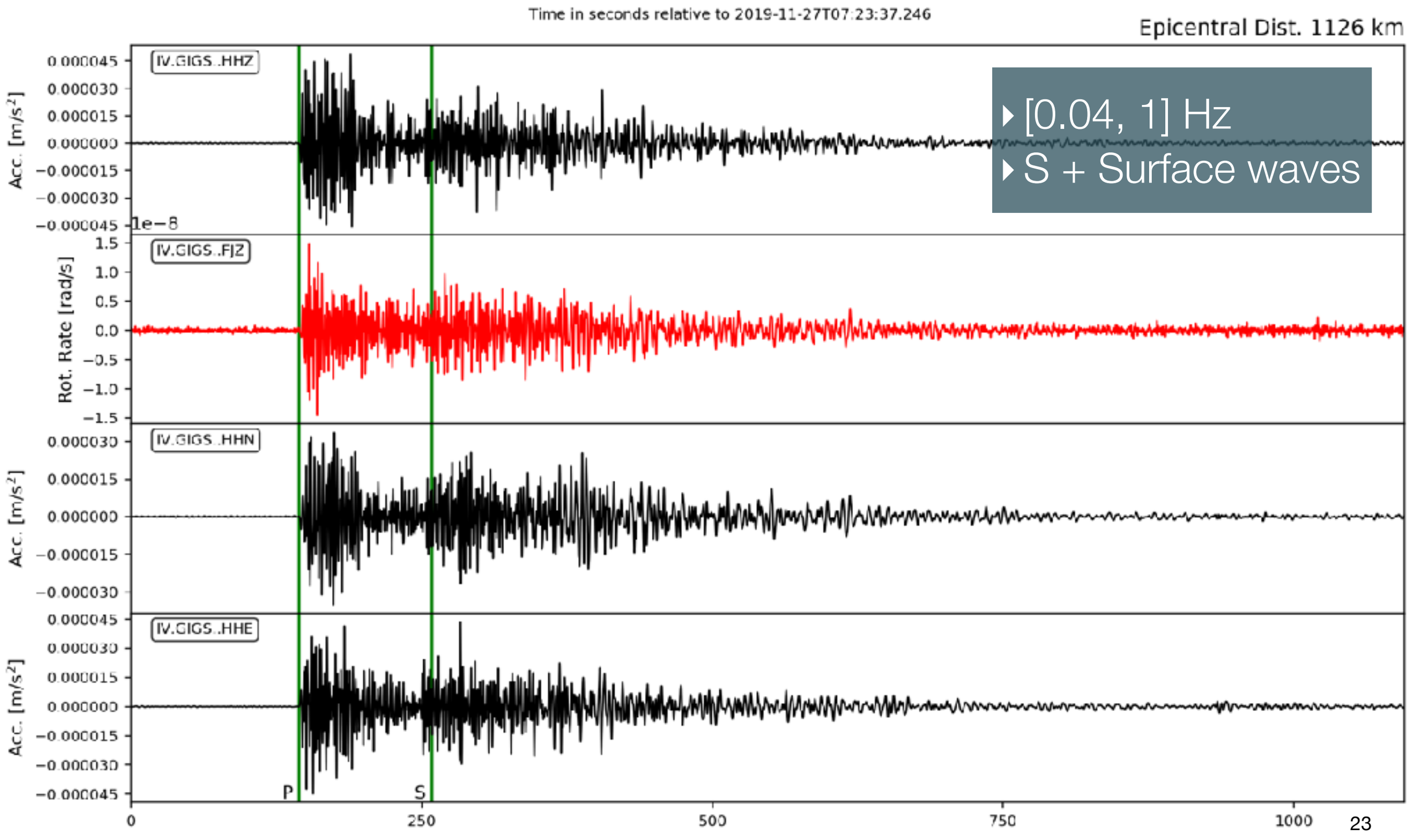


- [0.02, 0.25] Hz
- Th. θ = 76°
- Ext. θ = 73° ± 10°

Bosnia and Herzegovina, mb 5.4

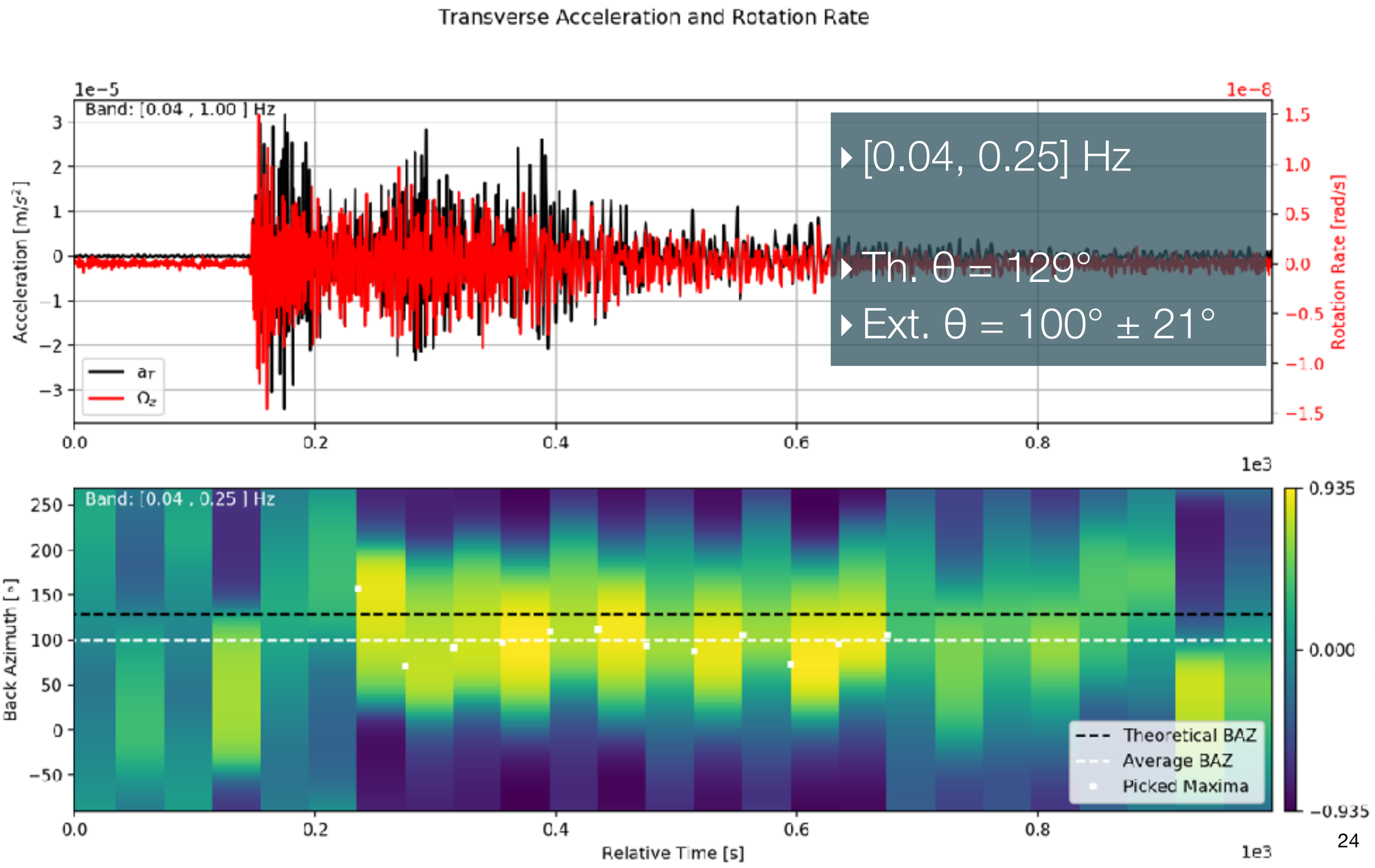


Crete, Mw 6.0



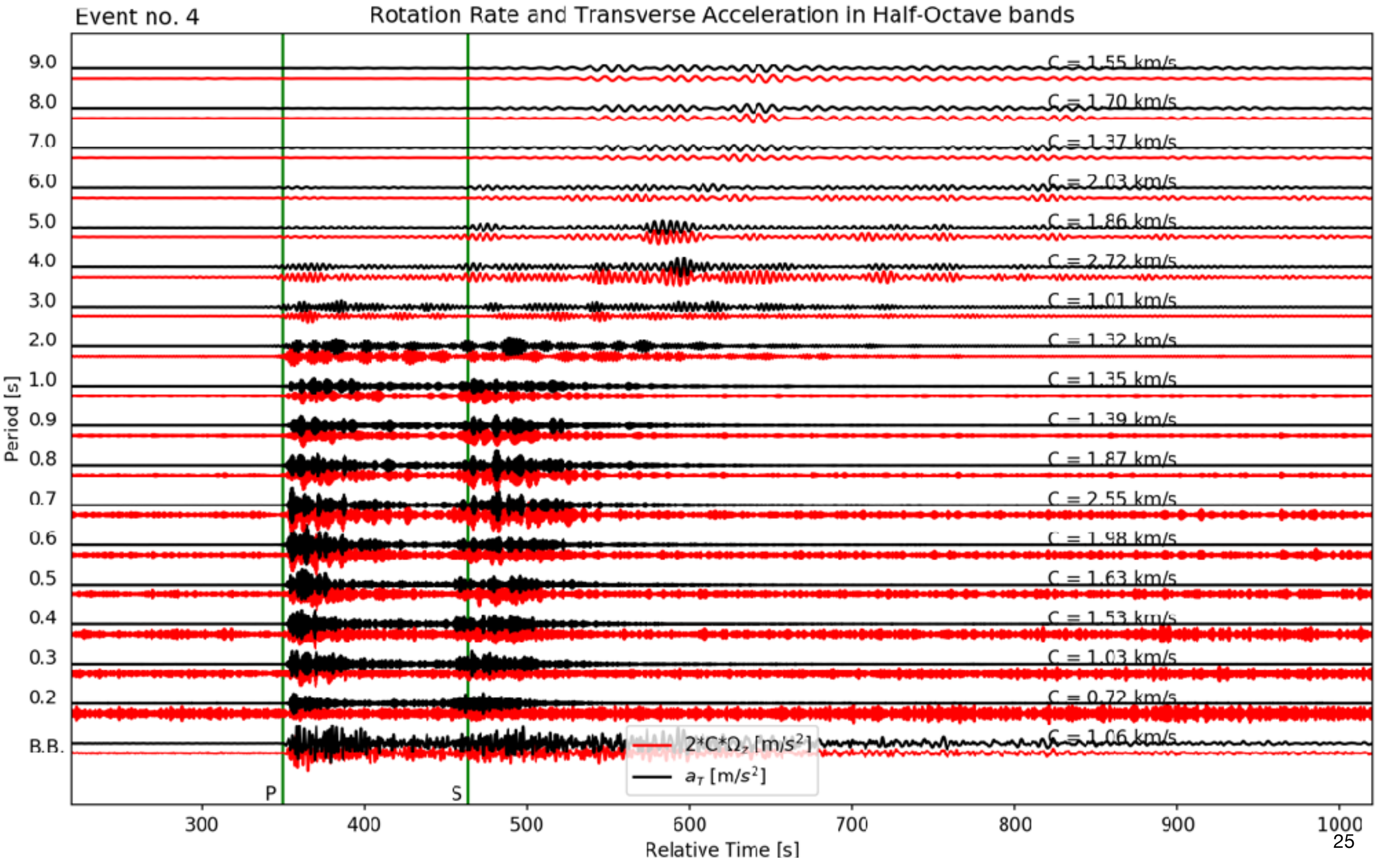
- [0.04, 1] Hz
- S + Surface waves

Crete, Mwp 6.0

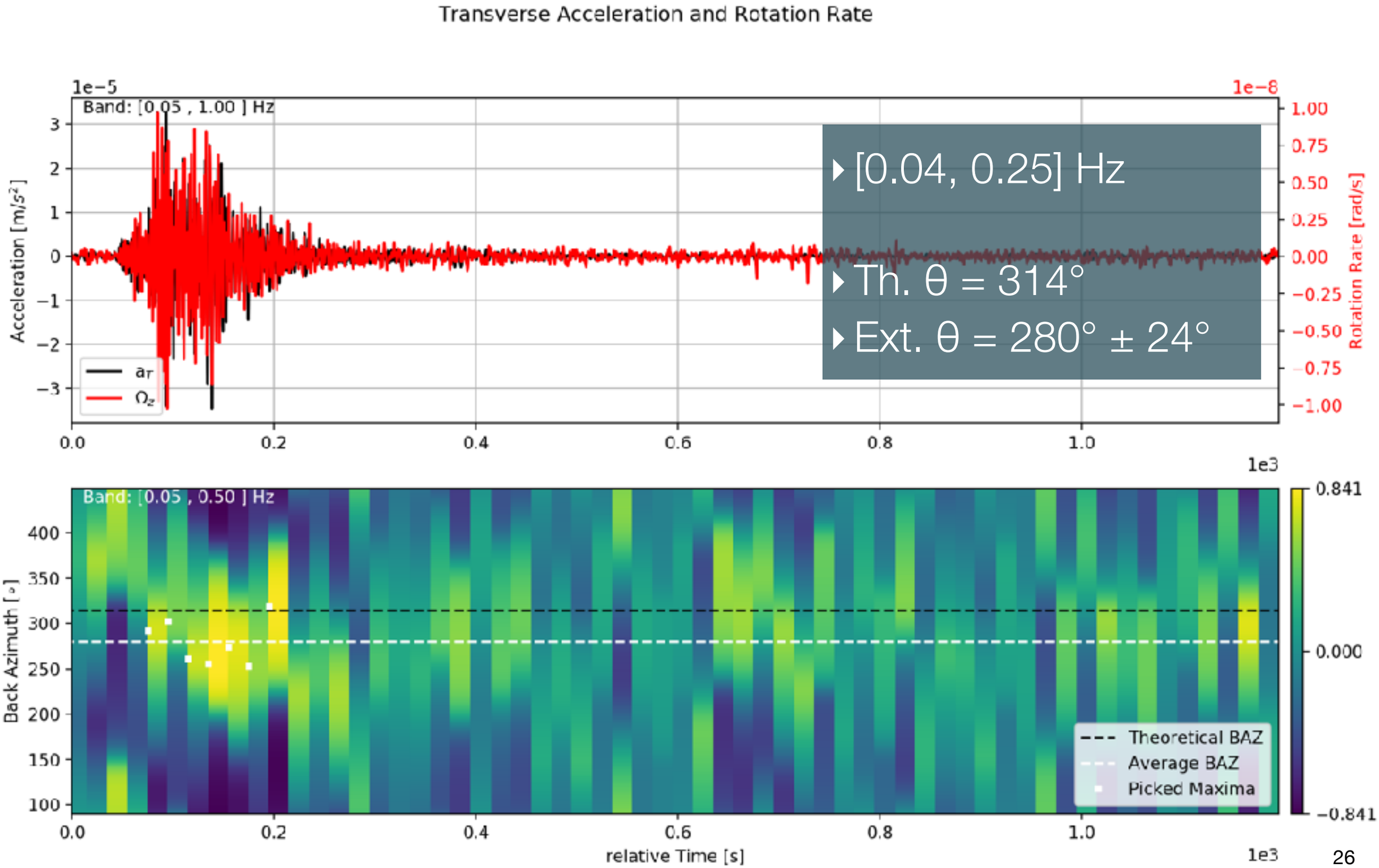


- [0.04, 0.25] Hz
- Th. θ = 129°
- Ext. θ = 100° ± 21°

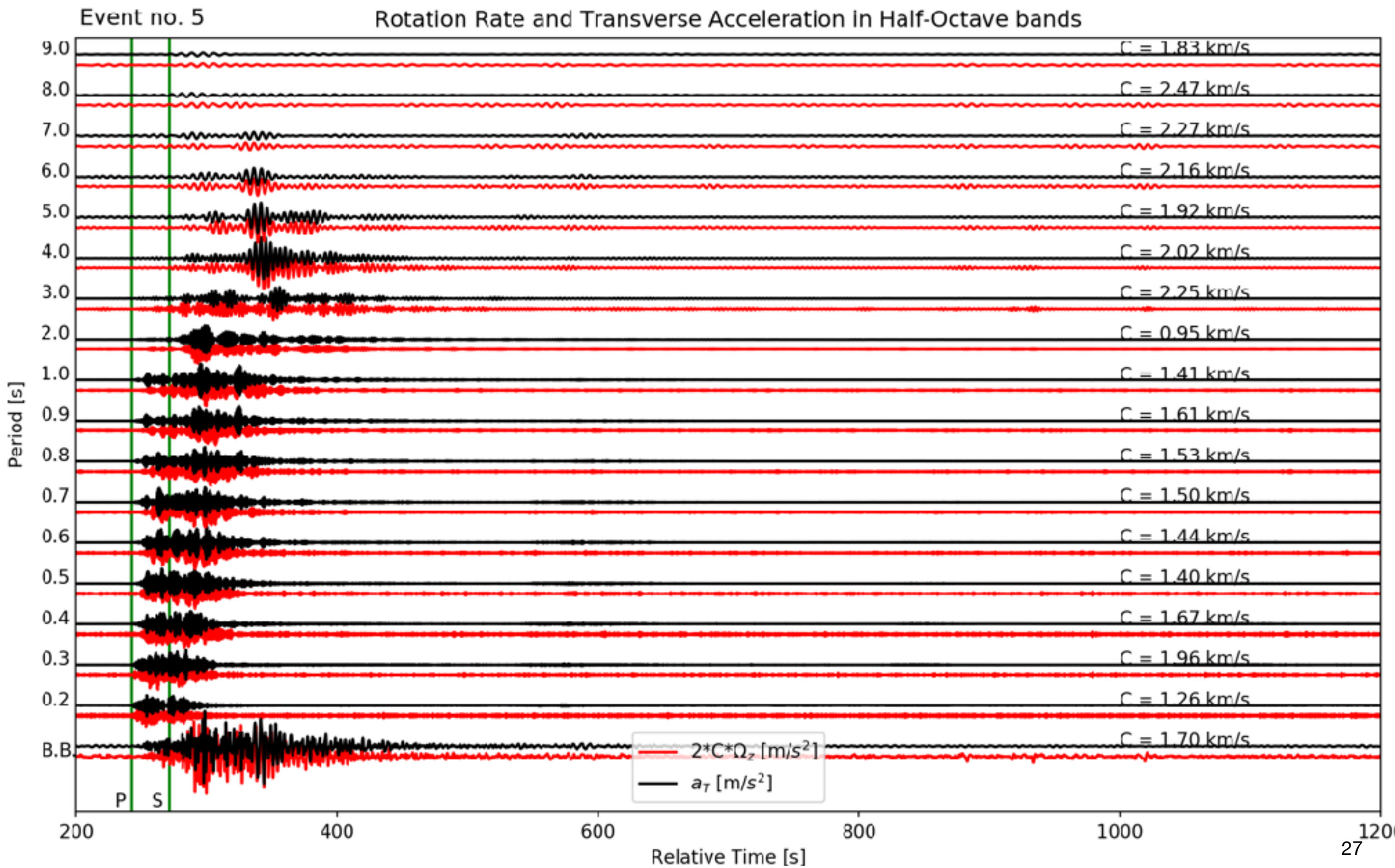
Crete, Mwp 6.0


Event no. 4
Rotation Rate and Transverse Acceleration in Half-Octave bands
Period [s]
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
B.B.
C = 1.55 km/s
C = 1.70 km/s
C = 1.37 km/s
C = 2.03 km/s
C = 1.86 km/s
C = 2.72 km/s
C = 1.01 km/s
C = 1.32 km/s
C = 1.35 km/s
C = 1.39 km/s
C = 1.87 km/s
C = 2.55 km/s
C = 1.98 km/s
C = 1.63 km/s
C = 1.53 km/s
C = 1.03 km/s
C = 0.72 km/s
C = 1.06 km/s
P
S
2*C*Ω_z [m/s²]
a_T [m/s²]
300
400
500
600
700
800
900
1000
Relative Time [s]

Mugello, M 4.5


Transverse Acceleration and Rotation Rate
Band: [0.05 , 1.00] Hz
Acceleration [m/s²]
Rotation Rate [rad/s]
1e−5
1e−8
aT
Ωz
[0.04, 0.25] Hz
Th. θ = 314°
Ext. θ = 280° ± 24°
1e3
Band: [0.05 , 0.50] Hz
Back Azimuth [°]
Correl. Coefficient
Theoretical BAZ
Average BAZ
Picked Maxima
relative Time [s]

Mugello, M 4.5


Event no. 5
Rotation Rate and Transverse Acceleration in Half-Octave bands
Period [s]
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
B.B.
C = 1.83 km/s
C = 2.47 km/s
C = 2.27 km/s
C = 2.16 km/s
C = 1.92 km/s
C = 2.02 km/s
C = 2.25 km/s
C = 0.95 km/s
C = 1.41 km/s
C = 1.61 km/s
C = 1.53 km/s
C = 1.50 km/s
C = 1.44 km/s
C = 1.40 km/s
C = 1.67 km/s
C = 1.96 km/s
C = 1.26 km/s
C = 1.70 km/s
P
S
2*C*Ω_z [m/s²]
a_T [m/s²]
200
400
600
800
1000
1200
Relative Time [s]

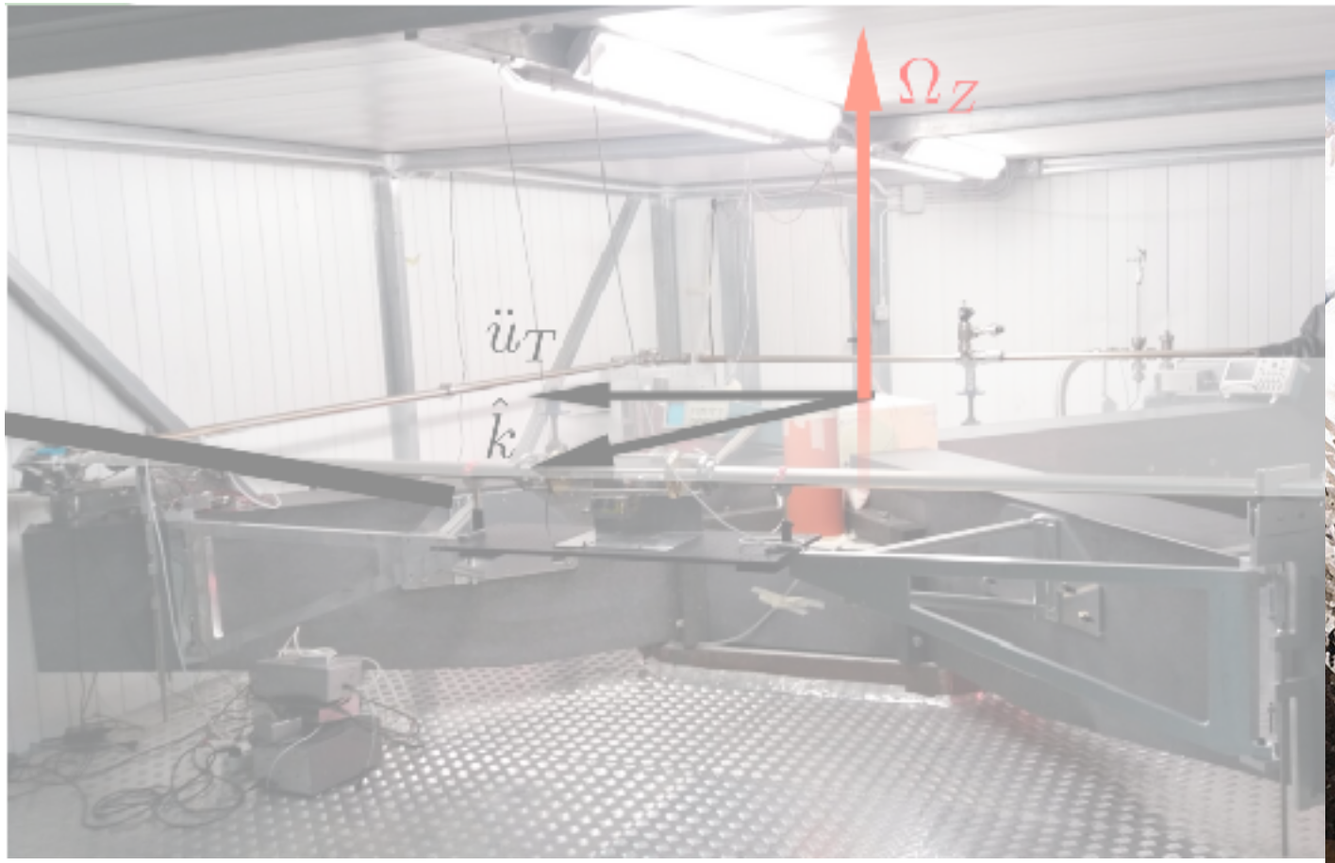
Discussion

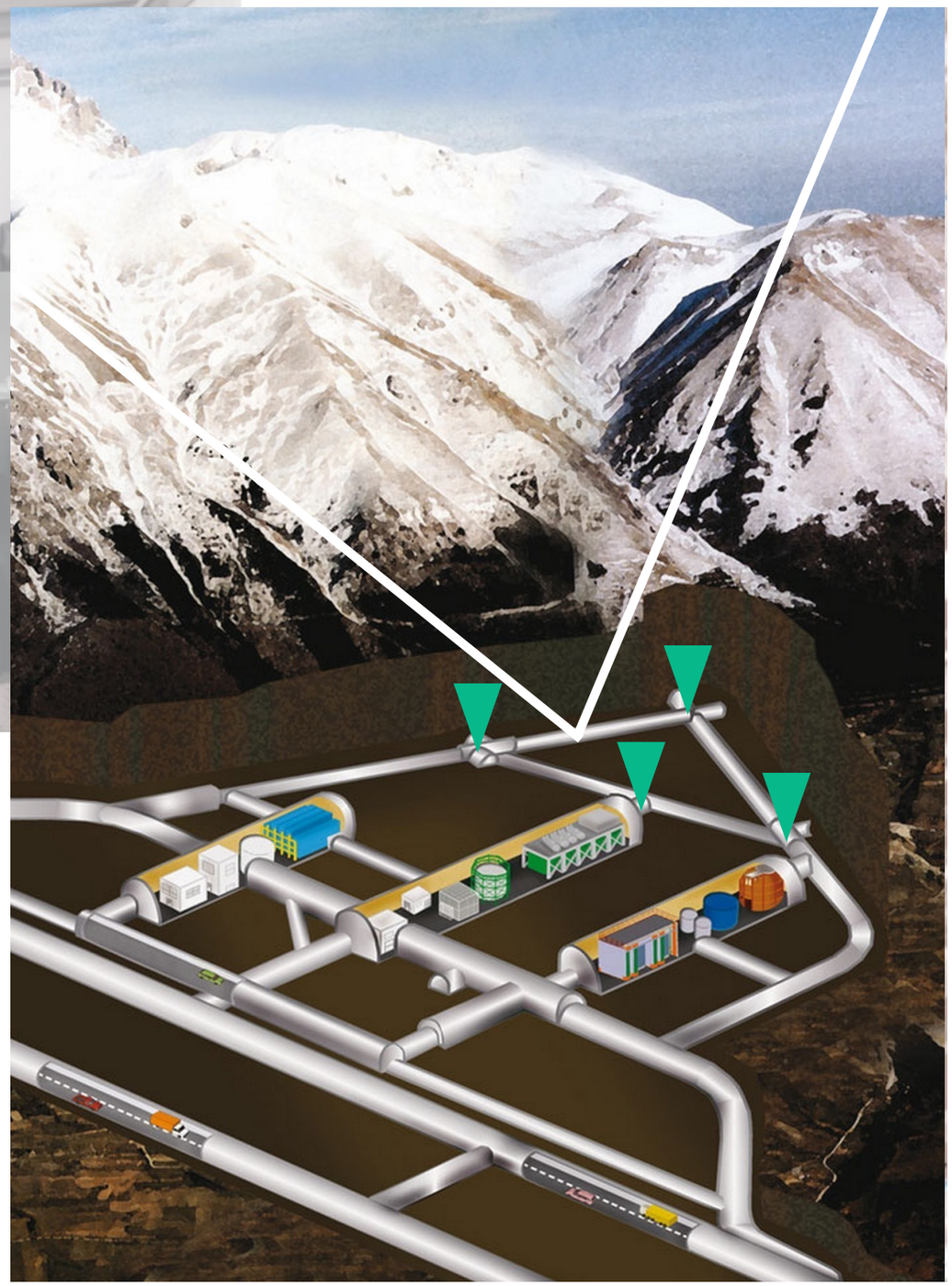
Event	True BAZ [°]	Local Ext. BAZ [°]
Albania 6.2	101	77 ± 23
Albania 5.4	100	76 ± 23
Bosnia and Herz. 5.4	76	74 ± 10
Crete 6	129	100 ± 21
Mugello 4.5	314	280 ± 24

- Sistematic underestimate → ? →
  - Lateral velocity variation
  - Effect of topography and setting
- Dispersion curves → Local structure

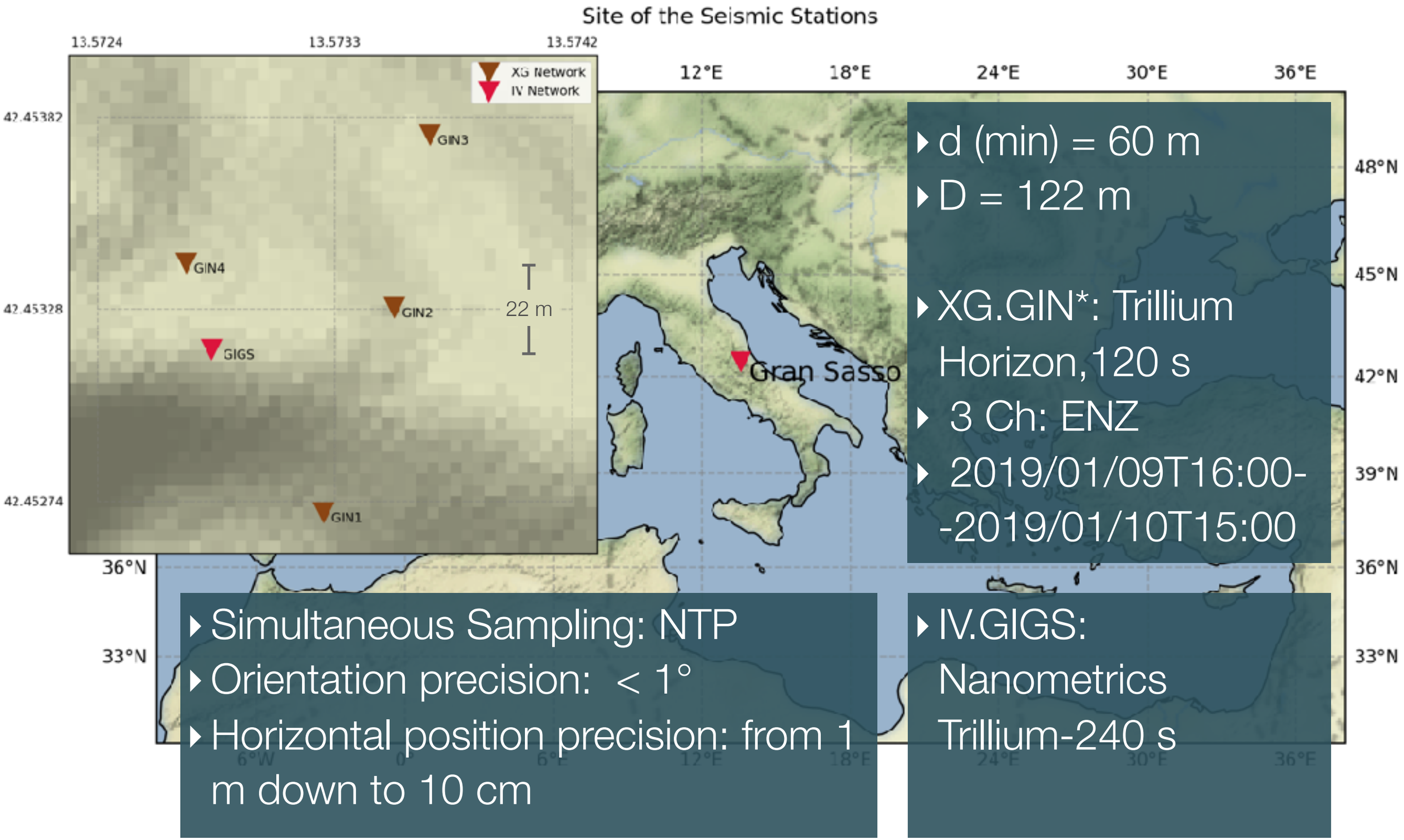
Greater and ‘isotropic’ sample of events is necessary

Observations: Array methods





Experimental Setup: XG Array

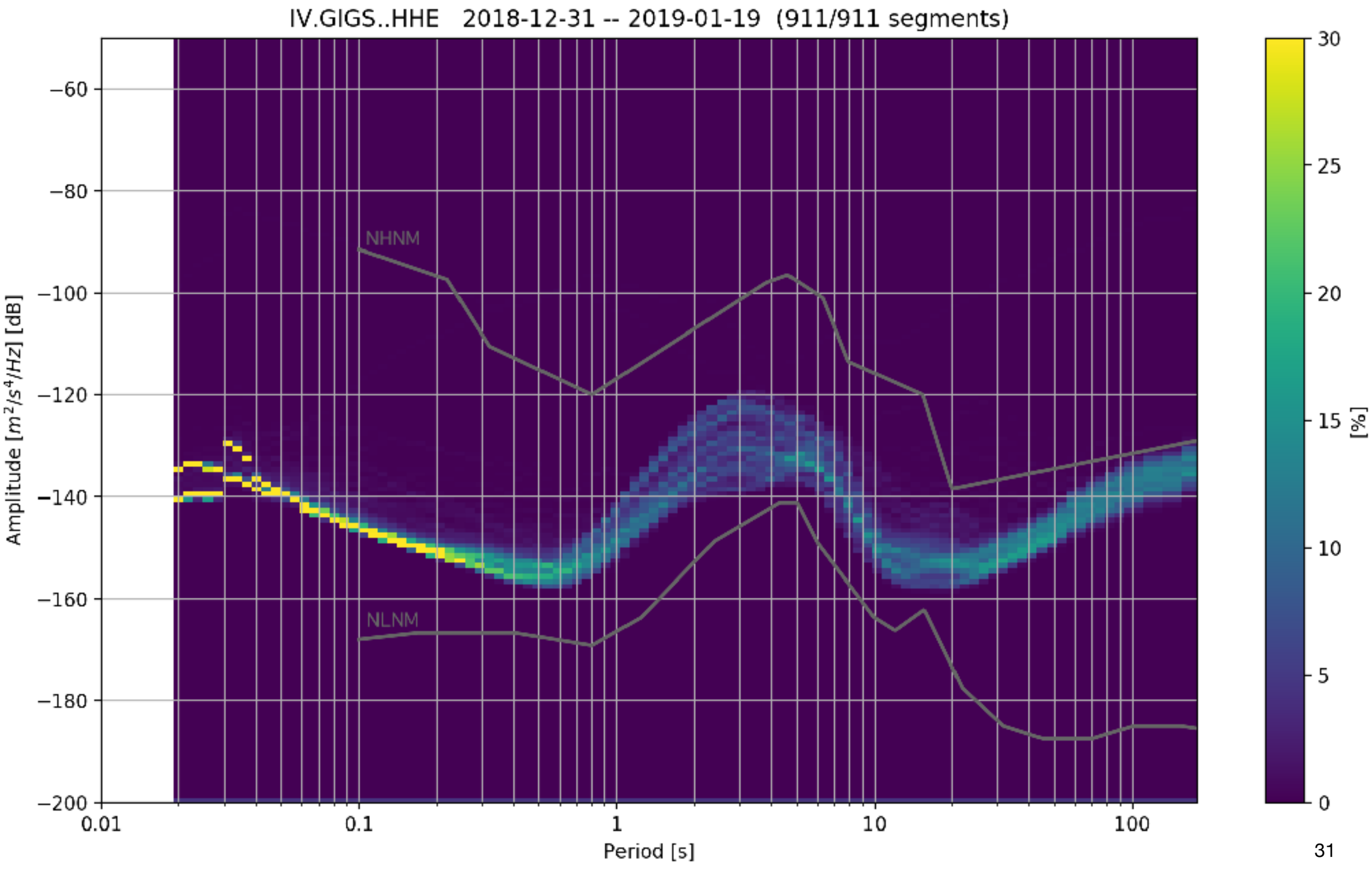


- d (min) = 60 m
- D = 122 m
- XG.GIN*: Trillium Horizon,120 s
- 3 Ch: ENZ
- 2019/01/09T16:00--2019/01/10T15:00

- Simultaneous Sampling: NTP
- Orientation precision: < 1°
- Horizontal position precision: from 1 m down to 10 cm

- IV.GIGS: Nanometrics Trillium-240 s

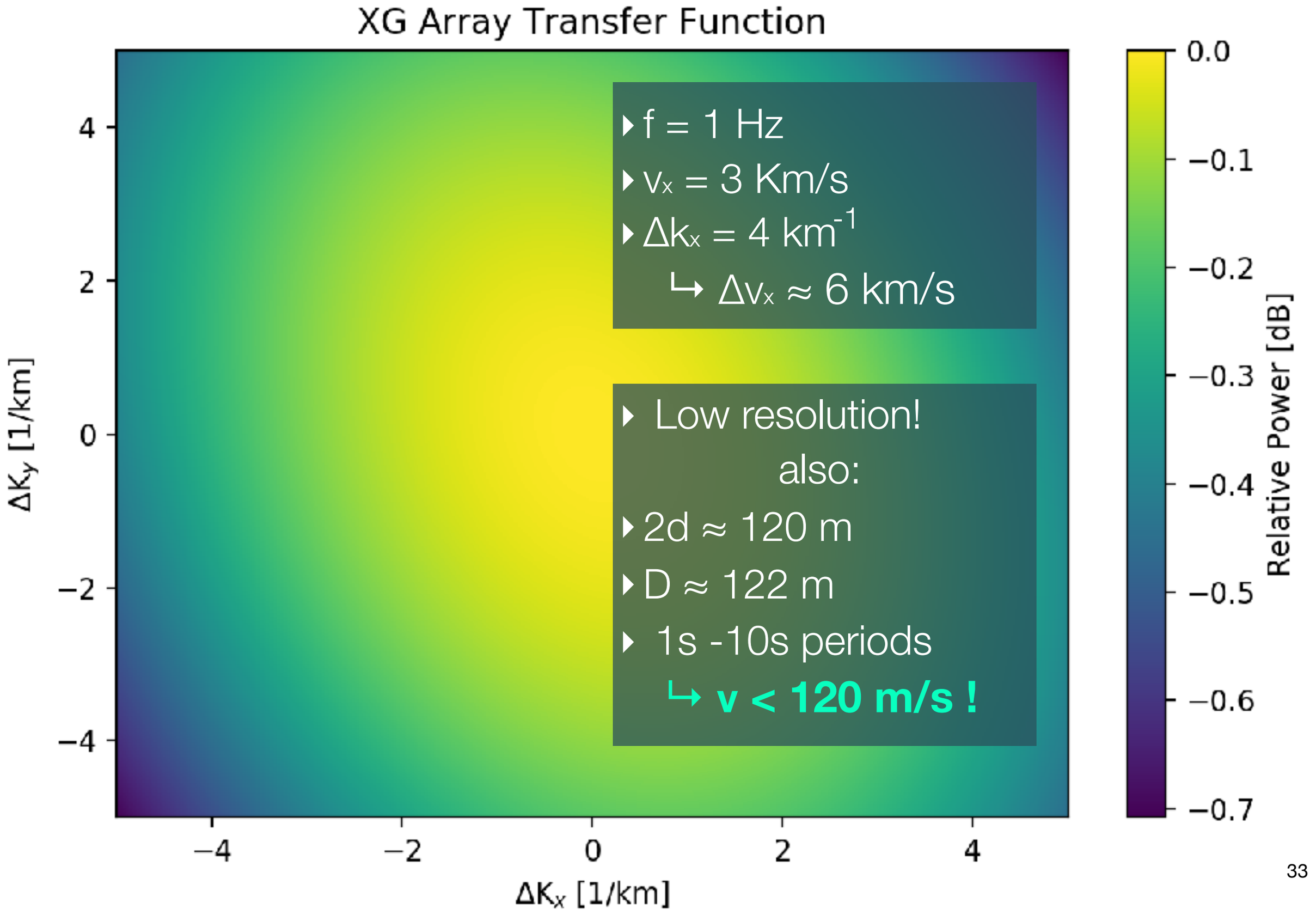
Observations: Microseism Data Analysis



Observations: Microseism Data Analysis

- **F-K**
  - **Feasibility**
  - **Test trough simulations (not showed in this presentation)**
- ADR + 3C
  - Feasibility
  - Test trough simulations
  - Data Analysis

Feasibility: F-K Analysis



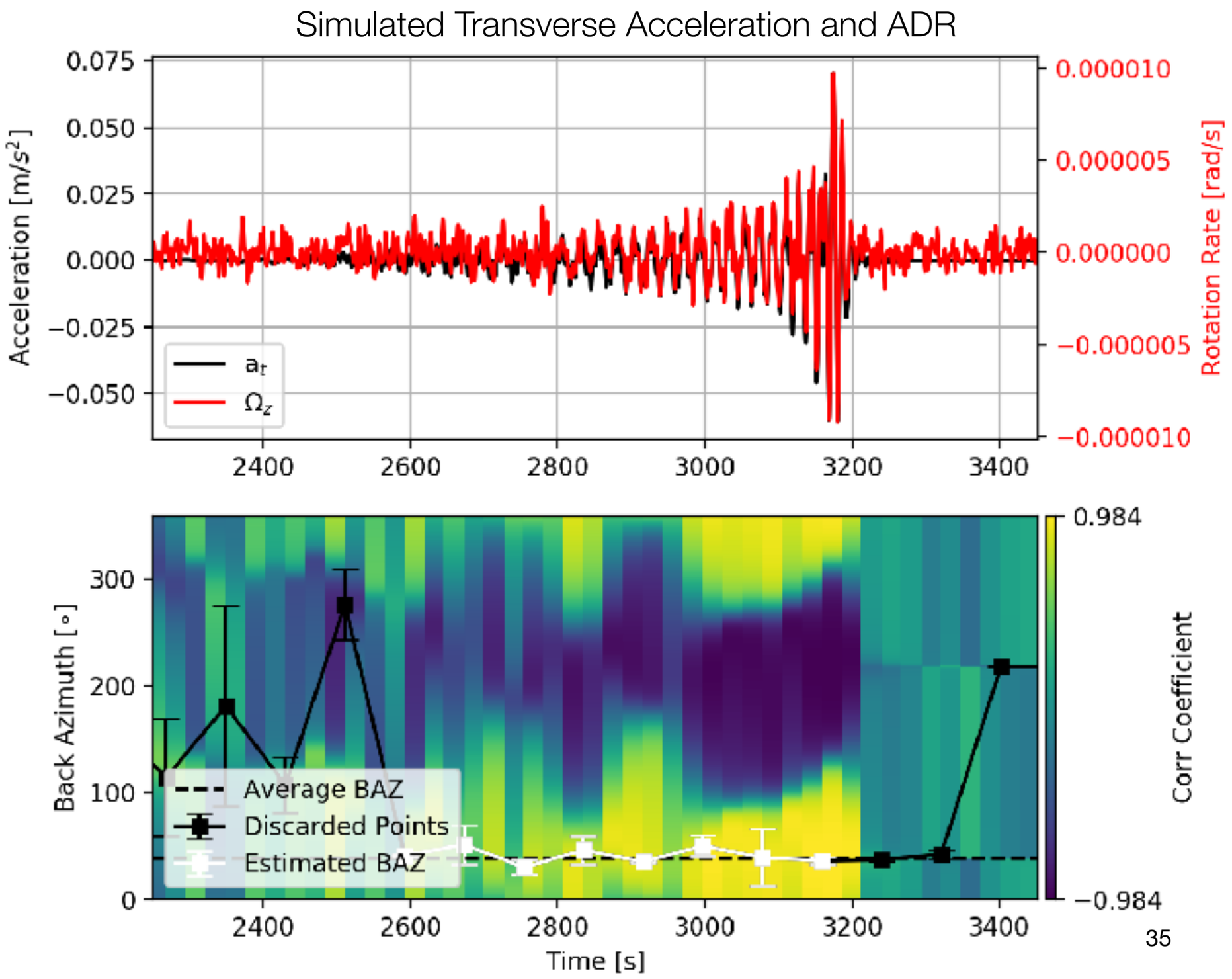
Observations: Microseism Data Analysis

- F-K
  - Feasibility
  - Test trough simulations (not showed in this presentation)
- ADR + 3C
  - Feasibility
  - Test trough simulations
  - Microseism Data Analysis

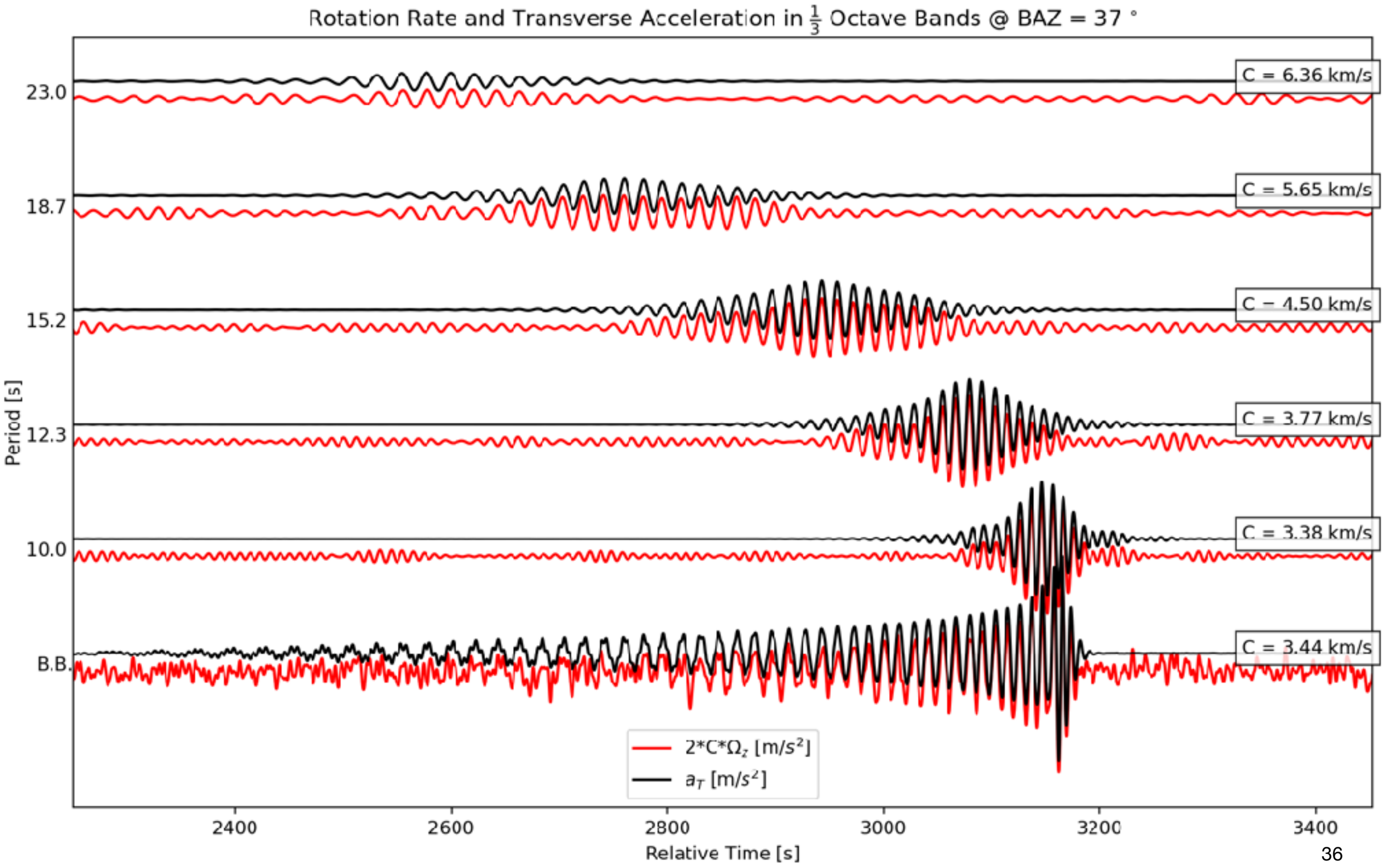
Feasibility: ADR - Simulation for XG Network

V = 1 km/s, f = 1 Hz **D ≈ 120 m** → **D < 0.25 km = λ/4**

- IRIS *Syngine:* translational data ADR for XG
- 5s min period
- 1D Earth model
- Tohoku Mw 9.1
- Coarser slices: median and MAD
- θ_{th} = 38°
- θ_{ext} = 38° ± 1°



Feasibility: ADR - Simulation



Observations: Microseism Data Analysis

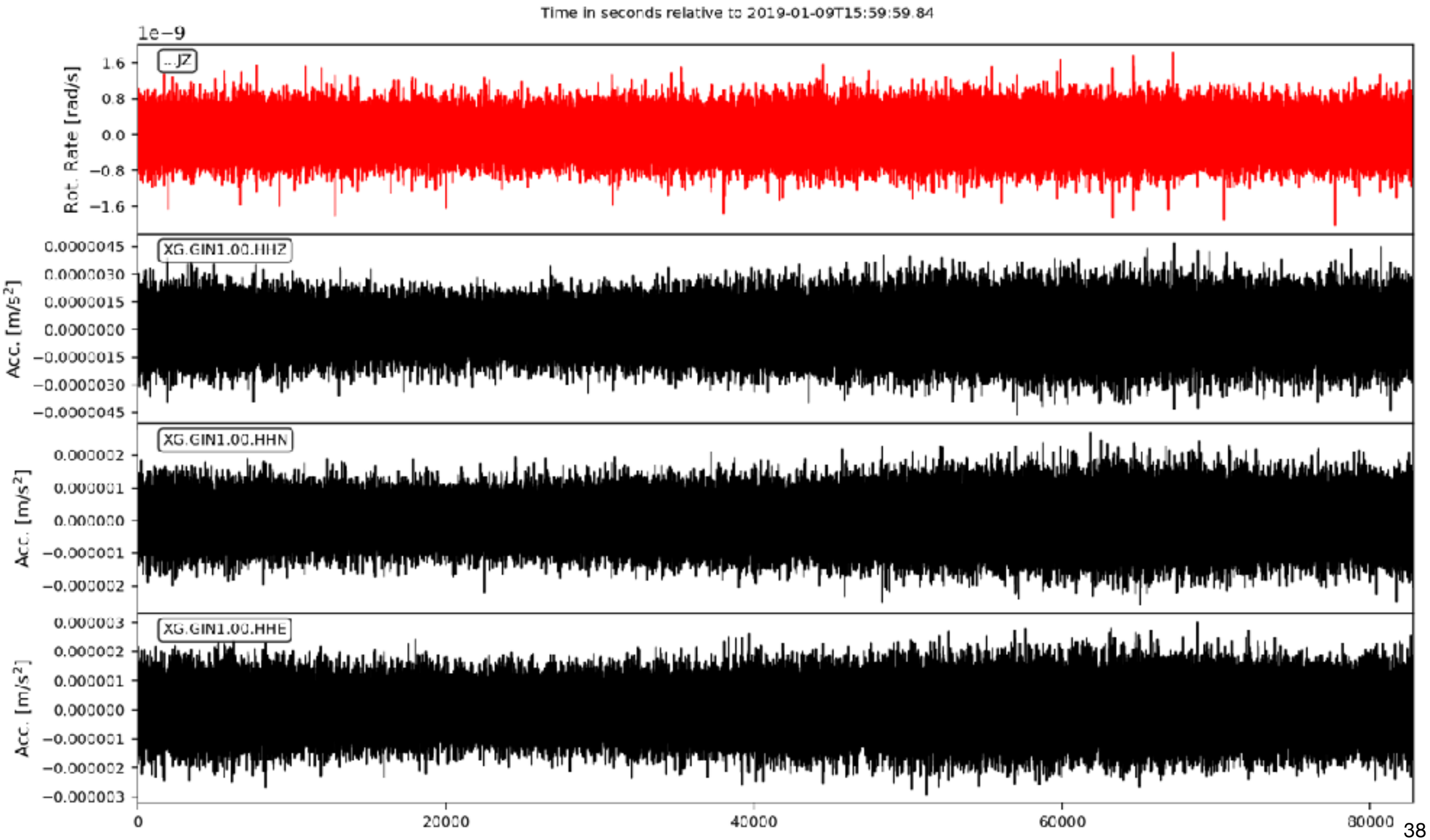
- **Why microseism?**

  - Understand generative mechanism: where do SH waves come from?

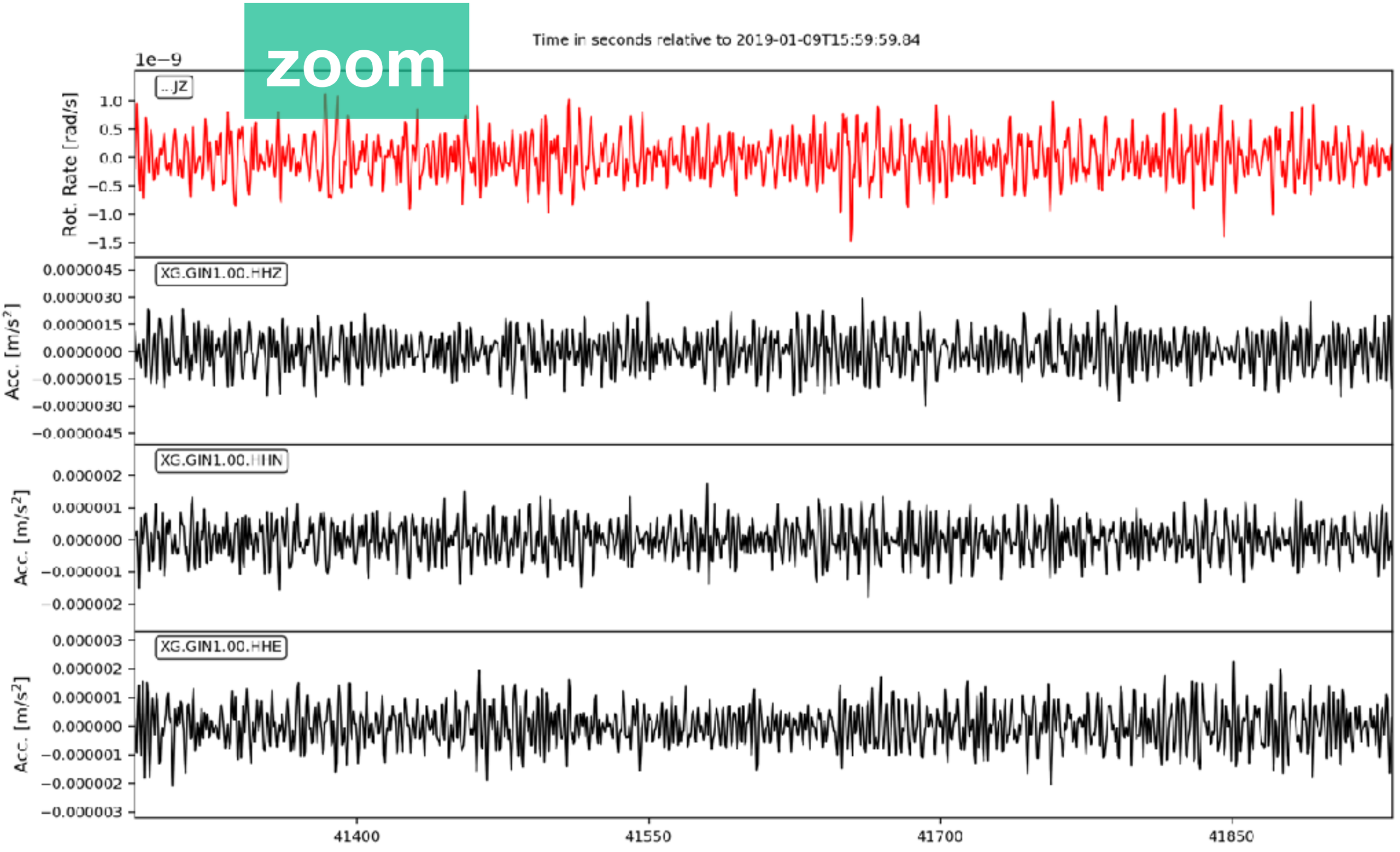
  - Ambient noise tomography: source isotropy assumption, so BAZ is essential

Observations: Microseism Data Analysis

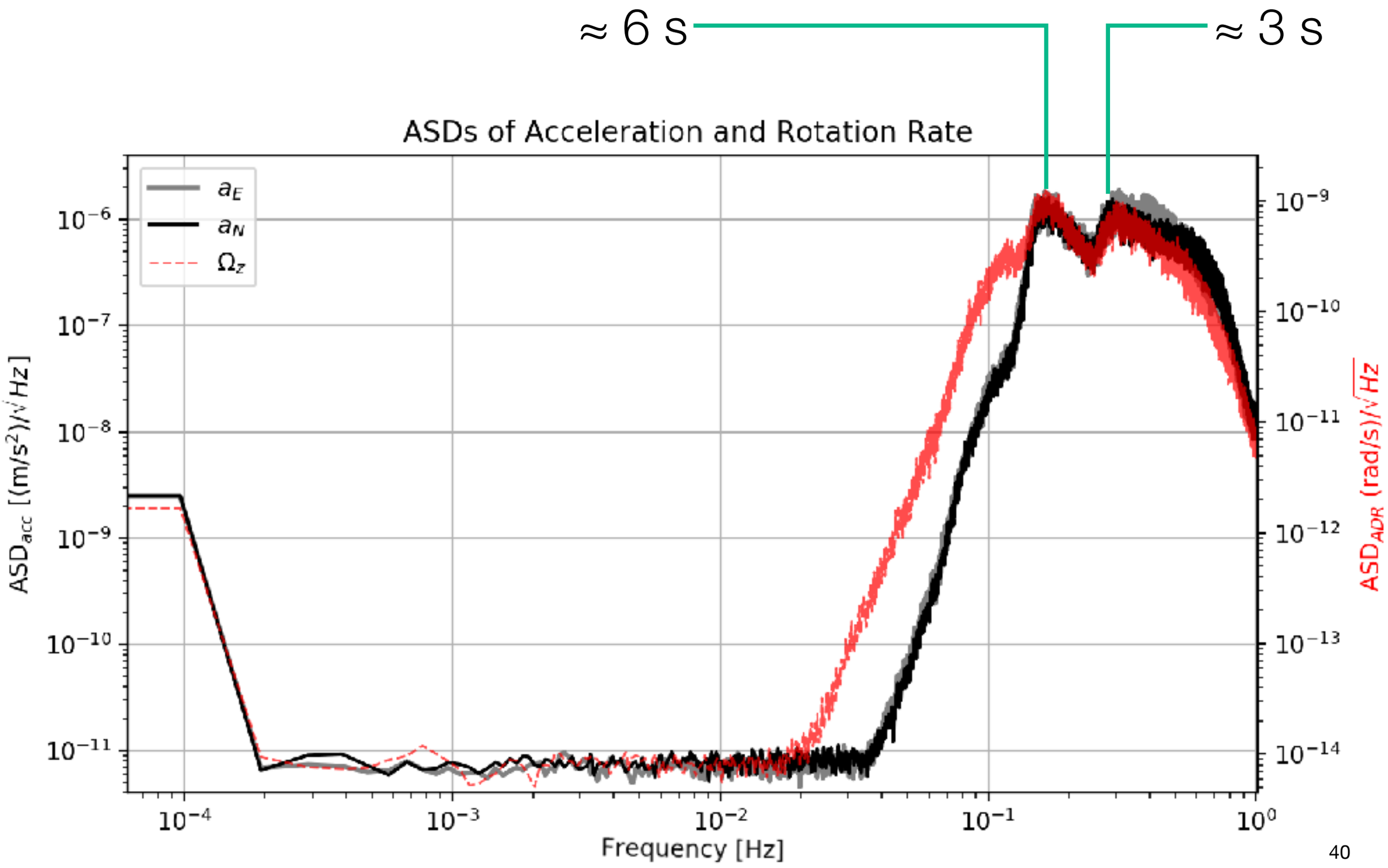
- Response correction
- [1, 10] s
- ADR
- vel. ↦ acc.



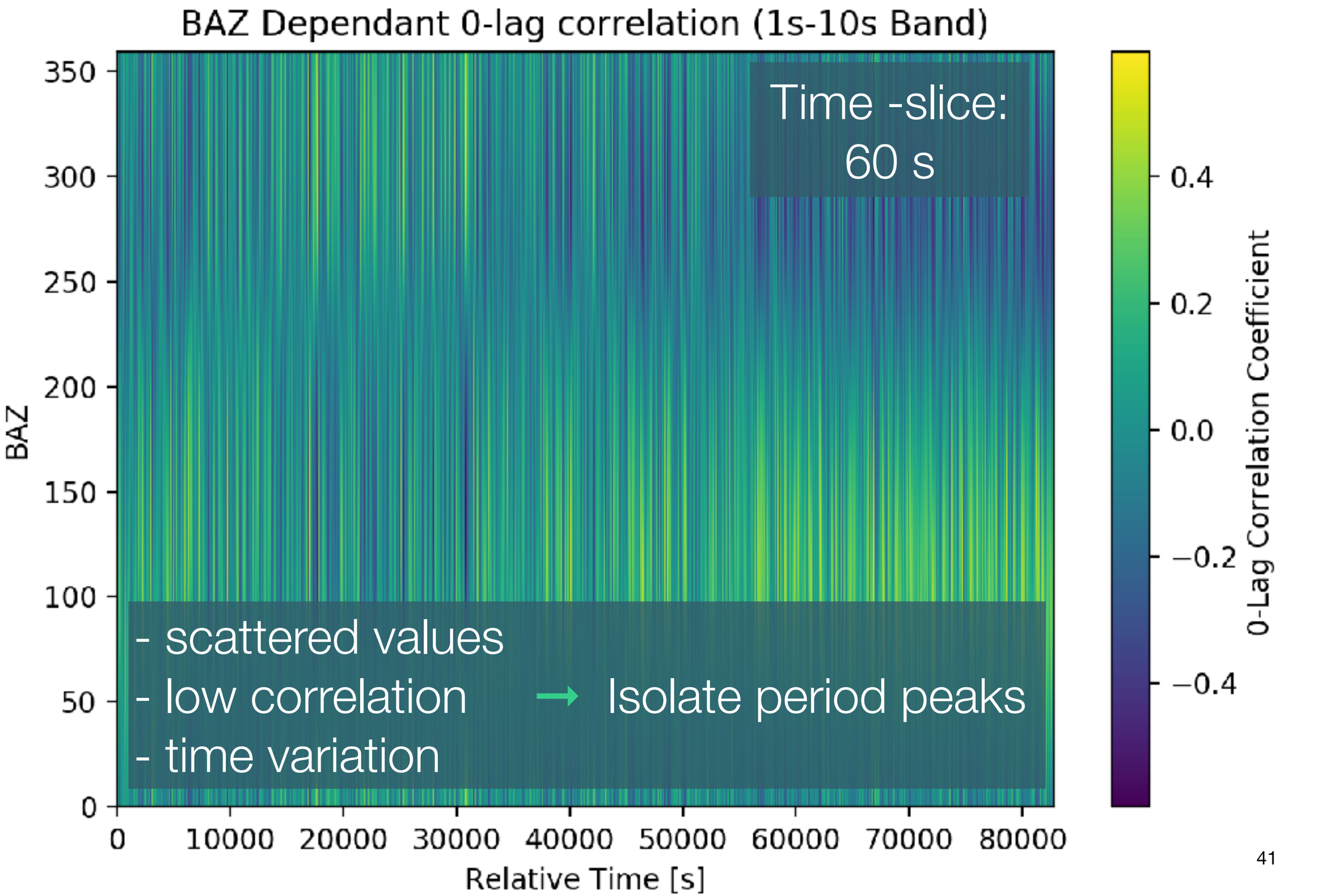
Observations: Microseism Data Analysis



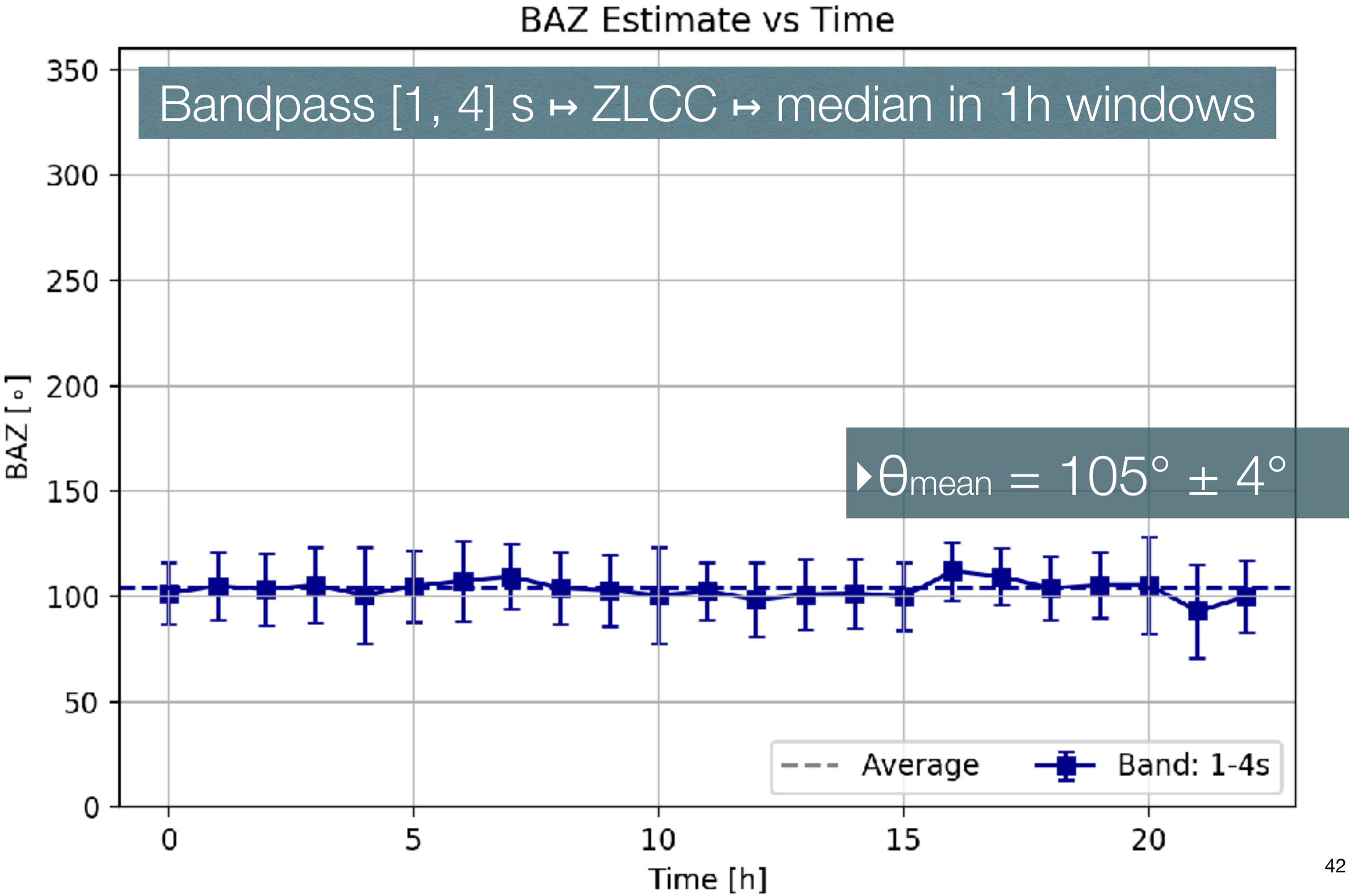
Observations: Microseism Data Analysis



Observations: Microseism Data Analysis

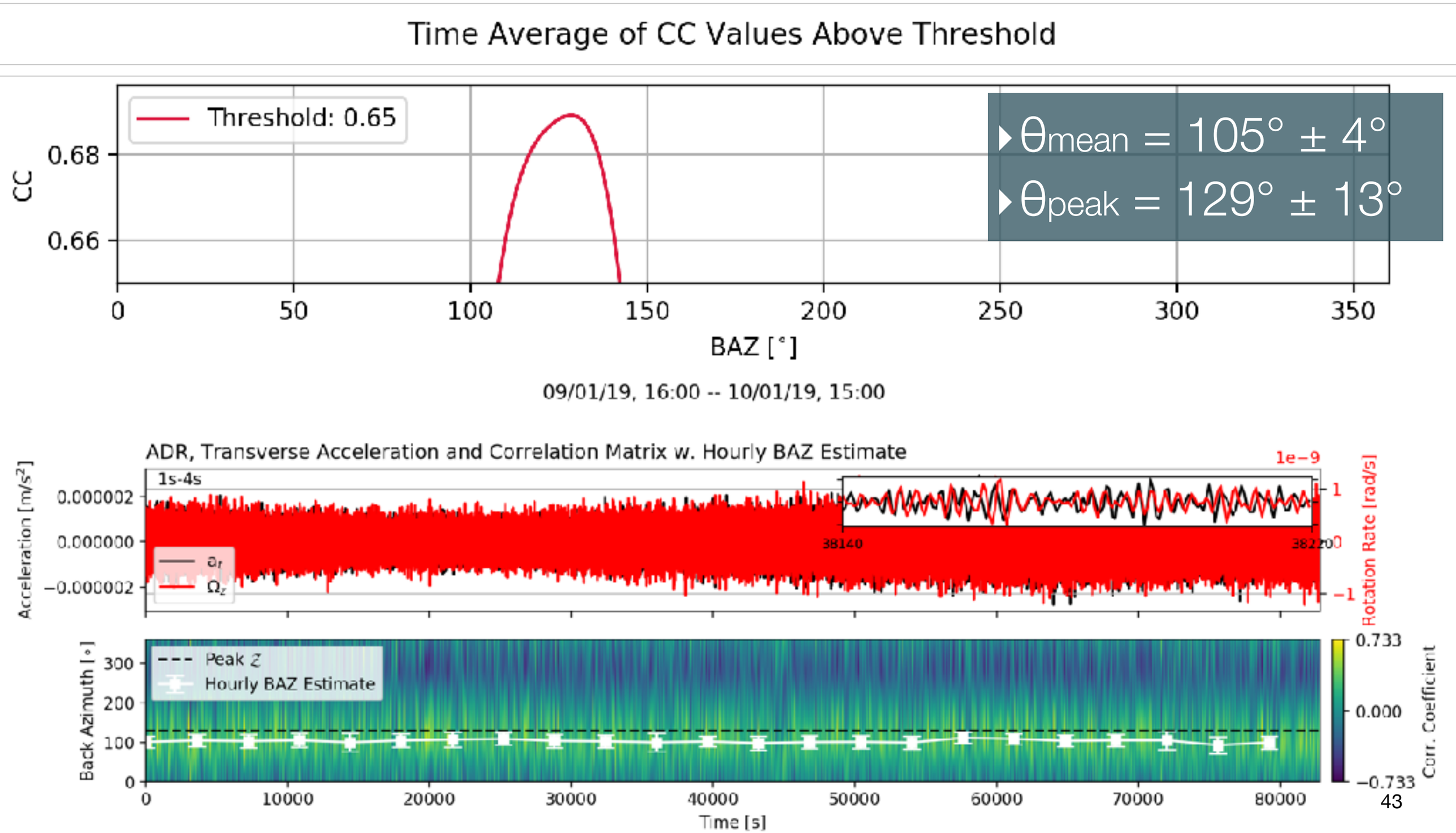


Observations: Microseism Data Analysis

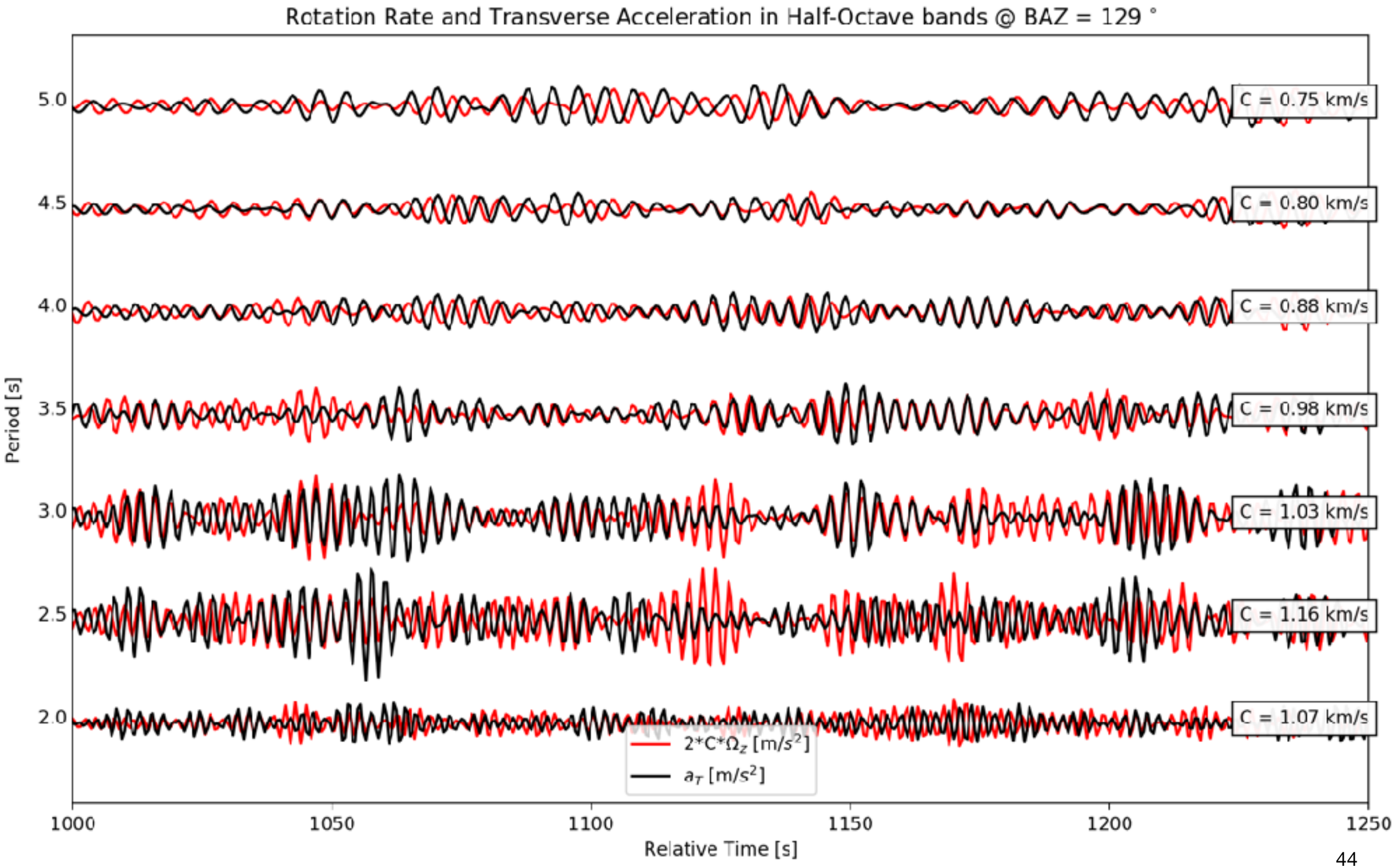


Observations: Microseism Data Analysis

Threshold → t-average → smoothing → $Z(\theta)$



Observations: Microseism Data Analysis



Observations: Microseism Data Analysis

Modeling P body-wave sources:

Sea waves: same f, opposing k

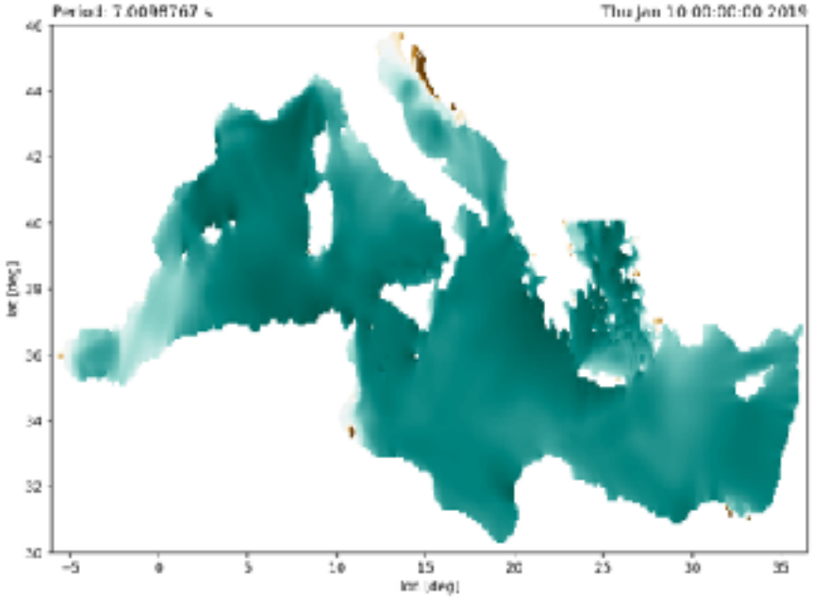
↓

pressure field w/o attenuation

↓

Fp: pressure spectral density from sea state (x, y, f, t)

IFREMER database



Potential: reflections in water transmission

↓

CRUST1.0

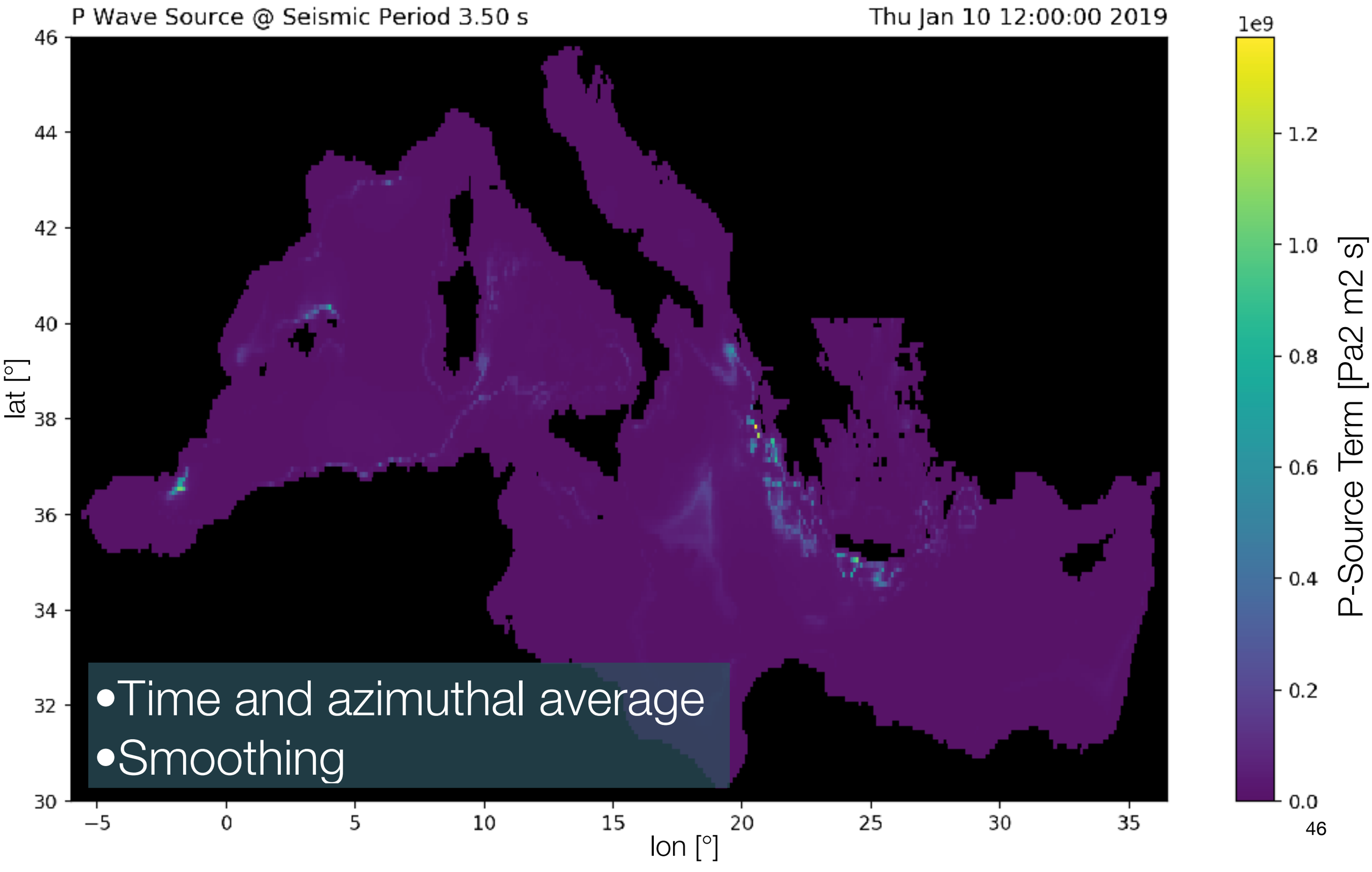
↓

site effects Cp (density, velocities, depth)

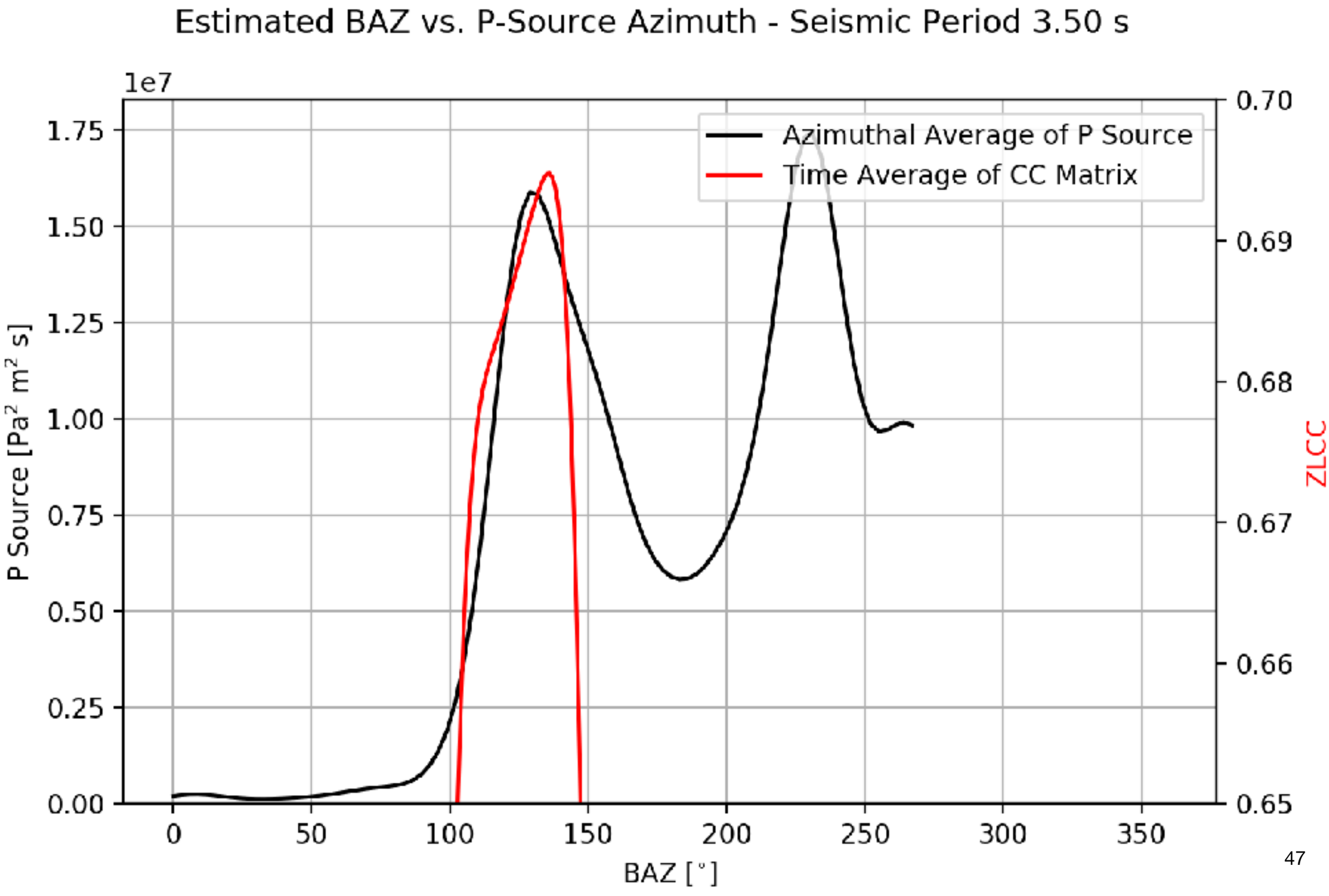
↓

$$P(x, f_2) = F_p(x, f_2) \times [2|C_P(x, f_2)|\frac{\rho_c(x)}{\rho_w}]^2$$

Observations: Microseism Data Analysis



Observations: Microseism Data Analysis



Conclusions

- Unable to deploy array for F-K (D > 1 km required):
  - 4C = 3C + ADR: suitable alternative

- Source identification:
  - seasonal variation: ~ year-long acquisition required

- P and Love waves sources:
  - Longer acquisition
  - Love waves sources should be modelled too

- Broader prospect - 6C:
  - Complete mode selectivity → Ground roll suppression
  - 3D direction → directional filter
  - Arrays?