Istituto Nazionale di Fisica Nucleare
Università degli Studi di Sassari
Sapienza Università di Roma
Istituto Nazionale di Geofisica e Vulcanologia
Università degli Studi di Napoli Federico II
Gran Sasso Science Institute – School of Advanced Studies – Scuola Universitaria Superiore

Summary of site characterization activities at the Sardinia candidate site for the Einstein Telescope

Matteo Di Giovanni

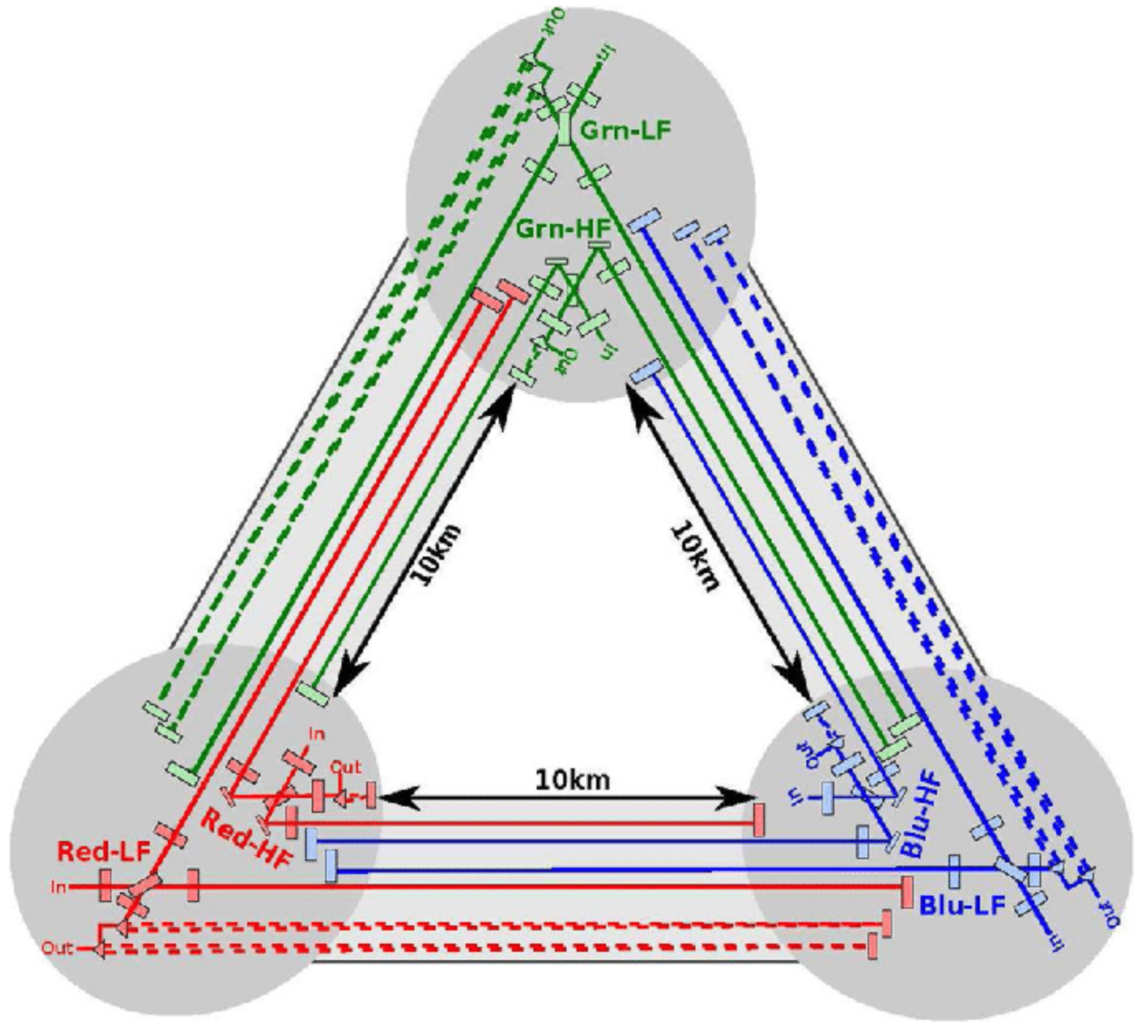
on behalf of the ET Sardinia site characterization team

Outline

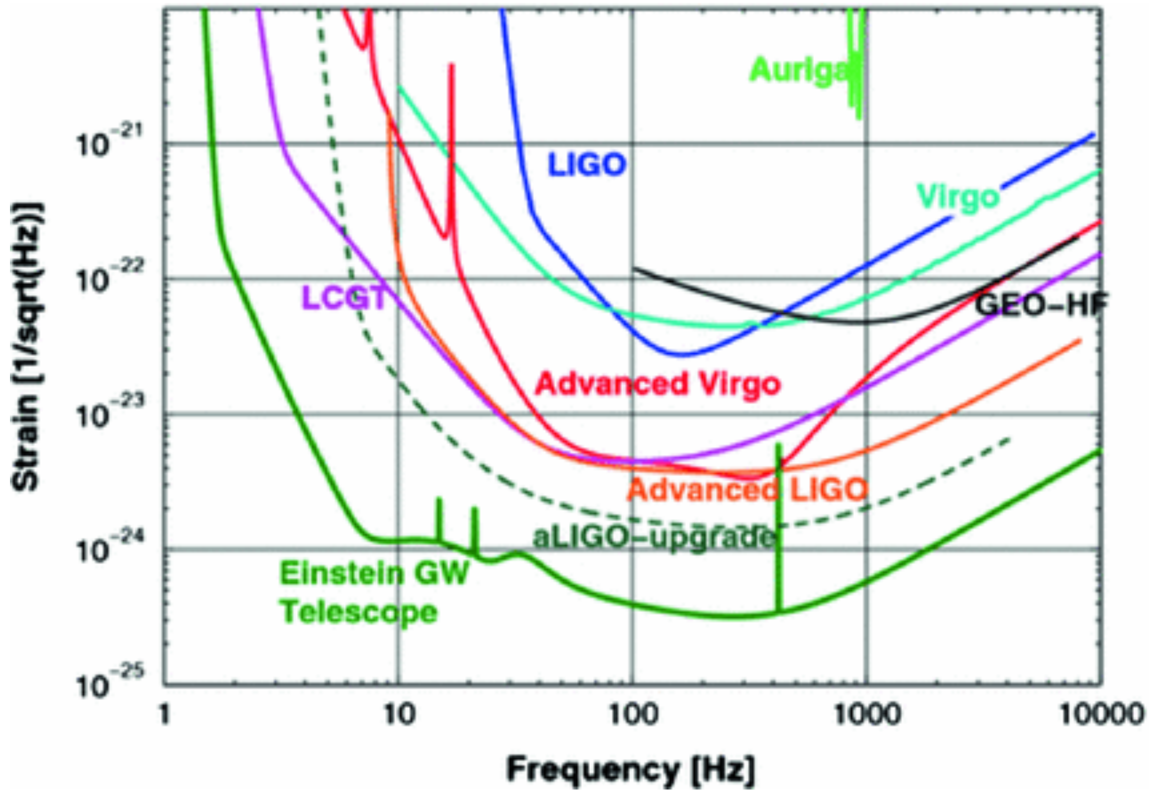
- Introduction;
- The Sardinia site;
- The permanent instrument network;
- Potential ambient noise sources;
- Characterization of the corners.

Einstein Telescope

The configuration of ET is aimed at providing a significant improvement in the sensitivity of a GW interferometer by reducing the influence of noise sources on the detector.



The proposed ET Triangle configuration

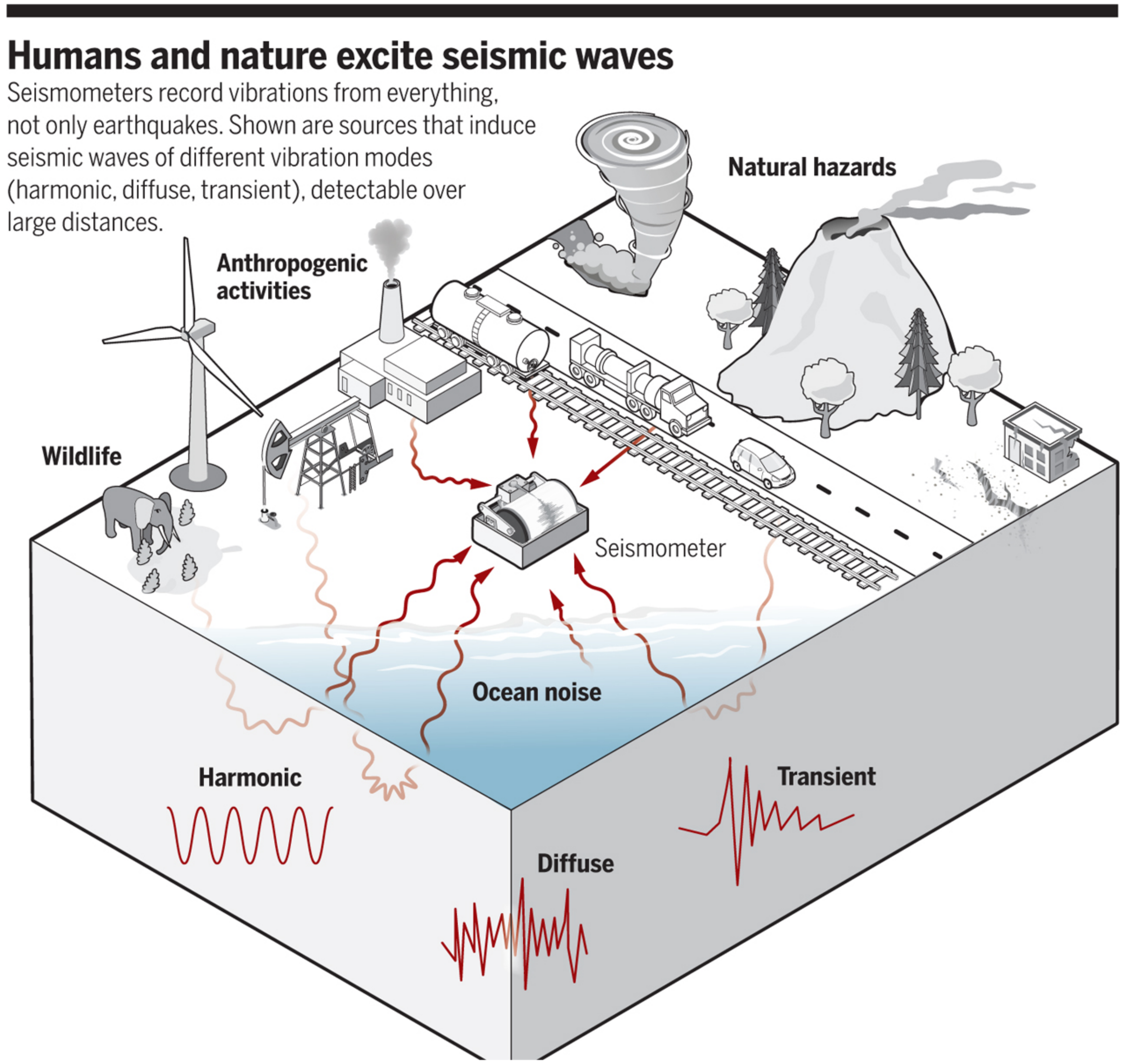


Currently, the official proposed configuration of ET consists of 3 underground detectors in a xylophone configuration (i.e. 6 detectors) nested in a triangular shape with 10 km-long arms. An alternative proposal has been done for two 15 km L shaped detectors in a xylophone configuration.

In both cases, having more detectors at the same place requires careful understanding of the local noise sources.

Understanding noise contributions

- ET will be much more susceptible to ambient noise;
- Characterization of ambient, seismic in particular, noise sources at low frequency is paramount;
- Seismic ambient noise can be of natural and human origin;
- Understanding the sources of seismic noise provides important information to design and adapt the detector's seismic isolation and control systems;



The candidate sites

Two official candidate sites:

- EMR Region (NL-BE-D);
- Sardinia (IT);

A third potential site has been identified in Lausitz (D).

The Sardinia site

Over the years, the Italian candidate site to host the 3rd generation gravitational wave (GW) detector Einstein Telescope (ET) has been the subject of thorough characterization studies that are still ongoing.

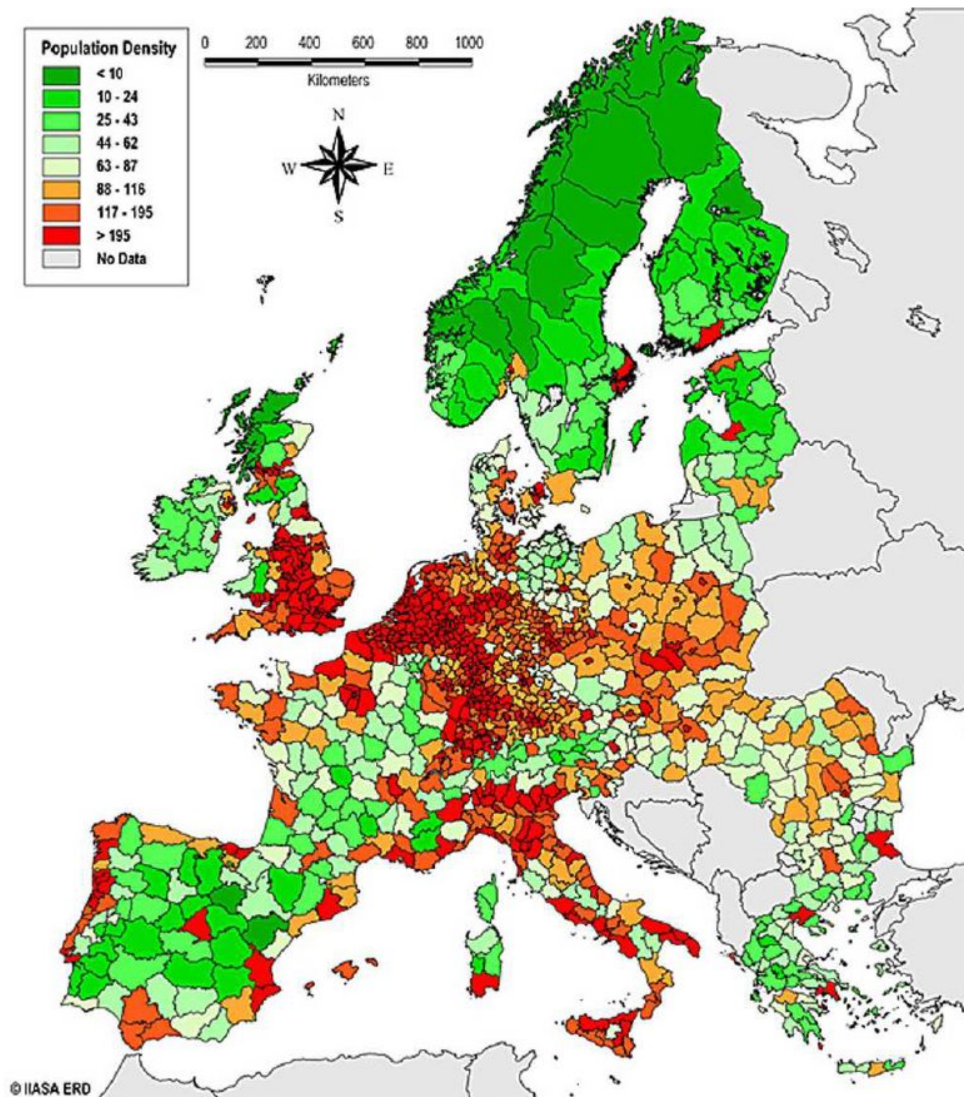
The most significative results obtained so far are included in the following set of publications

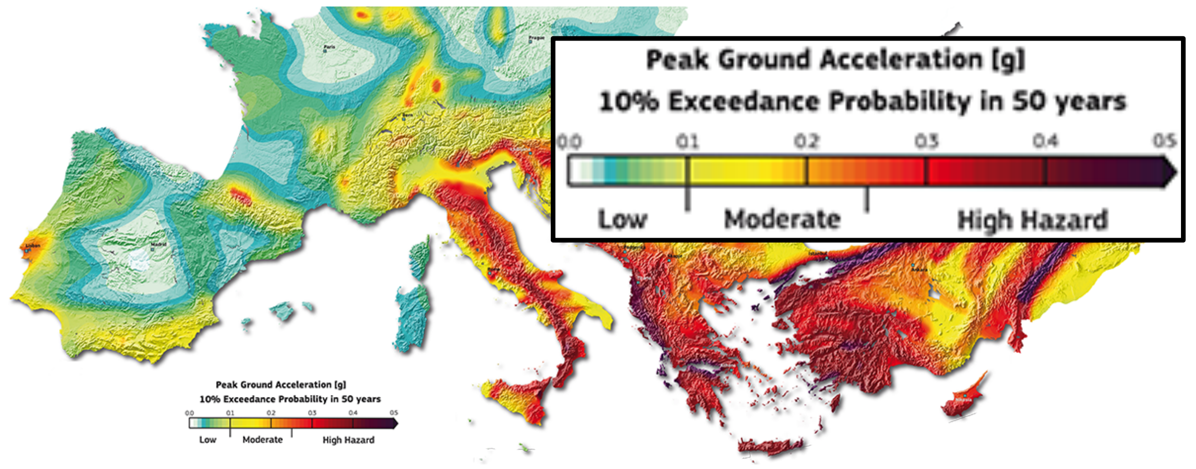
- Naticchioni et al. (2014) **DOI** 10.1088/0264-9381/31/10/105016
- Naticchioni et al. (2020) **DOI** 10.1088/1742-6596/1468/1/012242
- Allocca et al. (2021) **DOI** 10.1140/epjp/s13360-021-01450-8
- Allocca et al. (2021) **DOI** 10.1140/epjp/s13360-021-01993-w
- Di Giovanni et al. (2021) **DOI** 10.1785/0220200186
- Di Giovanni et al. (2023) **DOI** 10.1093/gji/ggad178
- Saccorotti et al. (2023) **DOI** 10.1140/epjp/13360-023-04395-2
- Naticchioni et al. (2023) Submitted to PoS

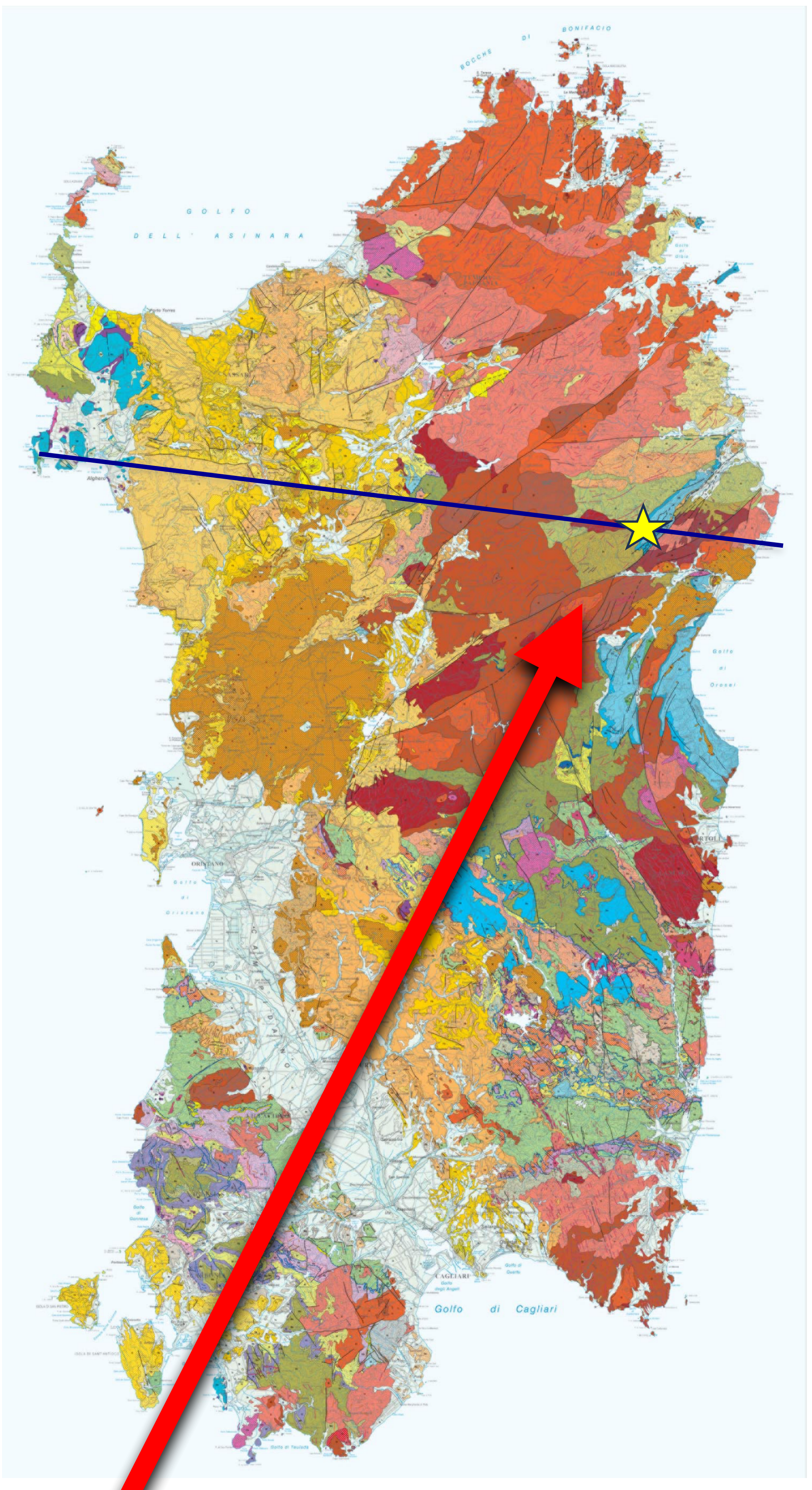
The Sardinia site

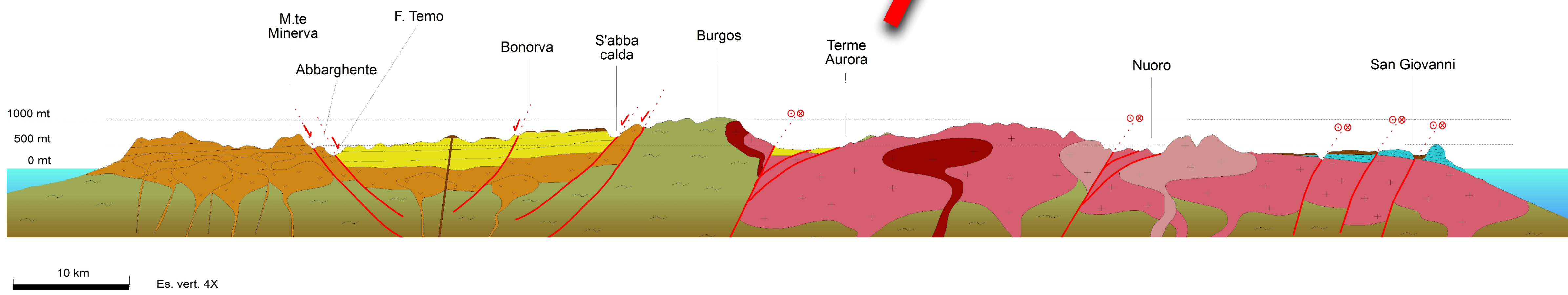
Sardinia was chosen for its unique features:

- low population density;
- very stable environment;
- low seismic hazard;
- among the lowest PGA (peak ground acceleration) values in Europe;
- The Sos Enattos area is located in the stable Variscan basement of Sardinia (geodynamic quietness, low anthropogenic and EM noise).





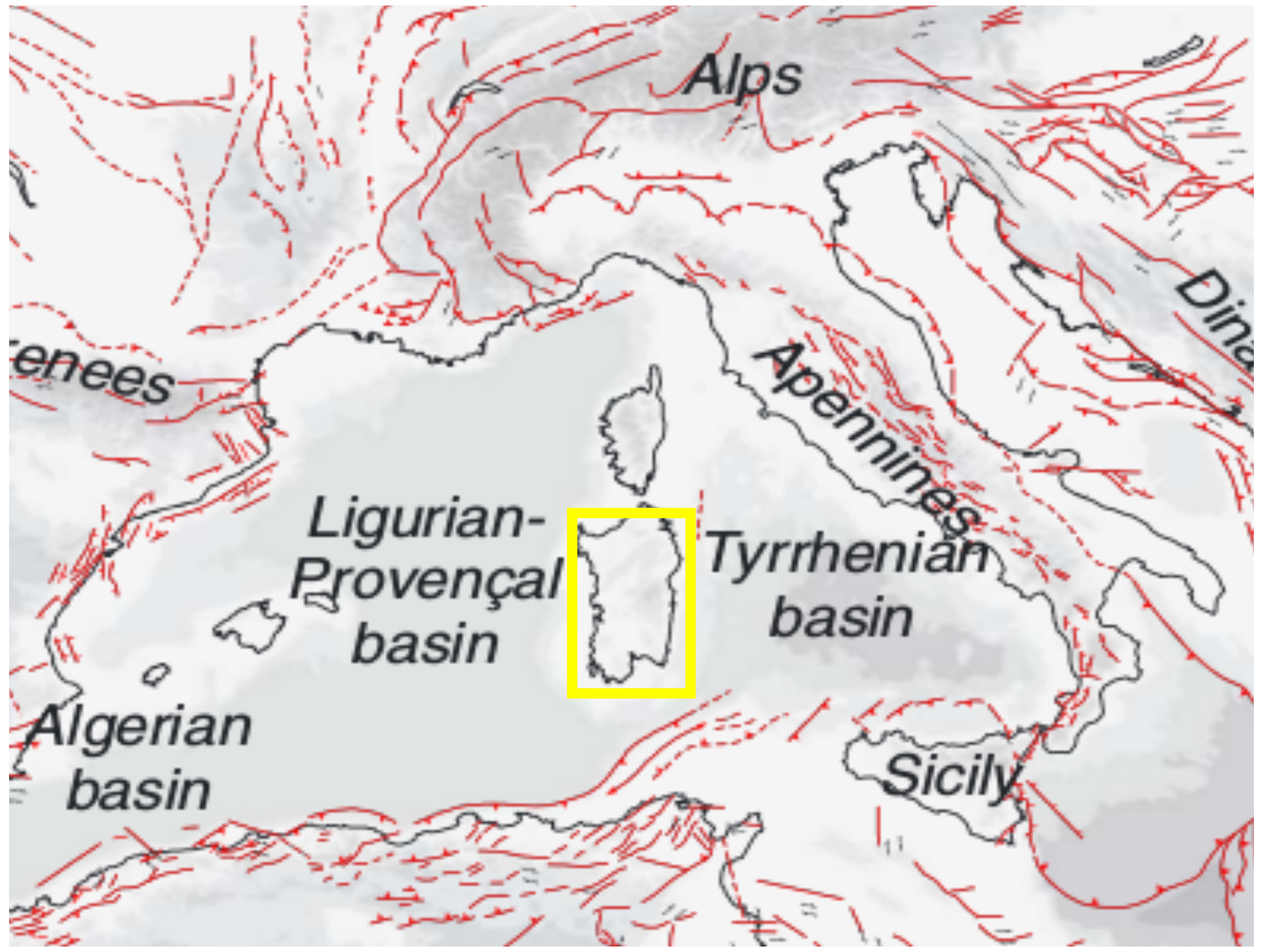


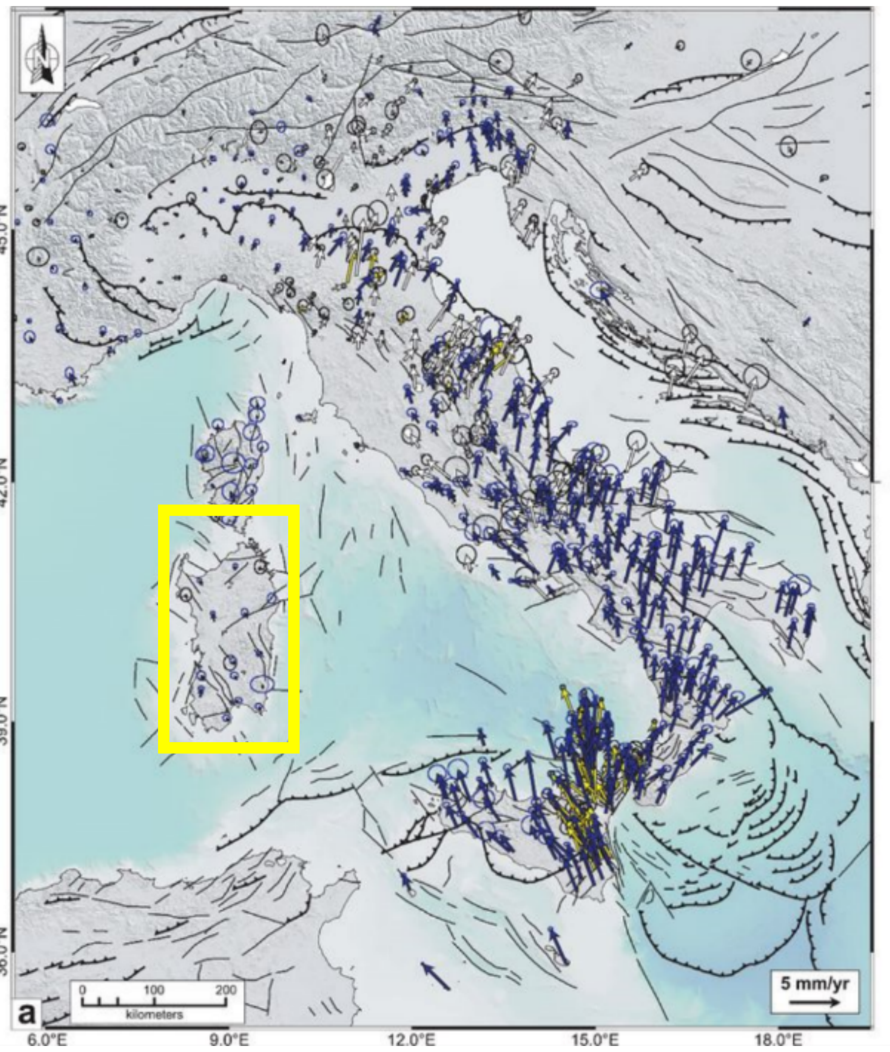


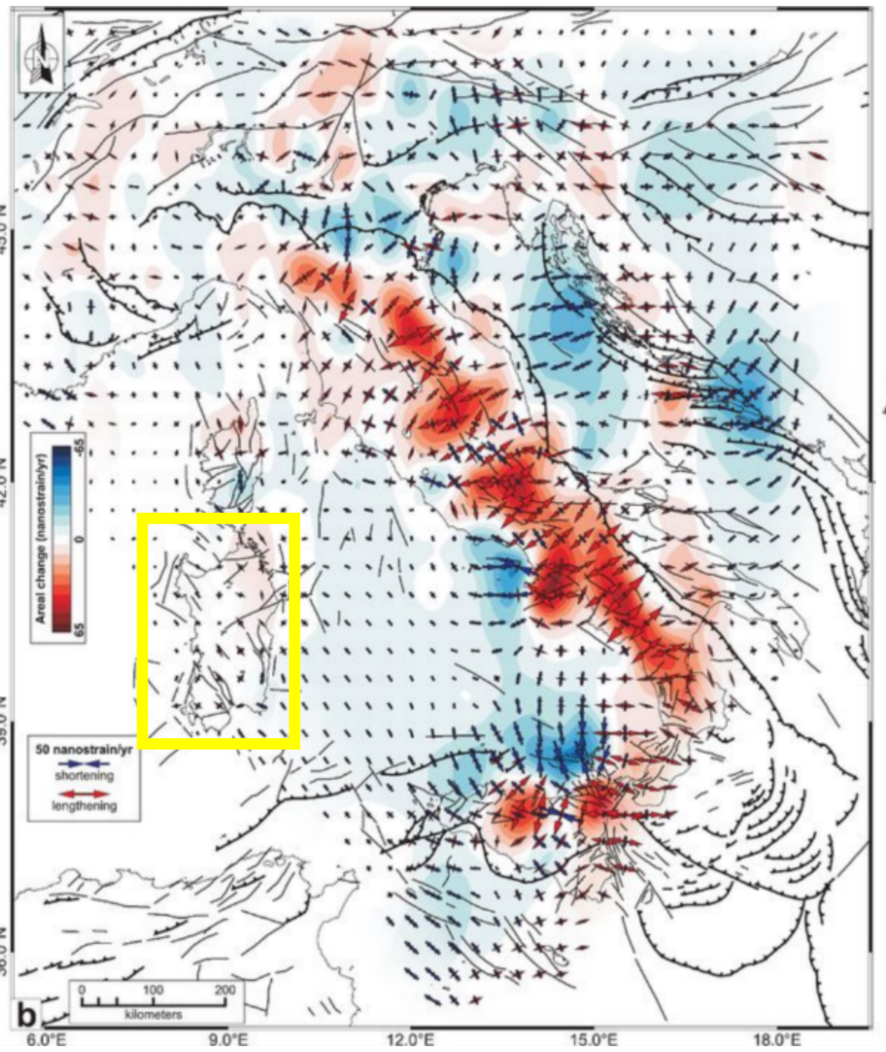
The Sardinia site

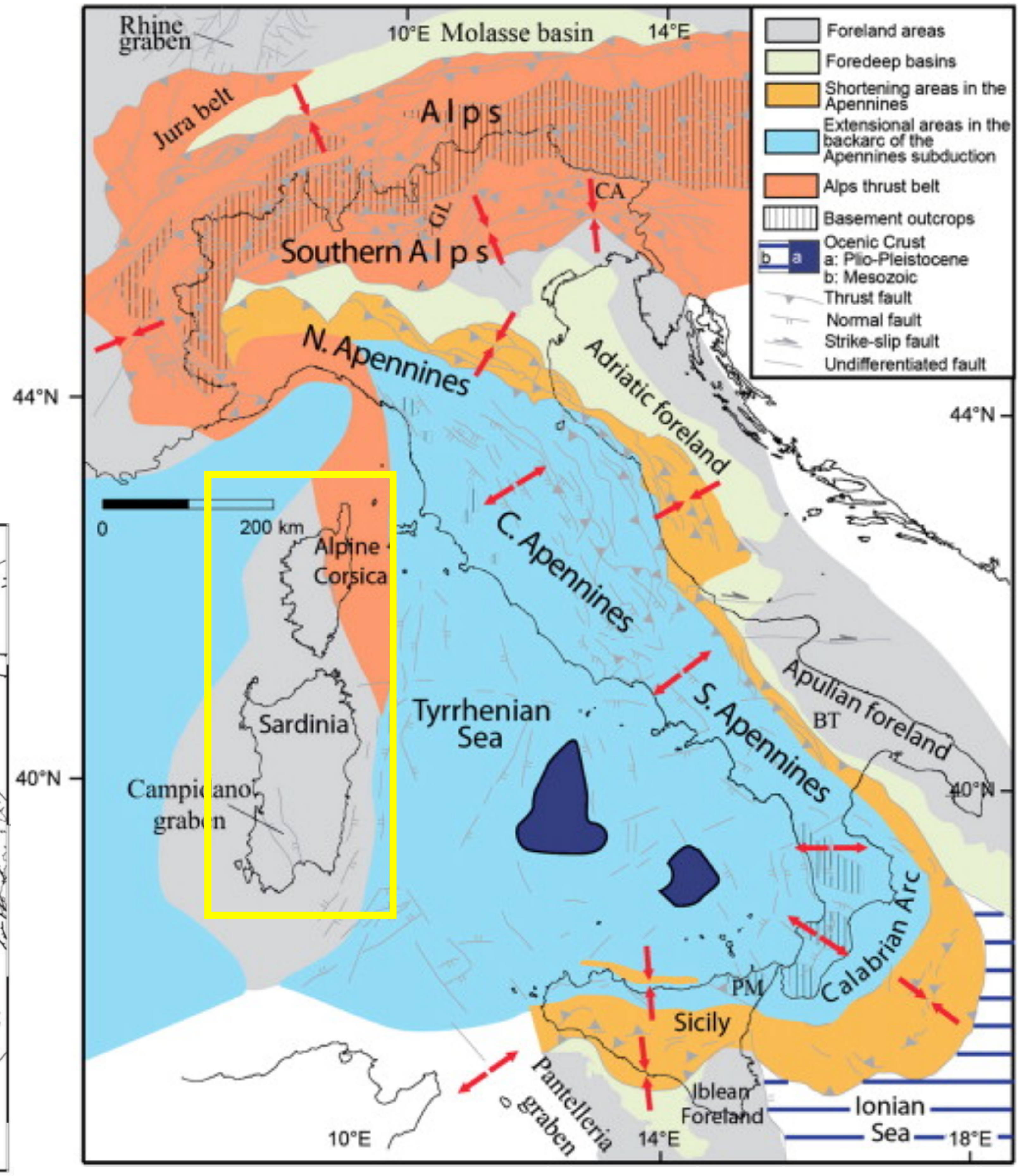
Sardinia and Corsica are on a separate microplate that is far from active fault lines and is very stable (low crustal deformation).

Unaffected by significative seismic activity.









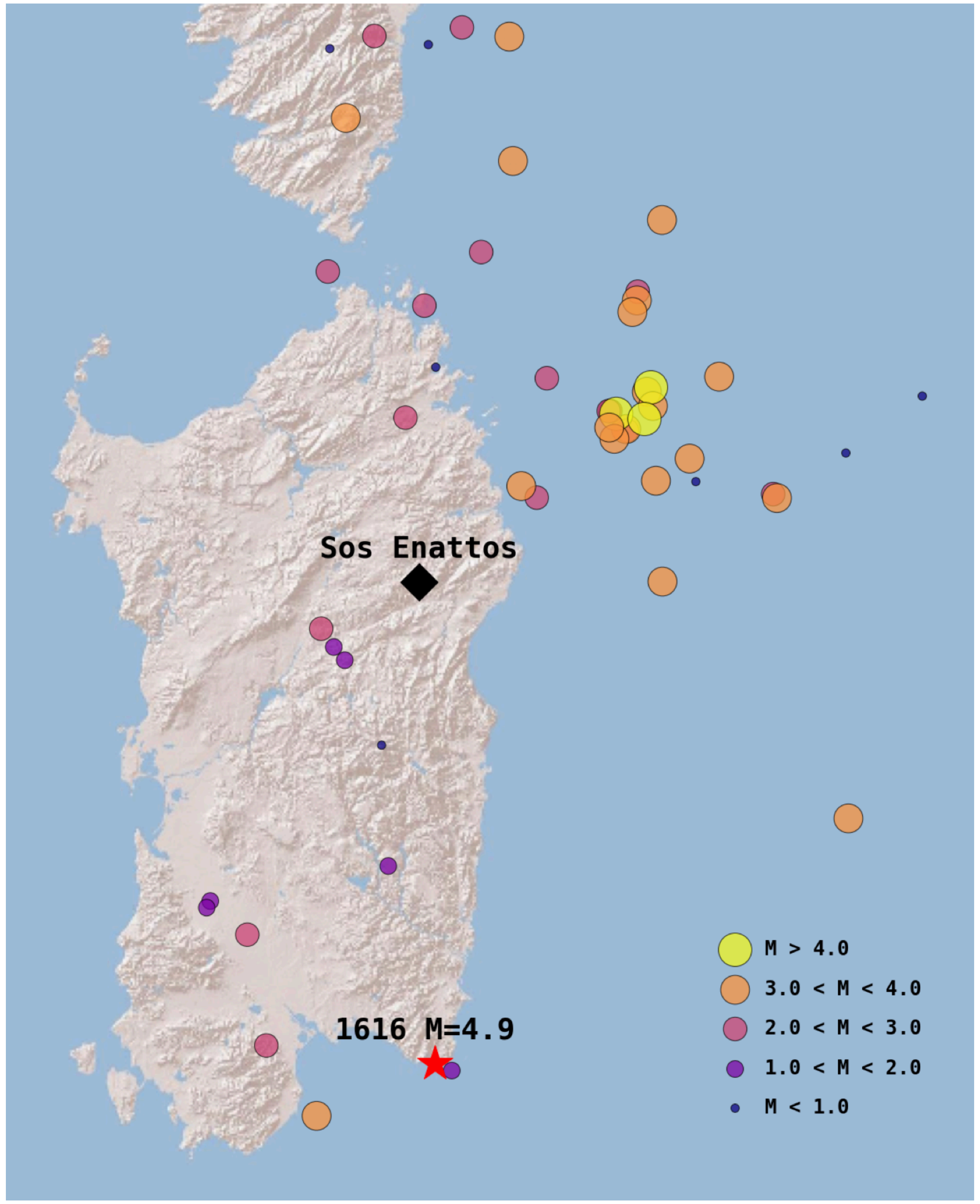
See also the talk by L. Cardello.

The Sardinia site

Since 1980, only 50 seismic events have been recorded In Sardinia. The events closest to Sos Enattos are all with M < 2.5.

Events with M > 3 occur offshore under the Tyrrhenian Sea.

Surveys in historical catalogues also report very sparse seismicity.



The Sardinia site

- in 2010, during the preparation of the first conceptual design of ET, several sites in Europe were studied for a 3G GW observatory. Among them, Sos Enattos in Sardinia appeared to be one of the most promising;
- The mine, although closed, was not abandoned. Therefore it provided the adequate manpower, infrastructure and experience to start underground characterization studies in 2014;
- Today, the mine is considered a regional heritage site and is open to guided tours. It also hosts the SarGrav laboratory and the Archimedes experiment;

Main well

Former mineral processing unit

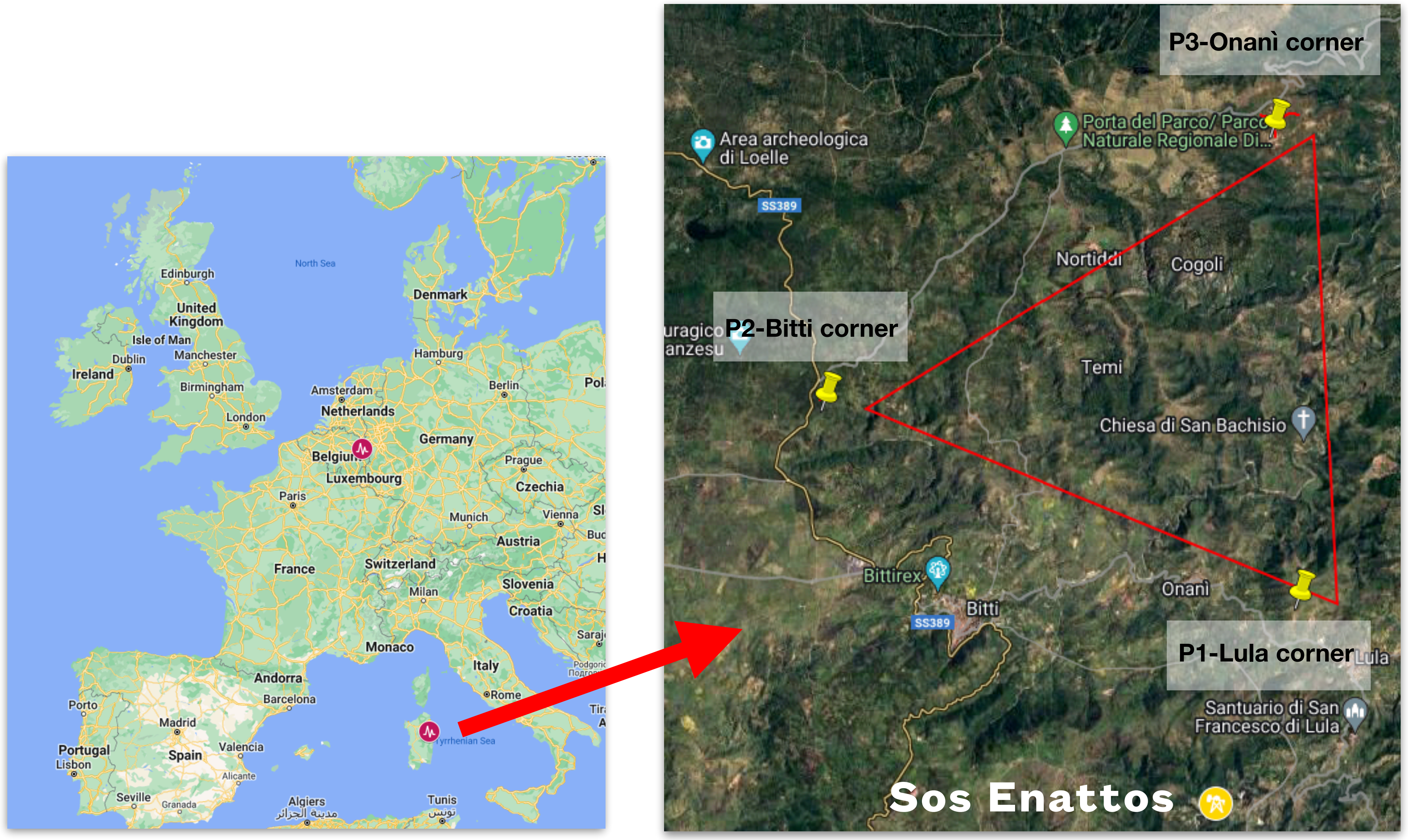
SarGrav laboratory

The Sardinia site

According to the current proposed orientation for the ET Triangle, the sites to host the actual vertices of the interferometer have also been identified.

The Onanì corner

The Bitti corner

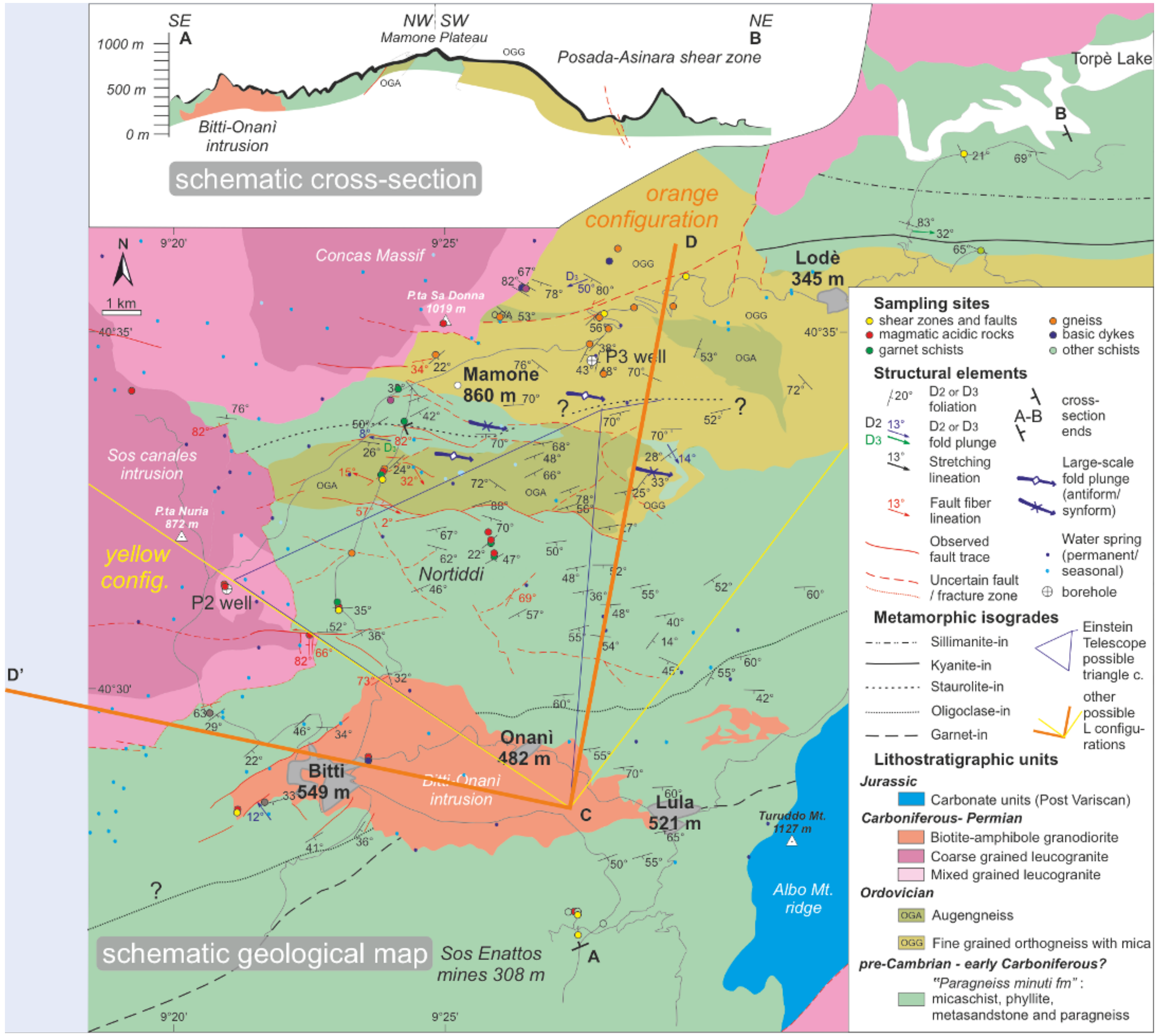


Proposed ET triangle orientation at the Sardinia Site.

The Sardinia site

The call for tender will also ask to study the L configuration.

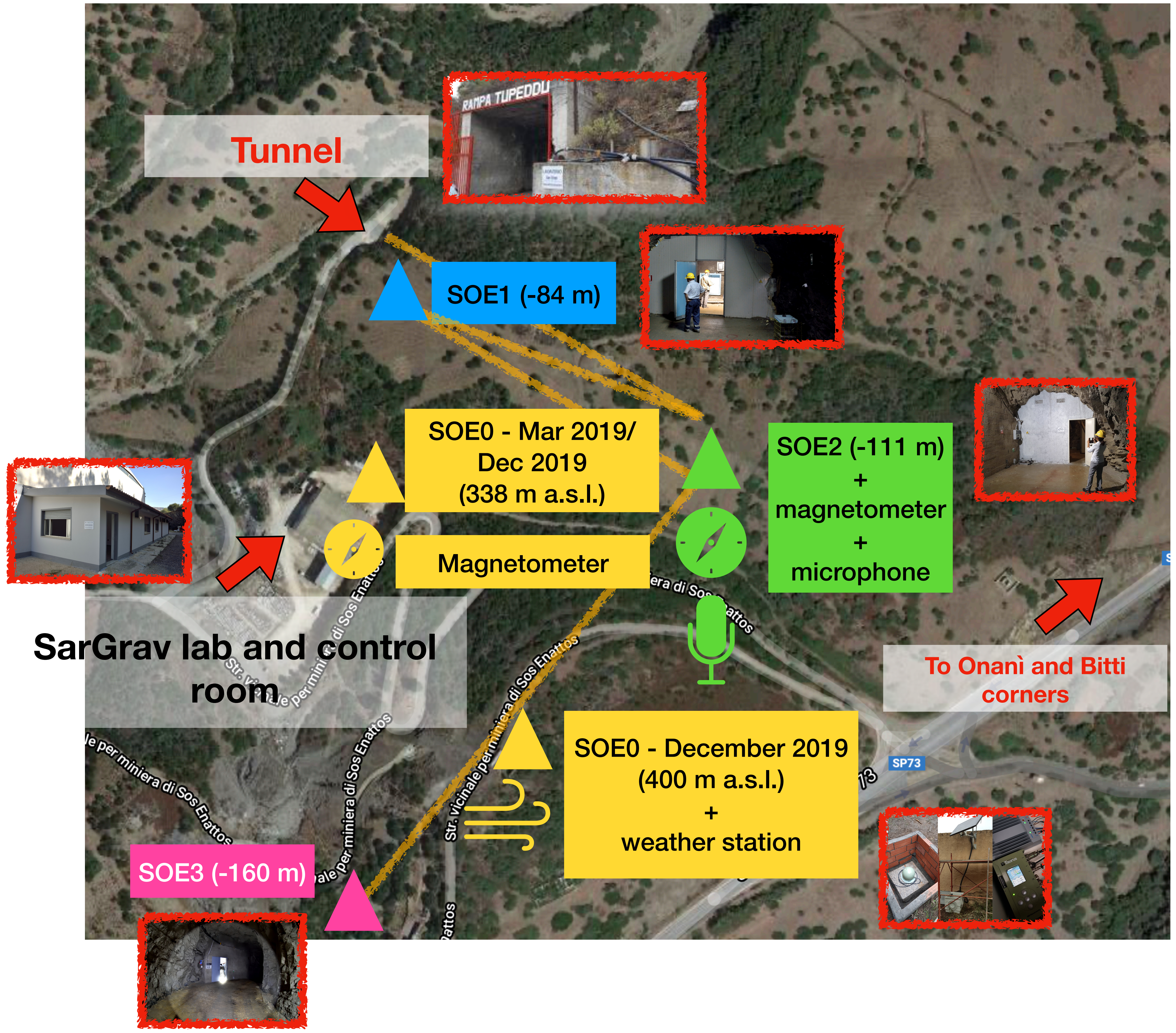
At the end of the call, the precise locations of the triangle corners and of the L end stations will be identified.



Permanent Instrument Network

Since 2019, in Sos Enattos there are:

- 4 permanent seismic stations for long term studies:
  - Surface: SOE0;
  - Underground: SOE1, SOE2, SOE3;
- 1 weather station;
- 1 microbarometer;
- High precision tilmeter as part of the Archimedes experiment;
- 2 microphones;
- 1 movable array composed of 8 short-period tri-axial seismometers;
- 3 magnetometers;
  - Surface: control room;
  - Underground: SOE2;
- All permanent seismic stations are provided with broadband seismometers (Trillium 240, 360 and 120 Horizon, Guralp 360);



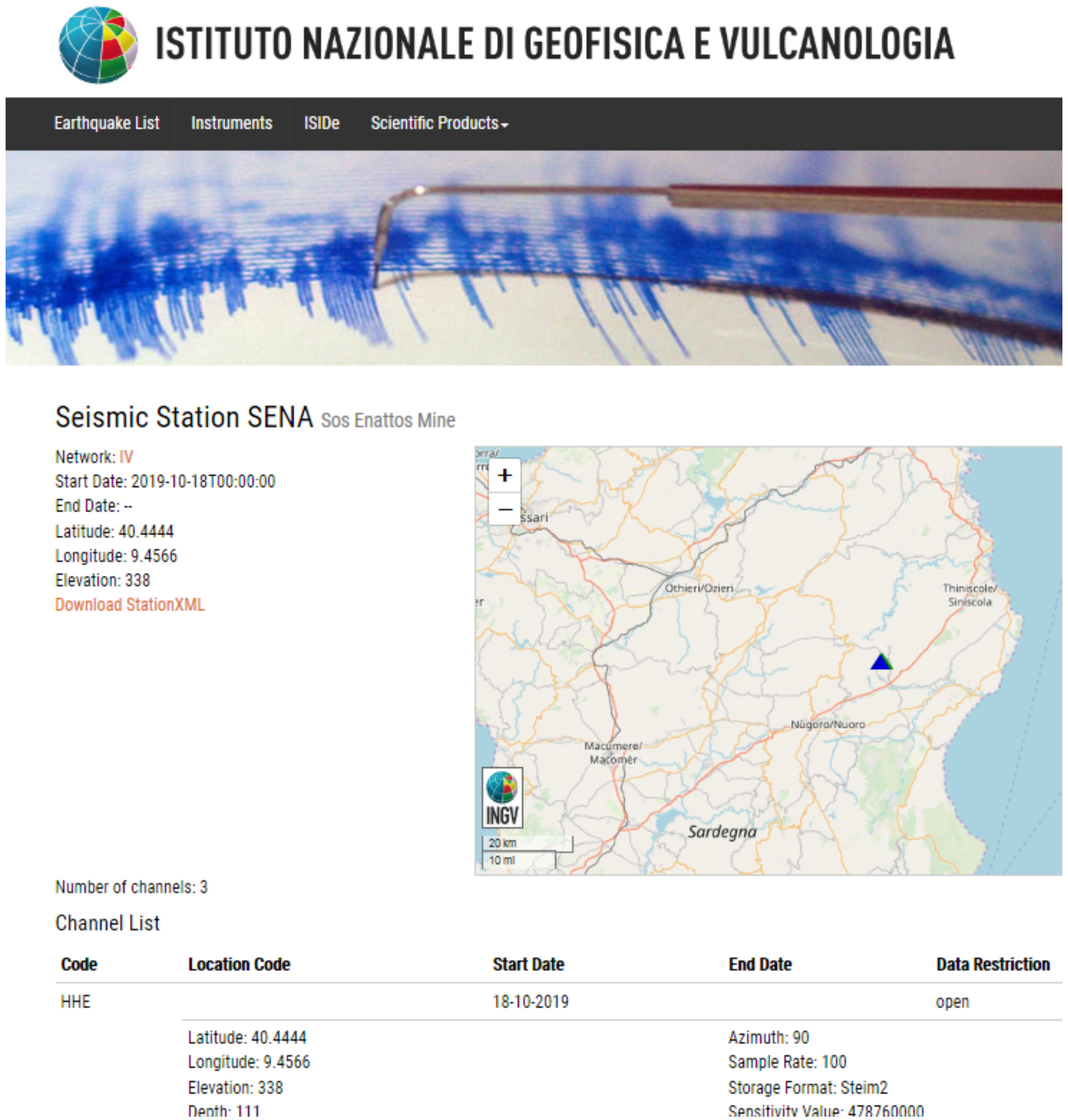
Permanent Instrument Network

In 2021, more permanent sensors have been installed at 2 of the proposed vertices (P2/3):

- 2 broadband seismometers on surface;
- 2 broadband seismometers in borehole;
- 2 magnetometers at P2

In the near future, more sensors will be installed also at P1.

Permanent Instrument Network



ISTITUTO NAZIONALE DI GEOFISICA E VULCANOLOGIA

Earthquake List | Instruments | ISIDe | Scientific Products

Seismic Station SENA Sos Enattos Mine

Network: IV
Start Date: 2019-10-18T00:00:00
End Date: --
Latitude: 40.4444
Longitude: 9.4566
Elevation: 338
Download StationXML

Number of channels: 3

Channel List

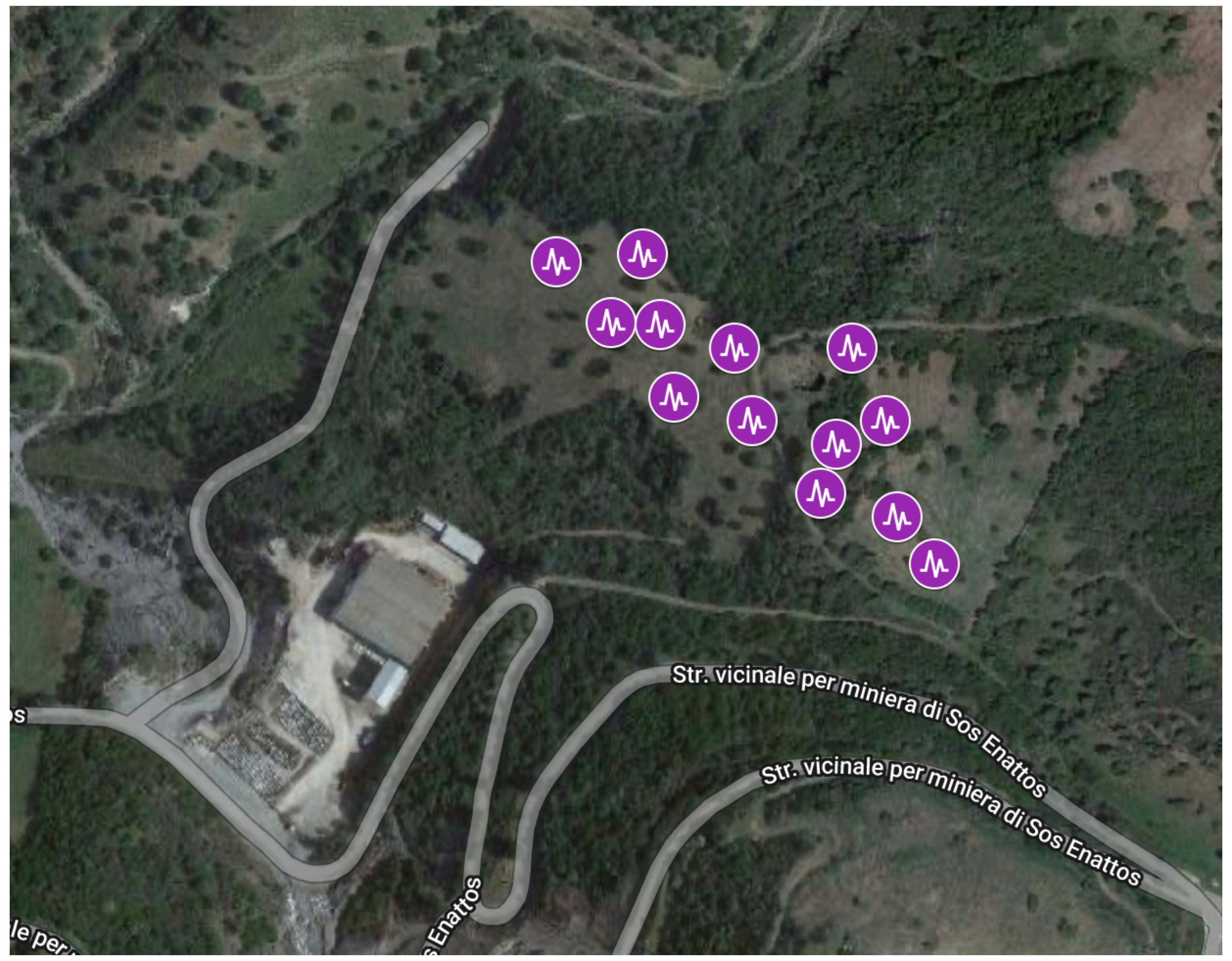
Code	Location Code	Start Date	End Date	Data Restriction
HHE		18-10-2019		open
	Latitude: 40.4444 Longitude: 9.4566 Elevation: 338 Depth: 111		Azimuth: 90 Sample Rate: 100 Storage Format: Steim2 Sensitivity Value: 478760000	

SOE2 station is integrated into the Italian national seismometer network of INGV. Station: **SENA**, network:

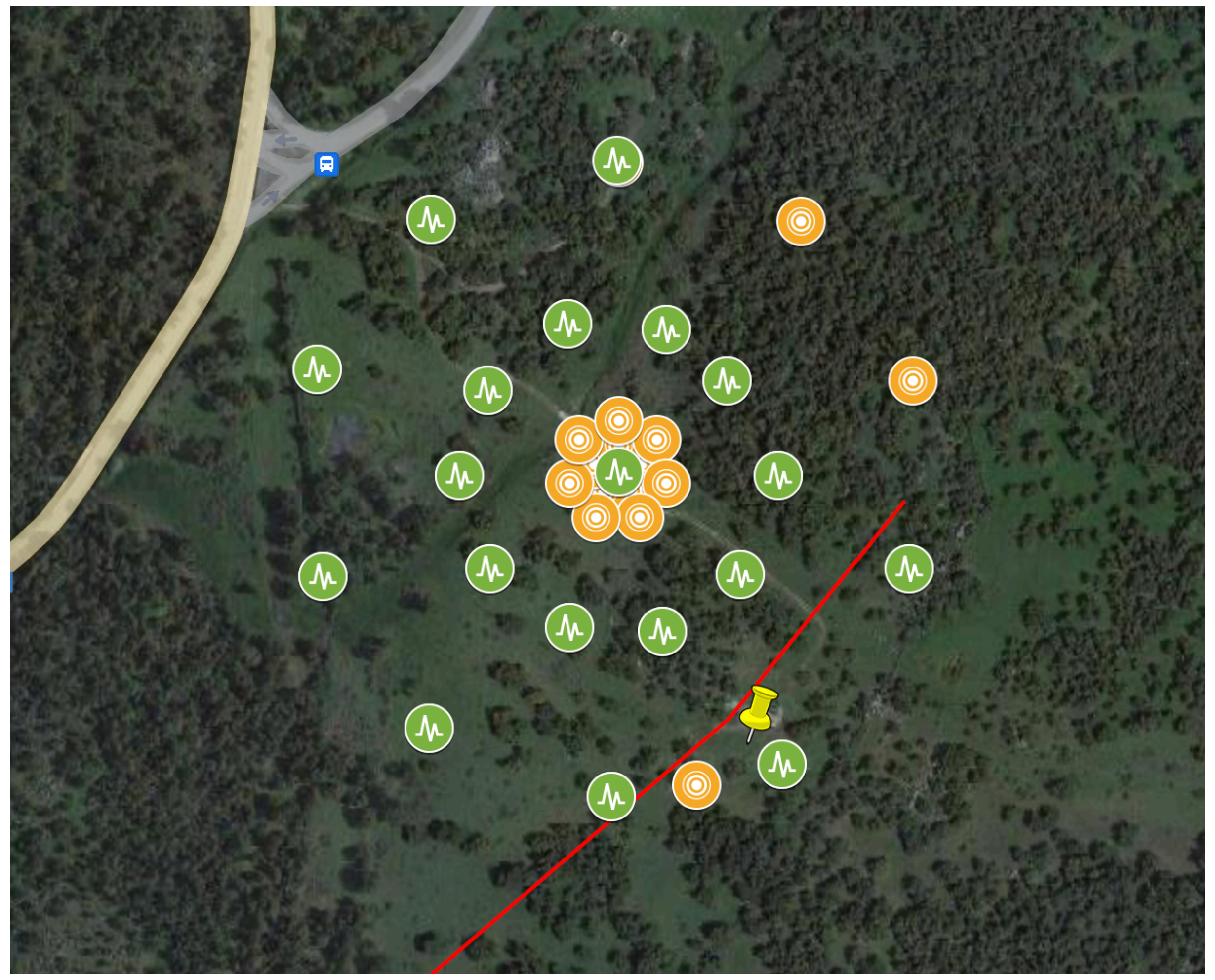
- IV (Italian National Seismic Network - INSN), 2019-2022/01
- MN (*Mediterranean Very Broadband Seismographic Network*) since 2022/02

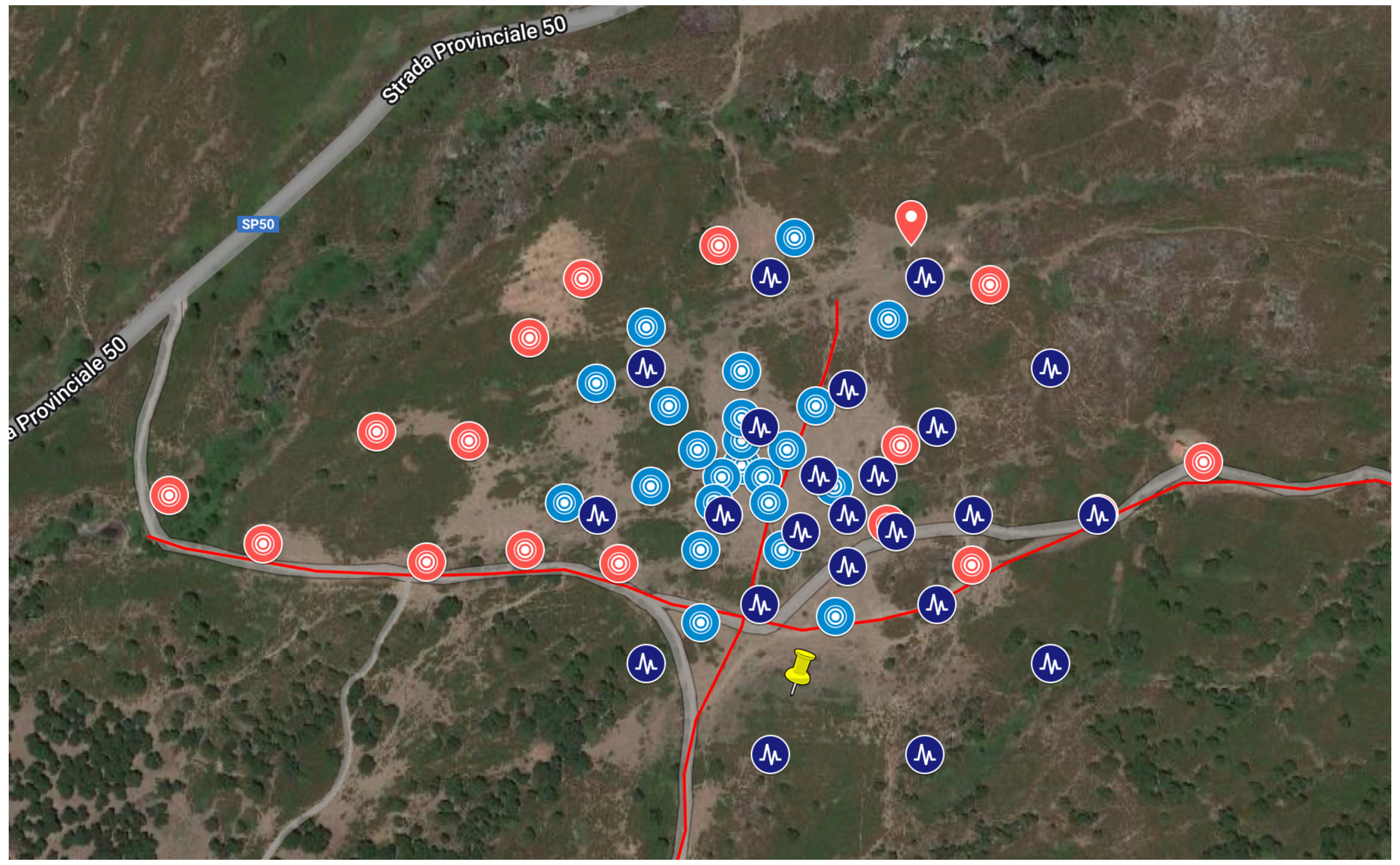
http://cnt.rm.ingv.it/en/instruments/station/SENA

Temporary Deployments



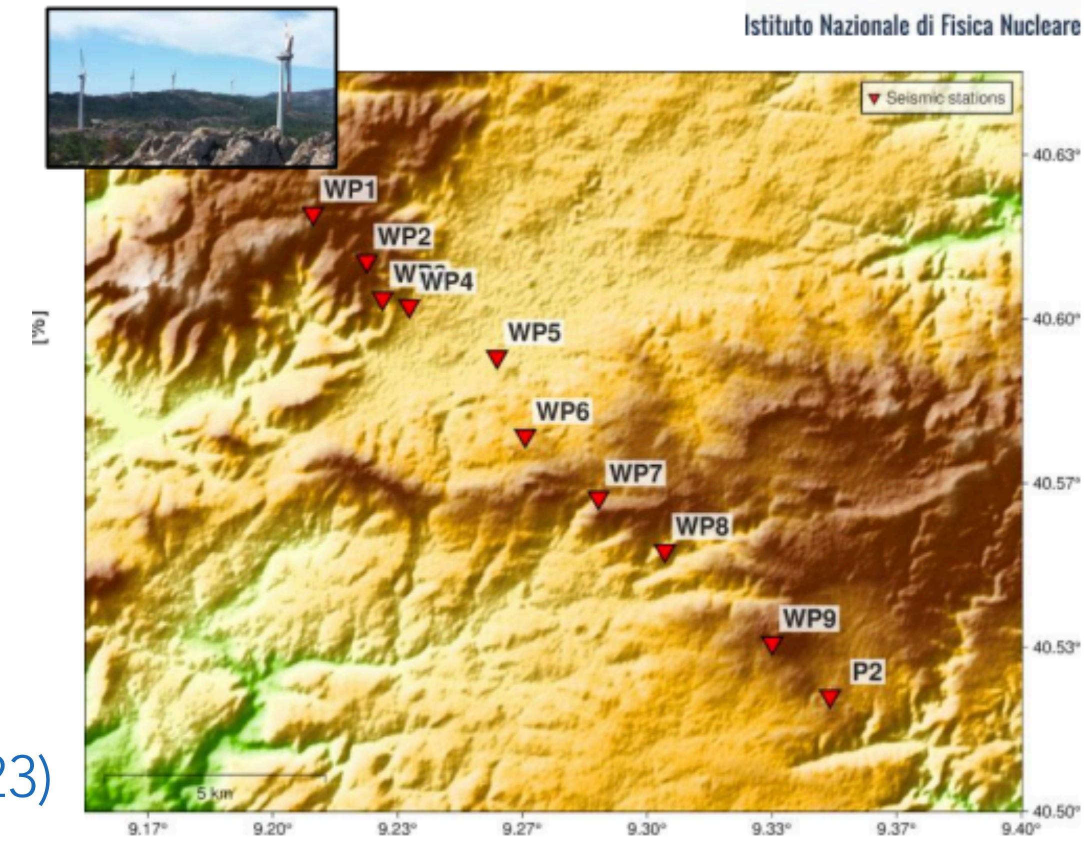
Sos Enattos - Broadband array (January 2021)


P2 broadband array + geophones (September 2021)



P3 broadband array + geophones (July & Oct 2021)

Aimed at characterization of the corners for seismic noise properties and NN purposes (correlation analysis).

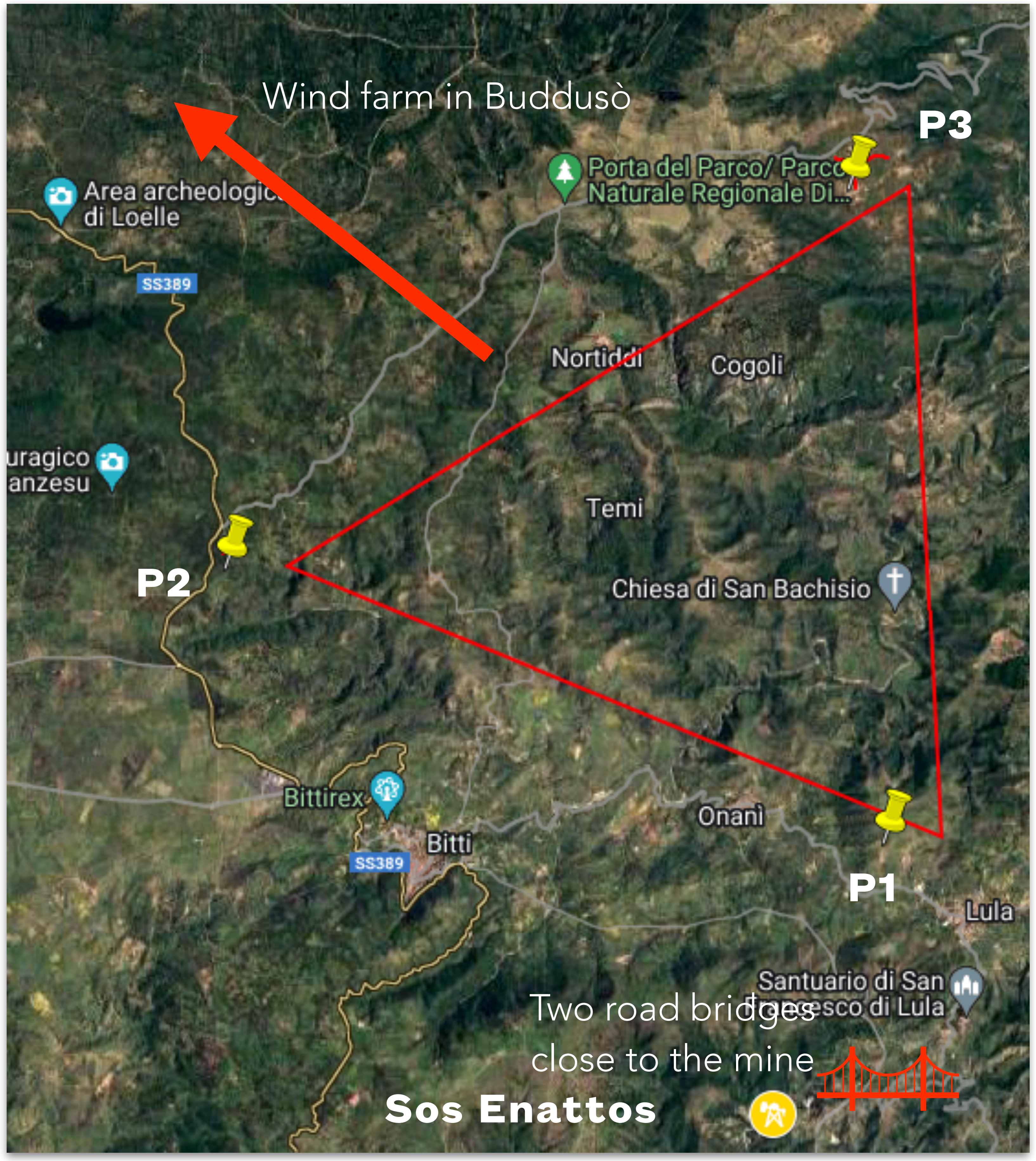


Broadband array (early 2023)

Potential noise sources

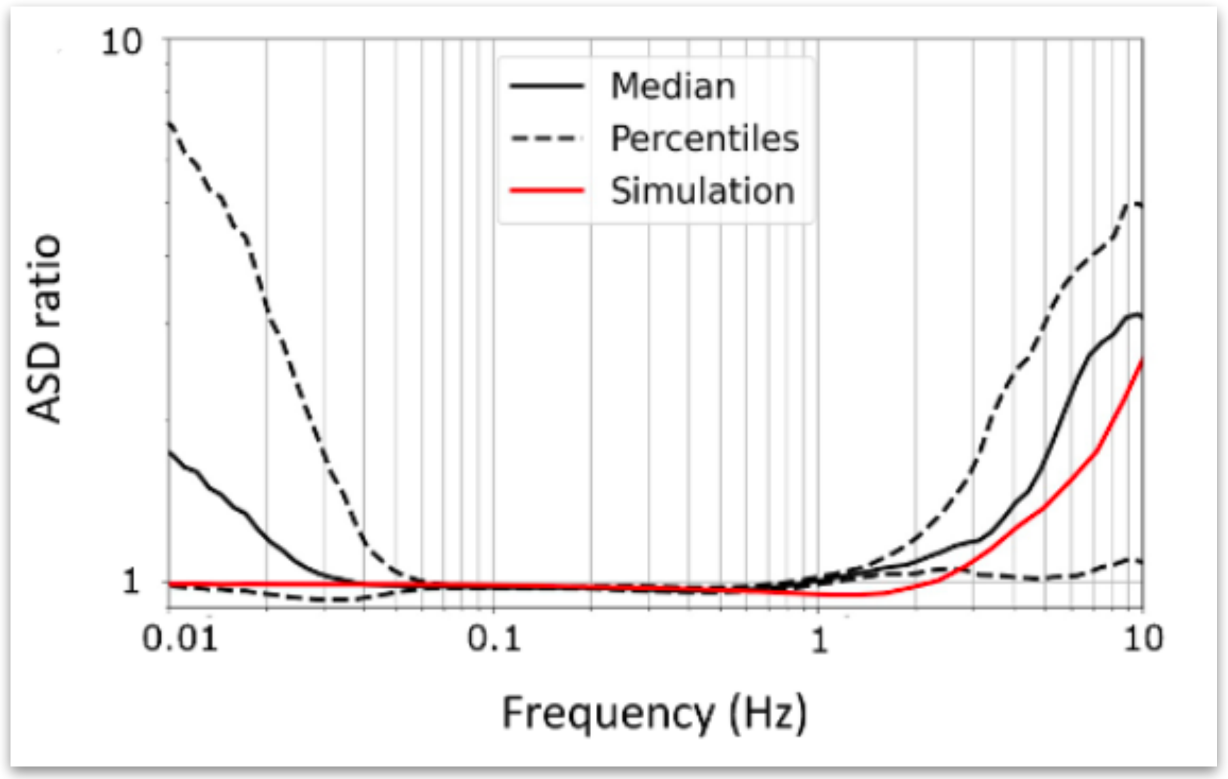
We identified some potential noise sources, both of natural and anthropic origin. Some of them have been clearly identified and characterized. Other are still being investigated to assess their contribution to the overall background noise in Sos Enattos.

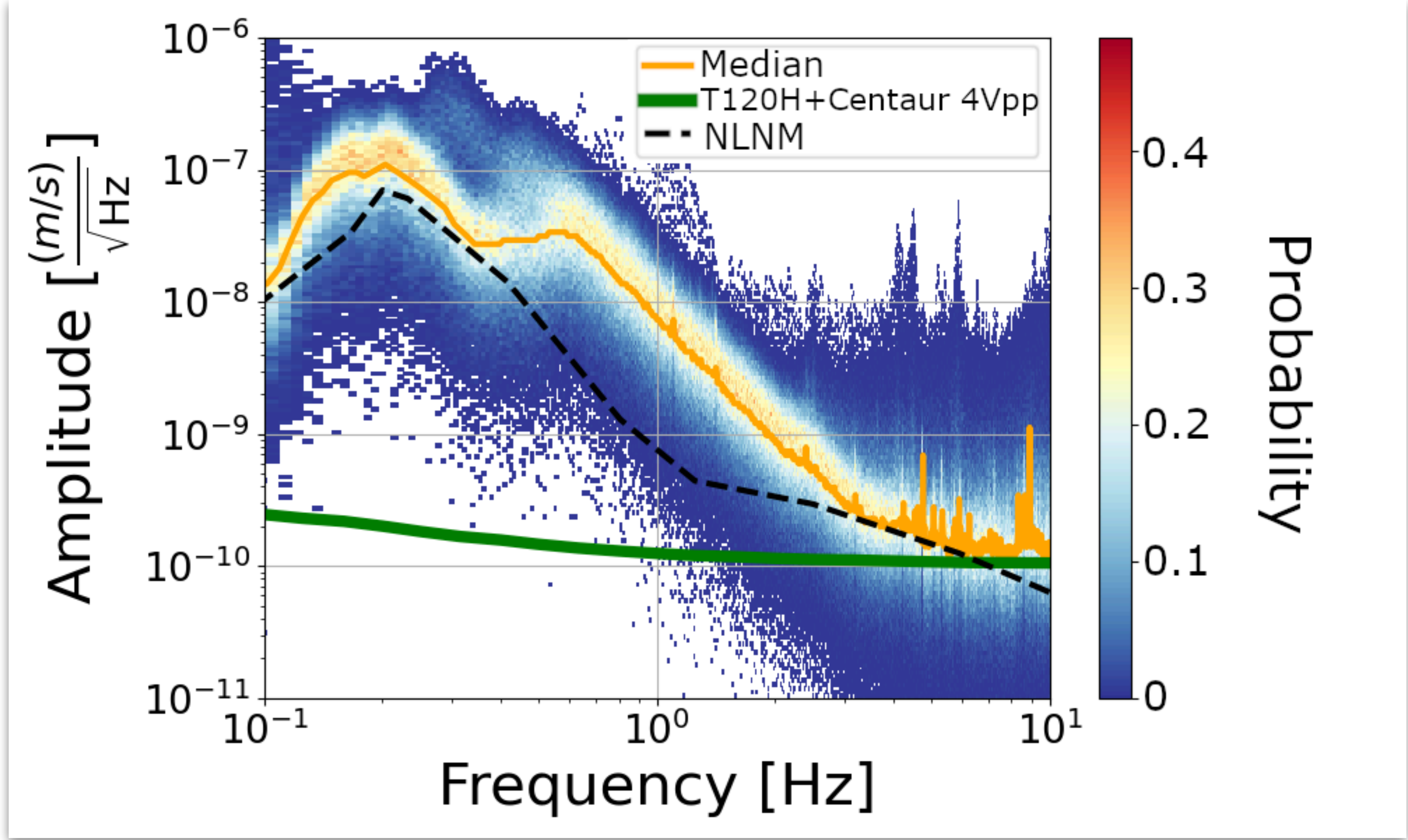
- Natural:
  - microseisms;
  - wind;
- Anthropic:
  - day/night cycle from human activities (mainly farming activities);
  - two road bridges in the neighborhood of the mine;
  - wind farms;
  - no other relevant infrastructures in the area.

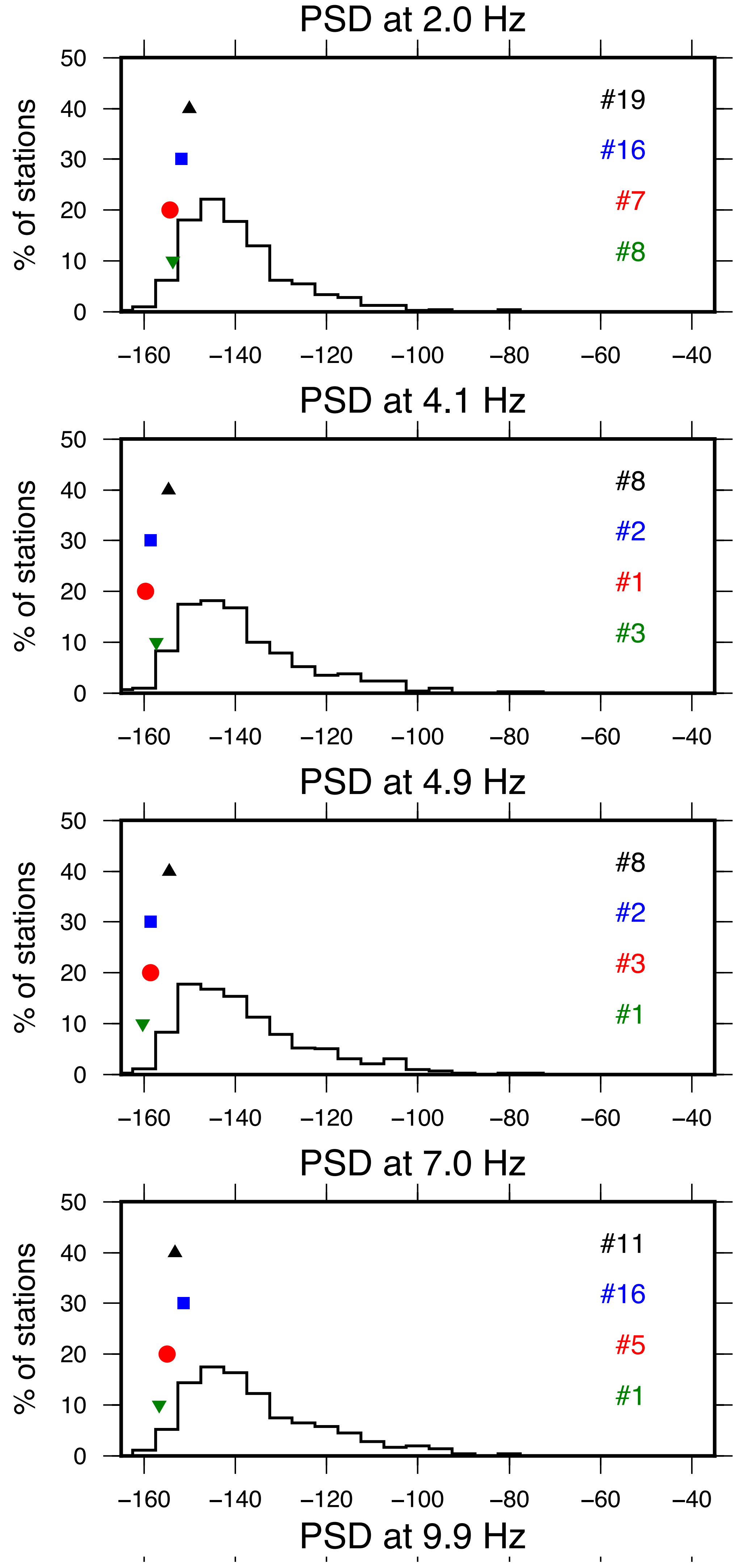


Noise levels

- Noise level in Sardinia are very low and hit the self noise of the seismometers;
- The seismic stations have an excellent raking between 2 Hz and 7 Hzwhen compared against other quiet seismic stations all around the world;
- For more details see Naticchioni et al. (2014, 2020) and Di Giovanni et al. (2021, 2023)

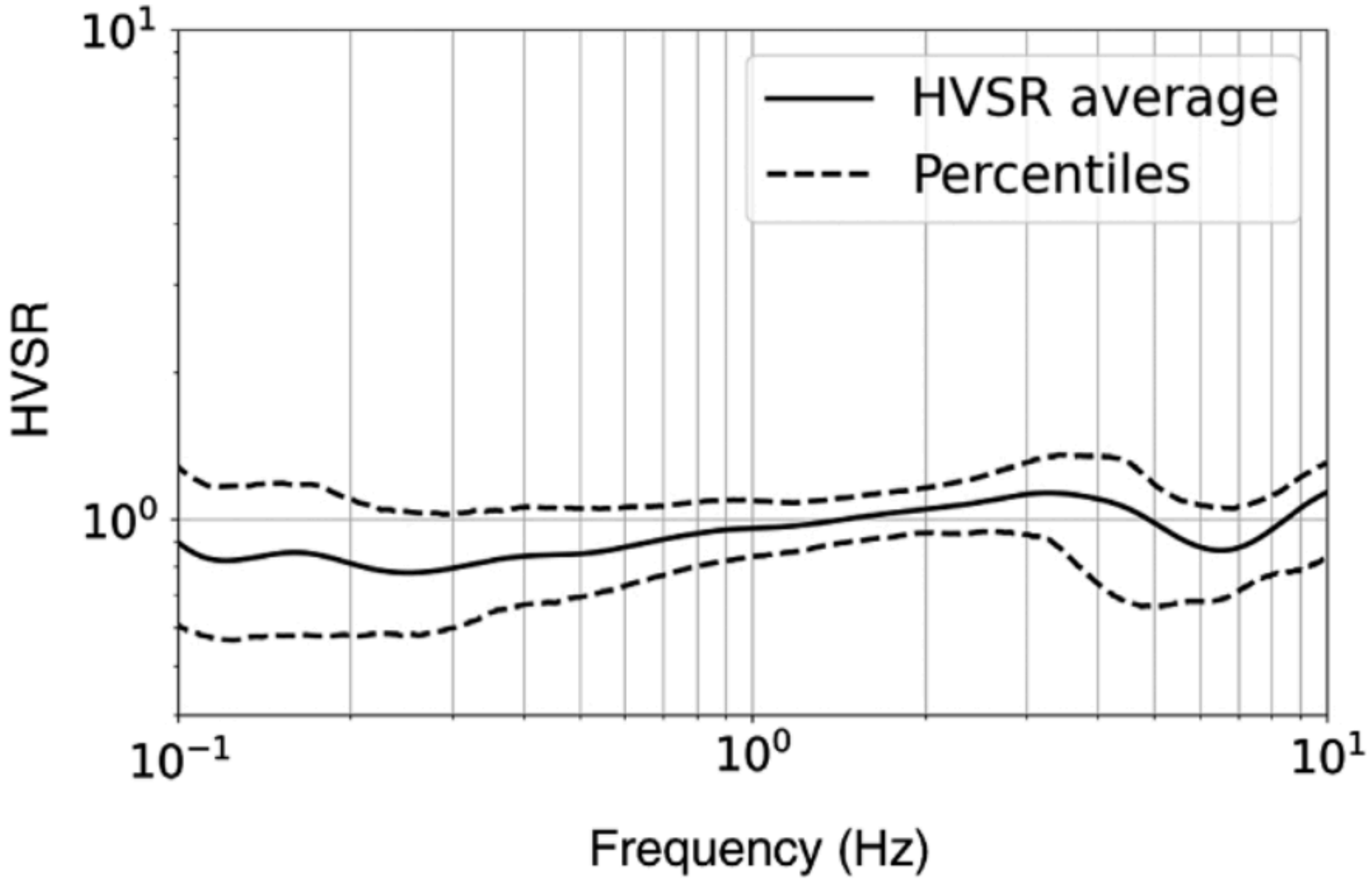


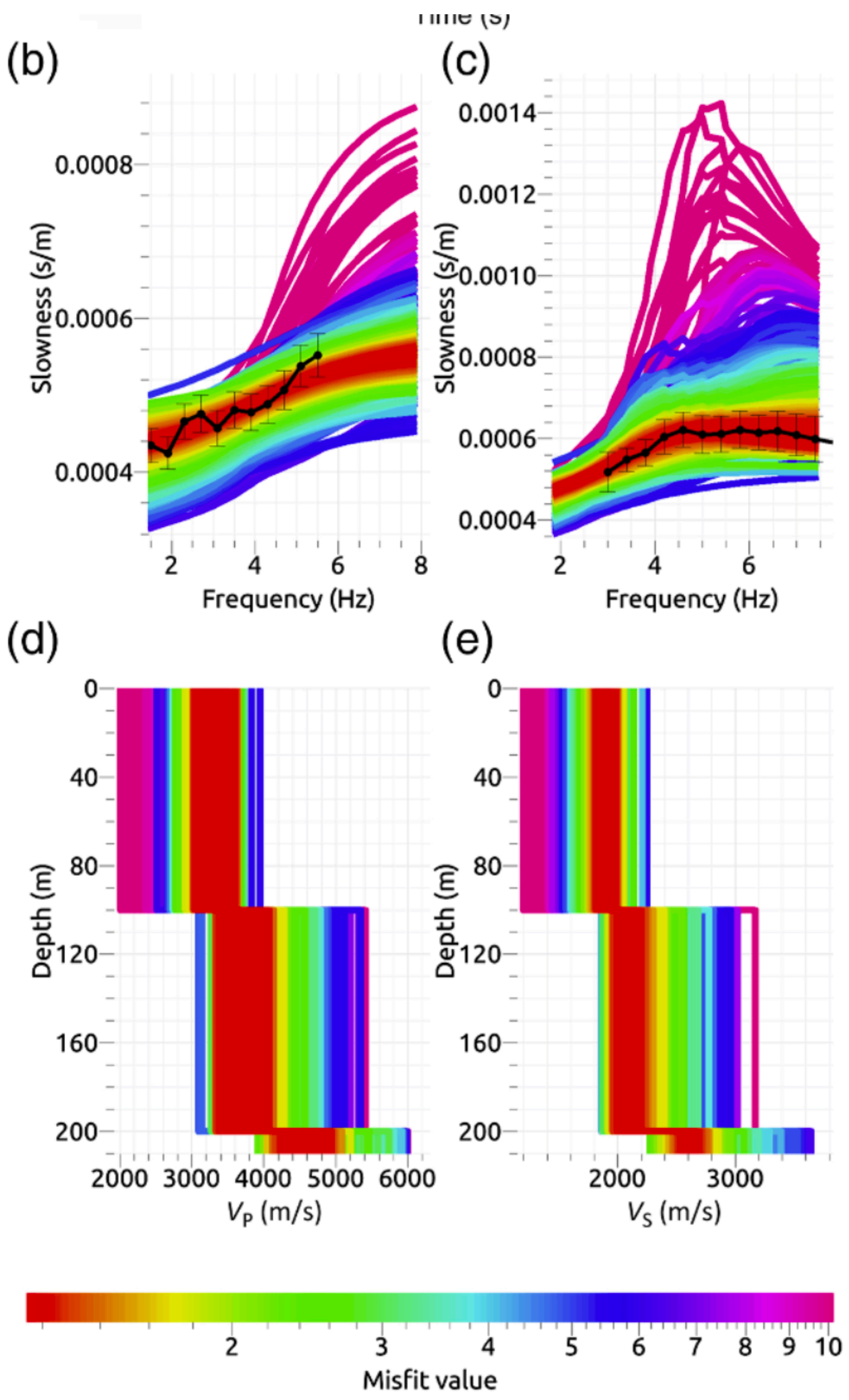




Seismic velocities

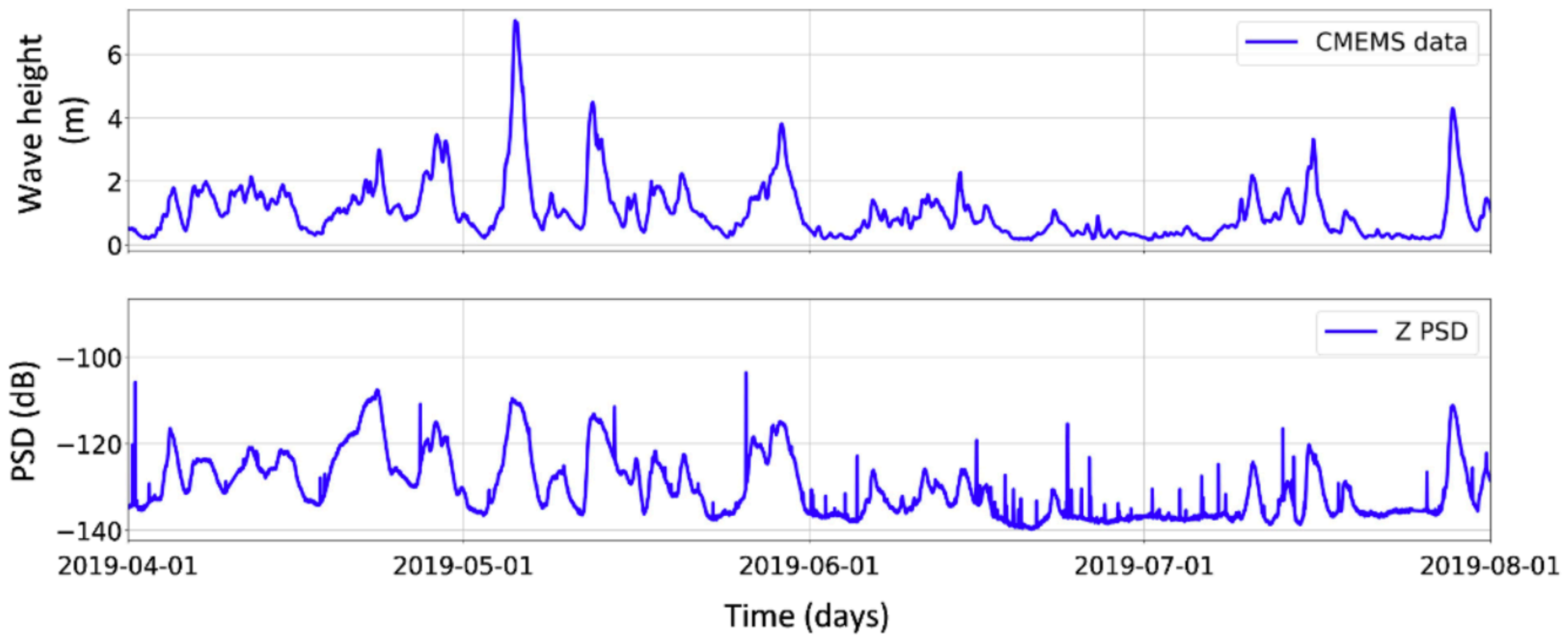
- Discontinuities in the composition of the underground layers may show up as resonances in the Horizontal-to-vertical spectra ratio;
- No peaks observed in Sos Enattos, using estimates of seismic velocities we get uniform soil up to 3 km underground



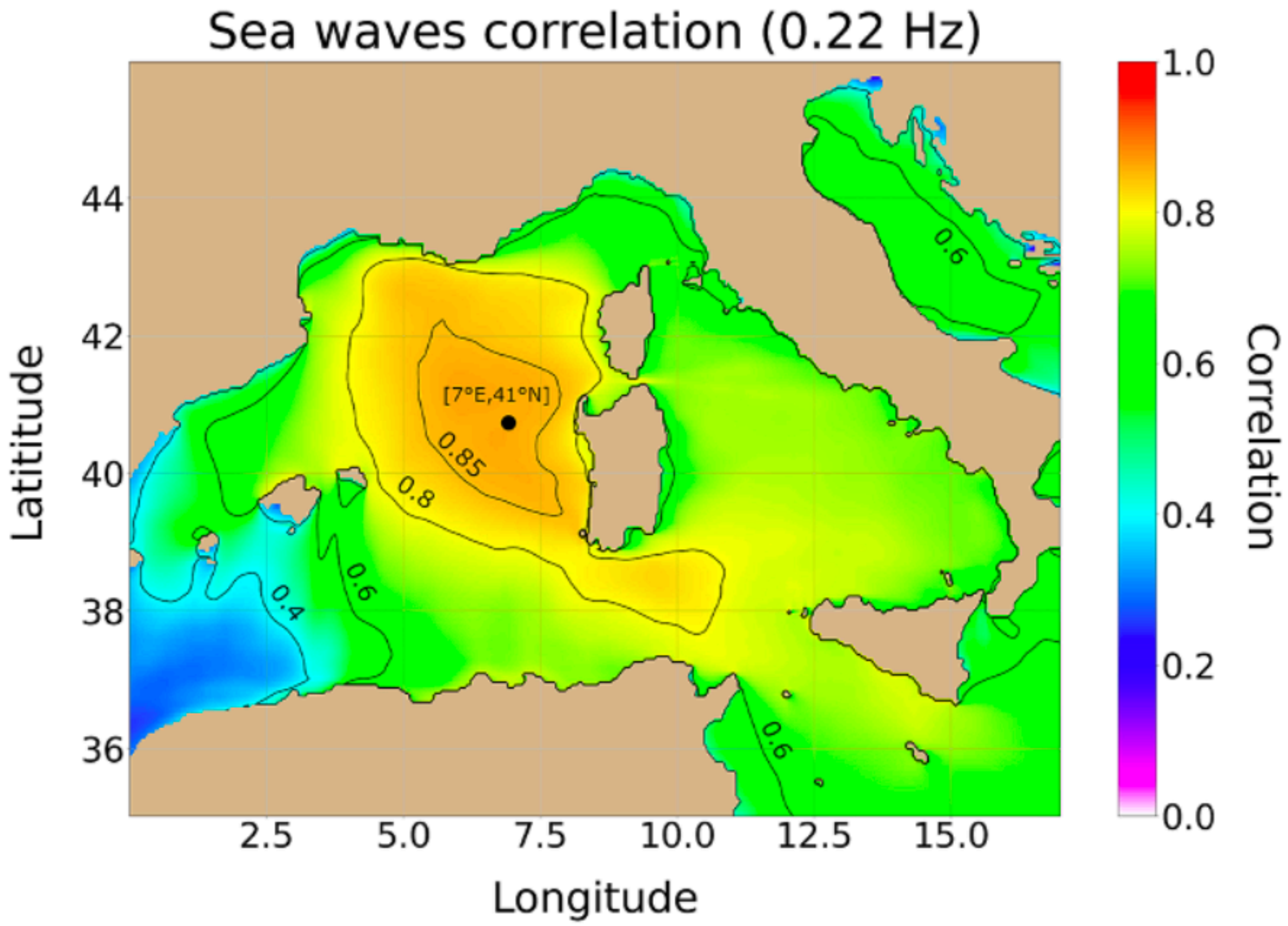


Ambient noise (natural sources)

- Using correlation and polarization analysis, we identified the region of the Mediterranean Sea that contributes the most to the generation of microseisms;
- The identified region is in agreement with previous seismological studies of the Mediterranean basin [Chevrot et al. 2007];



DOI 10.1785/0220200186



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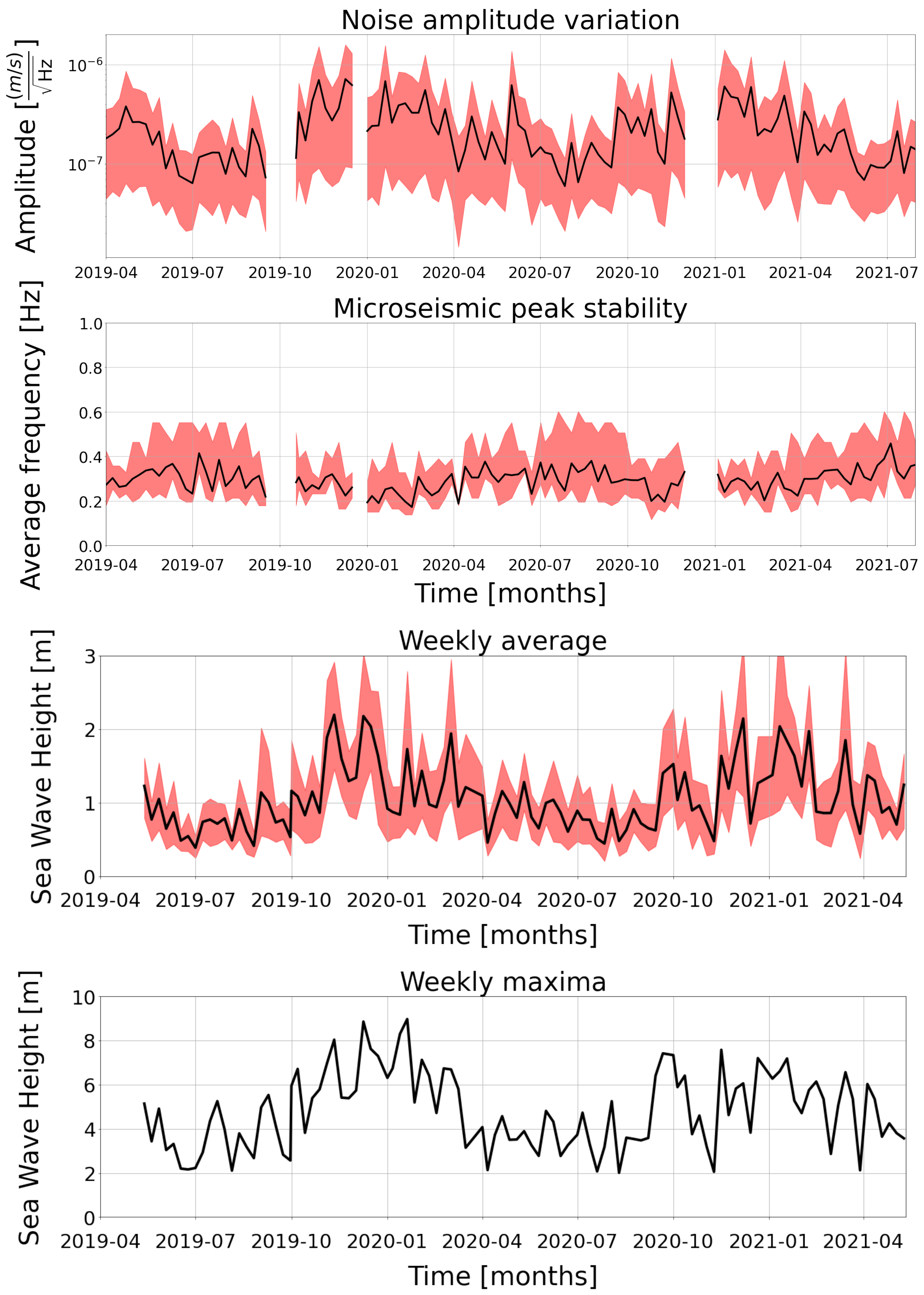
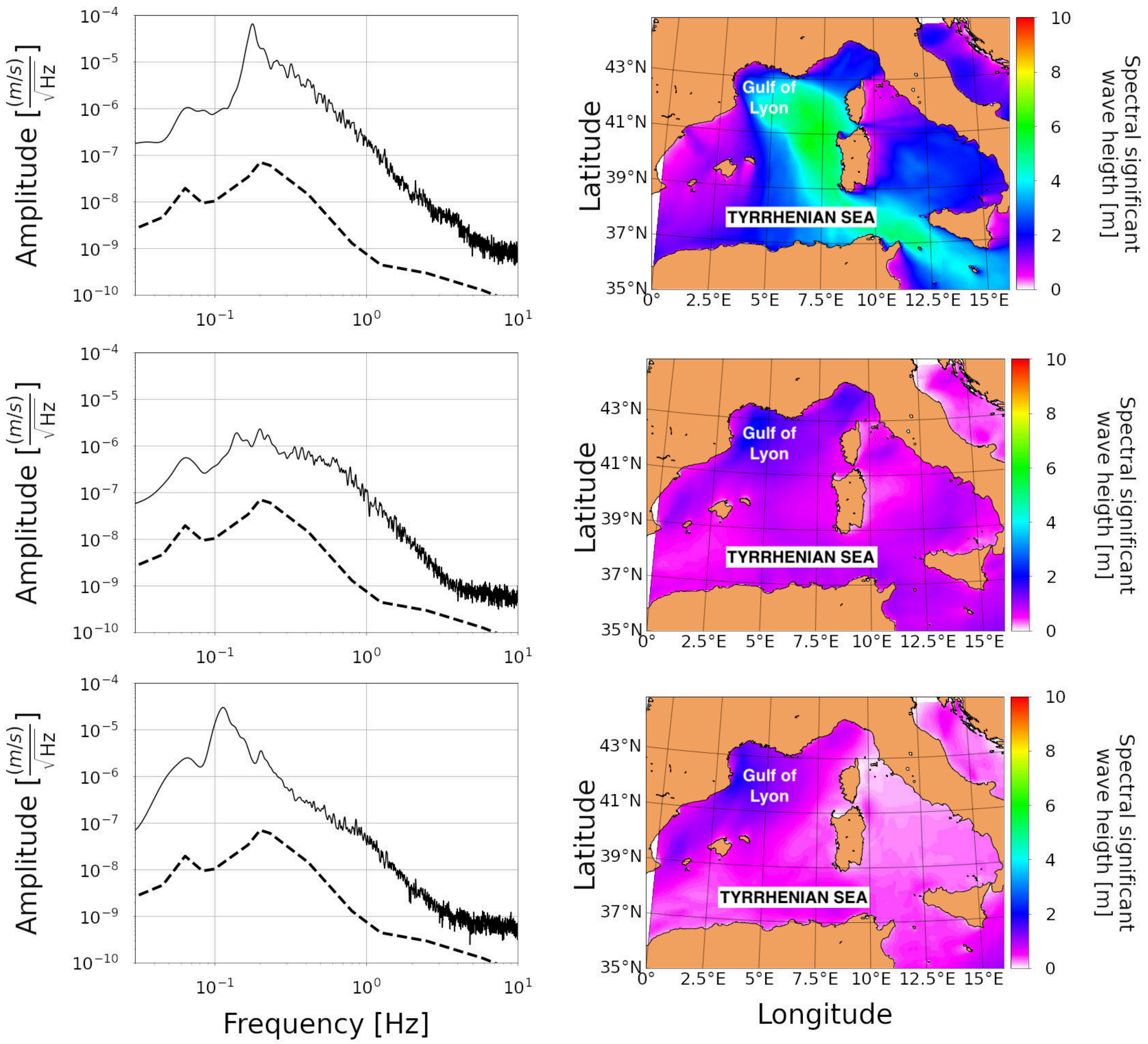
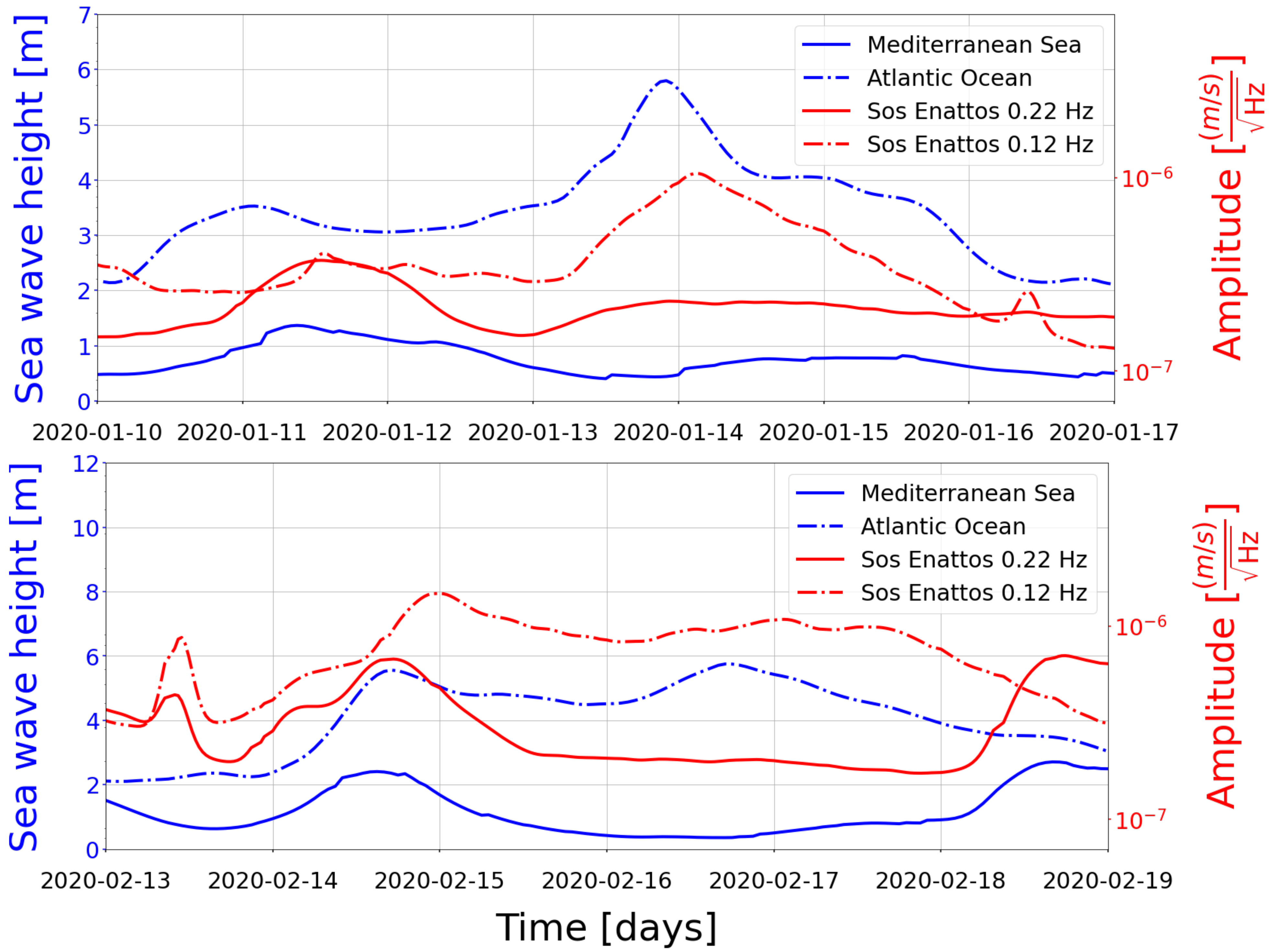
Ambient noise variations (natural sources)

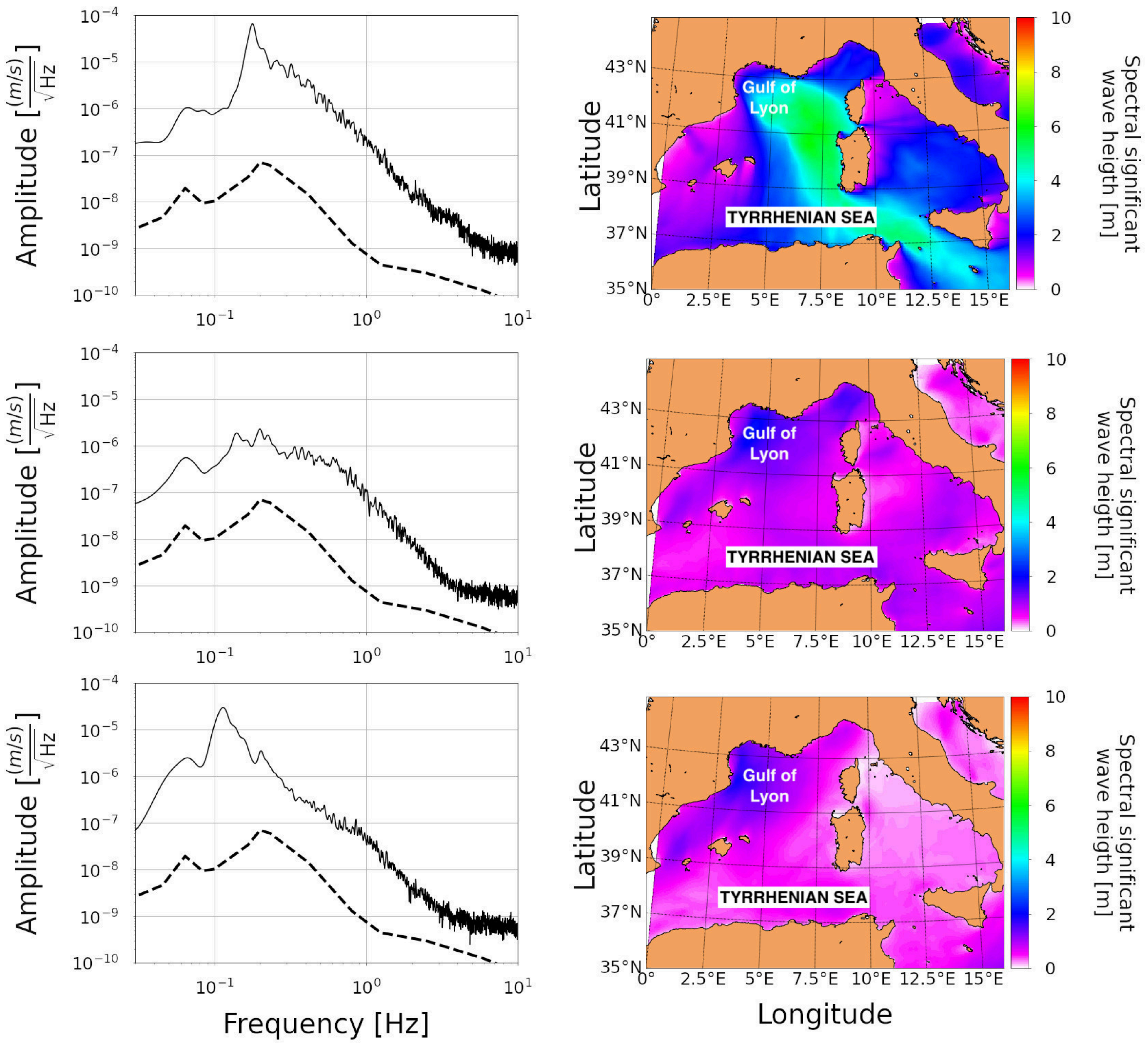




DOI 10.1093/gji/ggad178

Ambient noise variations (natural sources)

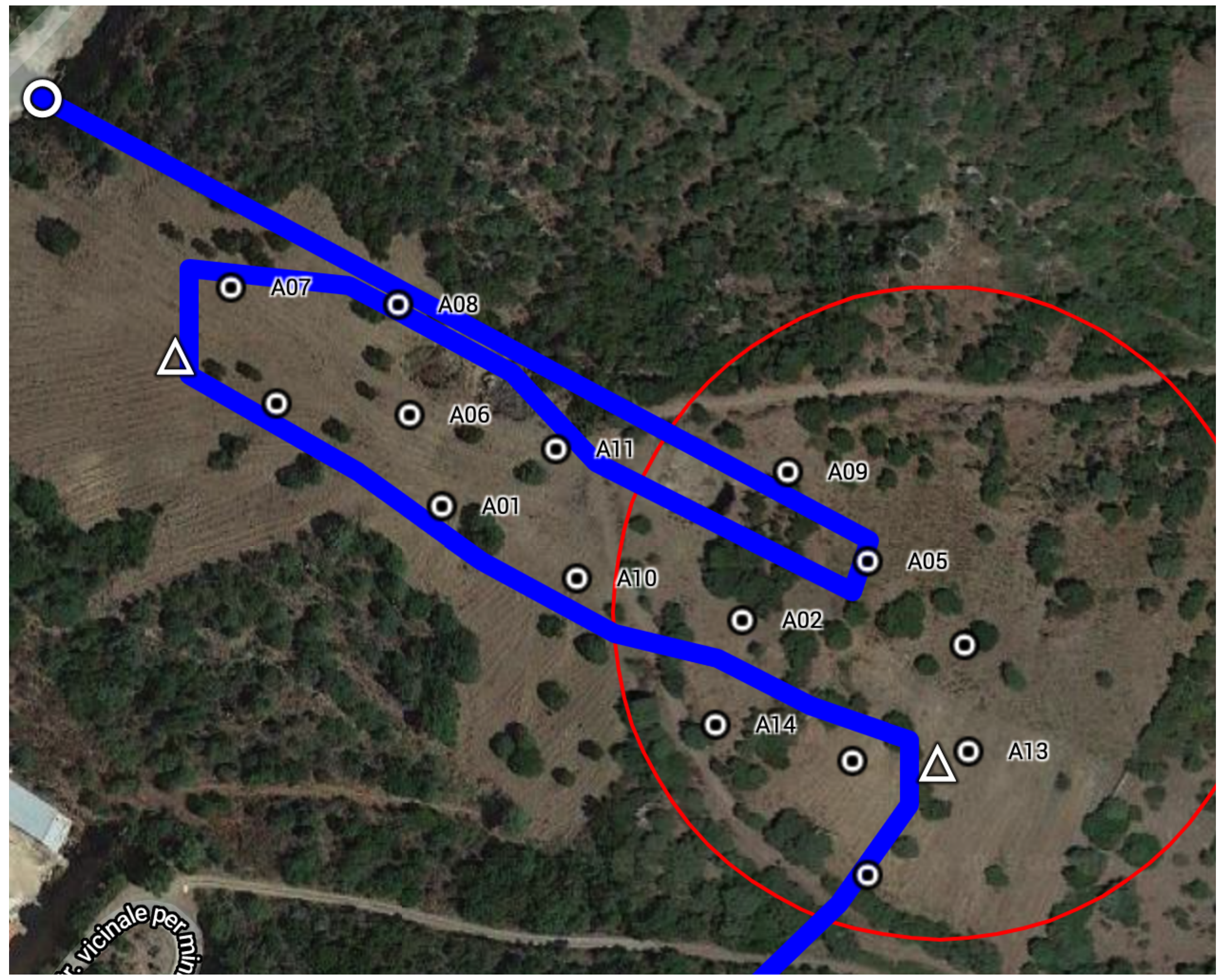


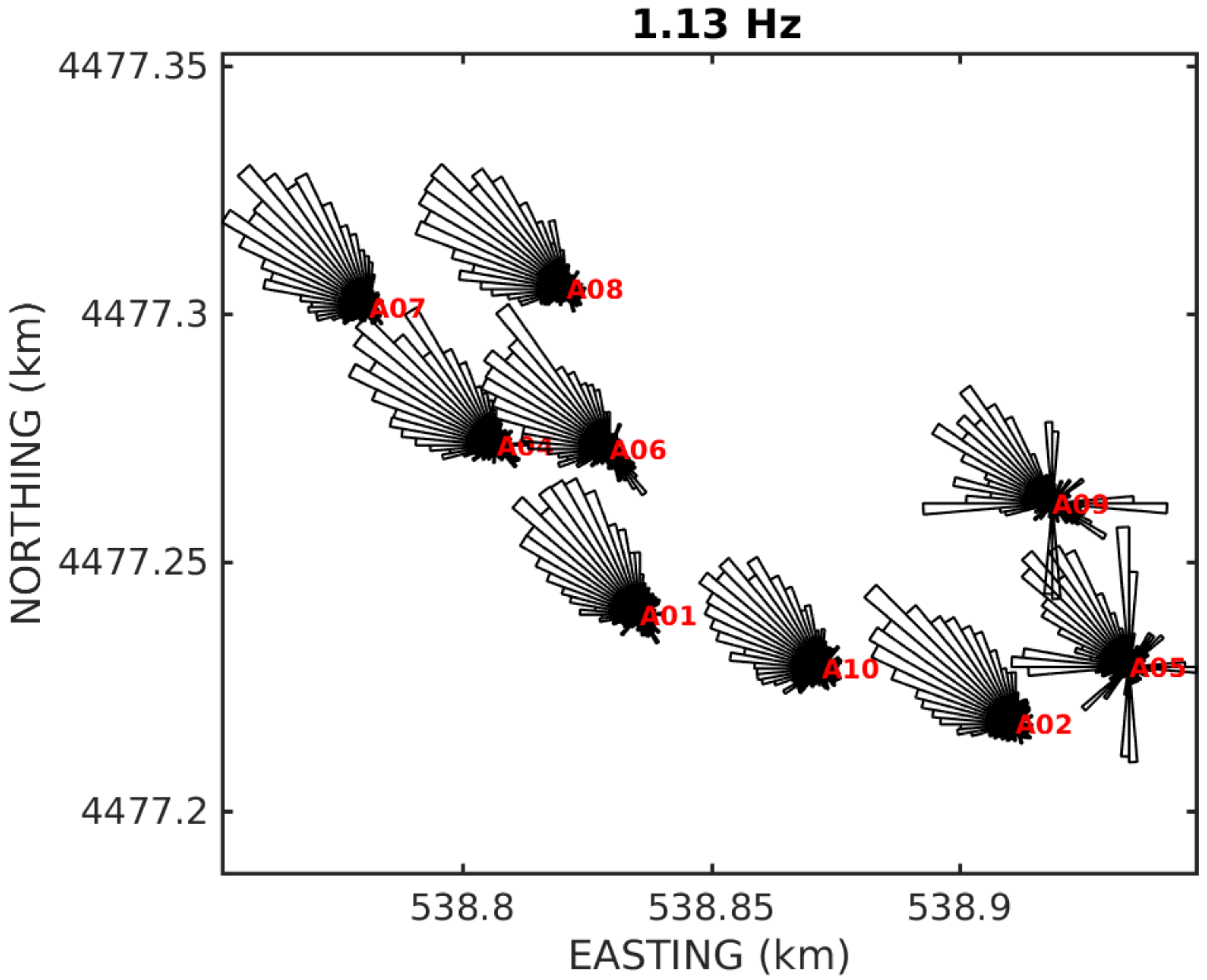


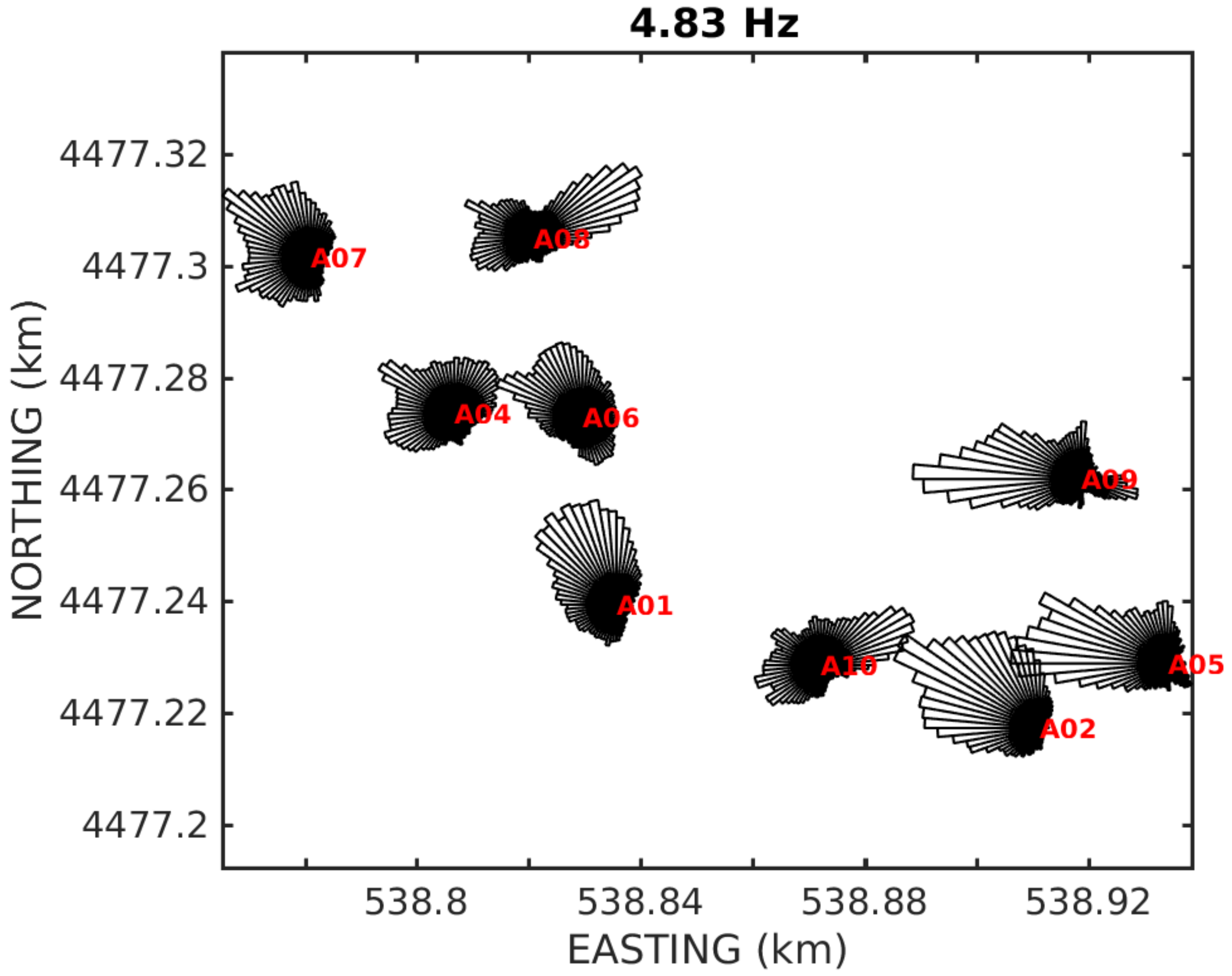
DOI 10.1093/gji/ggad178

Ambient noise (natural sources)

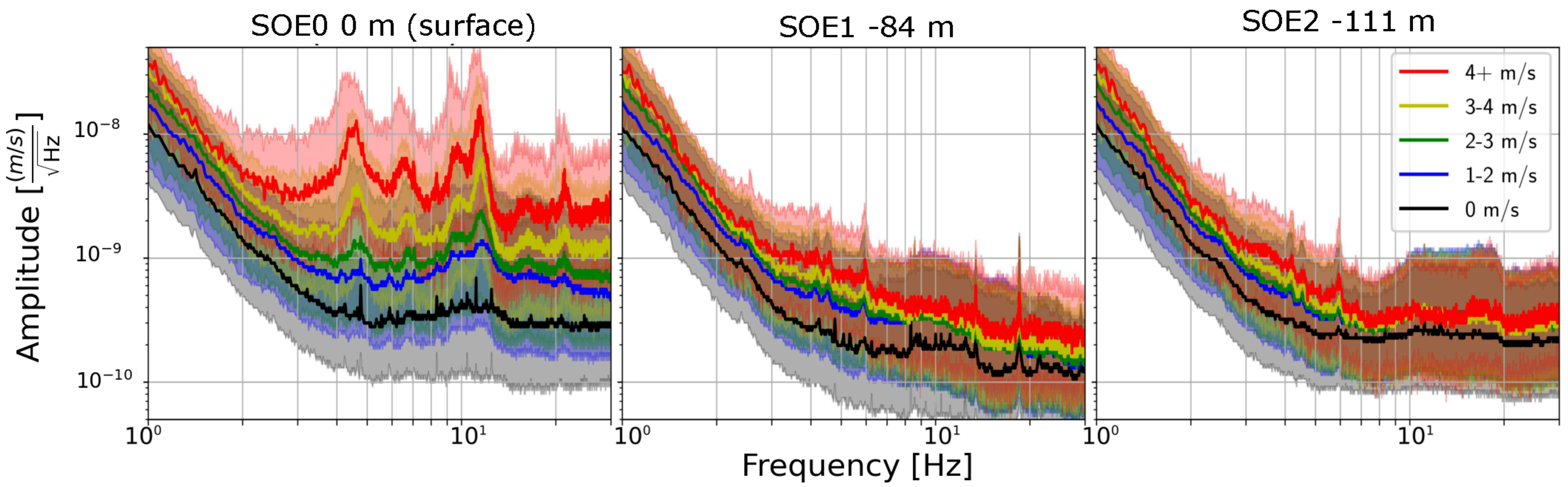
Array analysis confirms the direction of microseismic noise at low frequencies. At higher frequencies, the variability of polarization directions throughout the array deployment indicates a strong influence of topography.



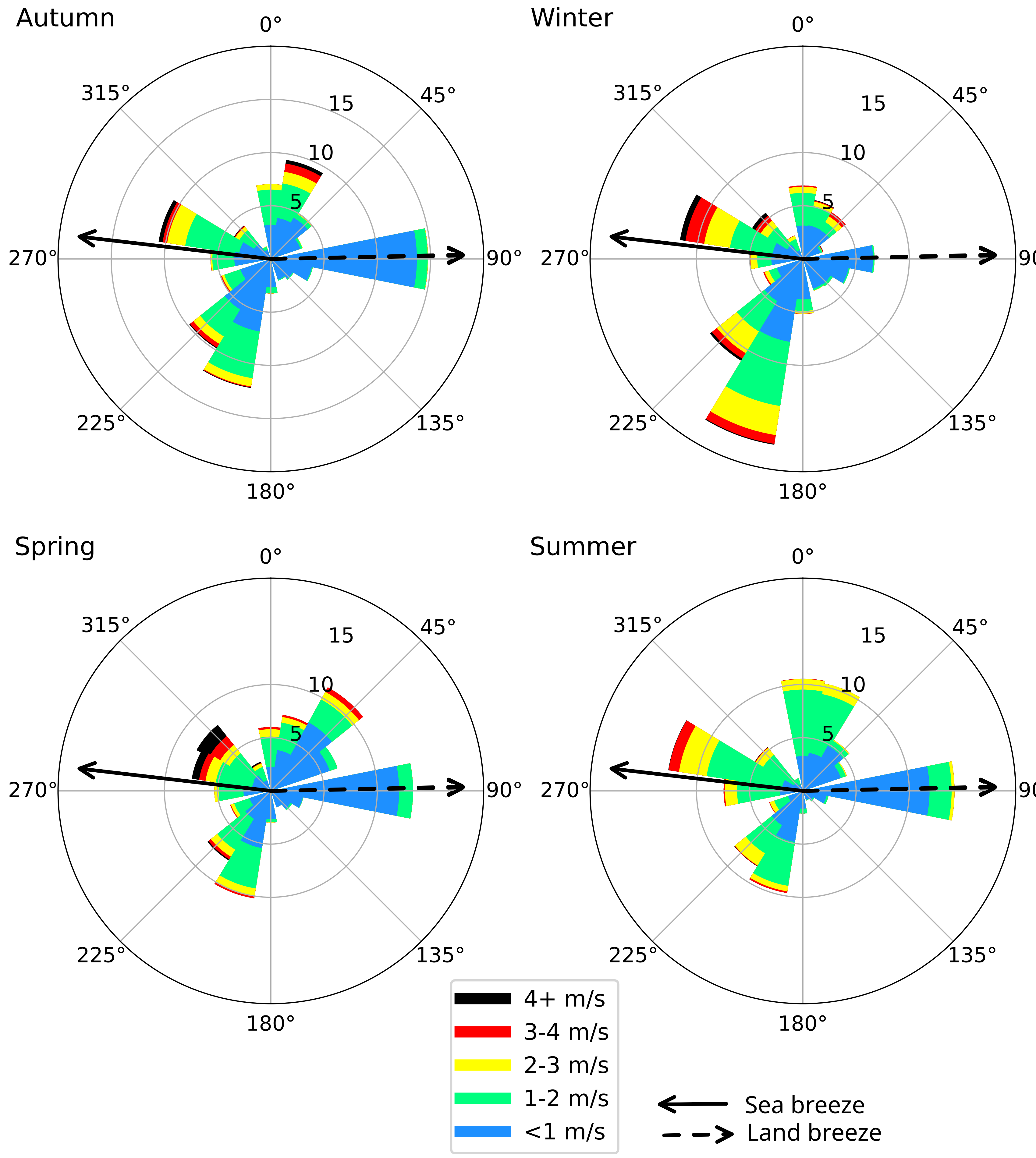


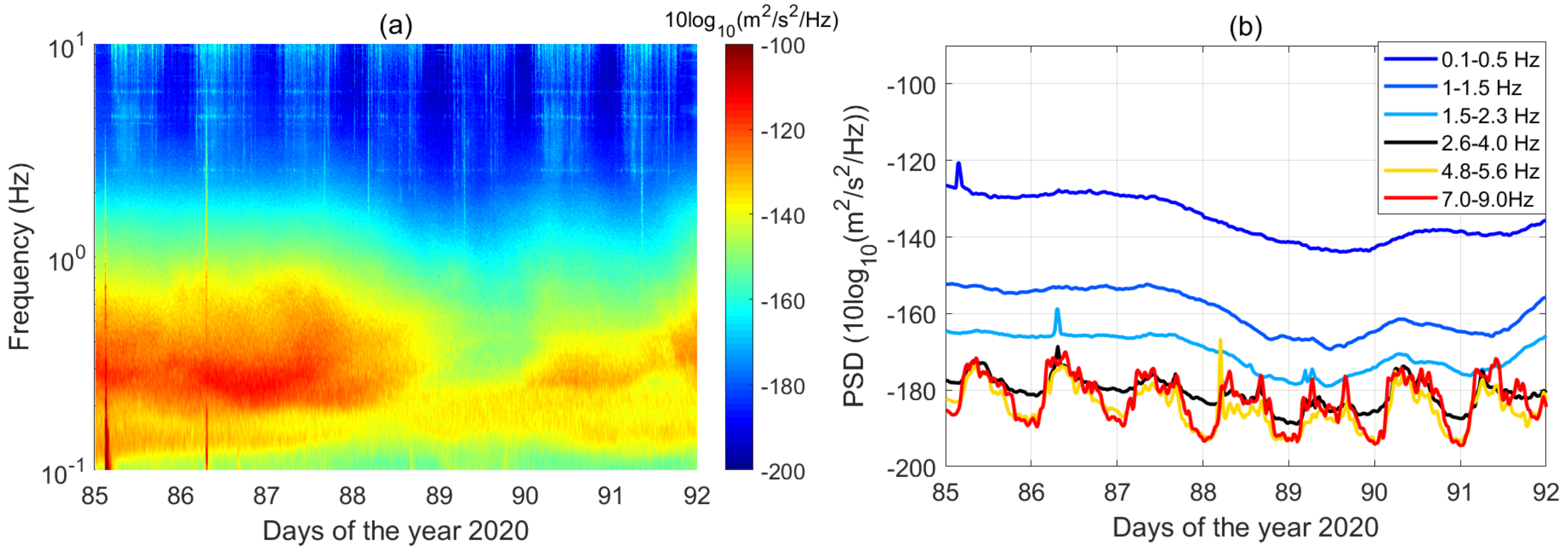


Ambient noise variations (natural sources)



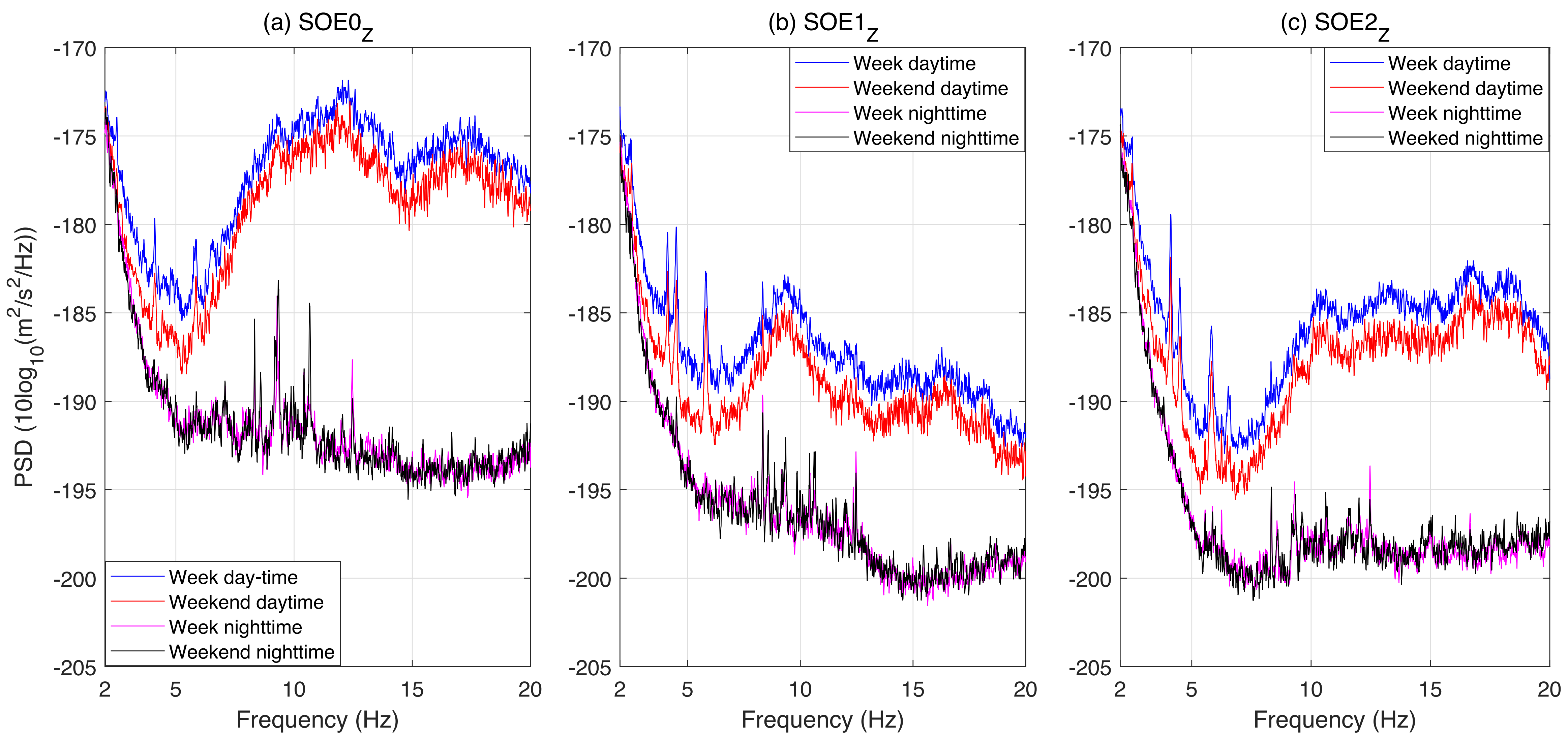
Wind effects



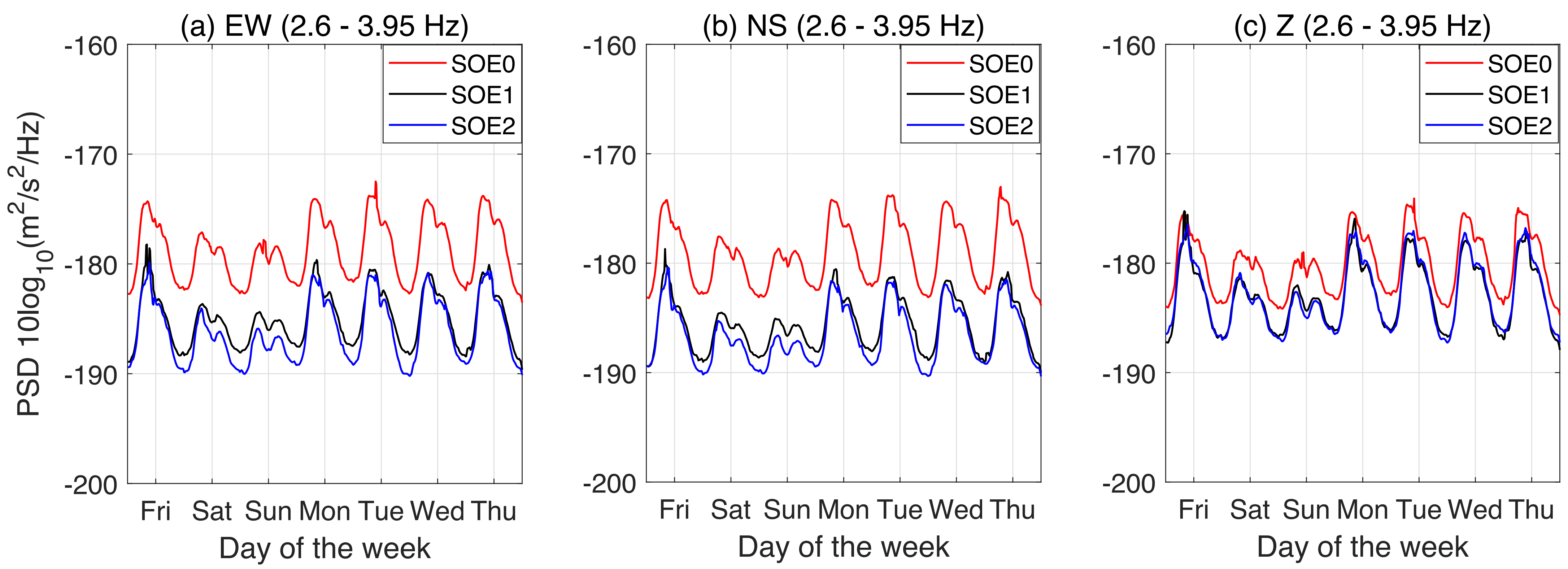


Natural to anthropogenic transition

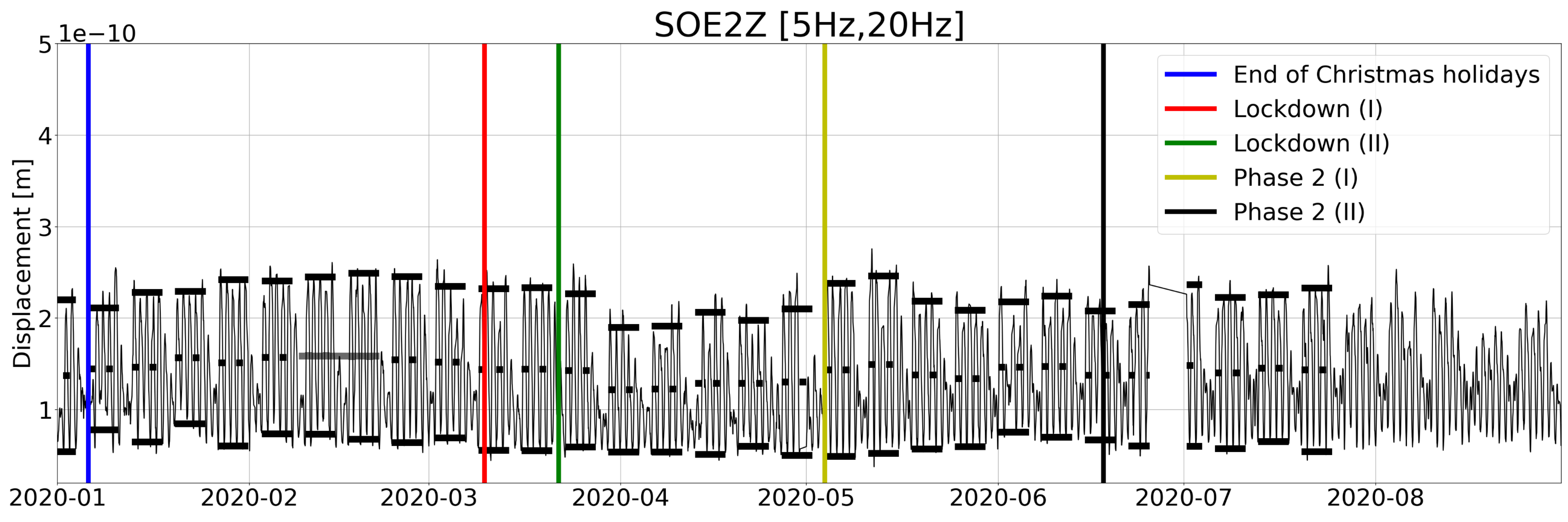
Ambient noise variations (anthropic sources)



Day/night - weekdays/weekend variations

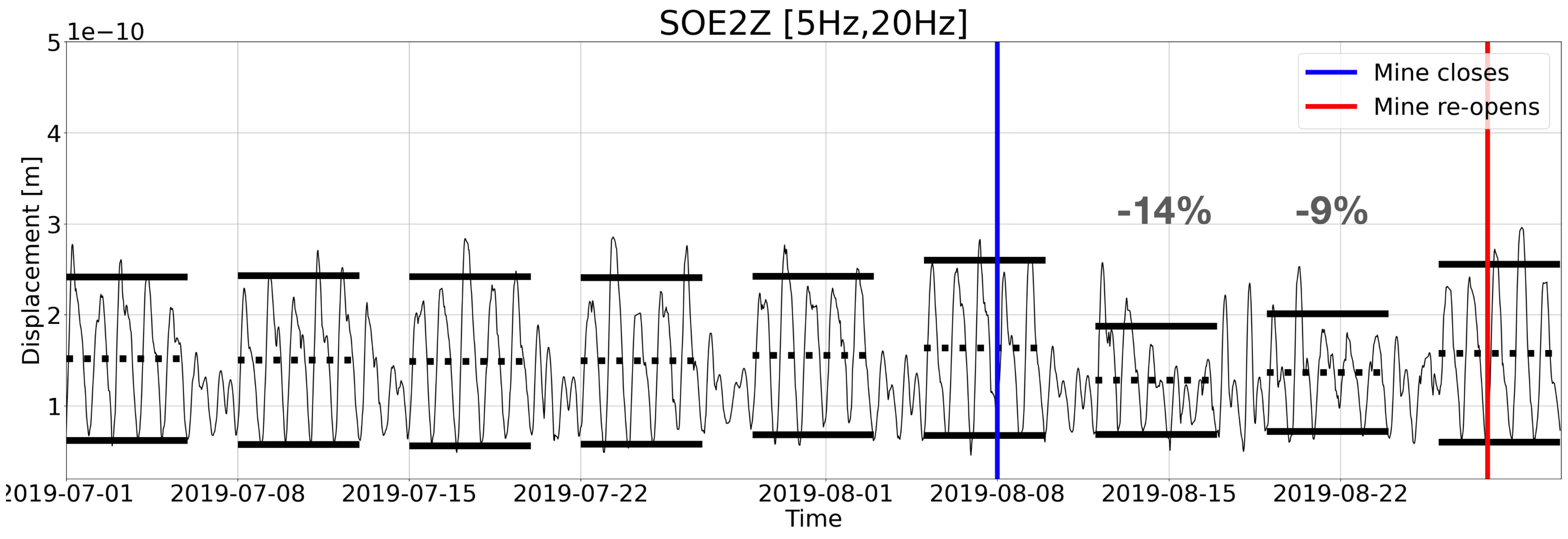


Ambient noise variations (anthropic sources)



Noise level variation during the 2020 COVID lockdown

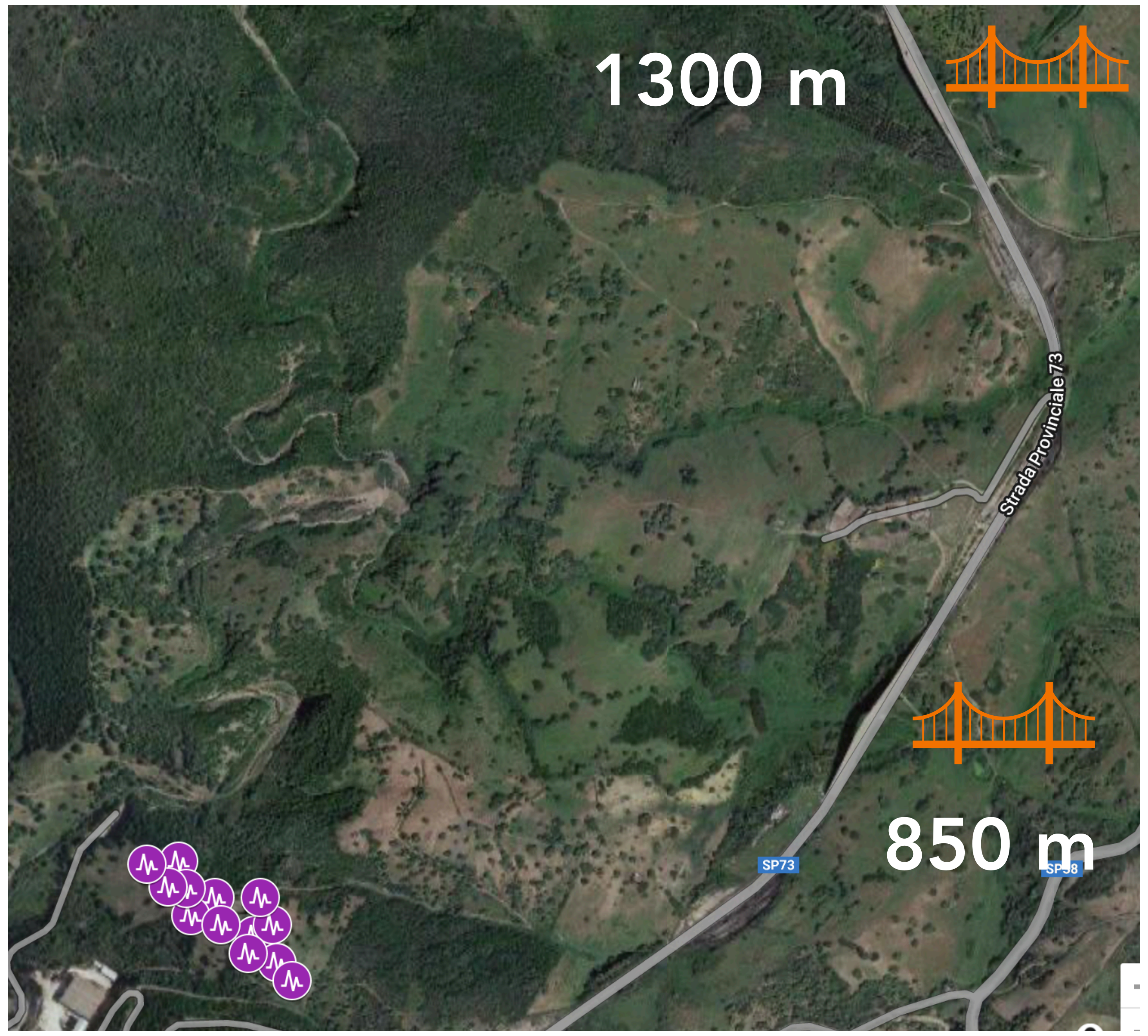
25% less anthropic noise during last week of lockdown with respect the the weeks before the lockdown.

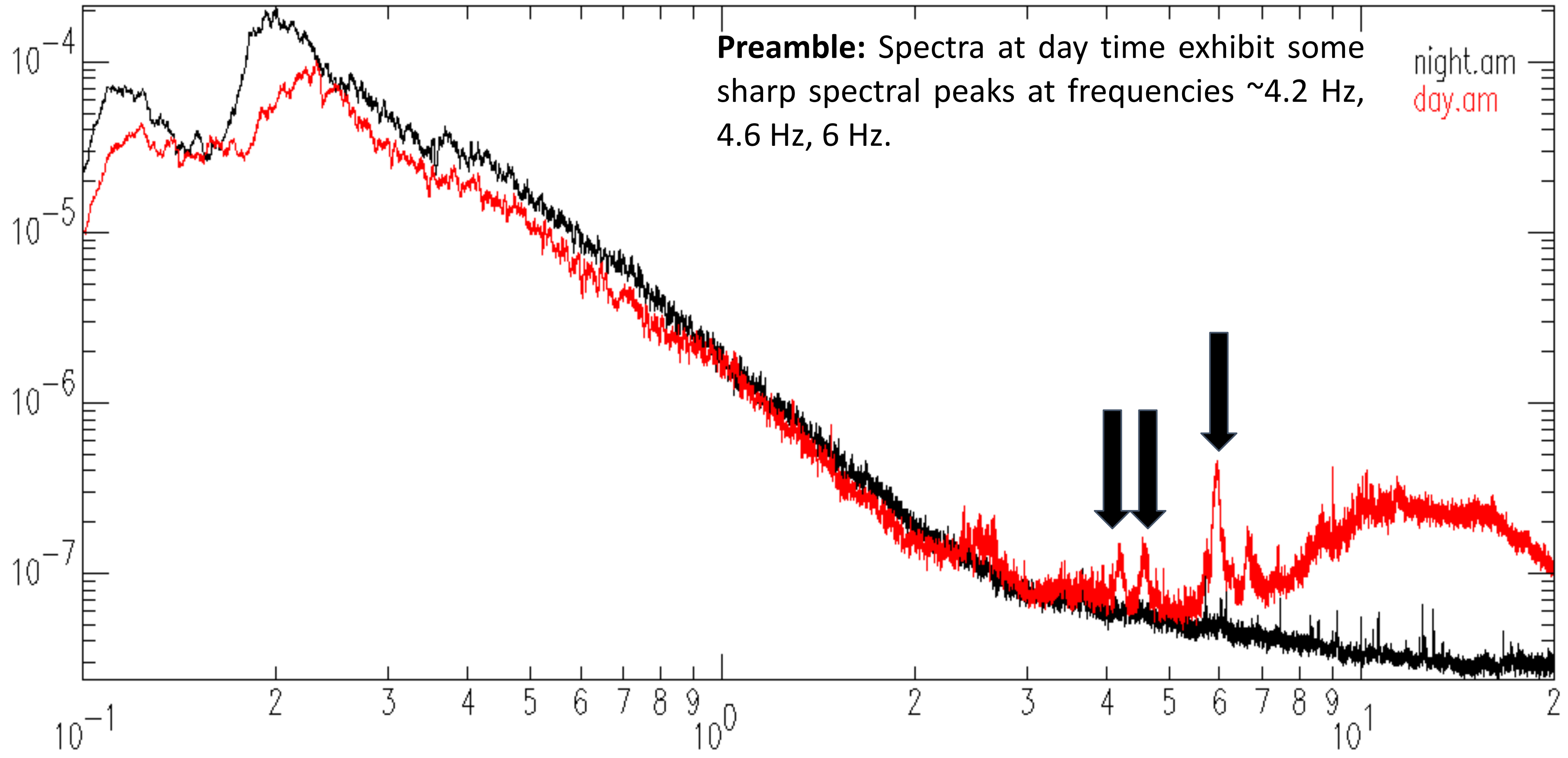


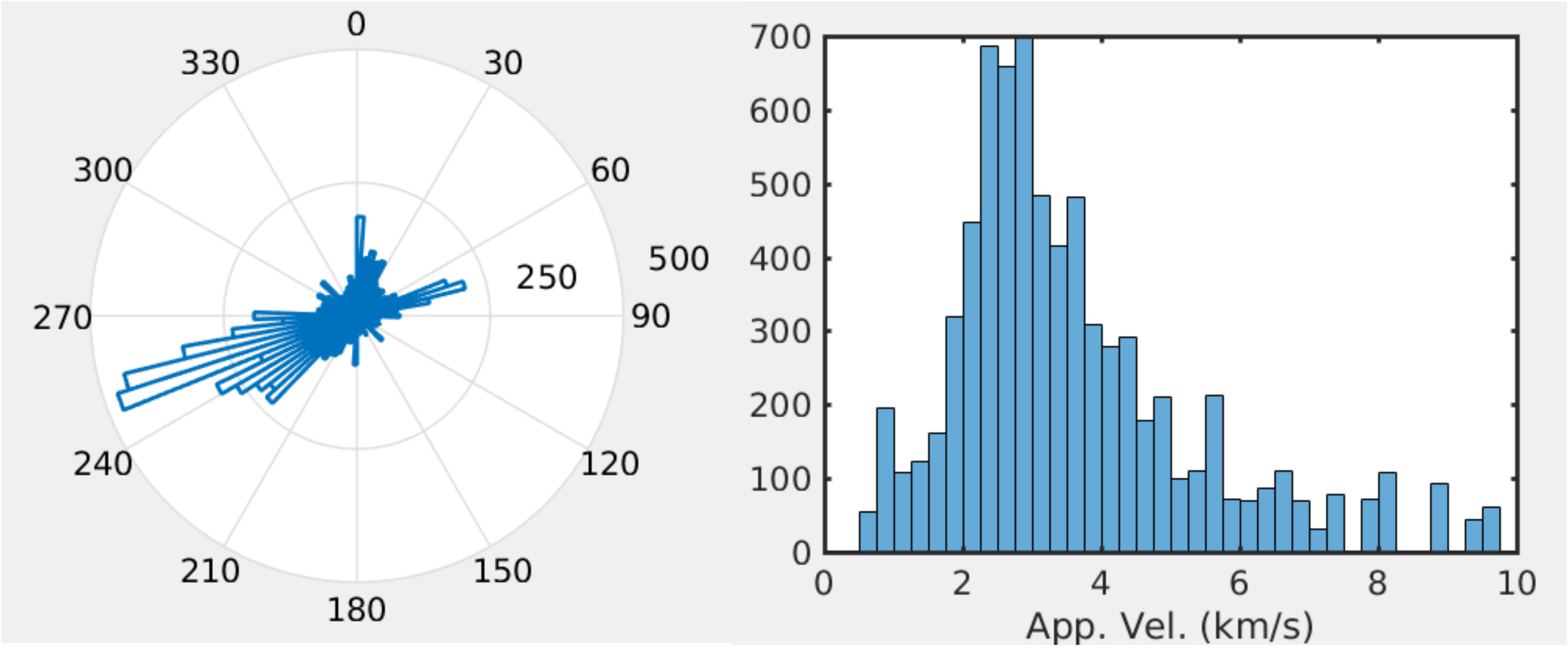
Noise level variation during the 2019 summer holidays

Identification of a noise source in Sos Enattos

- At the beginning of 2021, the deployment of a seismic array by INGV at Sos Enattos, revealed the presence of spectral peaks that seemed compatible with the presence of two road bridges nearby;





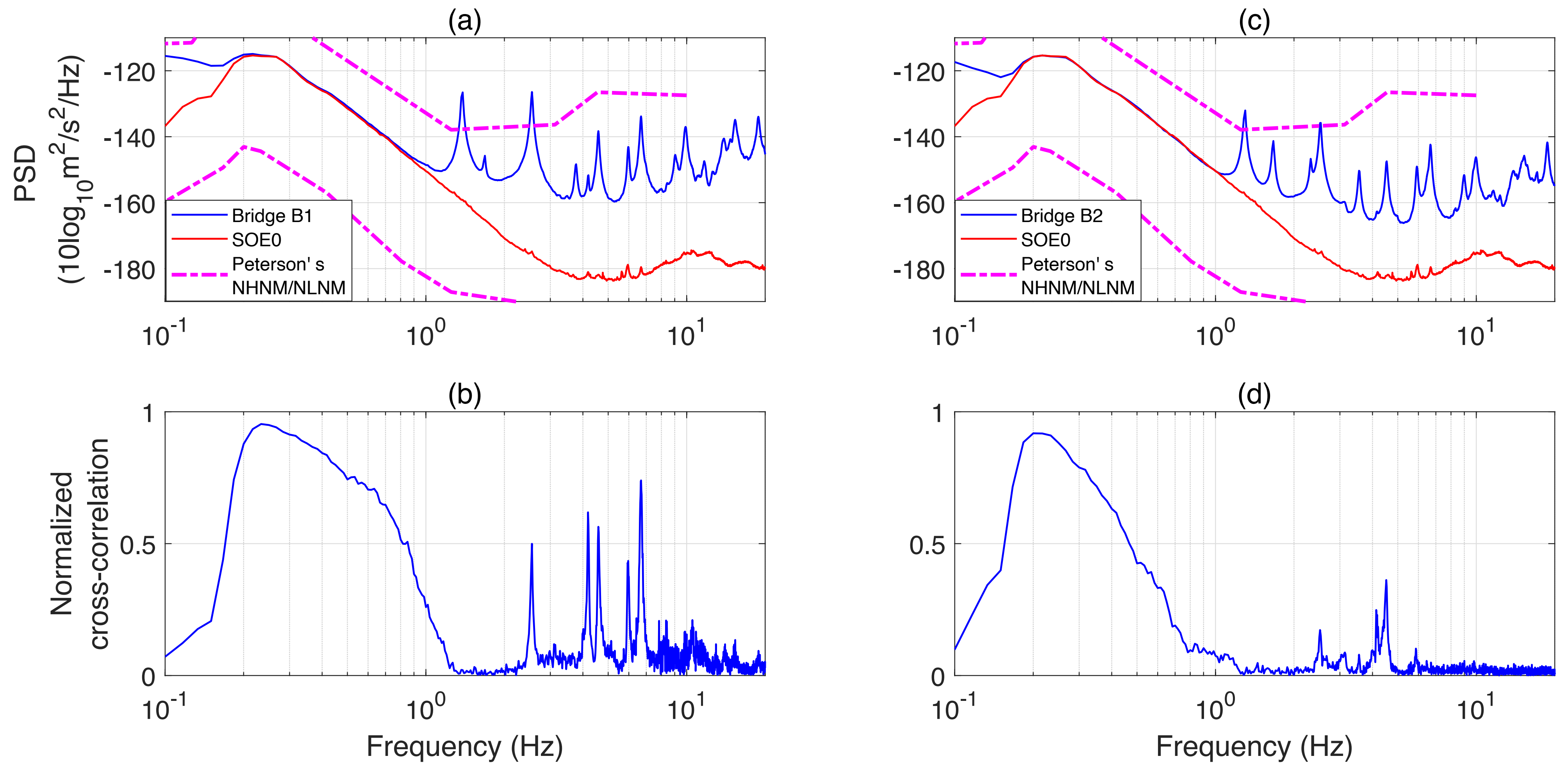


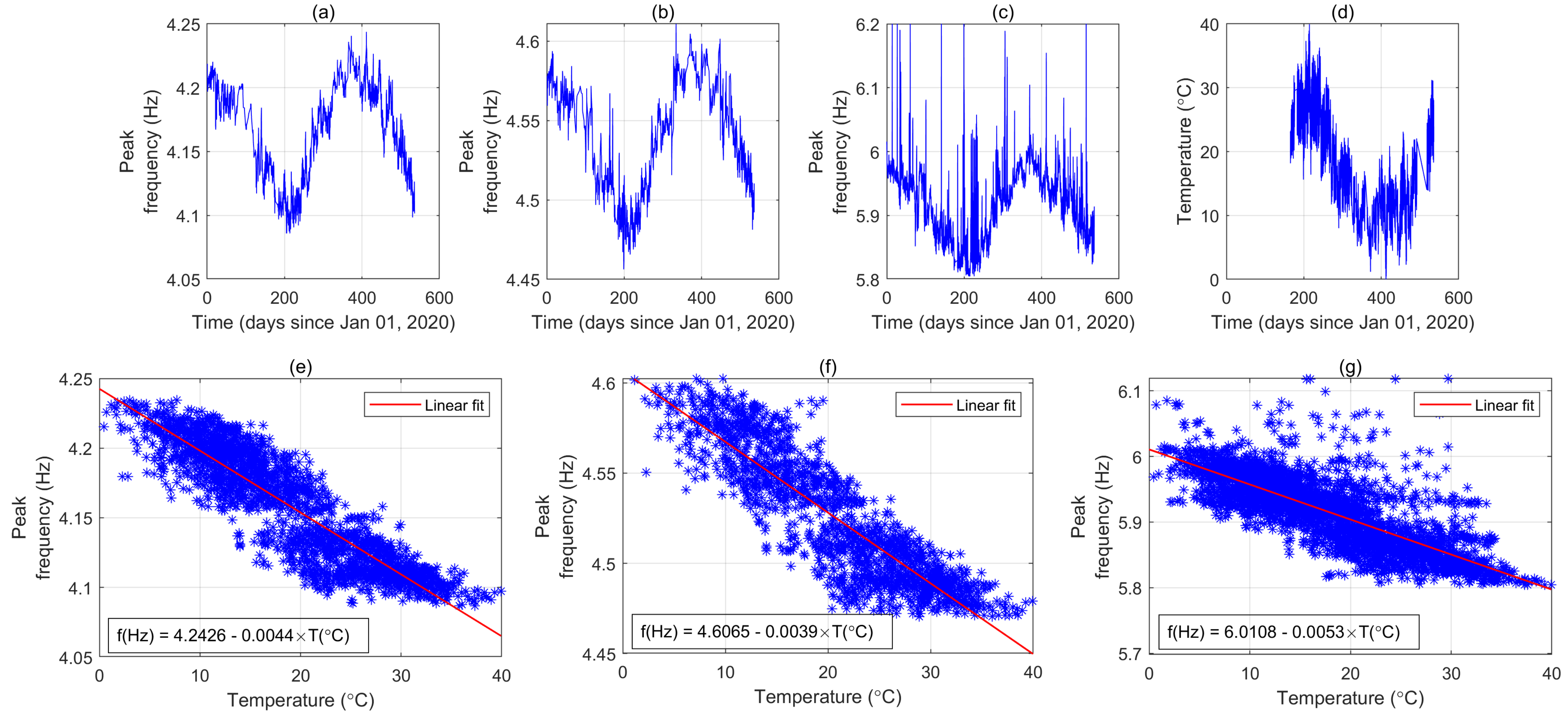
Identification of a noise source in Sos Enattos

- At the end of 2021, GSSI deployed 5 geophones for five days to confirm the origin of those peaks.

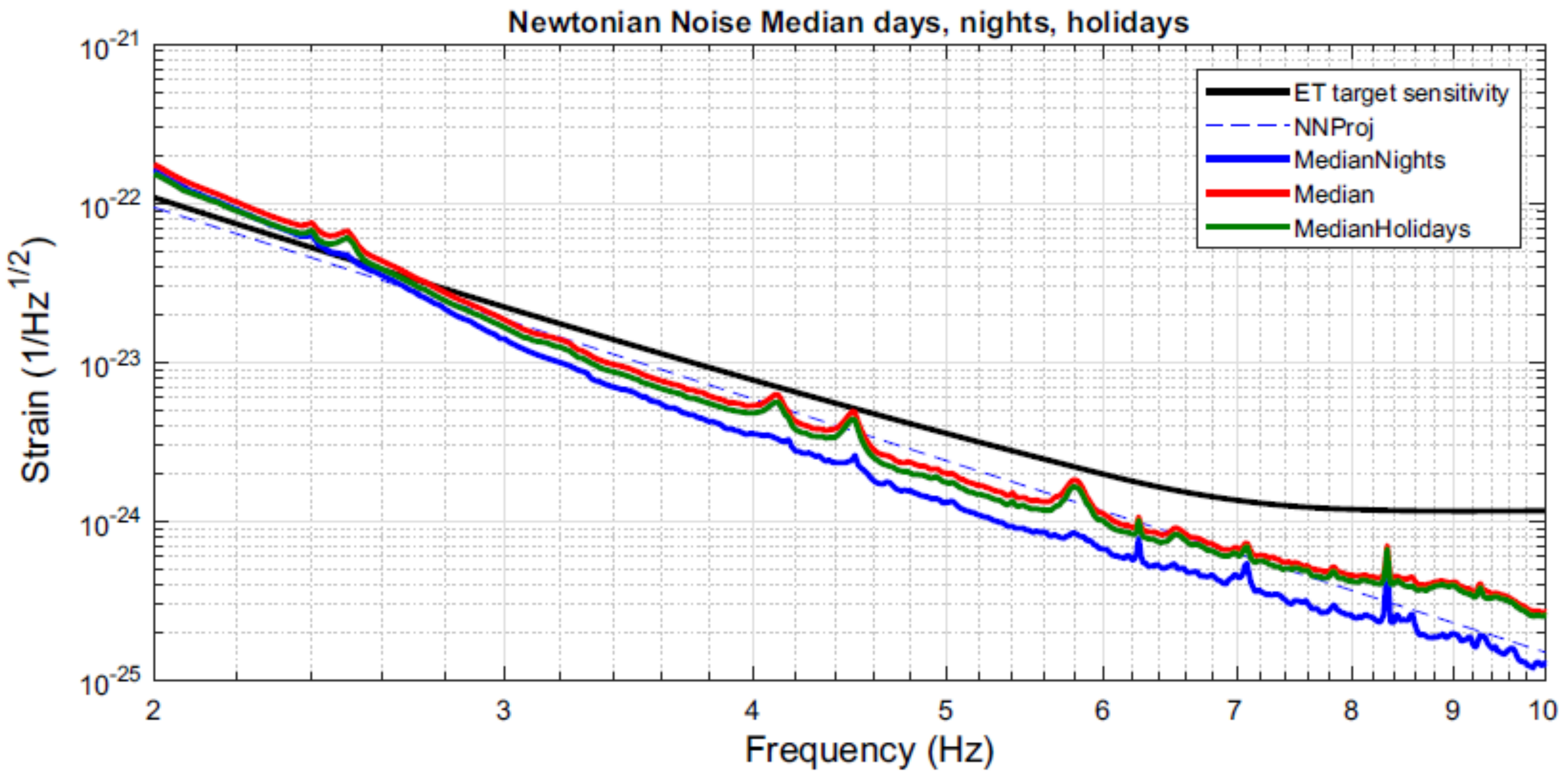
Identification of a noise source in Sos Enattos

- Spectral correlation confirmed the origin of those peaks;
- The distance of the bridges from the site is no more than 1.5 km;
- Those peaks also have a seasonal frequency drift with different rates;
- This may be caused by temperature variations that change the vibrational properties of the structures;
- Engineers observe drift to lower frequencies as the temperature increases and vice-versa as the temperature decreases;





Impact of glitches



Defining the Newtonian Noise ASD as:

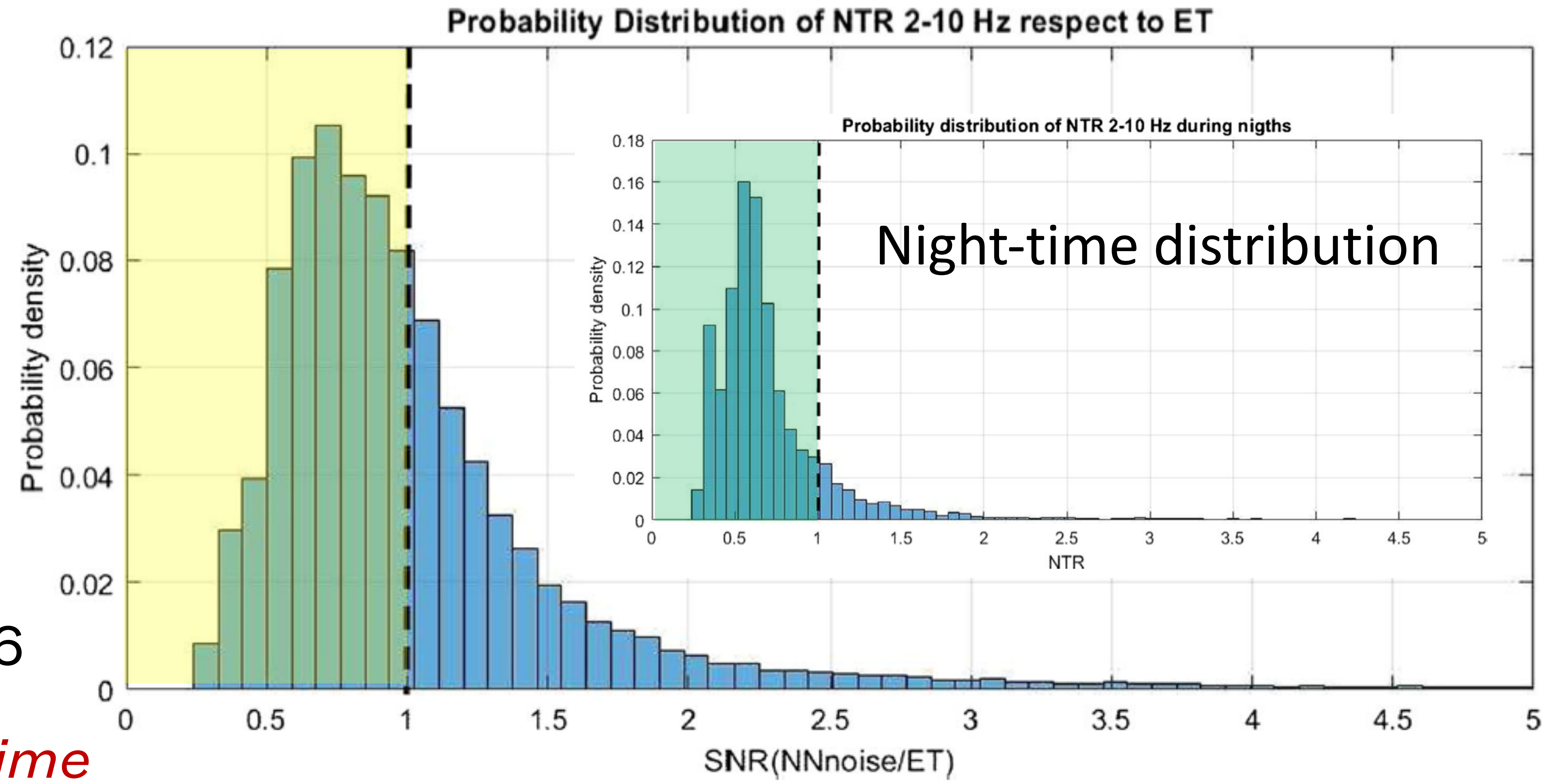
$$\tilde{h}_{NN}(f) = \frac{4\pi}{3} G\rho_0 \frac{2\sqrt{2}}{L} \frac{1}{(2\pi f)^2} \tilde{x}(f)$$

Defining the Noise-to-Target Ratio of the Newtonian Noise in 1 minute window (~IMBH duration in ET band)

$$\mathrm{NTR} = \sqrt{\frac{1}{\Delta f} \int df \frac{\tilde{N} * \tilde{N}}{S_h}}$$

PSD of NN

PSD of ET sensitivity

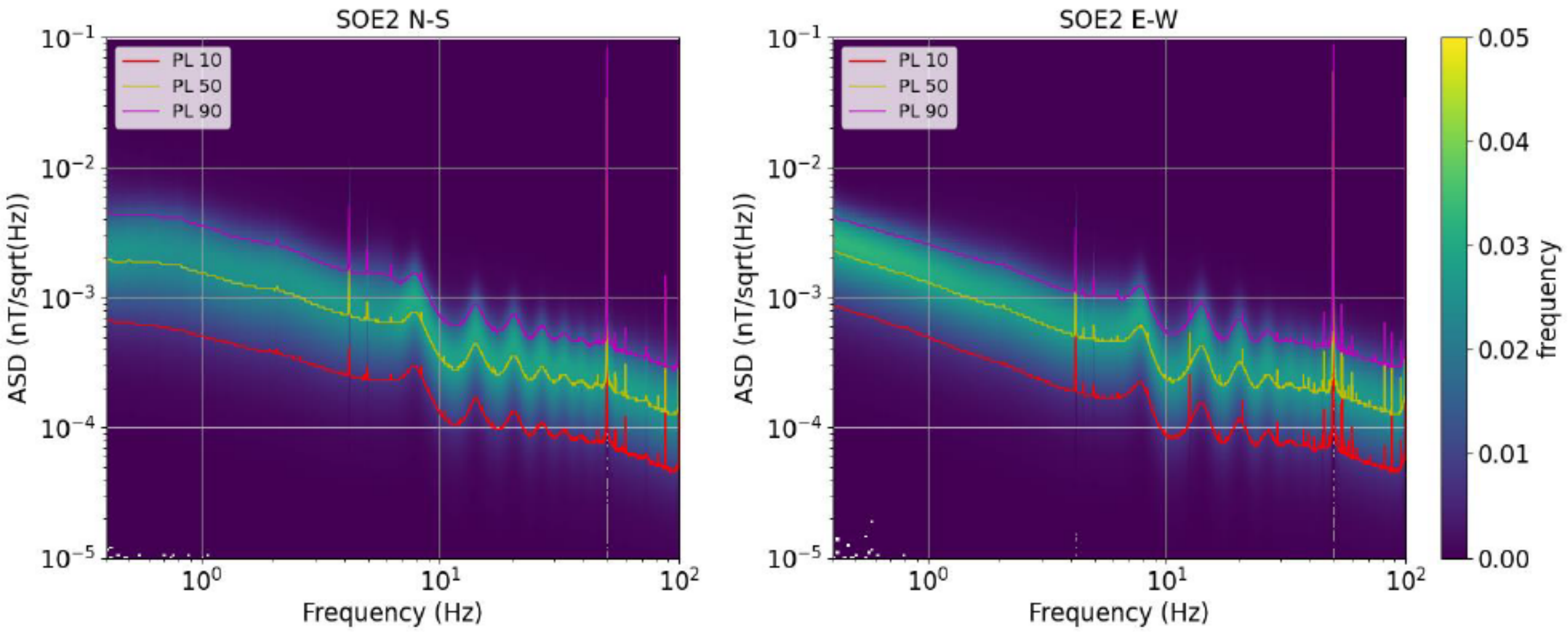


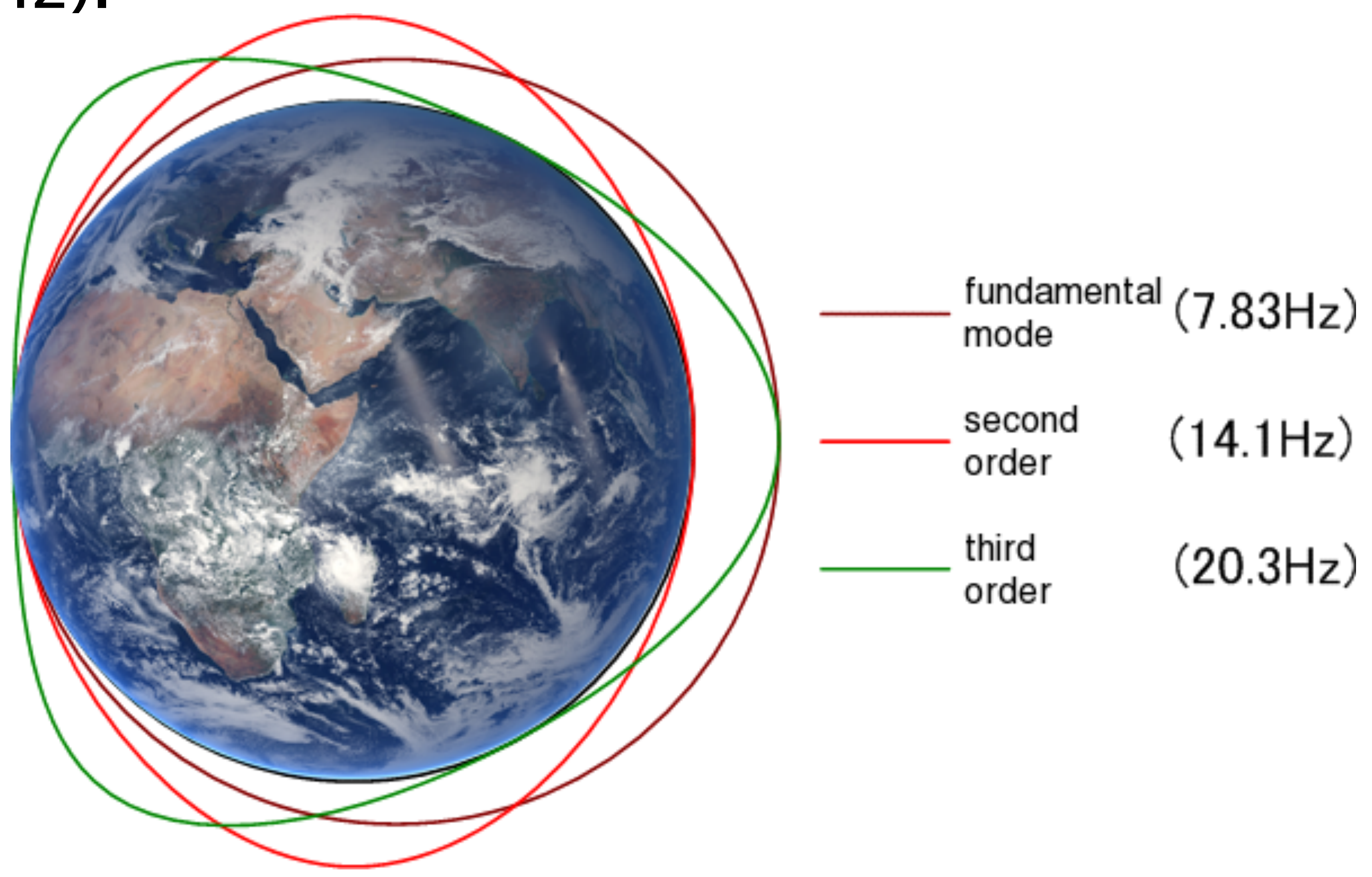
P(NRT<1)=0.6 , considering only the nights: $P(NRT<1)_n$=0.86

→*Need for moderate NN subtraction only for a limited time*

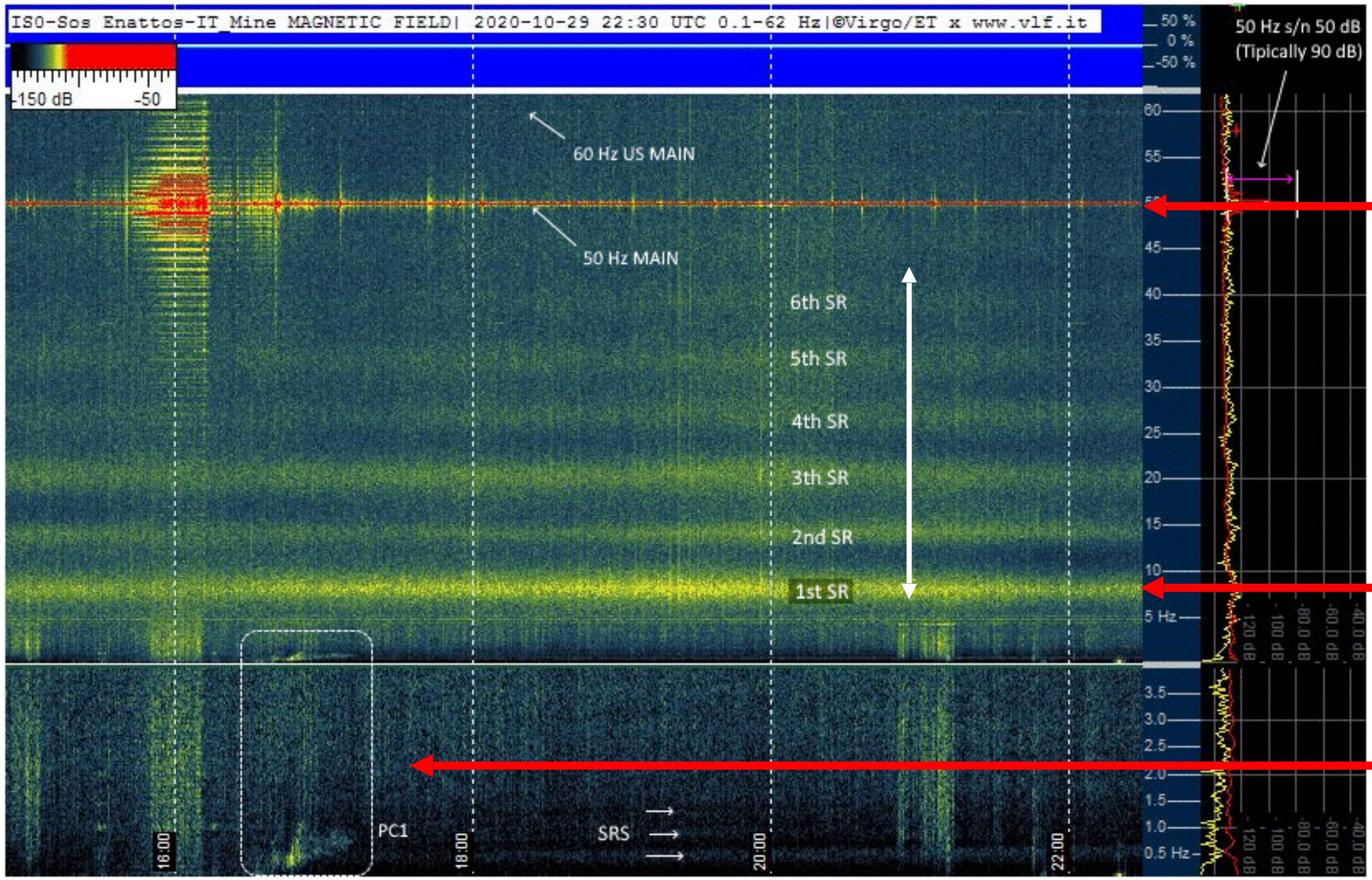
Magnetic noise measurements

- In the band of interest of ET the main direct disturbances come from ULF (10^{-3}-3Hz), ELF (3-$3 \cdot 10^{3}$Hz) up to VLF (3-30 kHz) bands;
- Main natural magnetic noise is in ULF and ELF, produced by resonance phenomena in the magnotosphere and/or in ionosphere cavities like Geomagnetic pulsations (0.2 Hz - 5 Hz) and Schumann resonances (5 Hz - 100 Hz);
- Main source of artificial noise in ELF are power lines (50 Hz - 60 Hz).





Magnetic noise measurements



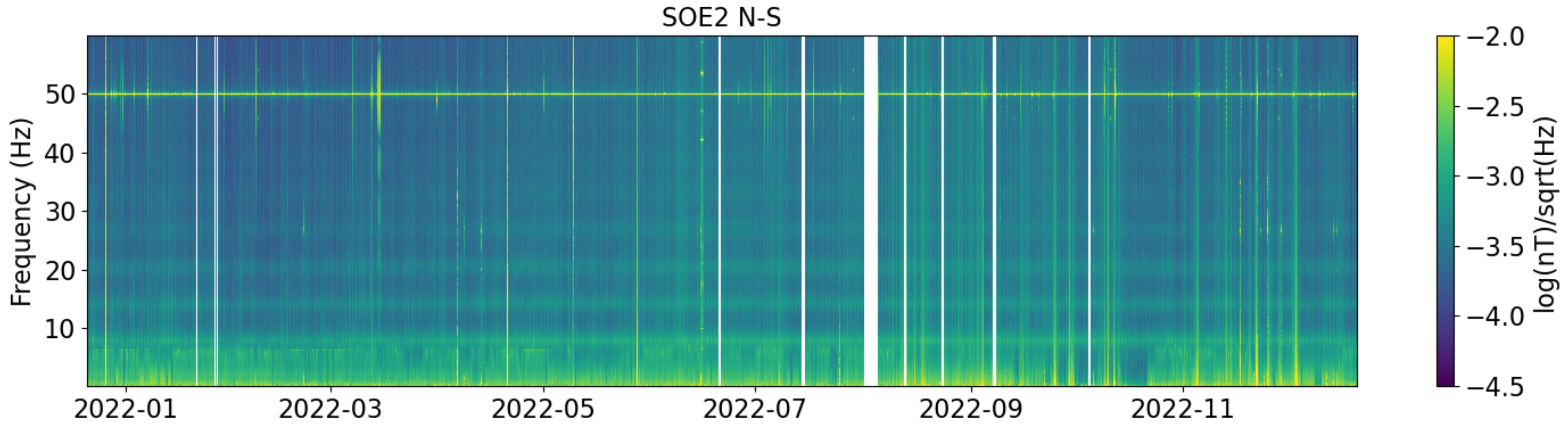
Power line (50 Hz)

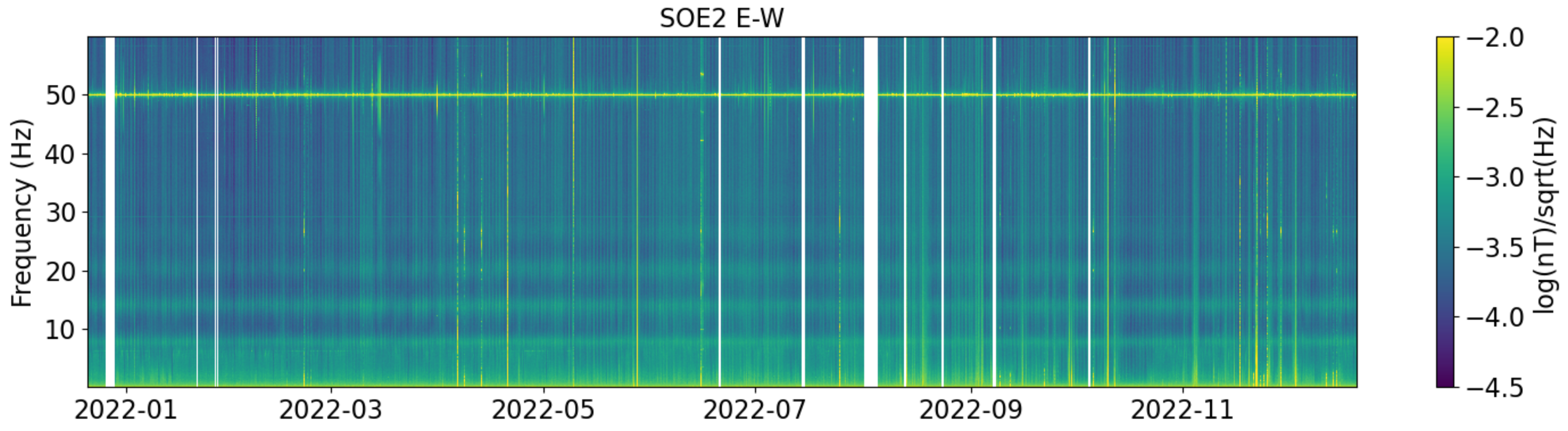
Schumann resonances

Geomagnetic pulsation

Magnetic noise measurements

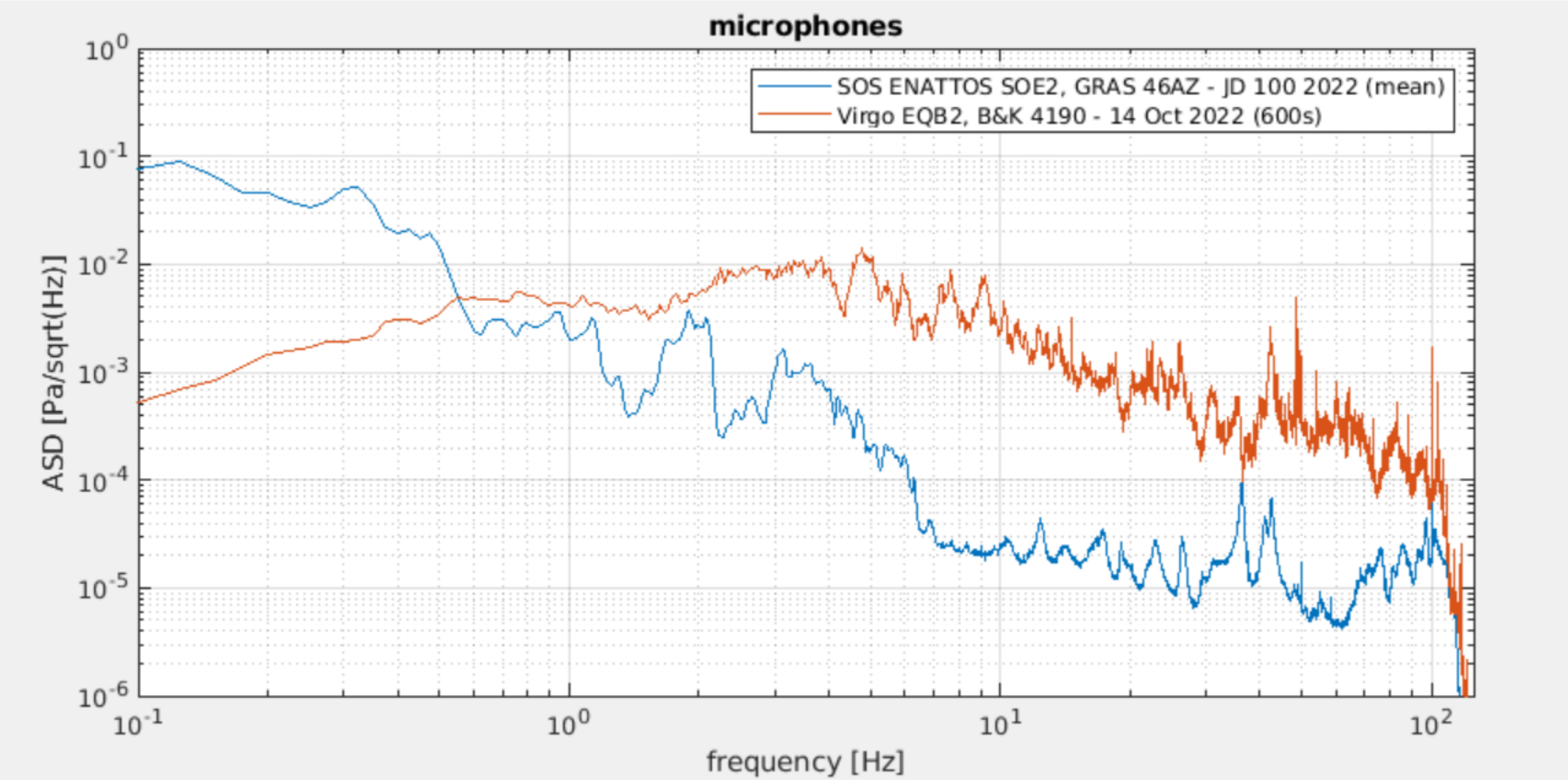
The long-term monitoring in a such quiet site, allows to clearly detect regular structure or periodic variability (mainly Schumann Resonances);

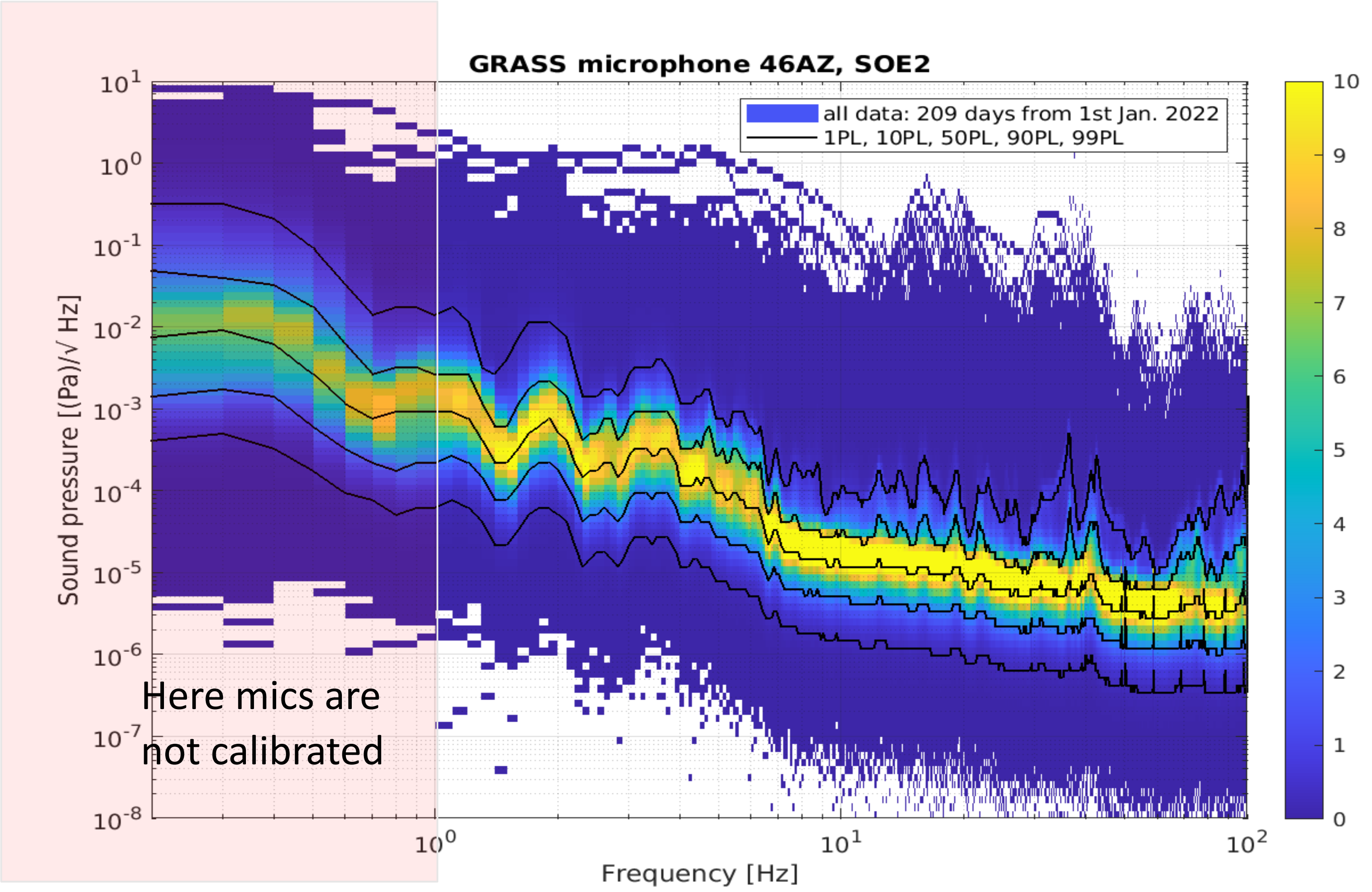




Acoustic measurements

- The Acoustic noise characterization is mainly performed inside the Sos Enattos former mine.
- Microphones (GRAS 46 AZ) are installed in surface (SOE0) and at each underground level (SOE1, SOE2, SOE3).
- Data available from December 2021 (SOE2) and from December 2022 (SOE0, SOE1, SOE3)
- Other microphones installed (for comparison) by Poland group
- Infrasound microphones at P2,P3: installation planned (GSSI), also for acoustic NN modeling.

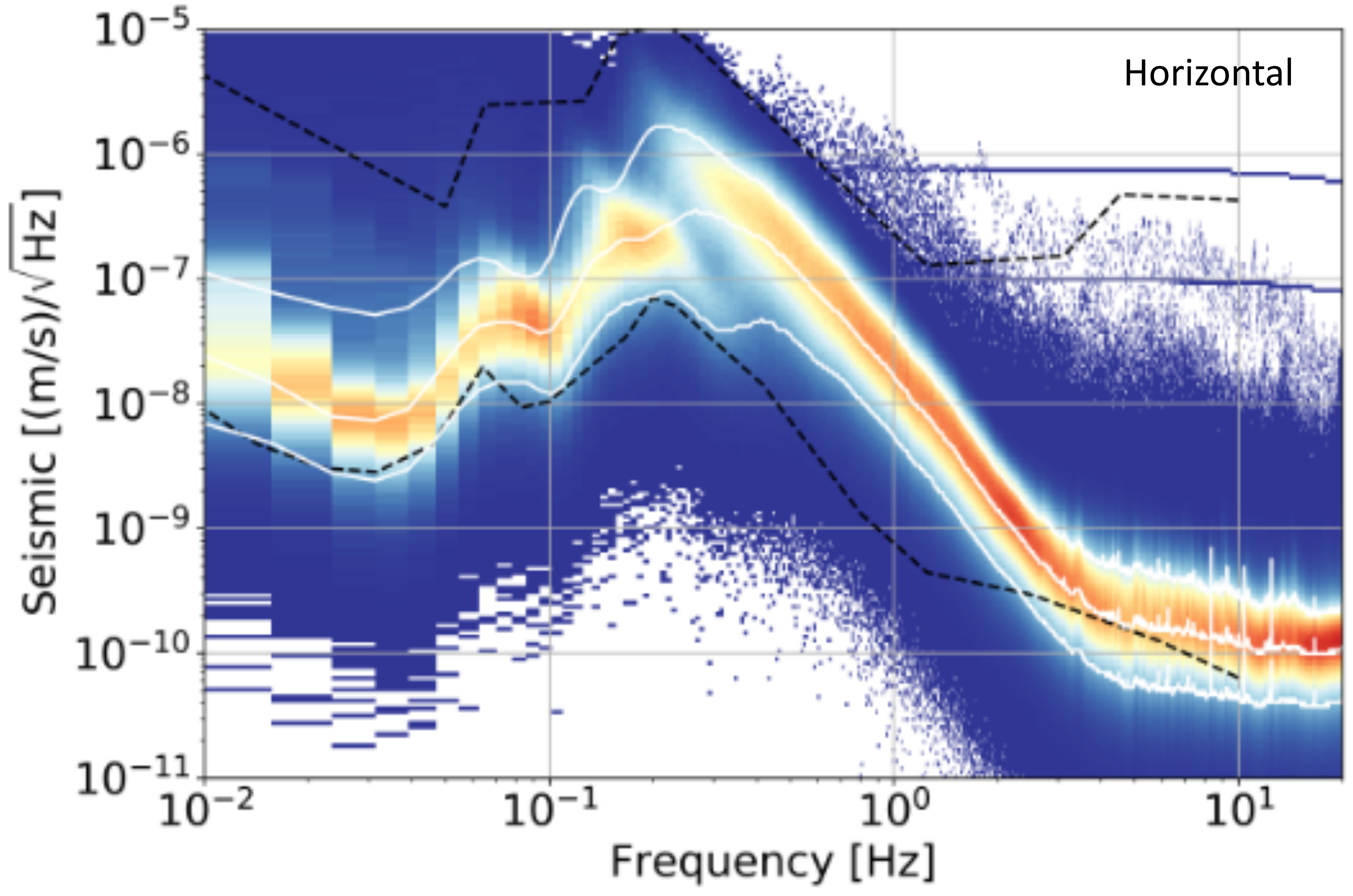


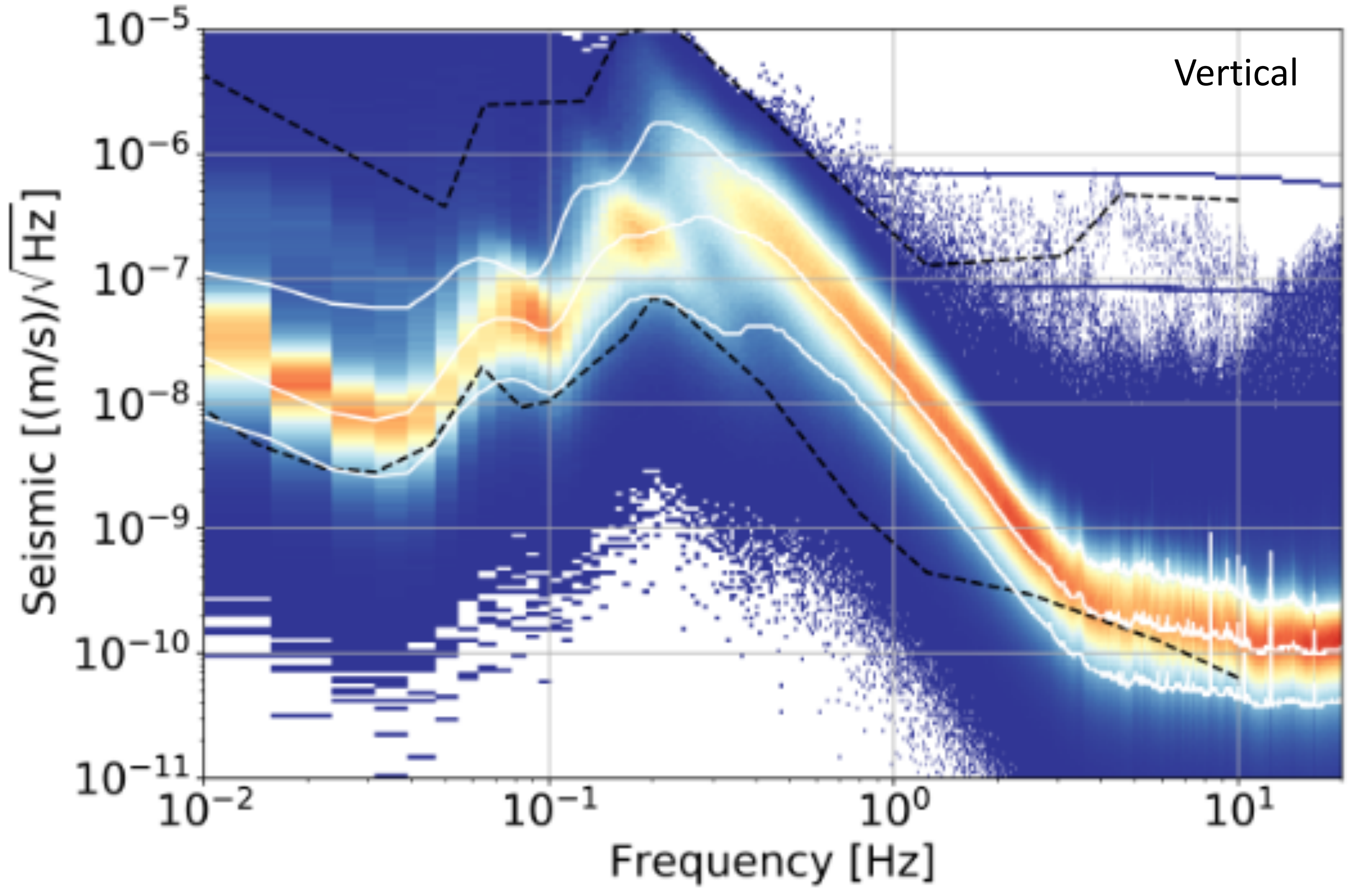


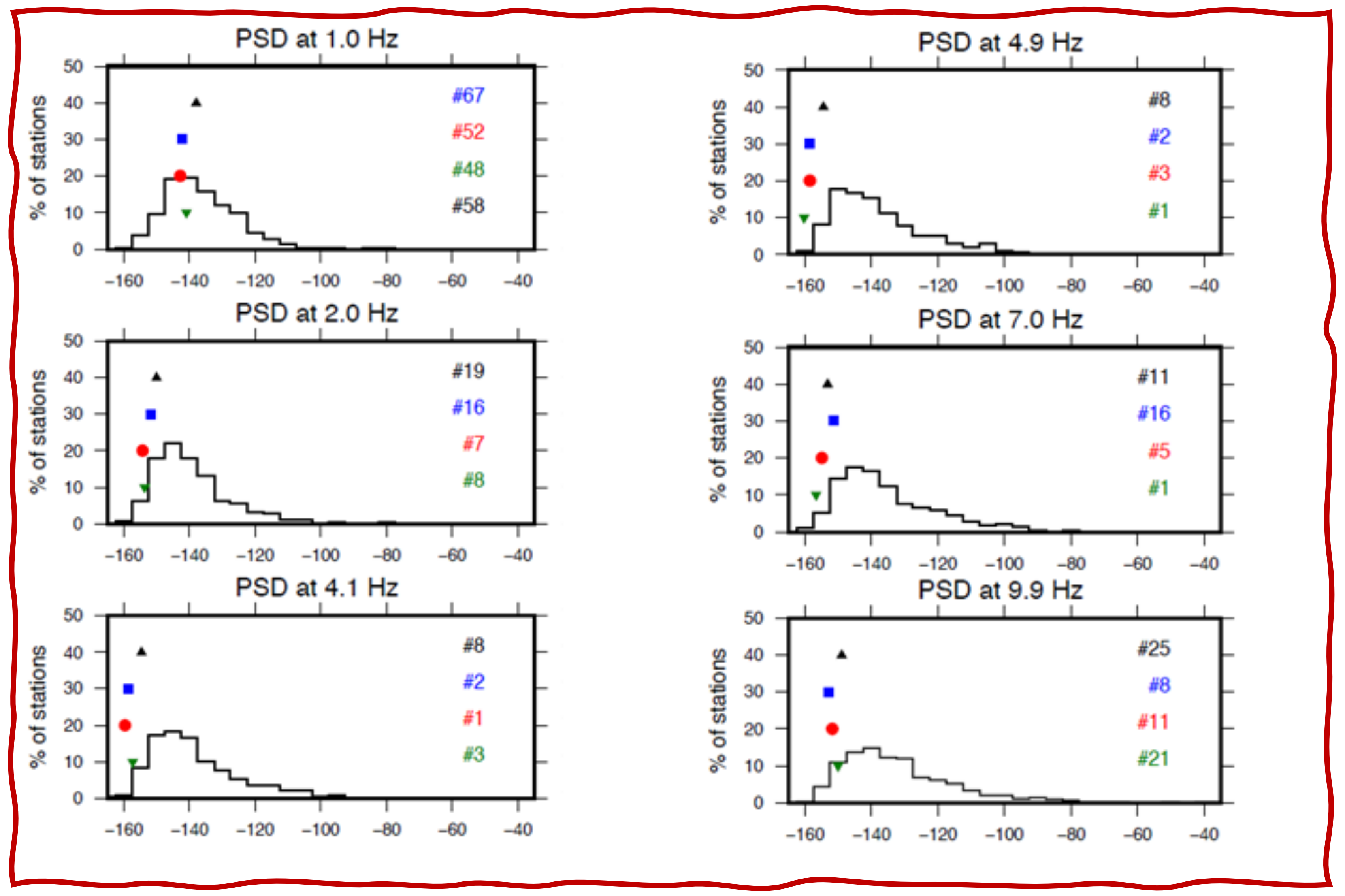
Characterization of the corners

Boreholes drilled in 2021 and sensors installed the same year. Installations improved since then.

Characterization of the corners



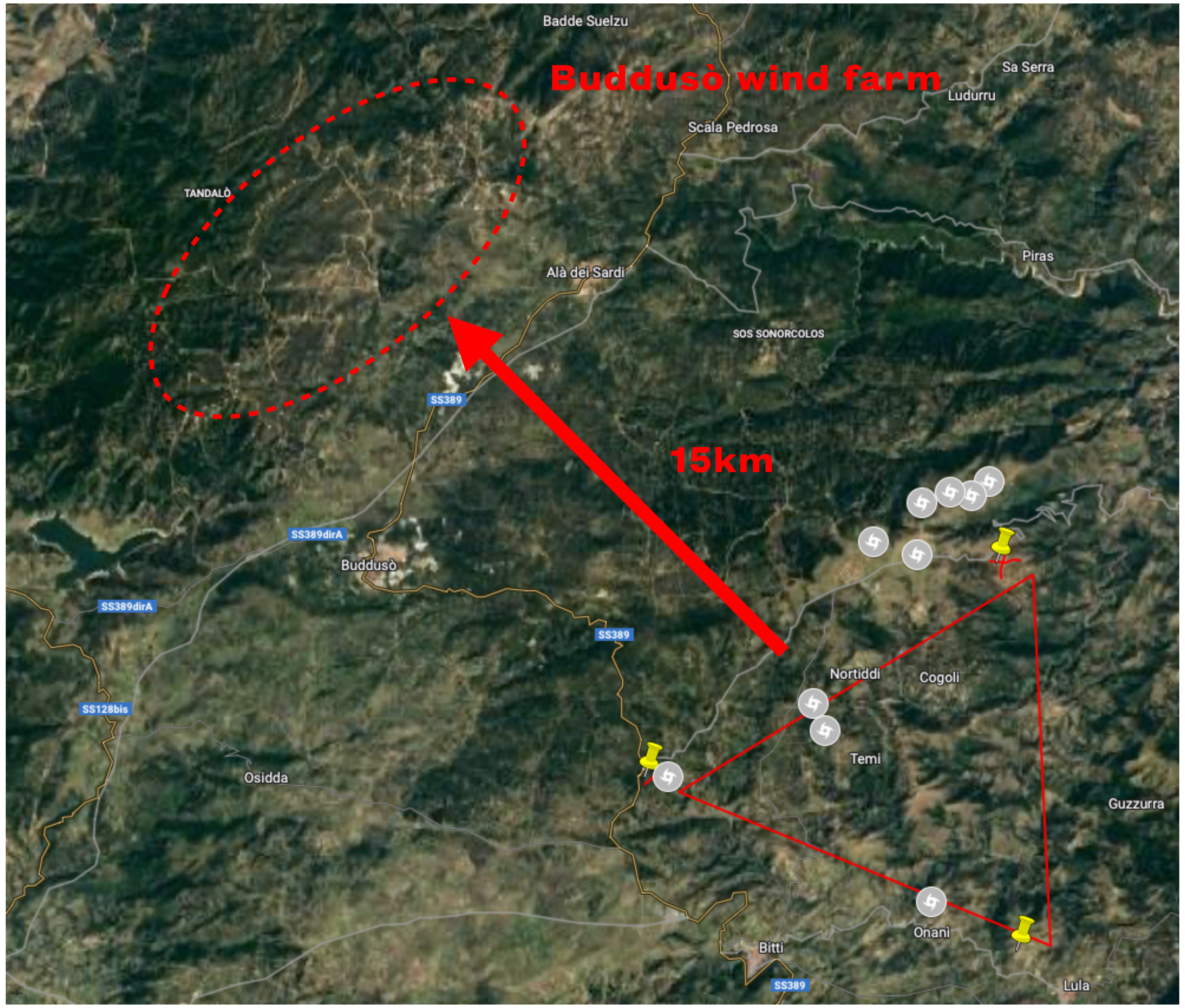




Very low noise background in the 2-10 Hz band, sometimes even **below** the Peterson's **New Low Noise Model**!

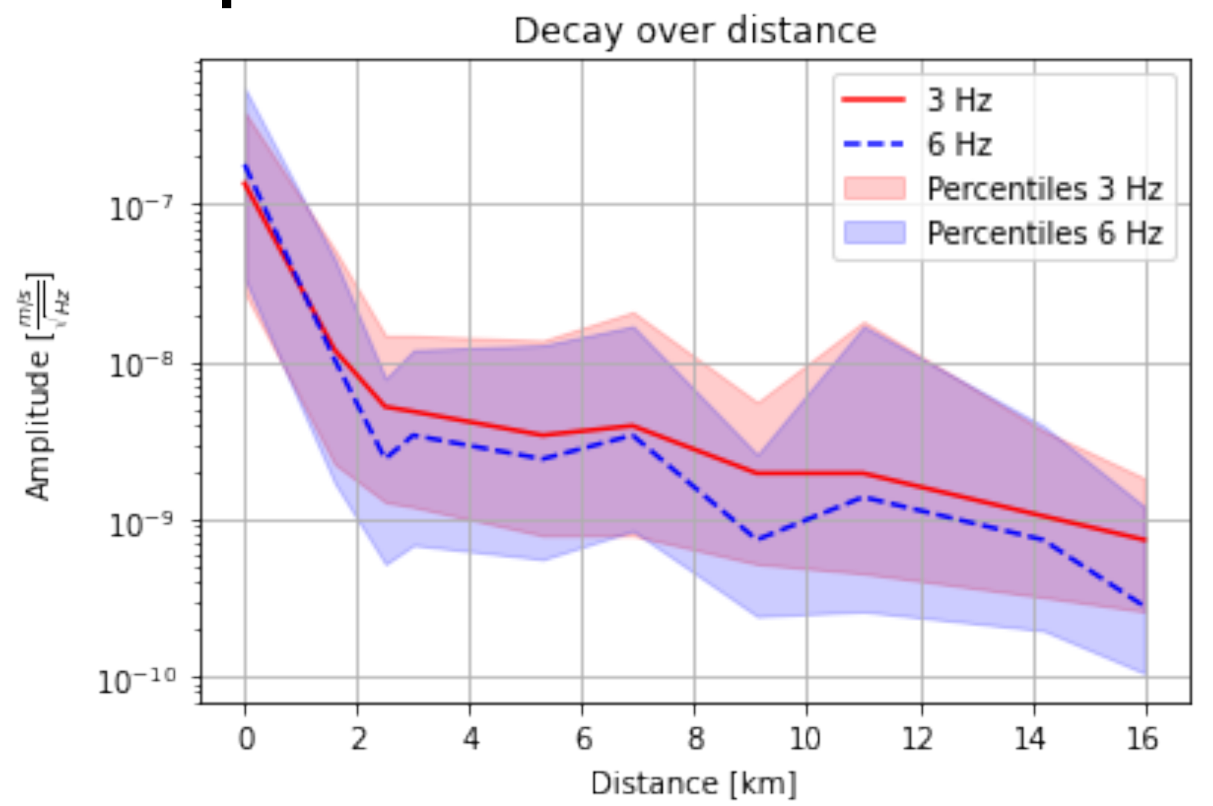
Wind turbines

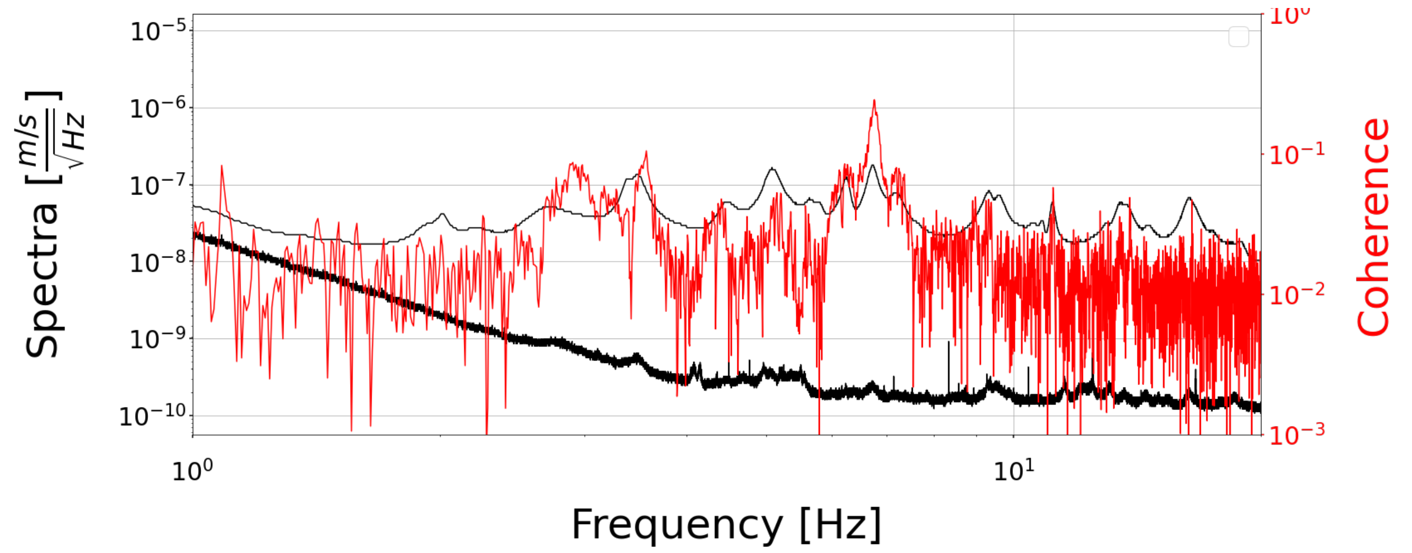
- Some small wind turbines are located in the area close to P2 and P3;
- According to *Westwood et al. 2015*, noise from small low-power turbines exhibits a significant attenuation already at 200m;
- At the moment, the our attention is devoted to the Buddusò wind park, 15 km away;
- According to studies for the Virgo site (Saccorotti et al. 2011), big wind parks can produce peaks at less than 2.5 Hz and visible up to 10 km.

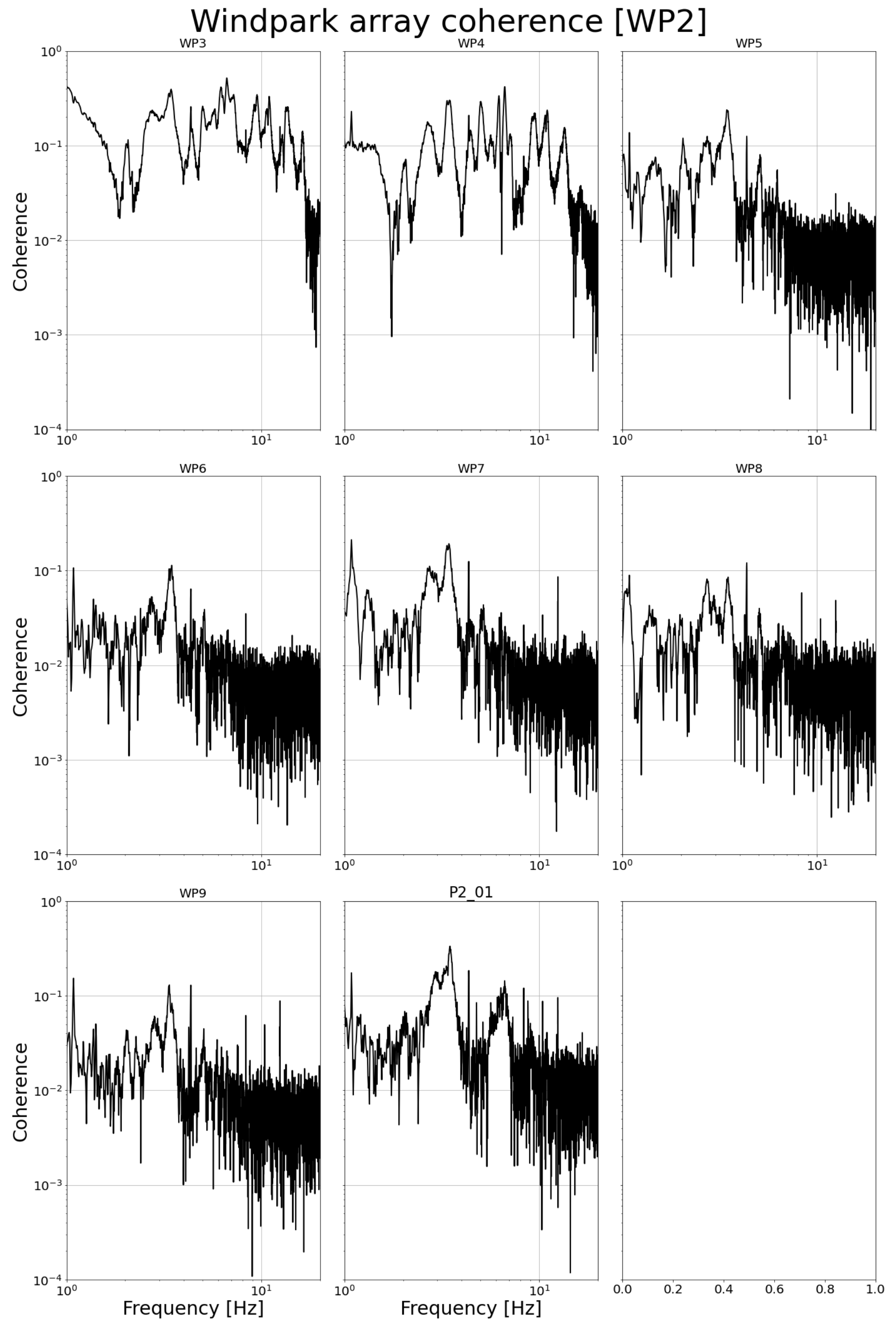


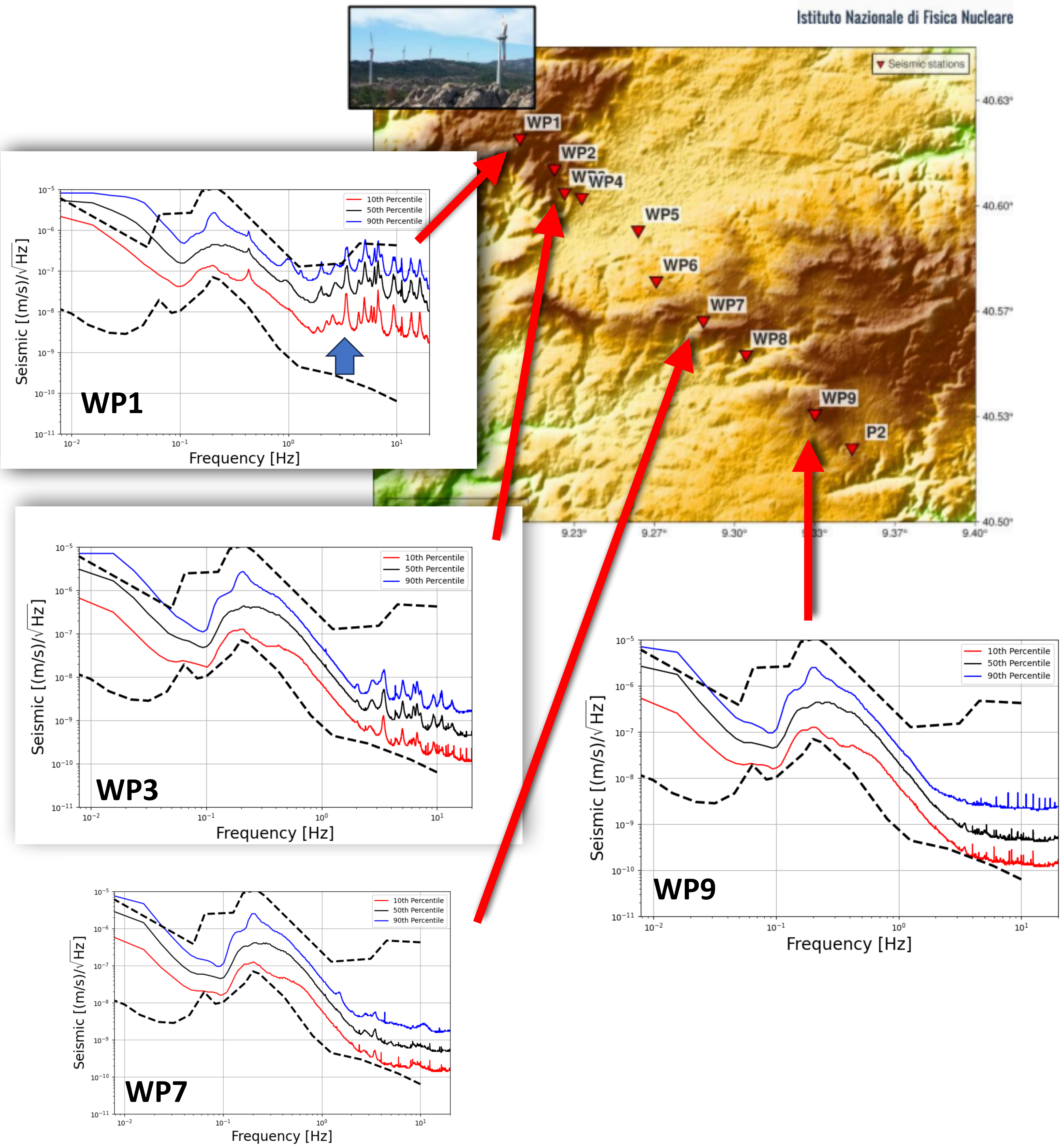
Wind turbines

- Recent deployment of a seismic array between the wind park and P2 issued the first results;
- Main peak at 3 Hz + harmonics









Conclusions

- Sardinia is geologically very quiet, far from active fault lines, and characterized by low anthropic noise.
- New and deep physical and geological characterization of the Sos Enattos area since 2019, where a large array of permanent sensors has been deployed. Two instrumented boreholes at the other two corners operative since 2021.
- Measurements show a peculiar very low level of seismic noise in the ET-LF band (2-10Hz), where the noise level match or goes even below the Peterson's NLNM! The projected (seismic) Newtonian noise is also compatible with the ET-D sensitivity curve.
- Low electromagnetic noise, acoustic noise measurement ongoing.
- Possible local sources of noise (e.g. wind farms) are under study.
- From the geological and physical point of view, Sardinia is an optimal candidate to host the Einstein Telescope, either in Δ or in L configuration!