

ET-PP

M4.1 Report

Site-specific Characteristics impacting ET performances

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1 Introduction

In this document we define the site characteristics that may have an impact on the performance of the Einstein Telescope (ET). The physical environment of experiments in modern fundamental physics plays an increasingly important role with great impact on infrastructure, cost, and science.

In particular, the environment has a crucial role in a third-generation gravitational wave (GW) observatory like ET. Site conditions (e.g. geological and geodynamical features, ground water) influence the construction feasibility, costs and lifetime of the infrastructure and, at the same time, may impact detector performance (e.g. underground water flow may produce Newtonian Noise) while environmental noises (e.g. seismic motion) have a direct impact on the detector sensitivity and duty cycle.

This document is divided into 6 different sections related to physical variables, to the geological and geotechnical aspects, to the measurement standards and procedures that must be carried out in the characterization of the Einstein Telescope candidate site, the status of characterization activities ongoing at the Sos Enattos and EMR candidate sites and to the study of the anthropogenic noise at the Sos Enattos site. Only since summer 2025 Lusatia has officially been recognized as a third ET candidate site and therefore it was not possible to adequately summarise the activities in Lusatia on such a short time scale in this report. Activities in Lusatia are ongoing and following the time line for the EMR candidate site with all studies completed by the end of 2026.

2 Site Characteristics - Physical Variables

In this section, we discuss the set of physical variables, and their measurements, which have an impact on ET's performance and operations.

2.1 Seismic Measurements

A thorough knowledge of the seismic field at the candidate sites carries crucial information both for the construction and operation of ET. It is important to understand the properties of the local wavefield in terms of frequency, amplitude and type of dominant waves and to assess its time variability, possibly identifying the seismic source. (Amann, Site-Selection Criteria for the Einstein Telescope, 2020) have already pointed out which kind of seismic measurements are suitable for site characterization. Long term measurements (one or more years of continuous seismic waveforms recordings from broadband instruments can be used to assess the seismic noise levels and its variability as a function of the seasons and anthropic activity. These measurements should be carried at several sites that allow the sampling of the candidate site area (e.g. stations placed at the three vertices of the infrastructure) simultaneously recording signals at surface and in boreholes at depth.

Short term seismic measurements (Amann, Site-Selection Criteria for the Einstein Telescope, 2020) on the other hand can provide detailed information about the physical properties of the subsurface rocks and the composition of the seismic wavefield. These require a certain number of stations (tens to hundreds) arranged in an array configuration with a spacing and configuration suitable to sample the target frequency bands and the isotropic or anisotropic properties of the expected seismic sources. These measurements can be conducted either passively (using the ambient noise) or by active surveys using sources such as vibrators. Host teams should provide these useful studies to assess how the ET duty cycle can be affected by ambient disturbances:

1. Correlations between the seasonal variations of the microseismic peak and the storm surge or wave heights in the surrounding oceans. Indeed, microseismic events could couple with the residual tilt of suspended elements of the ET detectors affecting the control loops. (Di Giovanni M. C., 2021) showed that in the Sardinia candidate site there is a clear correlation between the seismic noise at 0.22 Hz and the wave amplitude in the western Mediterranean Sea, including signatures from storms in the north Atlantic Ocean. We recommend monitoring the amplitude and variability of microseismic events at all the candidate sites, at least for a period of one year.
2. Effects of regional and local seismicity, both for natural events (earthquakes) or anthropogenic (e.g. quarry blasts). For the period of observation a catalogue of events should be provided, including the peak ground acceleration (PGA) or peak ground velocity (PGV). This can be useful to estimate the frequency and the amplitude of ground motions that we may expect at each site.
3. Similarly to point 2, the effects of the teleseismic phase arrivals should be provided, together with PGA and PGV. (Acernese, 2022)] showed that during the O3 observation run at Virgo the 65% of control losses due to earthquakes were caused by teleseismic phases.
4. Identification of potential local noise sources related to human activities (such as windmill parks, railways and so on) and their global effect at planned location for the infrastructure.
5. Based on the information provided by previous points, a statistical study of the resilience of the detector to the above-mentioned disturbances should be done, considering the ET design sensitivity and one (or more) target(s). An example is provided by (Allocca, 2021) focusing on the detection of intermediate-mass black holes (IMBH) constrained by seismic ambient noise data measured in Sardinia.

2.2 Gravimetry & Geodynamics Studies

The geodetic site characterization aims to study the low frequency response of surface and sub-surface

variable processes (i.e. processes on the time scale from few seconds up to few decades), thus concerning mainly the impact on the infrastructure lifetime and quality preservation. In particular, the focus is on the role played by sub daily, seasonal and slow varying processes induced by the groundwater cycle and other geodynamic and anthropic-induced ground deformations. The physical quantities to be monitored are:

- the local and instantaneous gravity variations.
- the gravity anomalies within the area of interest. Collecting all available gravity data available for the area and eventually planning a new dedicated survey to gain more details.
- the strain, strain-rates and tilt variations measured on the Earth surface and eventually below the surface. Differential deformations in a region may arise from regional geodynamic processes, hot springs and faults that provide pathways to the surface for water flowing, large gravitational slope deformations or groundwater level variations that cause deformations in sedimentary basins (poroelastic) as well as in limestones outcrops (elastic). Mapping the surface deformations and monitoring time dependent 3D deformations define the long-term stability of the monitored area. The simultaneous knowledge of the time variable gravity field and deformation field should allow us to discriminate processes due to overpressures (e.g. in confined aquifers or gas storage reservoirs) or mass flow in the ground (e.g. groundwater flow, tectonic/volcanic processes).

2.3 Magnetic Noise

Electromagnetic (EM) fields, with natural or artificial origin, are present almost everywhere in our environment and, depending on their intensity or frequency band, could act as a disturbance for any electronic equipment and for magnetic or charged materials. For this reason, they represent a significant source of noise for ET: indeed, noise generated by EM fields can affect the detector in different ways. First, the EM noise can directly couple with magnetic actuators placed on the suspended mirror, or also along the suspension chain; secondly, it can induce currents on electronic equipment, cables, and connectors, potentially affecting critical signals used for the interferometer control and producing, in this way, an indirect disturbance on the detector output. The first kind of coupling is more significant at low frequency (al. A. C., Magnetic coupling to the advanced Virgo payloads and its impact on the low frequency sensitivity, 2018) since the shielding of the vacuum chambers is not effective in this band, while the second is more important at higher frequencies (Nguyen P. et al. (2021))

The natural EM noise, in the ET frequency band, comes from resonance phenomena occurring in magnetosphere and ionosphere cavities (Bianchi, C. 2007). Between them, the most important, because of their intensity, frequency, and large-scale coherence, are the Schumann Resonances (SR). These are a set of broad peaks, in the extremely low frequency (ELF: 3-3000 Hz) band of EM spectrum, produced by the global lightning activity and propagating in the ionosphere (A. Nickolaenko, A. 2014). The first five SR modes are at 8, 14, 20, 26, 32 Hz; their intensity decreases with frequency. The SR are detectable, in quiet environments, from any location of the Earth, showing significant coherence even at far location (Coughlin M. W. et al. 2018) and present peculiar daily and seasonal variation (Satori, 1996). Given these characteristics they can directly limit the sensitivity of ET (Amann, Site-Selection Criteria for the Einstein Telescope, 2020) (Janssens, K. 2021) by acting as a local EM disturbance, but can also have an impact on search for stochastic gravitational waves, based on correlation between far detectors (Abbot B. P. et al. (2019)).

Other sources of natural EM noise also exist, especially at higher frequency; they are still related to atmospheric electric discharges and have larger frequency spectrum, typically ranging from 1 to 40 kHz (C. Bianchi, 2007). However, for these events the direct coupling is expected to be very low (al. A. C., Investigation of magnetic noise in Advanced Virgo, 2019) (Abbot B. P. et al. 2016) giving no significant contribution even for third generation gravitational wave detectors. Of course, exceptions are possible for lightning events very close to the detector (Acernese, 2022). At higher frequencies the natural sources are

very weak and only include cosmic EM in the high and very high frequency band (HF: 3-30 MHz, VHF: 30-300 MHz).

Apart from natural ones, a lot of artificial EM sources are present in our environment. At extremely low frequency, the main source is represented by power lines, while a large variety of electronic devices is an important noise source at very low frequency (VLF: 3-30 kHz) (Bianchi, C. 2007). Other contributions, most significant at higher frequencies (30 kHz – 300 MHz) come from radio communications (AM and FM), TV transmissions (VHF-UHF), mobile phones and automotive ignition (Bianchi, C. 2007). Due to their high frequency content, these EM fields cannot affect the ET detector directly in its frequency band but can produce disturbances in phase/amplitude RF modulation/demodulation of the laser beams used for locking and alignment purposes.

The physical variables that are representative of the EM noise are electric and magnetic fields. For low frequency measurement both electric and magnetic field probes can be used, even if magnetic probes are normally more compact. Instead, for high frequency measurement, electric field probes are better suited. The site characterization cannot include the noise produced by the electrical or electronic equipment that are necessary to manage and operate the full ET detector, but it is necessarily limited to the characterization of the site typical noises. Since the most relevant source is the natural noise at low frequency, namely the Schumann Resonances, and given the availability of small and compact magnetic field probes, with very high sensitivity in the ELF band, it comes that very convenient probes to use for the EM site characterization are coil induction broadband magnetometers. Such probes have typical frequency bands extending from fraction of mHz to several kHz, with intrinsic noise levels as low as 10^{-4} nT/Hz^{1/2} at 1 Hz: about one order of magnitude lower than the typical natural spectrum. Moreover, such probes are usually sealed, so they can be safely buried for more accurate and low noise measurements.

Since the SR have usually only horizontal magnetic field components, a set of two orthogonal horizontal magnetometers is often sufficient to monitor the most important fraction of SR dynamics in a given location, even if, in case of geological irregularities in the surrounding crust, a vertical magnetic component may arise (Nickolaenko, A. 2014), requiring a third vertical magnetometer for its monitoring.

2.4 Other Environmental Noises

Among the other environmental noises of interest, the variations of air pressure can lead to a source of noise for the gravitational wave detector. The noise will most likely be determined by the noise in the cavities and therefore it is impossible to measure it before the actual construction. However, some part of the work can already be done. We can measure the acoustic and barometric noise on the surface at the locations of the end stations of ET. The aim is to characterize the noise as it is now, including such characteristics as spectra, amplitudes, time variability, as well as identification of sources of noise. The sources can be related to weather - wind, rain, water flow, sea waves; seismic activity and noise, and be due as well to human activity. In the sites where underground facilities exist, we can estimate the transfer function of the noise on the ground to the underground.

Therefore, host teams should measure the following quantities:

- infrasound noise on the ground (frequency range 0.1Hz to 30Hz)
 - micro barometric noise - this is the low frequency extension of the infrasonic noise with frequency down to microhertz.
- weather at sites: temperature, wind, pressure, precipitation, humidity.

2.5 Summary of physical variables to be measured

In the following there is an incomplete list of physical variables to be measured that have been discussed in previous sub-sections:

- Seismic field. Properties of the local wavefield in terms of frequency, amplitude and type of dominant waves and assess its time variability, possibly identifying the seismic sources. Useful studies to assess how the ET duty cycle can be affected by ambient disturbances are the following (Naticchioni, et al., 2023):
 - Correlations between the seasonal variations of the microseismic peak and the storm surge or wave heights in the surrounding oceans.
 - Effects of regional and local seismicity, both for natural events and anthropogenic.
 - Effects of the teleseismic phase.
 - Statistical study of the resilience of the detector to the above-mentioned disturbances.
- Geodetic site characterization:
 - Local and instantaneous gravity variations.
 - Gravity anomalies in the area.
 - Strain, strain-rates and tilt variations measured on the Earth surface and eventually below the surface.
- Magnetic noise. Electromagnetic (EM) fields could act as a disturbance for any electronic equipment and for magnetic or charged materials. For this reason, they represent a significant source of noise for ET. EM noise can directly couple with magnetic actuators placed on the suspended mirror, or also along the suspension chain; secondly, it can induce currents on electronic equipment, cables, and connectors, potentially affecting critical signals used for the interferometer control and producing, in this way, an indirect disturbance on the detector output.
 - Natural EM noise.
 - Artificial EM sources
- Other environmental noises.
 - Acoustic and barometric noise on the surface at the locations of the end stations of ET: infrasound noise on the ground (frequency range 0.1Hz to 30Hz); micro barometric noise; weather at sites (temperature, wind, pressure, precipitation, humidity).

3 Site characteristics – geological, geophysical and geotechnical information

The construction of a deep (~300 m) and extensive underground infrastructure such as the Einstein Telescope (ET), with more than 30 km of tunnels and experimental halls, involves significant challenges. The main difficulties arise from the limited knowledge of geological conditions at large depths, where structures, faults, fractures, lithological variability, and alteration processes remain poorly constrained. These factors not only affect construction feasibility but can also influence the performance of the facility.

Sub-surface geology. Subsurface geology plays a central role. Variations in seismic amplitude may occur over short distances due to filtering, attenuation, or amplification, and a detailed understanding of these effects is required to model seismic terrestrial gravity noise. Geological heterogeneities such as lithological contrasts, fracturing, faulting, and water ingress must be carefully analyzed through integrated geological, structural, and rock-mechanical models, supported by detailed mapping and uncertainty assessments. Tunnel stability, subsidence, karst voids, earthquakes, and changes in groundwater circulation represent major risks that demand advanced predictive tools to anticipate geological behavior and environmental impacts. Site-specific effects caused by subsurface variability can strongly modify seismic wave propagation, requiring microzonation studies. These effects depend on the dimensions of geological bodies relative to seismic wavelengths, while attenuation is governed by elastic properties, degree of fracturing, porosity, groundwater

content, and fluid pressure. Since these processes directly influence ground vibrations, they have direct implications for detector control systems and seismic isolation. Comprehensive geological and seismic characterization is therefore indispensable for both construction safety and the scientific success of the ET.

Groundwater flow. Groundwater represents a critical challenge, as inflows into tunnels and shafts may be considerable depending on permeability. Such conditions often require drainage systems with powerful pumps, which can themselves introduce ambient noise at ET depth, while water flow in drainage tunnels may act as a source of gravity noise. Zones of high permeability can sometimes be treated with cement injections, but a reliable evaluation requires detailed hydrogeological investigations across different scales. While intact rock typically has low permeability, fractured masses can exhibit high values, making fracture connectivity and faulting decisive factors. Hydraulic conductivity, storativity, porosity, drainage efficiency, and pore pressures all need to be characterized in depth, often through borehole packer tests. Transient pore-pressure variations induced by excavation may trigger poroelastic responses or subsidence, while karstic formations add further complexity due to extreme heterogeneity in hydraulic conductivity. For this reason, hydrogeological models must integrate measured parameters such as water pressure, solute concentrations, porosity, and storativity into maps, cross-sections, and three-dimensional flow models, providing the basis for hazard assessments during both construction and operation.

Rock quality and geomechanical parameters. Geomechanical properties of the host rock determine tunnel stability and govern the propagation of seismic noise from the surface to the underground instruments. Collecting rock-mechanical data is essential for predicting rock-mass behavior, identifying potential hazards, and optimizing both technical solutions and economic planning. Relevant parameters include the presence of faults and fractures, elastic properties such as Young's modulus and Poisson's ratio, compressive, tensile, and shear strengths of intact rock and discontinuities, as well as in situ stress fields. These data are crucial for evaluating risks such as squeezing, wedge failure, swelling, subsidence, and excavation instability, all of which depend on excavation methods and geometry.

In summary, the realization of the Einstein Telescope requires an integrated and multidisciplinary approach to geological, hydrogeological, and geomechanical conditions at depth. A thorough and coordinated characterization of the subsurface environment is essential not only for construction feasibility and long-term stability, but also for guaranteeing the scientific performance of this next-generation gravitational-wave observatory.

4 Measurements standards and procedures for the characterization of the ET candidate sites

In this section we describe the measurement standards and procedures that must be carried out in the characterization of the Einstein Telescope candidate site for the physical variables listed in previous sections.

4.1 Long-duration Seismic Measurements

Broadband three-components high-class seismometers are required for the evaluation of the seismic levels measured at the candidate site area. They should be placed in vault and borehole installation ensuring a good contact with the surrounding rock and the best thermal insulation possible.

For the proper evaluation of the seismic background level, the 10th, 50th and 90th percentile of the acceleration proper spectral density (PSD) must be assessed in the 10⁻² - 20 Hz band. The PSD should be calculated following the McNamara & Buland method with an 1800 s window and 50% (900 s) overlap.

Broadband measurements should last at least two years. Host teams should assess the microseismic amplitude and its seasonal variations.

Borehole seismometer installations are required at the proposed corners of the ET infrastructure, at a depth at which the noise can be assumed representative of that one you will have in the ET caverns.

Underground borehole installation should be always paired with a surface-level installation, while where possible (e.g. former mines, underground laboratories) vault installations are recommended at different depths, to calculate the cross-correlation and amplitude-depth function. All the stations must be synchronized in time with a common timing reference (e.g. GPS timing).

Three-component measurements are required for the calculation of the H/V (horizontal to vertical) spectral ratio, providing information about the source mechanism of the noise as well as information about the local geological setup.

The stationarity of the background noise should be assessed by the measurements, evaluating the occurrence of transient noises (glitches lasting tens to few hundred of seconds) and their amplitude. Significant transient events (either of natural or anthropic origin) should be collected in a catalogue for the observation time. The host teams should also provide a historical log of seismic events in the candidate area. Seismometers must be chosen according to the ambient seismic-noise spectrum and should achieve a signal-to-noise ratio better than 10 between 3 and 10 Hz. Highest quality seismometers with self-noise below Peterson's global low-noise model in the relevant frequency band are to be used at least for the underground measurements. Installation should be done following the prescription provided by the company seller (see the (Bormann, 2012), chapt. 7 for a detailed description of seismic station installation.)

4.2 Short-duration Seismic Measurements

Short-duration measurements can be achieved using arrays of broadband and/or short-period seismometers (tens to hundreds). These measurements should provide information about the body to surface wave content of the seismic noise and the propagation characteristics like the surface-wave dispersion and its propagation direction. It is required that host teams provide array measurements at least in the areas surrounding the proposed corners of the ET infrastructure. Ideally, PSD should be measured by an array covering a larger extent than just the corner point. This would allow the generation of spectral noise distribution maps in four frequency bands: [0.5-2 Hz], [2-4 Hz], [4-10 Hz], [10-20 Hz].

Seismometers must be chosen according to the ambient seismic-noise spectrum and should achieve a signal-to-noise ratio better than 10 between 3 and 10 Hz. This requirement could be not achievable in underground installations and in general when the local natural background noise approaches the Peterson's low noise model (NLNM). In this case, the requirement could be relaxed to a factor 7 profiting from the higher level of stationarity of the seismic field (Amann, Site-Selection Criteria for the Einstein Telescope, 2020). Minimum and maximum aperture of the array should be chosen according to the Rayleigh-wave speeds in the considered frequency band (Amann, Site-Selection Criteria for the Einstein Telescope, 2020).

Performing array measurements, the host teams should provide an estimation of the surface wave dispersion curve, the characterization of seismic sources (e.g. unravelling the anisotropy of the seismic field), and the estimation of the modal content of the seismic noise. If there is evidence of local sources of noise (e.g. wind farms, railways, operating quarries, etc), they should be studied evaluating the properties of the associated spectral lines (e.g. amplitude with respect to the mean background, percentiles, stationarity, etc) in the band of interest. Short-duration measurements with seismic arrays should last a period of several weeks for a better understanding of the diurnal and the weekly variations in the seismic noise background.

Active seismic surveys based on reflection/refraction seismology should be performed in the areas covered by the seismic arrays, possibly complementing the seismometer array with lines of geophones (tens to hundreds of sensors), providing information about subsurface structures. Active seismic surveys should be performed in collaboration with the WD2 activities to maximize the scientific output of these measurements.

4.3 Gravimetry & Geodynamics Measurements

A gravimetric survey is worthy to gain a better understanding of the subsurface geology at the proposed ET sites. The availability of continuous gravimetric measurements at the ET site will also enable it to detect time-varying mass distributions. A complete annual cycle could be used for the detection of groundwater mass variations.

The regional surface deformations can be monitored by means of GNSS and InSAR techniques, possibly combining the two data sets. The regional differential deformation could be inferred using the existing GNSS stations within a radius of at least 80 km from the proposed site and covering a time span of at least 4 years. Time series of daily GNSS positions are well suited to infer the actual active tectonic motions (i.e. secular drifts) and consequently the strain-rate map of the region (the rate of change of the deformation). GNSS stations located in proximity of the ET site will provide useful data to study the response to groundwater cycle. For this study, at least one year of daily observations should be available. Long time series of ground deformation determinations, based on ascending and descending In SAR acquisitions, will be useful in characterizing the expected deformation in the full area of the proposed ET site. The available GNSS data should also be used as ground control points in the time series analysis to mitigate possible atmospheric artifacts.

4.4 Magnetic Noise Measurements

A set of at least 2 magnetometers are required for the characterization of the locations corresponding to the vertices of ET. The probes must be installed horizontally to increase the sensitivity to the Schumann Resonances (SR); the probe orientation should be north-south and east-west to help comparison with similar far stations. Eventually a third probe can be installed vertically to have a complete magnetic characterization of the selected location. The probes located in the surface should be buried at least for 20 cm underground to avoid possible distortion, at low frequency, produced by mechanical vibrations (Metronix MFS06e manual, s.d.). In case of installation in underground caverns or tunnels it is enough to firmly fix the sensor on the ground. If possible, the probes should be far enough from power lines or strongly emitting electric equipment, like pumps, air treatment units and so on. This is important to avoid possible probe saturation due to very intense electromagnetic (EM) emission occurring at selected frequencies, like 50 Hz.

Broadband induction coil sensors should be used, with an intrinsic noise not larger than $3 \cdot 10^{-2}$ nT/Hz^{1/2} at 10 mHz and $3 \cdot 10^{-6}$ nT/Hz^{1/2} at 100 Hz. The frequency range of the probes should be at least in the interval 1 mHz to 100 Hz

Suitable data logger, having input dynamic range compatible with the magnetometer output, at least 24 bits resolution, GPS disciplined timing and fully remotely configurable should be used. The sampling frequency to obtain a good monitoring of the SR should be at least 150 Hz since for a very quiet environment it is possible to detect up to the 9th SR at about 60 Hz (Nickolaenko, A. 2014), (Satori, G. 1996).

For a complete characterization of the site, data should be collected for a period of at least one year; this will allow more detailed indication about the daily/seasonal variations of the natural and artificial magnetic noise intensity, the spectral characteristic, and the typical time evolution. When possible, to get information about the characteristics of the underground environment, it is suggested to install at least a couple of probes with the same orientation, one in surface and one underground at one of the vertices. In this way a direct comparison between surface and underground magnetic noise would be possible.

Before the installation, especially for sensors placed at different levels, the recommendation is to perform a parallel sensor test, placing all the sensors horizontally and parallel, separated by ~2 meters and far enough from local electromagnetic noise sources. In this way the calibration of each probe can be verified, and defective sensors can be eventually individuated.

4.5 Other Environmental Noise Measurements

The other environmental variables to be measured are: infrasonic noise, micro barometric noise, and weather: temperature, humidity, wind, precipitation.

- Infrasonic noise

The measurements will be done using the Gras (or similar microphones). The microphones on the ground should be shielded from the wind and precipitation by tents/covers. The measurements should be done with the sampling frequency of at least 250Hz. The duration of the measurements should cover one year - although the measurements can be restricted to short - one-week campaigns covering different seasons.

To perform the infrasound measurement is suggested to use a microphone with a sensitivity of 8 mV/Pa with a frequency range from 0.1 to 10 kHz. Installation should be done following the prescription provided by the company seller.

- Weather data

The weather information should be collected either from dedicated stations at the locations close to the planned locations of ET end stations, or from public weather stations in these locations if they exist. Temperature, humidity, precipitation rate should be sampled with the frequency of 1 per minute, while the wind speed should be measured with the frequency of 1Hz. The measurements of temperature, humidity should be done at the height of 1.5 above the ground. Ideally the wind measurement should be done by placing the sensor at a height of about 10 meters, and distant at least 15 meters from buildings or trees.

4.6 Geological and Geotechnical measurements

An extensive investigation campaign is needed to reconstruct the stratigraphic sequence of the subsurface and to characterize the geotechnical and lithological properties of the soils and rocks. The activities included the execution of deep geognostic boreholes, in situ measurements, sampling of undisturbed cores, and a range of geophysical prospecting techniques. The program should include the realization of boreholes, collection samples for laboratory analysis and the execution of in situ tests like permeability, dilatometric, and hydraulic fracturing tests, complemented by gas monitoring, geophysical logging to provide high-resolution data on rock properties and fracture patterns. Groundwater behavior may be monitored by using piezometers. A broader understanding of subsurface structures can be provided by complementary surface geophysical investigations, including seismic reflection profiling, geoelectrical prospecting, and magnetotelluric surveys.

5 Status of Characterization Activities at Candidate Sites

5.1 The Sos Enattos Candidate Site

Sardinia, and particularly Barbagia, are a unique environmental, geological and seismic system in Italy and probably in Europe. Belonging to a geological platform distinct from the Italian one, the very low seismic activity (Stucchi M., 2011) and a very low population density (Union, 2019). make them a unique and extremely promising ecosystem for all those scientific research activities that require an environment as quiet as possible, where seismicity, acoustic noise and vibrations of anthropic origin are among the lowest observed on the globe. These conditions are indispensable for the search for gravitational waves, for

gravitational physics experiments and for geophysical observations or even for the recording of seismic events on a local, regional or global scale.

The very low seismic, acoustic and electromagnetic noise found in the area surrounding the Sos Enattos mine (Lula, NU), thanks to a measurement campaign started in 2010, with funding from the European Commission in FP7, have elected it as a candidate site to host the Einstein Telescope.

The area of the Sos Enattos mine, now dismissed but still manned for environmental safety, was selected as one of the candidate sites to host ET. The mine is in Sardinia, 30 km northeast of the city of Nuoro, and includes a complex network of tunnels (50 km total length). Nowadays, through one of these tunnels, named Rampa Tupeddu, is possible to reach a depth of about 160 m. Since 2018, the mine hosts SAR-GRAV, a laboratory for fundamental physics research in low-ambient-noise environments that also provides a research and development infrastructure for ET.

The area identified to host the infrastructure has been equipped with an extensive array of measurements stations deployed and improved during the last five years.

A long-term monitoring of the seismic noise at the site started on March 2019 and is currently ongoing. Four stations were instrumented for this purpose: SOE0 at ground level (400m asl), and the three underground stations: SOE1 (at -84m), SOE2 (at -111m) and SOE3 (at -160m). Each station is equipped with at least a broadband triaxial seismometers. Furthermore, the mine hosts 1 high precision tiltmeter (Archimedes

prototype, 1 weather stations, 2 microbarometers, 3 magnetometers and 3 microphones (see Figure 1 for a map of all the sensor location).

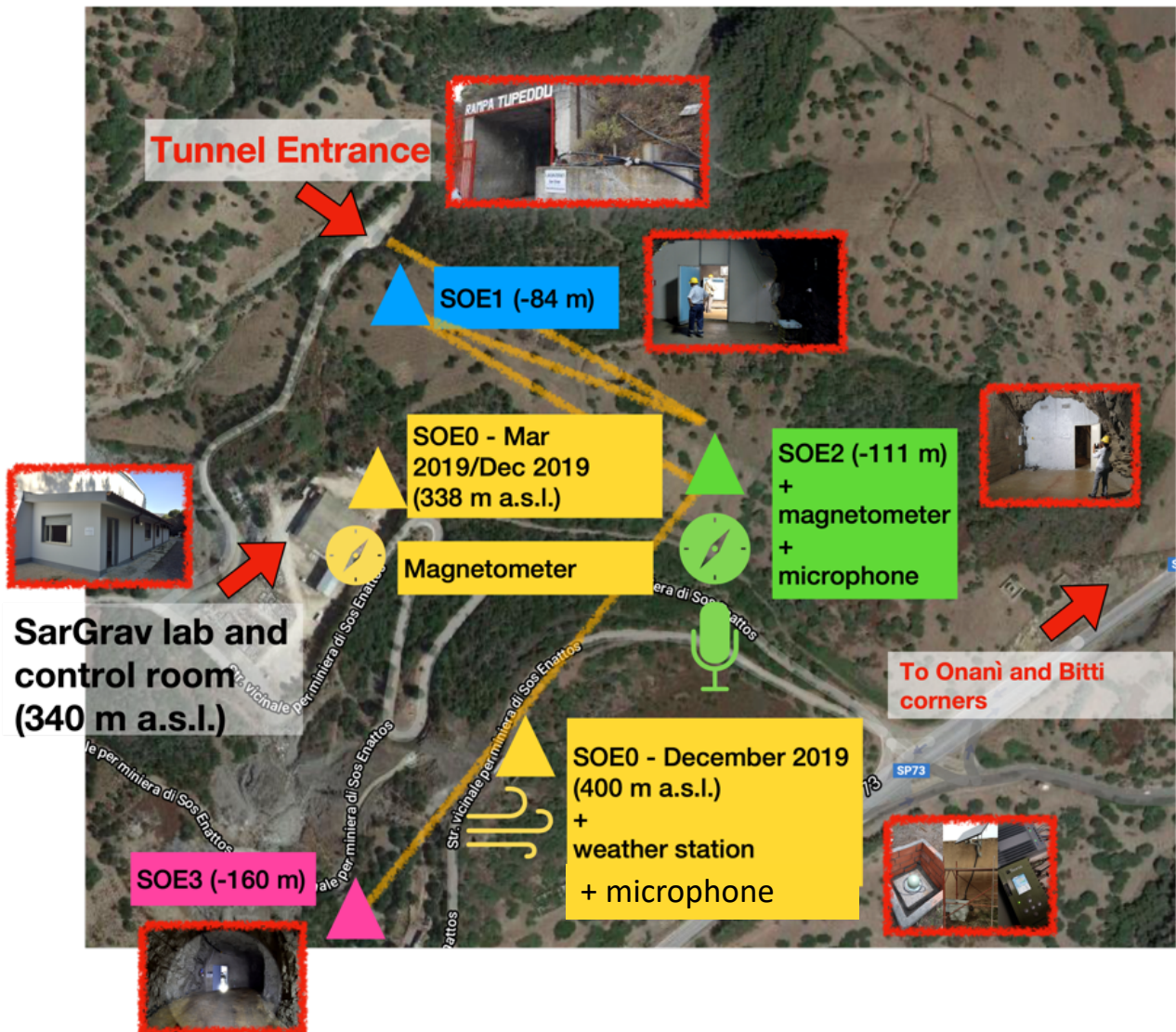


Figure 1. Permanent measurement stations at the Sos Enattos mine since 2019

The seismic monitoring of the Sos Enattos site, in the Lula area, is carried out in collaboration with INGV, resulting in a strong synergy between the two research institutes. Moreover, the INGV project MEET-FABER (PNRR funds) for a geophysical observatory at Sos Enattos to understand the geodynamics of the Earth will strengthen the collaboration for the geophysical characterization activities, including the enhancement of the installed array of broadband triaxial seismometers, which allows to study on a long term-scale the feature

of the seismic background noise at Sos Enattos, the variability of local sources of noise, and to derive the spectral ratio of the horizontal to vertical (H/V) ground motion.

Since 2021 a long-term measurement characterization of the area around the Sos Enattos mine is on-going, in particular at two possible corners (either in triangle or L configuration) of ET in Sardinia, named Bitti (P2) and Onanì (P3), where two boreholes have been drilled down to a depth representative of the ET infrastructure, i.e. about 250-300m (see Figure 2). Two broadband borehole seismometers have been successfully installed at surface and inside the boreholes at a depth of ~ 250 m. An optical fiber strain-meter



Figure 2. Bitti (P2) and Onanì (P3) corner boreholes.

has been also buried in each borehole. P2 and P3 areas have been investigated by a combined approach including active seismic and geoelectrical surveys performed on the crystalline rocks exposed.

The characterization of the local seismic field at surface has been completed with the deployment of the seismometer array at the two corners for periods of two weeks. P2 has been equipped as well with magnetometer and a weather station.

Temporary arrays have been deployed to identify, localize and quantify possible local sources. In particular, a temporary array of short-period seismometer has been deployed along the line from P2 to the large windpark of Buddusò, that is located about 15km away from the permanent station; the data provided by this deployment allowed to estimate the seismic noise injected into the ground by the wind mills, understanding the propagation through the local rocks and the attenuation of the noise with the distance and allowed a better definition of the preserved area around the ET candidate site.

A detailed geological structural analysis has been completed at P2 and P3 corners and a geological structural map of the whole Sos Enattos area has been produced.

The results of site characterisation activities have been presented at conferences: TAUP 2019 and 2023, XI ET Symposium (2020-2024), GWADW 2021 and 2023, and ET-SPB workshops held in 2021, 2022 and 2023.

The results of the five years-long characterization have been published in [L Naticchioni et al 2020 *J. Phys.: Conf. Ser.* **1468** 012242], [M. Di Giovanni et al, *Seismological Research Letters* (2021) 92 (1): 352–364], [A. Alloca et al., *Eur. Phys. J. Plus* 136, 511 (2021)], [A. Alloca et al., *Eur. Phys. J. Plus* 136, 1069 (2021)], [M. Di Giovanni et al., *Geoph. Journal Int.*, 234,3 (2023)], [G. Saccorotti et al., *Eur. Phys. J. Plus* 138, 793 (2023)], [L Naticchioni et al 2023, *PoS Proc. Sci. (TAUP 2023)* 110], [G. Diaferia et al. 2024, accepted for publications by *Geophysical Journal International*.

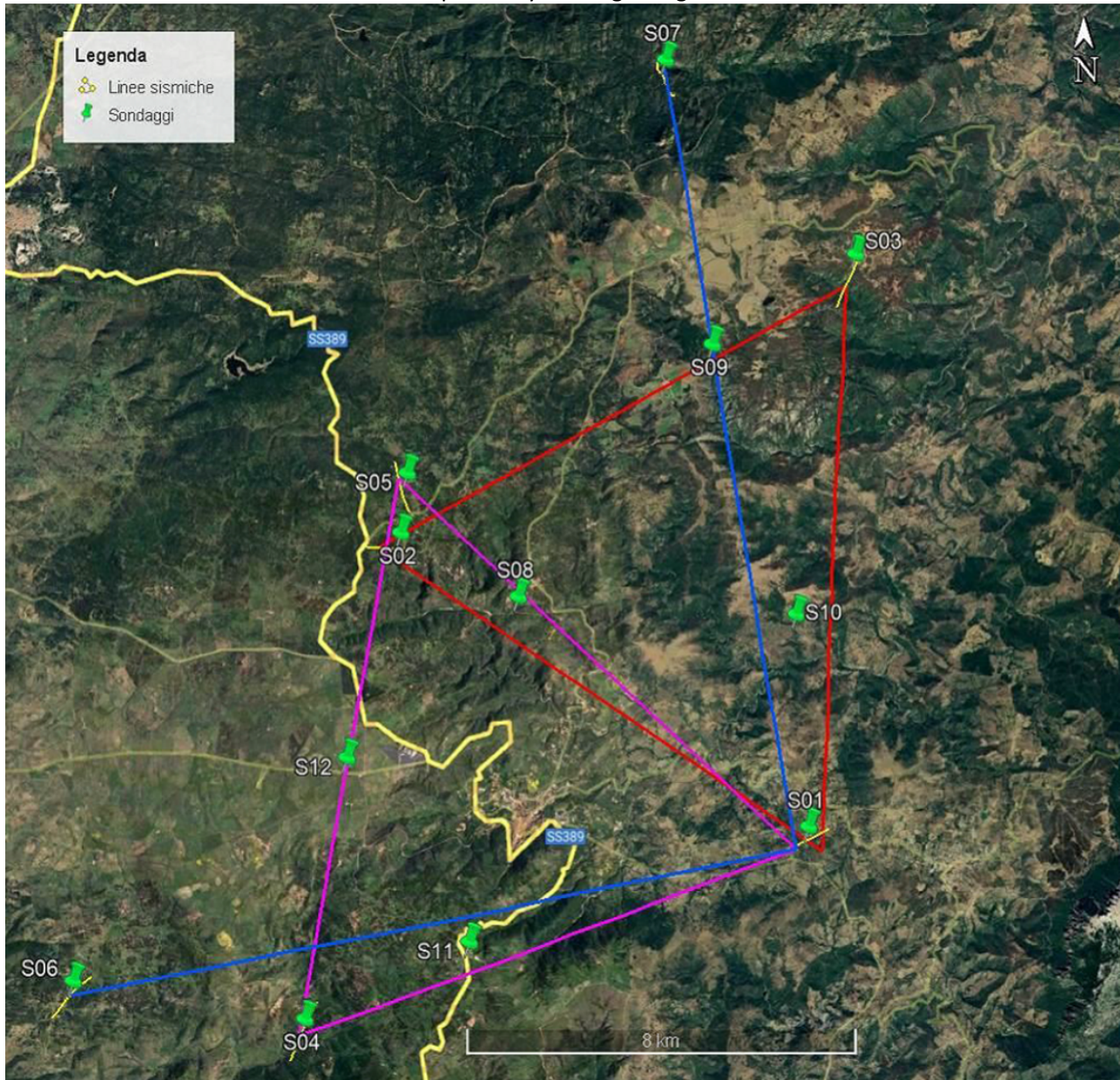
Currently there is ongoing a preliminary feasibility study by a private company that is considering both triangular (six interferometers inserted in a system of tunnels and caverns with an equilateral triangle layout on a side about 11 km) and L shape (two interferometers inserted in a system of tunnels and caverns with an 'L' layout on a side about 16 km) configurations. The study will face all the aspects concerning the realization of the infrastructure: Modelling and Layouts; Preliminary cost estimate (excavation); Evaluation of TBM configuration and tunnel monitoring; Preliminary indications on the management of excavated lands and rocks; Preliminary strategy on the management of excavated soil and rock.

Considering the results of characterization studies, the local sources of noise (the main one is the windmill park in Buddusò), the knowledge of the local geology, three possible geometries are under investigations:

two for the triangle and one for a possible L (see Figure 3). The pre-feasibility study is expected to be completed by June 2025.

In parallel, further characterization measurements are ongoing: additional measurement stations are going to be installed at corners under study; an acoustic measurement campaign is ongoing to confirm the theoretical assumptions on the turbulence models used in the calculations of the Newtonian Noise induced by atmosphere and to confirm the minimum depth of the ET infrastructure; a gravimetric campaign will take place in the next months.

The characterization activities will be completed by the beginning of 2025.



Studies are ongoing to quantify the impact of measured site characteristics on ET detector.

Figure 3. ET geometries under study in the Sos Enattos area.

5.2 The EMR Candidate Site

Status Update per August 2025

The Euregion Meuse-Rhine (EMR) site characteristics appear to be favourable to host the Einstein Telescope. The unique soil allows for dampening vibrations and building the research infrastructure in a relatively quiet landscape. The region offers strong research institutes and academia, and world-class high-tech industry. Furthermore, the infrastructure and international living and business climate are attractive. A gravitational waves infrastructure has already been established with the ETpathfinder and ETEST research centres and the Einstein Telescope Education Centre.

Subsurface characterization activities have been carried out through a tight integration of the technical disciplines involved: geology, geophysics, hydrogeology, geotechnology, and civil engineering.

Before 2024, four boreholes were realized, of which three were equipped with seismometers measuring noise. Also, all existing historical geological information was integrated and interpreted to build a baseline subsurface structural geological model that formed the basis of the 2024 drilling campaign.

Starting 2024, funds were released for the feasibility study, and the project was accelerated to fully characterize the subsurface in the search area and to confirm the baseline geological model. Technical focus remained on gathering and analysing geo-data to characterize the subsurface, develop a noise impact assessment, and de-risk construction feasibility and costs.

The 2024 drilling campaign of 12 boreholes has recently been completed (see below). Workshops are ongoing to evaluate the cores from all finished boreholes and to develop an updated geomechanical understanding of the search area. In general, good quality rock has been encountered allowing convergence of the search area to a most likely triangle trajectory scenario.

For 2025, the location and trajectory of the most likely triangle has been slightly updated based on the full evaluation of all data from the 2024 drilling campaign (see Figure 4a). A 2025 drilling campaign was defined including six boreholes, to focus on the foreseen vertices and to investigate the geological conditions as well as noise budget at these locations, at the planned ET depth of 150m below sea level. By August 2025, one borehole was completed, three are being drilled and two are planned for Q4.

Geological model

- The subsurface model has been updated with new geological, geomechanical and geophysical data. All new subsurface data (such as core logs, rock stress tests and water flow measurements) are being stored centrally and integrated into a consistent model. An integrated conceptual geological model has been developed and is being updated on the fly, as new results from boreholes are being produced. Evaluation of this model has resulted in small updates of the trajectory of the triangle and formed the basis of the 2025 drilling campaign
- The structural geology data in the overall geological model have been refined using the results of an Active Seismic campaign along acquisition lines close to the foreseen vertices and along the foreseen legs, supplementing the core data from the boreholes and allowing a seismic time to depth calibration. See Figure 4b for an example line. These lines are still undergoing an improved depth migration which is expected to further optimize the geological model.

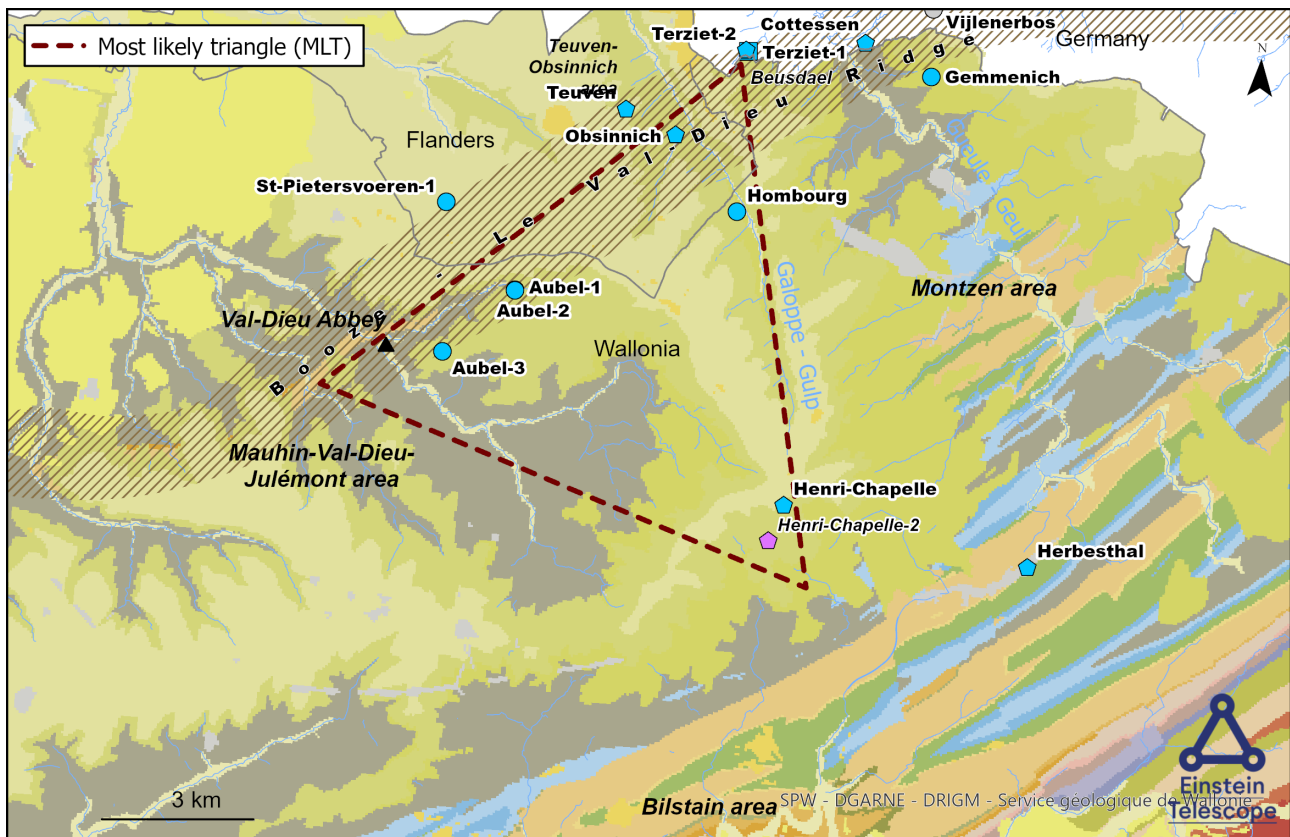


Figure 4a. Most Likely Triangle (EMR site), based on the updated geological model resulting from the 2024 drilling campaign, and the basis for the remaining drilling campaign and noise model measurements.

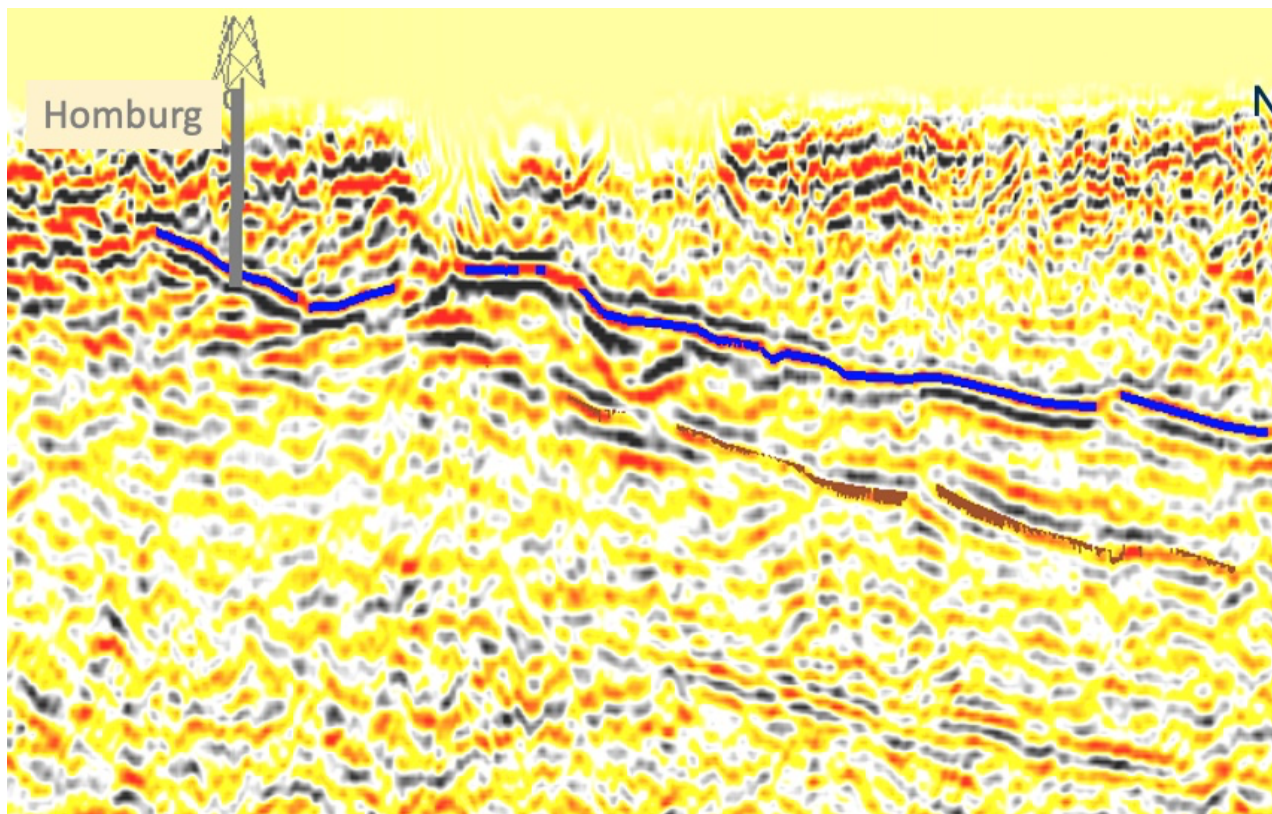


Figure 4b. Active Seismic line to refine the structural geological model away from cored boreholes. Top Dinantian (blue line) ties very well with Homburg well and allows extrapolation in southern direction along triangle leg.

Noise measurements and modeling

- As of August 2025, only subsurface noise data from the station downhole Terziet are available. Additional sub-surface noise stations were planned to be installed and to start measurements in Q1 this year but due to equipment production delays by the contracted company in Canada these measurements have been postponed.
- Production issues have been resolved, and the first new sensor has recently been installed down the Teuven borehole. We expect this sensor to come online momentarily. Another three new sensors will be installed downhole at locations Obsinnich, Vijlen and Herbesthal and are expected to come online by the end of Q3-2025.
- The final three sensors at the foreseen vertices' locations, and at the planned depth for ET, (150m below sea level) will become operational in Q1-2026, or sooner immediately following completion of the final boreholes.
- Meanwhile *surface* noise measurements are being conducted using 700 mobile sensors at the surface as passive seismic stations to develop a regional noise map at the surface, see Figure 4c for a location map of these sensors. We expect the first regional surface noise models early Q4-2025. These surface stations will complement the 7 subsurface seismic stations to develop a regional sub-surface noise model, expected early Q2-2026.
- These surface sensors are also being used to measure noise from wind turbines to supplement existing wind turbine noise measurements. The activities include the development of recommendations to mitigate this type of noise and to advise on the development of regulations and permits for companies interested in deploying wind turbines.
- Magnetic noise sensors have been purchased and are being deployed to complete an adequate model at the vertices' locations following completion of the boreholes in Q1-2026.

Civil engineering

- Geo-technicians have become fully involved in updating the geological subsurface model by logging and evaluating cores for their geotechnical characteristics and to determine the rock's properties and suitability for tunnelling.
- The Facilities and Infrastructure team is developing initial construction models based on this conceptual geological model and its associated geomechanical data.
- An effective interface has been set up with ETO and the instrumentation teams in the Collaboration to discuss the impact of detector designs on civil engineering construction alternatives and the overall construction cost.



*Figure 4c: Network of 700 noise sensors set up in passive seismic mode to develop a regional **surface** noise model, and to supplement sub-surface noise measurements to develop a regional subsurface model.*

Hydrology

- Water flow measurements and pressure tests are being executed at selected completed boreholes with specialized equipment and are being fed into an overall 3D subsurface ground water model. This model will be used to estimate the risk and mitigation of water encounters during tunnelling and to develop mitigating measures to seal off and remove excess water during the operational phase of ET.
- An important update of the subsurface hydrogeological model is expected late Q4-2025.

6 Impact of anthropogenic noise: the case study of Sos Enattos site

In the bandwidth [1,10] Hz, the seismic noise of anthropogenic origin is expected to represent the major perturbation to the operation of the infrastructure, and the site that will host the future detector must fulfill stringent requirements on seismic disturbances.

Seismic arrays have been deployed in proximity of the Sos Enattos mine and in the P2 and P3 area to identify, localize and quantify possible local sources. In the following paragraphs, the studies at the Sos Enattos site are reported.

6.1 Anthropogenic noise around the mine

Signals of anthropogenic origin have a transient nature, and their spectra are characterized by a wide spectral lobe spanning the [3,20] Hz frequency interval. Around the mine area, one may recognize narrow spectral peaks within the [3,8] Hz frequency range superimposed to this wide lobe. Results from slowness analyses suggest that the origin of these peaks is related to vehicle traffic along the main road running east of the mine. For further details see (G. Saccorotti et al., 2023).

Sos Enattos is located within the Hercynian basement of Paleozoic rocks, formerly mined for lead and zinc until 1996. Today, it hosts the SarGrav laboratory for geophysical and fundamental physics experiments. A temporary 15-element seismic array was deployed in early 2021, with data compared to permanent underground seismometers. Broadband sensors were chosen to capture very low background noise.

Analysis of power spectral densities (PSDs) indicates two distinct regimes. Below 3 Hz, the noise field is dominated by oceanic microseisms from the Mediterranean and occasionally the North Atlantic. Above 3 Hz, anthropogenic noise dominates, particularly from vehicle traffic on Provincial Route 73 (SP73). Spectrograms reveal broad spectral lobes between 3–20 Hz and narrow peaks (3–8 Hz), the latter linked to vehicle-induced bridge oscillations.

Slowness and polarization analyses show that the noise is primarily composed of Rayleigh waves generated by vehicles. Wave velocities range from 2 to 4 km/s. Vehicle tracking confirmed that narrow spectral peaks around 6 Hz are associated with bridge resonances along SP73, as validated by geophone measurements directly at the bridge sites.

Spatial autocorrelation (SPAC) and dispersion analysis of Rayleigh waves revealed a dispersive behavior, with phase velocities decreasing from ~ 3 km/s at 5 Hz to ~ 1 km/s at 15 Hz. Inversions suggest shear-wave velocities of 500–800 m/s near the surface, increasing to 2.7–2.9 km/s at depths of 110 m. These results align with independent estimates from quarry blast experiments, demonstrating regional consistency.

The findings confirm that Sos Enattos is one of the quietest sites globally in the 1–10 Hz band, with anthropogenic noise localized and manageable. Mitigation measures could include resurfacing road segments and reinforcing road subgrades to reduce vibrations by up to 57%. Additionally, underground construction naturally attenuates Rayleigh waves, further reducing potential disturbances.

The Sos Enattos mine exhibits excellent conditions for hosting the Einstein Telescope, with very low natural seismic noise and anthropogenic contributions primarily from road traffic. The study demonstrates that with targeted mitigation strategies and underground placement, the site can support the demanding requirements of third-generation gravitational wave detection.

In Figure 4 the array geometry is reported. The geometry was markedly asymmetrical, reflecting the main elongation of the topography.

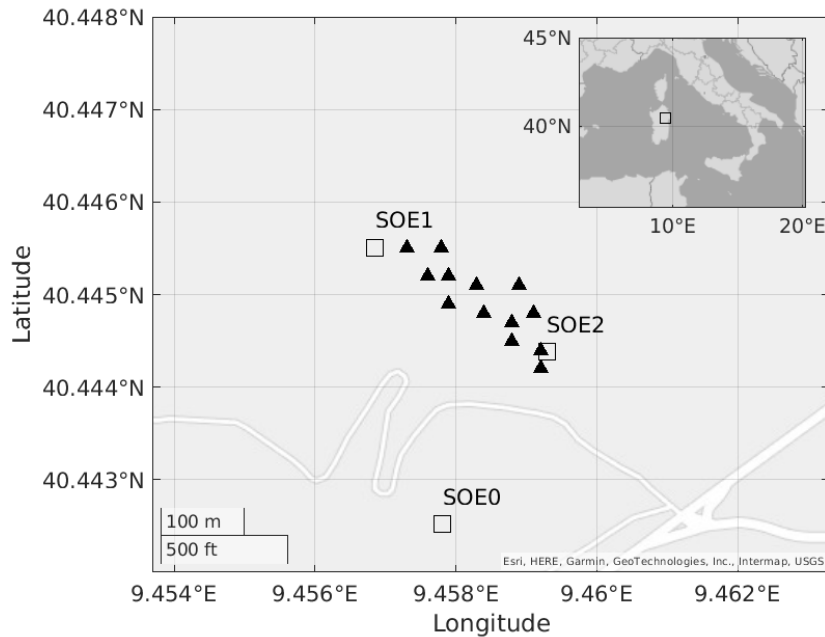


Figure 4. Map view of the array deployment (black triangles). The inset shows the location of the study area with respect to Sardinia and peninsular Italy.

In Figure 5 the typical power spectral densities (PSD) evaluated at all the array elements during 2-h-long windows at night and day times is shown. These sample PSDs evidence clearly that the contribution of anthropogenic sources becomes dominant at frequencies above 3 Hz. A clearer picture of the actual contribution of human activities to the noise spectrum is depicted by the panels in the right column of Figure 5, which show the ratio between the array-averaged PSDs obtained at day and night hours. These plots further confirm that the anthropogenic contribution to the noise spectrum becomes significant at frequencies above a ≈ 3 Hz. For comparison, the same calculations have been extended to data from the underground station SOE1, located within a mine gallery beneath the array (see Figure 4). The attenuation of the spectral power between the surface and underground recordings amounts up to 20 dB, consistently with the factor-10 amplitude decay estimated by (Di Giovanni M. C., 2021). As expected, the day-to-night spectral ratios at the underground site are the same as those estimated at the surface array (Fig. 2, panels b, d, f). In addition, a quite narrow spectral peaks can be observed at frequencies 2.5, 4.5, and 6 Hz. In Figure 6 the time-frequency decomposition (spectrogram) for a 1-h-long recording at the vertical components of the array is illustrated. Energy related to human activities is associated with transient signals; generally, the different frequency bands outlined above appear to be mutually coupled, even if their relative importance varies with time. In particular, the transient wave-trains are characterized by broad spectral lobes spanning the [8, 20] Hz frequency interval, occasionally associated with narrower spectral peaks spanning the [3,6] Hz frequency band.

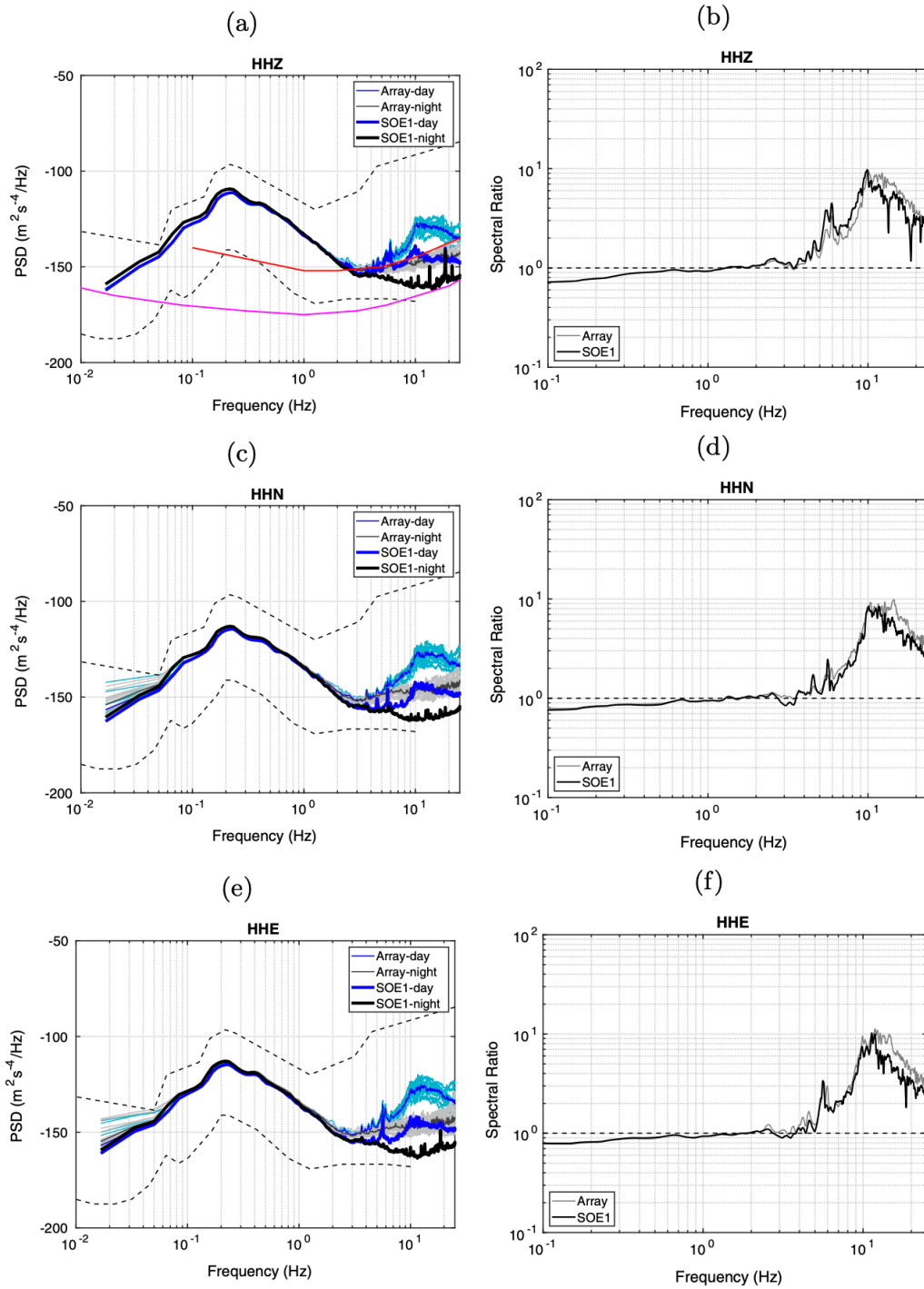


Figure 5. Typical acceleration power spectral densities (PSD) obtained at the Sos Enattos array for the vertical (a), NS (c) and EW (d) components of ground motion. Cyan and gray lines refer to the PSDs obtained at individual array elements during day and night time-intervals, respectively; thicker lines are the array-averaged spectra. Blue and black lines are the corresponding spectral estimates from underground station SOE1. Dashed black lines indicate the New Low- and High-Noise Models (J. Peterson Open-File, 1993). The red and magenta lines in panel a respectively indicate the self noise of Lennartz LE3D-MKIII 1 s and Nanometrics Trillium compact 120 s seismometers. The night- and day-time intervals respectively are 00:00–02:00 UTC and 5:30–7:30 UTC on February 2, 2021 (day-of-year 33). Plots in panels b, d, f show the ratio between the day- and night-time spectral estimates at both the surface array and underground station.

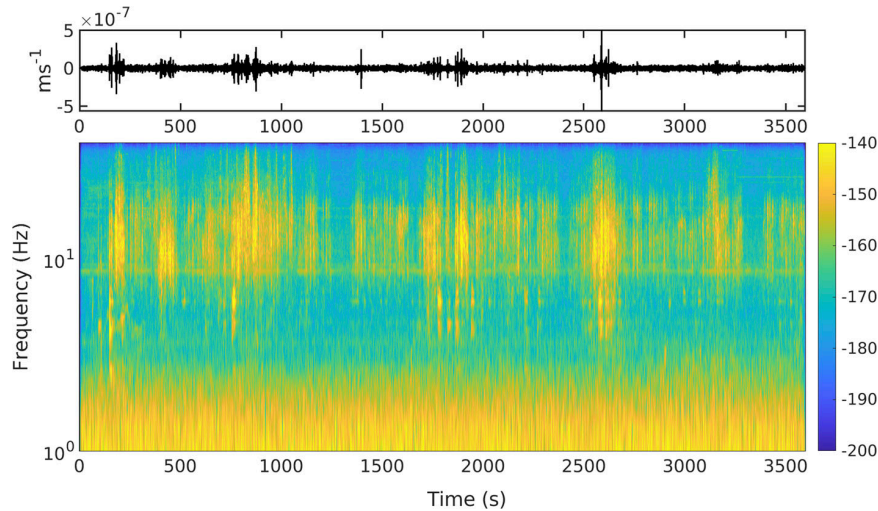


Figure 6. (top) Sample vertical-component recording of ground velocity at an array station. Data are band-pass filtered over the 1–25 Hz frequency band to tropogenic noise have already been published and will be incorporated into the document.

6.2 Seismic noise characterization for the Buddusò-Alà dei Sardi Wind Park

Wind turbines generate considerable seismic noise and interfere with sensitive instruments, such as permanent and temporary seismic sensors installed nearby, hampering their detection capabilities.

A study to investigate the seismic noise generated by the Buddusò-Ala dei Sardi (BAS) wind park in northeastern Sardinia, Italy. With 69 turbines producing 138 MW, this wind park is one of the largest in Italy and is located approximately 13 km from the candidate site of the Einstein Telescope (ET), a third-generation gravitational wave observatory. For a detailed description of the study, please refer to (G. Diaferia et al., 2025). A map of the area and seismic array configuration is shown in Figure 7.

The WINES experiment (Wind turbine Noise assEsSment) deployed a linear array of nine broadband seismic stations between the BAS wind park and the ET candidate site. Data were collected over eight weeks in 2023 and analyzed through spectrograms (see **Error! Reference source not found.**) and power spectral densities (see **Error! Reference source not found.**), and polarization methods to identify noise sources and propagation. Additional permanent borehole and surface stations (P2 and P3) located near the ET site provided complementary data.

The analysis revealed four dominant spectral peaks at 3.4, 5.0, 6.8, and 9.5 Hz, associated with vibration modes of turbine towers (see **Error! Reference source not found.**). Noise amplitude increased with blade rotation rates and remained detectable up to 13 km away, with the 3.4 Hz peak being the most persistent. Polarization analysis confirmed the wind park as the primary noise source, and amplitude decay modeling suggested a damping factor $\alpha \approx 2$, consistent with the crystalline geology of the region.

Borehole measurements at ~250 m depth demonstrated effective noise suppression compared to surface sensors, though small residual peaks persisted in the 3–6 Hz range during high turbine activity. Overall, the seismic quietness of the ET candidate site remains largely preserved, but wind-farm contributions are non-negligible in specific frequency bands.

The BAS wind park generates detectable seismic noise that propagates over significant distances due to the favourable geological conditions. Although borehole installations at the ET site suppress much of the surface noise, small peaks in the target frequency range persist under high wind-turbine activity. These findings emphasize the importance of continuous monitoring and potential mitigation strategies to safeguard the ET's detection capabilities.

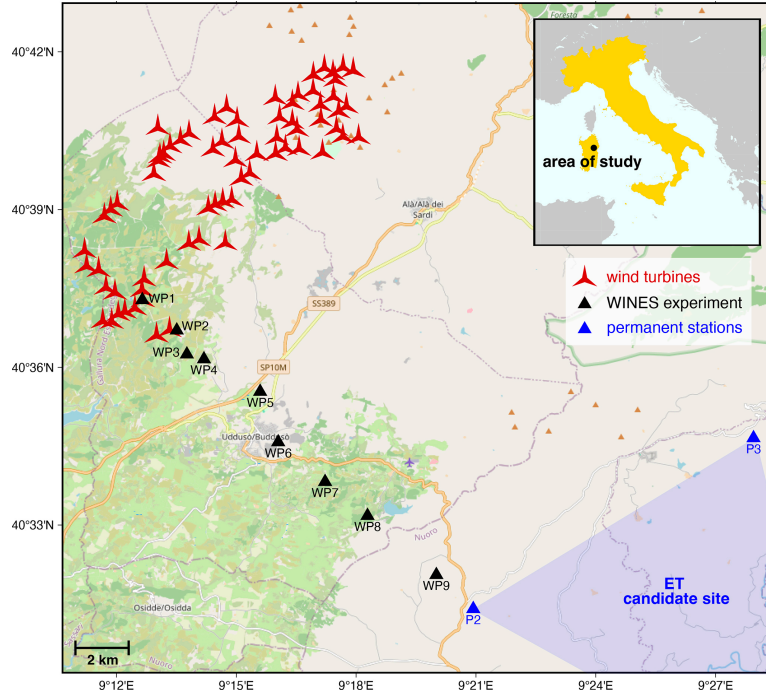


Figure 7. Map of the study area. The turbines of the BAS wind park are in red. Black triangles indicate the location of the seismic stations installed within the WINES experiment. P2 and P3 (in blue) indicate the permanent stations located at two of the three vertices of the ET candidate site. The map tile is from © OpenStreetMap contributors 2024, distributed under the Open Data Commons Open Database License (ODbL) v1.0.

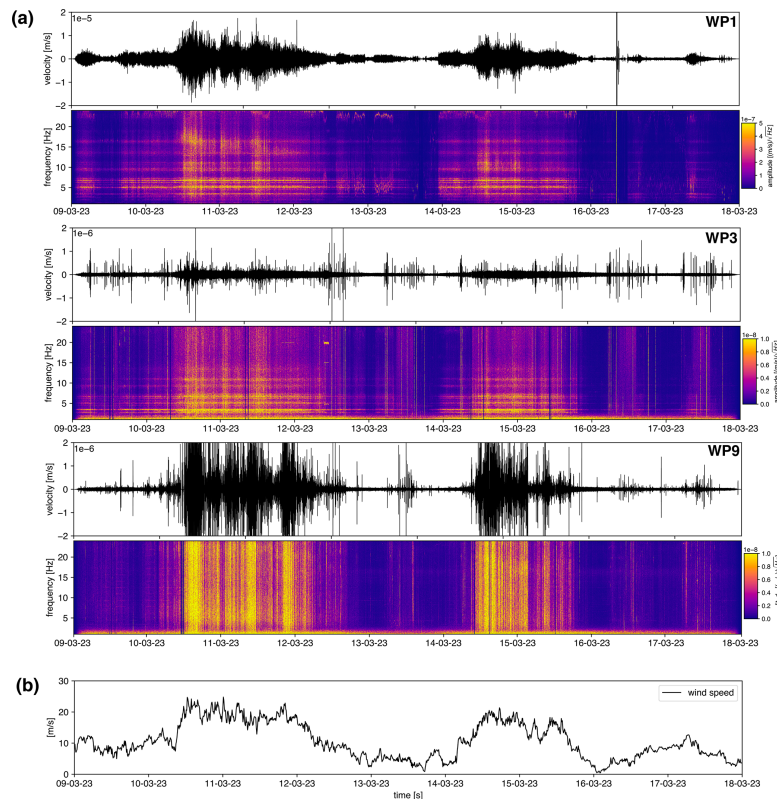


Figure 8. (a) The 10 d long seismic recording (zcomponent) and spectrogram for stations WP1, WP3, and WP9. (b) Time series of wind.

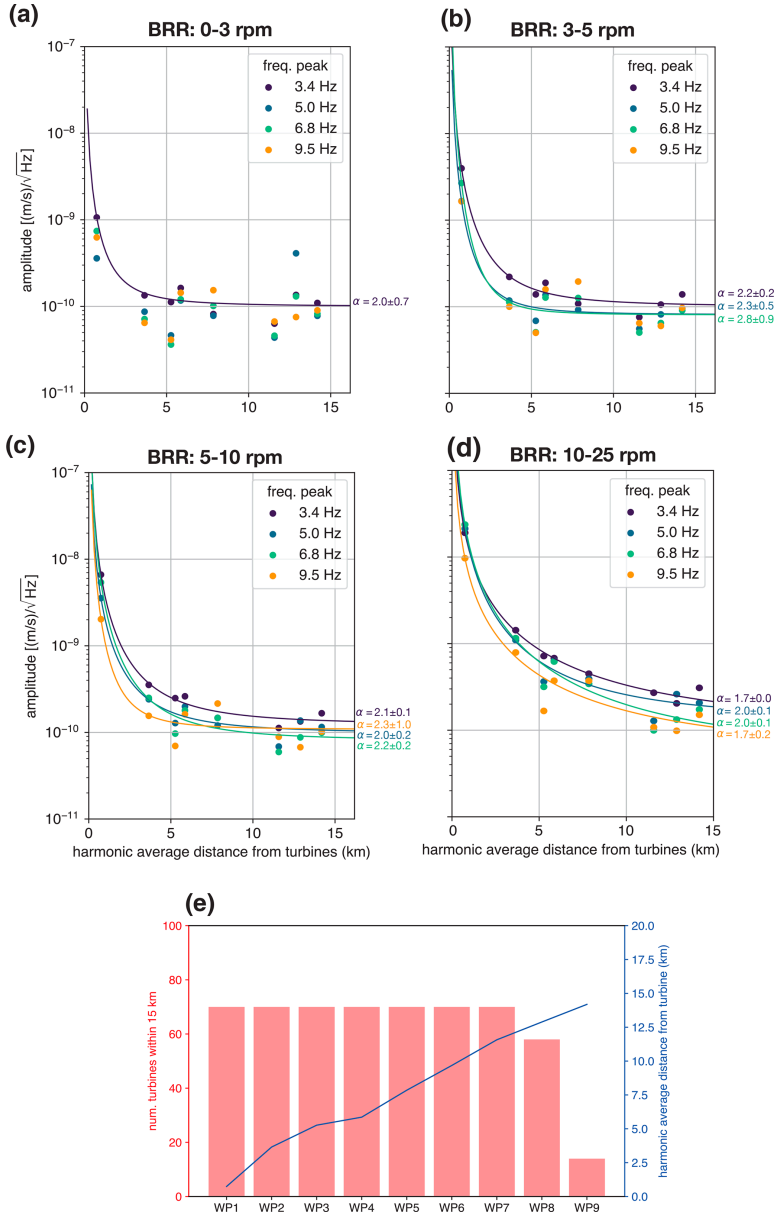


Figure 9. (a–d) Decay of spectral amplitudes of the frequency peaks at 3.4, 5.0, 6.8, and 9.5 Hz as a function of harmonic average (r_H) from wind turbines in different BRR ranges across the wind park. The fitted curves follow the expression $A \sim r_H^{-\alpha}$. (e) In red, the number of wind turbines in a 15 km radius of each station of the WINES experiment. In blue, the values of harmonic average distance from each station to the turbines. The histogram represents the number of turbines within 15 km of each station.

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