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AdriaArray temporary deployment in the Po Plain and Sardinia (Italy)

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Abstract

We present the deployment and performance of 17 temporary broadband seismic stations installed in Northern Italy and Sardinia as part of the AdriaArray project. These stations aim to densify the national seismic network, especially in areas with historically sparse coverage such as the Po Plain and Sardinia. We describe here the network design and site selection that follow high-quality standards developed during previous large-scale European seismic experiments. Despite challenging environmental and anthropogenic conditions, the stations recorded high-quality data, enabling both local and teleseismic event detection. We analyze the seismic noise characteristics across the network using probabilistic power spectral densities and observe that stations installed in sedimentary basins typically show higher noise levels at short periods, while stations in rock sites – especially in Sardinia – generally perform better. The use of different sensor types and installation methods also influences noise behavior, particularly in the long-period components. Despite the diverse conditions, the stations allow for the recording of both local and teleseismic events. The addition of the 4P stations improves the network's detection threshold by approximately 0.4 magnitude units in Sardinia and 0.2 in the North Italy. The open-access data from this deployment contribute to AdriaArray's broader goals of advancing seismic imaging and geodynamic interpretation in the Mediterranean region.

Keywords: Seismic network; AdriaArray; Po Plain; Sardinia, broadband seismic stations

1. Introduction

Large scale seismic experiments are usually planned to gather new high-quality data to reach ambitious research goals, such as the imaging of subduction zones, significantly improving the resolution of the lithospheric and mantle tomographies, and developing dense earthquake catalogs to better characterize fault systems. Focusing on the European-Mediterranean region in the past 15 years, the largest initiatives include: Iber-Array (Díaz et al., 2010), AlpArray (Hetényi et al., 2018), PACASE (Schlömer et al., 2024), all devoted to studying the Earth's shallow and deep structures. Their ultimate goal is to provide data products, such as tomographies (e.g. Lu et al., 2018; Kästle et al., 2022; Menichelli et al., 2023), earthquake catalogs (e.g. Bagagli et al., 2022; Hofman et al., 2023), maps of seismic noise field (e.g. Lu et al., 2022), gravity maps (e.g. Zahorec et al., 2021), Earth discontinuity maps (e.g. Bianchi et al., 2021; Michailos et al., 2023, Kalmár et al., 2025) that enhance seismic hazard assessments and advance geodynamic models and interpretations.

AdriaArray (AdA) is the last of such large experiments. It is an ambitious collaborative project (Kolínský et al., 2025) officially started in 2022, aiming to unravel the complexities of the Adriatic plate within the Mediterranean geodynamic framework. The AdriaArray scientific program currently involves a large number of researchers from around the world. To date, more than 60 institutes from ~30 countries have joined the AdA initiative.

The Adria microplate plays a crucial role in the regional plate tectonic setting, influenced by the motion of the two major plates, Africa and Eurasia. However, key questions remain regarding the specific areas where Adria undergoes deformation, the location of its active boundaries, and the underlying processes driving its tectonic evolution (e.g. Kissling, 2024 and references therein). In particular, the subducting slabs surrounding Adria are fundamental to its geodynamic evolution, yet their geometries and potential connections to Adria itself require new, higher-resolution tomographic images. Beyond Adria, the surrounding regions – including the Tyrrhenian and Pannonian basin and the mountain belts encircling Adria – actively contribute to the deformation of the broader region. These dynamic processes generate significant geohazards such as earthquakes, tsunamis, landslides, flooding, volcanic activity, and sea level rise, posing substantial societal risks both regionally and across Europe. Addressing these critical scientific objectives necessitates not only the collection of new data, but also the development of innovative, multidisciplinary approaches for their analysis and interpretation. At the core of the AdriaArray initiative is the acquisition of broadband seismic data from a dense network of stations. This includes temporary deployments to improve the coverage and geometry of existing permanent broadband networks operated by various seismic services across Europe. About 440 temporary stations from 23 mobile pools from 14 European countries were made available and deployed as part of the AdriaArray Seismic Network (Kolínský et al., 2025). The high-quality standards of instrumentation and installation is a key to guarantee the success of such an international project, particularly given the diversity of instrumentation types among the participating stations.

Focusing on the Italian peninsula, the National Seismic Network (RSN, Rete Sismica Nazionale, Margheriti et al., 2021) currently presents two main gaps in the broadband data coverage: the Po Plain (mainland) and the Sardinia region (island). These gaps arise from different challenges. Although the Po Plain is characterized by a moderate to high rate of seismicity, the widespread anthropogenic noise, the difficulty of identifying suitable sites, and the high cost of borehole installations have historically discouraged the deployment of permanent seismic stations. In contrast in Sardinia, the scarcity of seismic events (Meletti et al., 2020; Anselmi et al., 2020) has made the installation of permanent stations a low priority.

To temporarily fill these gaps, in this work we describe the contribution to the AdriaArray Seismic Network in the Po Plain and Sardinia in terms of site selections and installations of temporary stations, data quality and data management. The deployment and maintenance of 17 temporary broadband stations were led by Istituto Nazionale di Geofisica e Vulcanologia (INGV) and resulted from a fruitful collaboration between University of Twente (The Netherlands) for the Po Plain stations and University of Kiel (Germany), Istituto Nazionale di Fisica Nucleare (INFN, Italy) and University of Sassari (Italy) for the Sardinia deployment.

2. The contribution to AdriaArray Seismic Network: network 4P

Here we describe our temporary station concept and site selection scheme used for the station network 4P (https://www.fdsn.org/networks/detail/4P_2022/) deployed in Italy, that allows us to provide high quality seismic data to the AdriaArray project.

Following the AdriaArray program's recommendation to address broadband gaps in permanent networks, we deployed 17 temporary stations from different institutions. Combined with the permanent sites in Italy, our deployment reduced critical gaps and achieved a more uniform coverage of the Po Plain basin and the Sardinia region (Fig. 1). This deployment ensured that no location is more than 30-40 km from the nearest seismic stations (see Fig. 6 in Kolínský et al., 2025). We follow the same high-quality standards of site-search and installation protocols established during the previous AlpArray Seismic Network deployment (see AlpArray Technical Strategy, www.alparray.ethz.ch/organisation/documents/), extensively described in e.g. Molinari et al. (2016) and Hetényi et al. (2018).

The first set of stations provided by the University of Twente was installed in the Po Plain and surrounding areas starting in December 2022. The second set, provided by Geophysical Instrument Pool Potsdam (GIPP), was deployed in Sardinia beginning in September 2023. The installation of these temporary stations was made possible through a fruitful collaboration between INGV and University of Twente, University of Kiel, University of Sassari and INFN. Together we coordinated planning activities, shared best practices and followed common guidelines for site selection and station installation.

The large-scale morphology and geology of the 17 sites are diverse: eight are located within or along the hilly margins of the Quaternary deposits of the Po Plain basin (e.g. Molinari et al., 2015); one is situated in the granitic terrain of the Central Alps (Bigi et al., 1990); four in the Sardinian Variscan basement (Funedda et al., 2014); one in the Campidano Quaternary deposit of Sardinia (Allevi et al., 2025); three on Sardinian volcanic rocks (Carmignani et al., 2015).

The collected data is available through the INGV EIDA (European Integrated Data Archive) node and has been fully open from the beginning of stations operations, according to the general open data policy of INGV (https://data.ingv.it/docs/principles/), in line with international recommendations (e.g. EPOS-European Plate Observing System, Freda et al., 2018). The open data policy has enabled the INGV Earthquake National Surveillance Center to incorporate the data into real-time event locations. Real-time communication was also crucial for timely checks of station performance and for ensuring a prompt response to any station failure.

2.1 Station configuration

We employed two different temporary station configurations depending on the instrument providers. In the Po Plain and northern Italy, we installed the pool provided by the University of Twente; except for the sensor and digitizer, all other electronics were supplied by INGV. Each station consists of the following components: Trillium 120s Post Hole sensors (at site IT05A an INGV Trillium Horizon 120s was installed), Centaur 3-channels digitizer with >141 dB dynamic range (100 *sps* sampling rate), GPS antenna, mobile router for real-time data communication (Teltonika or LR77 router), mobile antenna 4G-LTE and a 65Ah battery. In Sardinia, the sensor, digitizer and router were provided by GIPP and other electronics and mechanical support were supplied by the University of Sassari and INFN. Each Sardinian station consists of: Trillium Compact 120s or Trillium 120s QA sensors, EDR210 digitizer with >141 dB dynamic range (100 *sps* sampling rate), GPS antenna, mobile Teltonika router for real-time data communication, mobile antenna 4G-LTE and a 65Ah battery, all housed within a water-proof box.

At sites without mains power, stations are powered by one or two solar panels, providing a total peak power of 120W-150W to ensure continuous real-time communication. The routers can be remotely controlled, rebooted, and switched on or off via SMS (Short Message Service). Data is streamed in real-time to INGV servers located in Rome, Pisa or Milan, while also being stored locally on flash cards. Without additional power input, each station can sustain real-time operation for approximately five-six days.

For free-field installations, sensors are typically buried – 30 cm deep for the TC120 and 100-150 cm for the T120PH. The electronics are housed in plastic boxes placed inside small shelters, buildings, or beneath the solar panels mounted on L-shaped frames secured to pallets. Sensor thermal insulation varies by installation type: for in-house installations (four cases), insulation is provided by mineral wool and a polystyrene box, whereas for buried sensors, insulation is naturally ensured by the surrounding soil.

As part of the AdriaArray project, we deployed a total of 8 Trillium 120s PH, 1 Trillium Horizon 120s, 5 Trillium Compact and 3 Trillium 120s QA.

2.2 Site selection

There are well-established general field procedures and guidelines for site selection (e.g. http://www.passcal.nmt.edu/content/instrumentation/field-procedures-3; Forbriger, 2012) which must be carefully interpreted in the light of the specific objectives and constraints of each seismic experiment. Our site scouting was guided by the following main principles. In the Po Plain, we first assessed whether sites previously used for the AlpArray project (see Molinari et al., 2016 and Govoni et al., 2017) were still available and suitable for our deployment. Since we used Trillium 120s Post Hole sensors, which require burial and cannot be installed indoors, site suitability was a critical factor. We prioritized sites where the digitizer and all the electronics could be sheltered in a small building while the sensor could be buried outside. After contacting the owners of former AlpArray sites in northern Italy, we selected and reoccupied four locations, installing the sensors outside the small buildings that had hosted the former STS-2 sensors (IT02A/former A287A, IT03A/former A283B, IT04A/ former A284A, IT09A/former A307A). At IT05A, installed at the former AlpArray A289A site, we deployed a Trillium Horizon 120s owned by INGV Bologna. Unfortunately, this station was robbed (sensor, digitizer and electronics) after ∼3 months of operation, and we decided not to reinstall at this site.

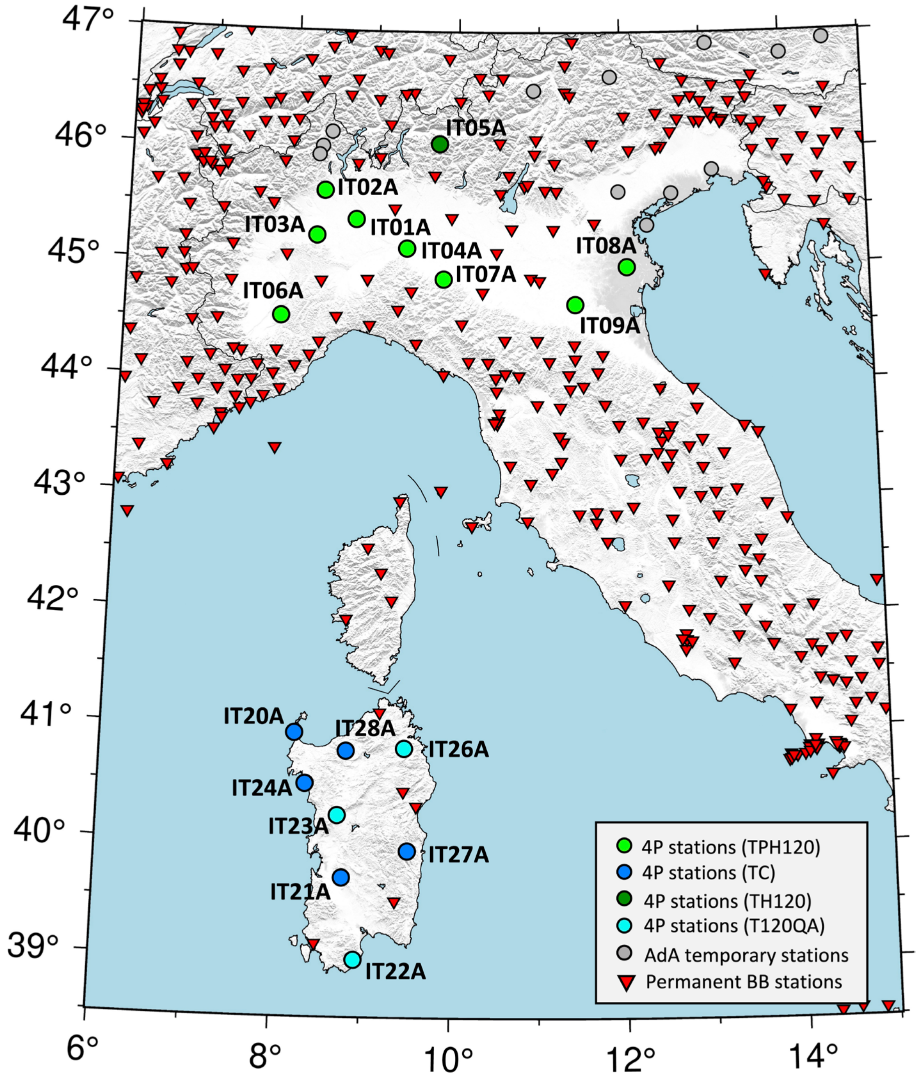

Figure 1. Zoomed map of the AdriaArray broadband seismic stations around north-central Italy, with the permanent stations (inverted red triangles) and the AdriaArray temporary stations (circles, colored and gray). The colored circles represent the location of the 4P-network stations installed. The color code indicates the sensor type at each site: TPH120=Trillium PostHole 120s (light-green); TC=Trillium compact 120s (blue); TH120=Trillium Horizon 120s (green); T120QA=Trillium 120s Q/QA (cyan). See Table 1 for more details.

Across northern Italy and in Sardinia we scouted twelve new locations following a few basic criteria. To minimize fieldwork, we began site selection in the office by researching possible locations online and contacting local authorities and/or private owners to secure installation permissions. Preliminary checks on platforms like Google Earth helped assess site accessibility, safety, and the availability of necessary resources such as power, communications, and clear sky visibility for GPS. However, before the final installation, we always visited the potential sites.

We preferred locations easily accessible by car and secure against vandalism or accidental damage. Nevertheless, at two sites in the Po Plain we experienced damage to the buried sensors due to unexpected excavation work which could not have been foreseen. The Po Plain is a highly urbanized and intensively used area, and to minimize the risk of vandalism, we had deliberately avoided clearly marking the exact location of the sensors. However, unforeseen activities – agricultural operations in one case and municipally authorized construction work in the other (from an office unaware of the sensor's presence) – led to damage at two stations: one at IT02A in March 2025, and another at IT04A in July 2023. The latter sensor was reinstalled in July 2024 after undergoing repair. These incidents suggest that, for long-term deployments, clearly marking the sensor location may be advisable – even at the risk of potential vandalism.

To reduce high-frequency noise, we aimed to maintain distances of 2-3 km from railway and highways and 100-600 m from minor roads, while avoiding proximity to cities, towns, industrial sites, rivers, livestocks, trees, etc. These conditions were challenging to satisfy especially in the heavily developed Po Plain. Because broadband sensors are sensitive to long-period noise from temperature and pressure fluctuations, as well as horizontal tilt caused by traffic, people, and structural movements of the buildings, we sought to minimize these effects by burying sensors as deeply as possible (up to 1.5-2 m). When installation inside a building was unavoidable, we opted for small structures to reduce interference and we ensured thermal insulation of the sensor. Our final installations reflect a balance among these requirements; in a few cases we had to compromise. For instance, at IT01A station, to avoid rice fields and to ensure site security, we placed the sensor in the courtyard of a farmhouse. Similarly, IT08A was installed in the courtyard of an uninhabited house within a small town near the Po river to enhance safety.

2.3 Installations and final configuration

The installation of the 9 stations in northern Italy was carried out between December 2022 and March 2023, while the 8 stations in Sardinia were installed between September 2023 and May 2024. The final station configuration is shown in Fig. 1 and clearly illustrates how the AdriaArray temporary stations fill critical gaps in the permanent Italian Seismic Network (Margheriti et al., 2021), particularly in its broadband coverage. The main stations information is provided in Table 1. As described above, the station IT05A operated only for a few months due to the theft of the equipment; however, the site is now under consideration for hosting a future permanent INGV station.

We implemented three sensor housing types in this temporary deployment (as described in Molinari et al., 2016 and Orfeus Station Book, https://orfeus-eu.org/stationbook/): free-field (8 sites), urban free-field (8 sites) and building installation (1 site). In this context, "free-field" refers to sensors located less than 5 m below the surface and at distances exceeding one building height from surrounding structures. "Urban-free-field" sites are similarly shallow (less than ~5 m below surface) but situated within a distance roughly equivalent to one building height from nearby structures (often inside small one-story buildings). "Building" installations are those within the footprint of multi-storey buildings. Examples of urban-free-field and free-field sites are shown in Fig. 2 (a and b respectively). All urban free-field sites have sensors installed within 5-8 meters of a building, under the assumption that the building's natural frequency does not significantly affect the long-period horizontal components. Site conditions mainly consist of soft-soils, which facilitated digging of the sensor vaults, although in two cases we installed the sensor on a concrete basement. Most stations are powered by solar panels, with data transmitted in real-time to the INGV EIDA node. In a few sites in the Po Plain, particularly during foggy winter periods, the solar panels occasionally failed to recharge the batteries, resulting in data gaps of several days. Sensor leveling was determined using a level and the orientation using a magnetic compass. However, we are aware of possible errors due to unexpected local magnetic anomalies, especially in buildings. At the time of writing, the Po Plain stations have been dismantled between March and June 2025 stations, while the stations installed in Sardinia are still functioning and the dismantling is foreseen for March 2026.

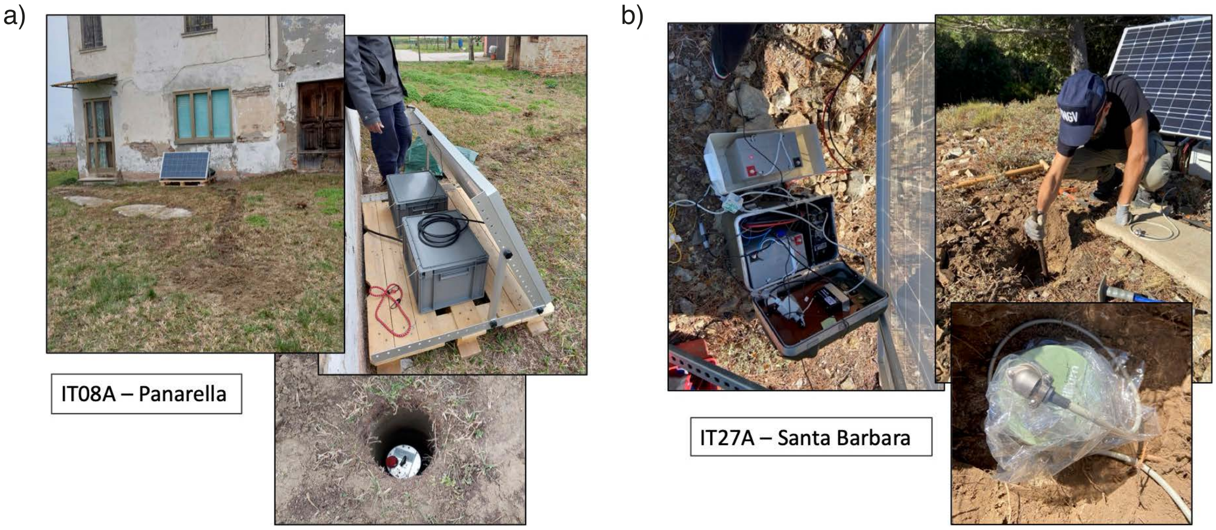

Figure 2. Examples of free-field installation configurations. The stations are: (a) IT08A in Panarella in the Po Plain; (b) IT27A in Sardinia.

Table 1. List of the AdriaArray temporary stations installed in Italy by INGV since 2022, with station name, coordinates, start and end time, type of housing, sensor (TC = Trillium Compact 120 s; TPH120 = Trillium Post-hole 120s; TH120 = Trillium Horizon 120s; T120QA = Trillium 120s Q/QA), digitizer and percentage (%) of available data on INGV-EIDA archive during the installation time range (in case of stations that are still recording the end date considered for the calculation of data completeness is October 1st, 2025). The network code is 4P for all stations.

Station name	Lat	Lon	Elevation (m)	Site name	Start time	End time	Housing class	Sensor sits on	Sensor type	Digitizer type	% data in EIDA
IT01A	45.379418	8.768451	174	Cassolnovo (PV)	2022-12-12	2025-06-09	Urban free-field	Soft soil	TPH120	Centaur	83.7
IT02A	45.622598	8.361122	413	La Torre, Gattinara (VC)	2022-12-12	2025-04-30	Free-field	Soft soil	TPH120	Centaur	94.5
IT03A	45.237928	8.288635	190	Tricerro (VC)	2022-12-12	2025-06-26	Urban-free-field	Soft soil	TPH120	Centaur	95.4
IT04A	45.137131	9.383602	103	Padulino, Costa De Nobili (PV)	2022-12-12	2025-06-26	Urban-free-field	Soft soil	TPH120	Centaur	51.5*
IT05A	46.047153	9.761312	1784	Foppolo (BG)	2023-01-25	2023-04-30	Urban-free-field	Concrete	TH120	Centaur	99.0
IT06A	44.535805	7.880076	399	Costamagna (CN)	2023-02-28	2025-03-01	Urban-free-field	Soft soil	TPH120	Centaur	90.3
IT07A	44.873936	9.836959	182	Castell’Arquato (PC)	2023-03-02	2025-06-09	Urban-free-field	Soft soil	TPH120	Centaur	93.9
IT08A	44.983948	12.069651	60	Panarella (RO)	2023-03-01	2025-06-30	Urban-free-field	Soft soil	TPH120	Centaur	98.0
IT09A	44.660509	11.435935	45	Oasi La Rizza, Bentivoglio (BO)	2023-03-01	2025-06-30	Free-field	Soft soil	TPH120	Centaur	88.0
IT20A	40.942843	8.204215	123	Stintino	2023-09-27	-	Free-field	Rock	TC	EDR-210	84.4
IT21A	39.7018	8.7798	139	Geomuseo Masullas	2023-09-28	-	Urban-free-field	Soft soil	TC	EDR-210	97.7
IT22A	38.98942	8.9235	134	Pula	2024-05-14	-	Building	Concrete	T120QA	EDR-210	99.6
IT23A	40.23697	08.71566	637	Macomer	2024-03-15	-	Free-field	Soft soil	T120QA	EDR-210	73.3
IT24A	40.506969	8.3486389	97	Torre Poglina (Alghero)	2023-09-28	-	Free-field	Soil	TC	EDR-210	94.3
IT26A	40.814805	9.462162	278	Berchideddu (SS)	2023-09-30	-	Free-field	Soft soil	T120QA	EDR-210	76.6

* The station IT04A was not recording from July 2023 to July 2024 due to a sensor damage (see text for more details).

Station name	Lat	Lon	Elevation (m)	Site name	Start time	End time	Housing class	Sensor sits on	Sensor type	Digitizer type	% data in EIDA
IT27A	39.9340036	9.51583703	1158	Parco Santa Barbara (NU)	2023-09-28	—	Free-field	Rock	TC	EDR-210	89.9
IT28A	40.7895527	8.7995600	249	Su Cuile Martis	2023-09-28	—	Free-field	Soil	TC	EDR-210	95.7
* The station IT04A was not recording from July 2023 to July 2024 due to a sensor damage (see text for more details).											

3. Network performance

3.1 Seismic noise level

After acquiring the data, we computed the Probabilistic Power Spectral density (PPSD) using the direct Fourier method (Cooley and Tukey, 1965) with the ObsPy software package, following the approach of McNamara and Buland (2004). The PPSDs help identify the most probable ambient noise conditions and have become a standard tool for assessing station performance, detecting artefacts related to station operation, evaluating episodic cultural noise, and analyzing overall station quality and Earth noise levels at each site.

The quality of our temporary installations is largely influenced by the regional setting. Figure 3 compares the PPSD medians for vertical and horizontal components at sites in northern Italy and Sardinia, along with the Peterson's New High Noise Model (NHNM, Peterson 1993). In general, our temporary stations exhibit ambient noise levels below the NHNM across most frequencies, with the exception of long-period horizontal components in Sardinia. As expected, stations located in sedimentary basins – such as those in the Po Plain and the Campidano Basin (Sardinia, IT23A station) – show higher noise levels at short periods ($T < 1$ s) compared to stations installed in mountainous regions of northern Italy (IT02A and IT05A) and Sardinia. At intermediate periods, noise levels are dominated by primary and secondary microseismic peaks, with higher amplitudes observed at basin sites. Notably, the shape of the primary microseismic peak differs between stations in northern Italy and Sardinia, likely reflecting the stronger influence of sea waves on the island. At long periods (20-120 s) vertical component noise levels average around –155 dB at the Sardinia sites, whereas they are about 170-165 dB at the northern Italy stations. The horizontal components are, on average, 20 dB higher, and four Sardinia stations (IT22A, IT23A, IT24A, IT26A) exceed the NHNM by ~5-10 dB. These elevated long-period horizontal noise levels are largely attributed to atmospheric pressure changes and wind (e.g. Webb, 2002), temperature variations, the sensor-to-ground coupling and, for installations on soft sediments, seasonal changes in soil properties due to temperature variations and water content (Wolin et al., 2015). The ~15 dB discrepancy between the vertical components of stations installed in North Italy and Sardinia can be found in differences in sensor type (also in terms of stability and sensor mass) and installation configuration. In Sardinia we mainly installed TC and T120QA sensors, which have a declared average self-noise level of ~165 dB (in the 20-120 s period band) while in North Italy we mainly installed T120PH sensors, which feature a declared self-noise approximately 20 dB lower.

The spatial distribution of median seismic noise levels across different frequency bands (Fig. 4) reveals distinct patterns related to both anthropogenic and environmental factors. At 0.1 s (10 Hz), the noise level (Fig. 4a) is higher in densely populated regions – which often coincide with sedimentary basins – and in coastal areas. In the Po Basin, characterized by intense anthropogenic activity, noise levels exceed those in Alpine stations by 30 to 60 dB and those in the Apennines by 20 to 40 dB, reflecting the impact of urbanization and industrial infrastructure.

At 1 s (1 Hz) (Fig. 4b), a period that often marks the transition from high-frequency anthropogenic noise to the secondary microseismic peak, noise levels remain elevated by 15 to 30 dB higher in the Po Plain, Sardinia, and the coastal zone of western Liguria relative to other areas. In the Po Plain, this amplification is mainly due to human-induced vibrations that excite also the natural resonance frequencies of the sedimentary basin, typically within the 1-4 s range (e.g. Luzi et al., 2013). In Sardinia and Liguria, the elevated noise level likely results from a shift and broadening of the secondary microseismic peak toward higher frequencies, possibly due to local oceanographic or bathymetric conditions.

At 50 seconds (0.02 Hz, Fig. 4c), spatial variations in noise are largely independent of geographical and geological context. In this frequency band, low-noise areas mainly reflect sensor type and installation quality. The darkest blue

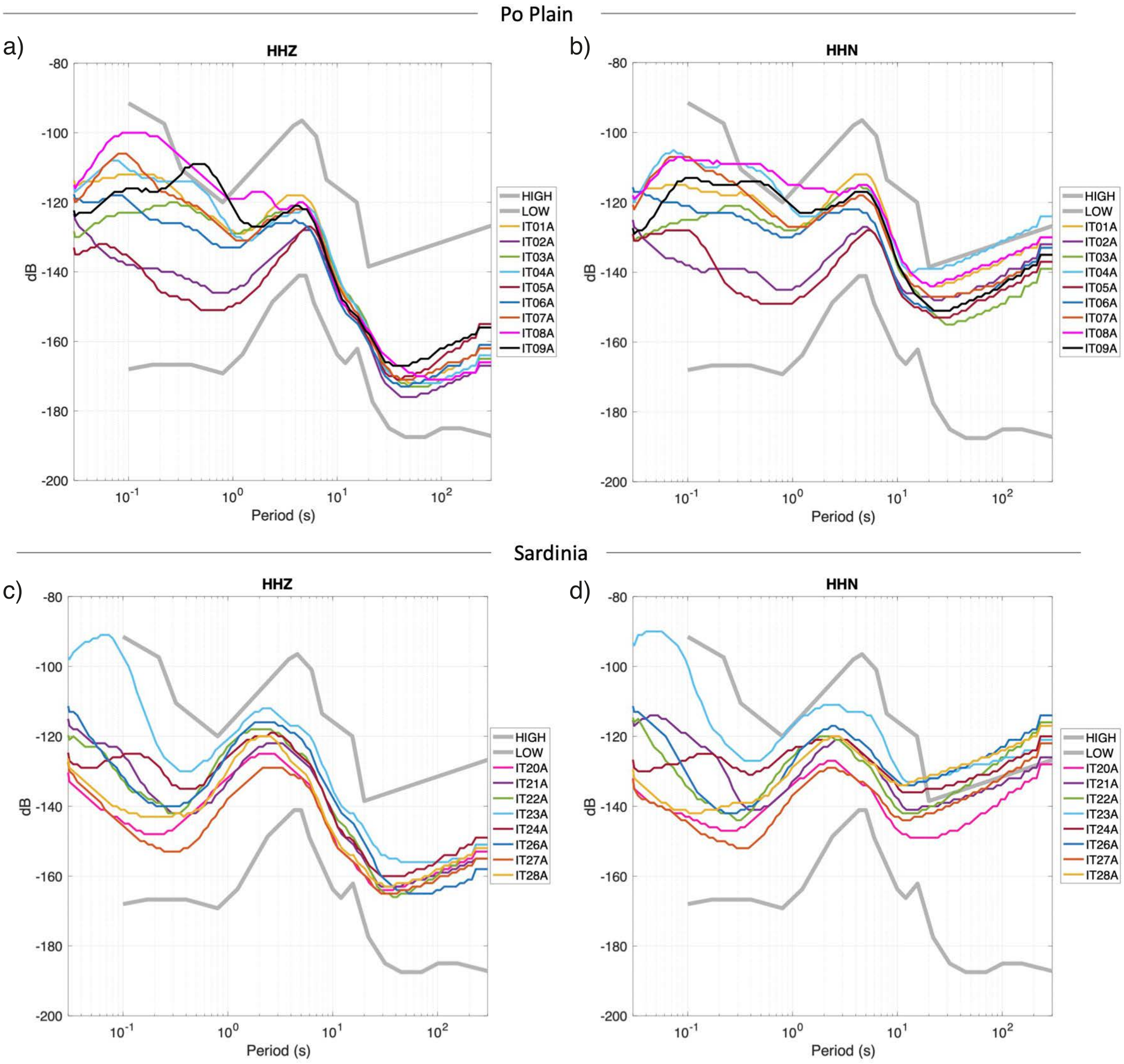

Figure 3. Median curves of the power spectral densities for the operating 4P stations during the period from beginning of operation (see Table 1) and 31 January 2025 (or end of operation if before) divided in regions of installation (Po Plain-northern Italy and Sardinia). Each line represents a single station. The light grey lines correspond to the NHNM and NLNM models. (a) Vertical component and (b) north-south horizontal component of the stations in northern Italy. (c) Vertical component and (d) north-south horizontal component of the stations installed in Sardinia.

markers correspond to (very) broadband instruments, with average long-period self-noise between −190 dB and −180 dB, such as the STS2 and Trillium Posthole 120s. In contrast, most sensors of the Italian permanent network are Trillium 40s or Trillium Compact models, which have a typical long-period self-noise between −150 dB and −170 dB. Under optimal conditions – quiet sites with careful installation and insulation – these sensors can achieve noise levels close to their self-noise floor. Other national seismic networks, such as those in Slovenia and Switzerland, predominantly deploy (very) broadband sensors, resulting in significantly lower long-period noise level.

These observations underscore the need of employing high-sensitivity, very broadband sensors with low self-noise characteristics when the goal is long-period seismology and imaging of the deep Earth structure.

In this context, a few sites were instrumented during both the AlpArray and AdriaArray experiment but with different broadband sensors (STS-2 and Trillium Posthole 120s, respectively). This provides an opportunity to compare the noise levels recorded by the two instrument types, under the assumption that ambient noise sources remained approximately stationary when averaged over a sufficiently long time period. For two representative sites –

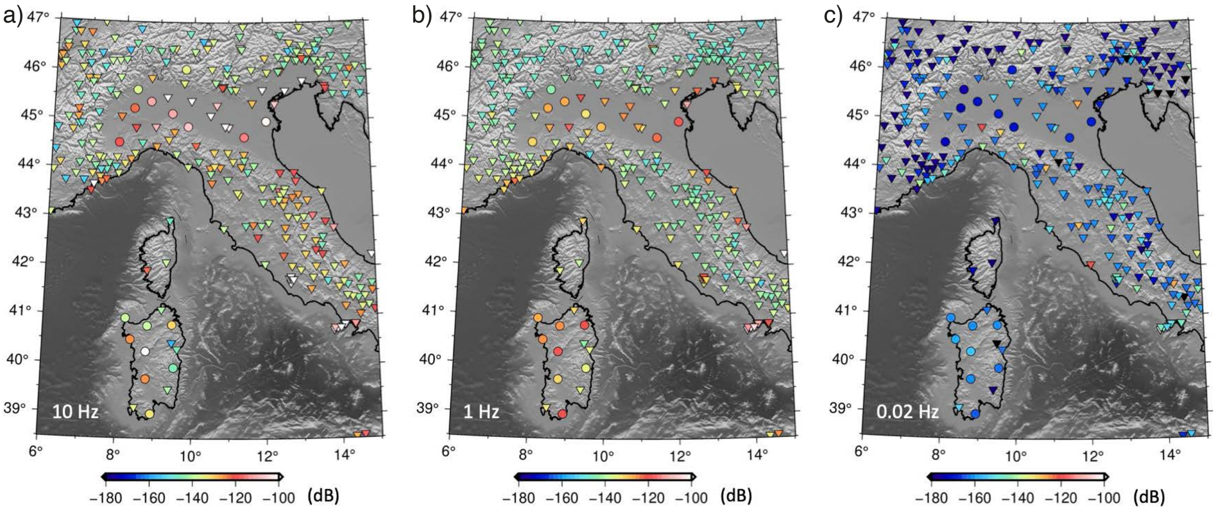

Figure 4. Map of the median value of the power spectral densities at different frequencies – (a) 10 Hz; (b) 1 Hz; (c) 0.02 Hz (50 s) – for the operating 4P stations (circles) and permanent broadband stations (inverted triangles) during the entire recording period.

Gattinara (4P.IT02A/Z3.A287A) and Tricerro (4P.IT03A/Z3.A283B) – Fig. 5 presents the comparison of the vertical component noise levels, showing the 10th, 50th (median), and 90th percentiles as recorded by an STS-2 (AlpArray) and a Trillium Posthole 120s (AdriaArray).

At both sites, the STS-2 was installed inside a small building, whereas the Trillium Posthole 120s was buried approximately one meter deep and located about eight meters away from the building, in an outdoor setting. Overall, the median noise curves from the two sensors are comparable. However, differences emerge at short periods (high frequencies), where the Trillium Posthole consistently records lower noise levels – approximately 5 dB less than the STS-2 for periods shorter than 0.5 s at Gattinara, and below 0.2 s at Tricerro. This is likely due to the attenuation of high-frequency signals in the buried installation. At long periods, a notable difference appears only at Tricerro, where the STS-2 exhibits 3-4 dB lower noise than the Trillium for periods longer than 50 s. Furthermore, the spread between the 90th and 10th percentiles is greater for the Trillium Posthole 120s sensor,

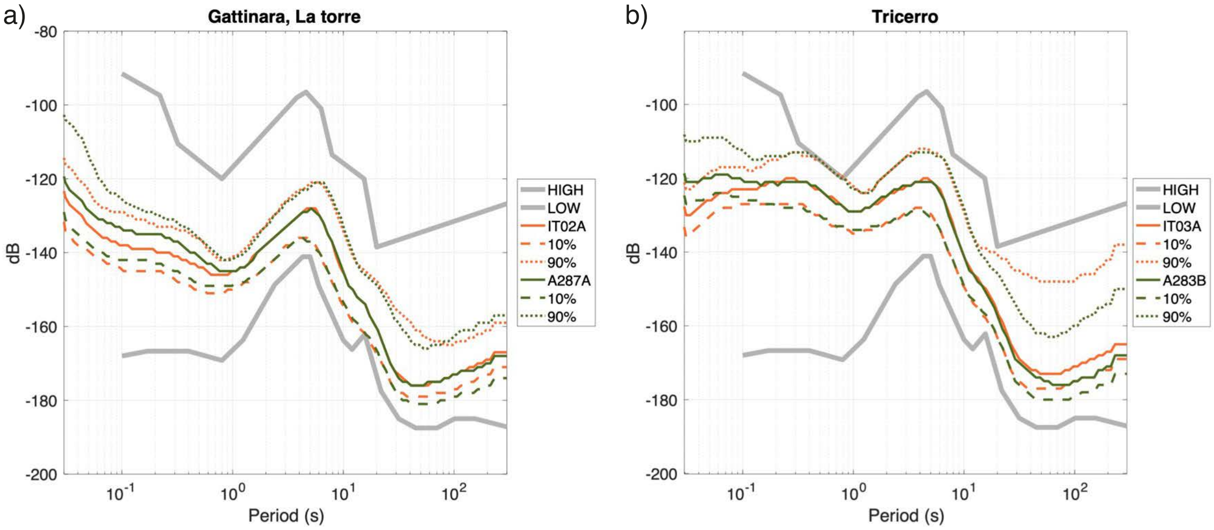

Figure 5. Comparison of the 90% (fine dashed lines), 10% (dashed lines) and median (solid lines) of two different type sensors installed at the same site during the AdriaArray project (orange lines, Trillium Posthole 120s) and the AlpArray project (green lines, Streckeisen STS-2) for two sites: a) Gattinara, la Torre (VC) (station 4P.IT02A – AdriaArray, and Z3.A287A – AlpArray) and b) Tricerro (VC) (station 4P.IT03A – AdriaArray and Z3.A283B – AlpArray).

suggesting that direct burial may result in less stable conditions and non-optimal thermal insulation, which in this case relies solely on ground insulation.

We also analyzed the temporal variation of seismic noise levels across multiple frequency bands. Specifically, we computed the 24-hour running mean of the median PPSD values at 0.033 s (30 Hz), 0.1 s (10 Hz), 0.2 s (5 Hz), 1 s (1 Hz), 10 s (0.1 Hz), and 20 s (0.05 Hz), from each station installation date through February 2025. Figure 6 illustrates the results for two representative sites: IT03A located in Tricerro (Po Plain) and IT22A in Pula (Sardinia). The station IT03A clearly shows high frequency noise levels, particularly at 0.1 s (10 Hz), 0.2 s (5 Hz) and 1 s (1 Hz), a clear anthropogenic signature characterized by consistently elevated levels on weekdays that decrease over weekends, as evidenced by the recurring low peaks. We also observed, in line with Poli et al. (2020), marked reduction in noise levels during major holiday periods – notably during the two weeks around January 1st and August 15th. These drops are especially pronounced in August 2023 and January 2025. At long periods, noise levels display a seasonal modulation, with higher peaks during the winter months and lower peaks in summer. Conversely,

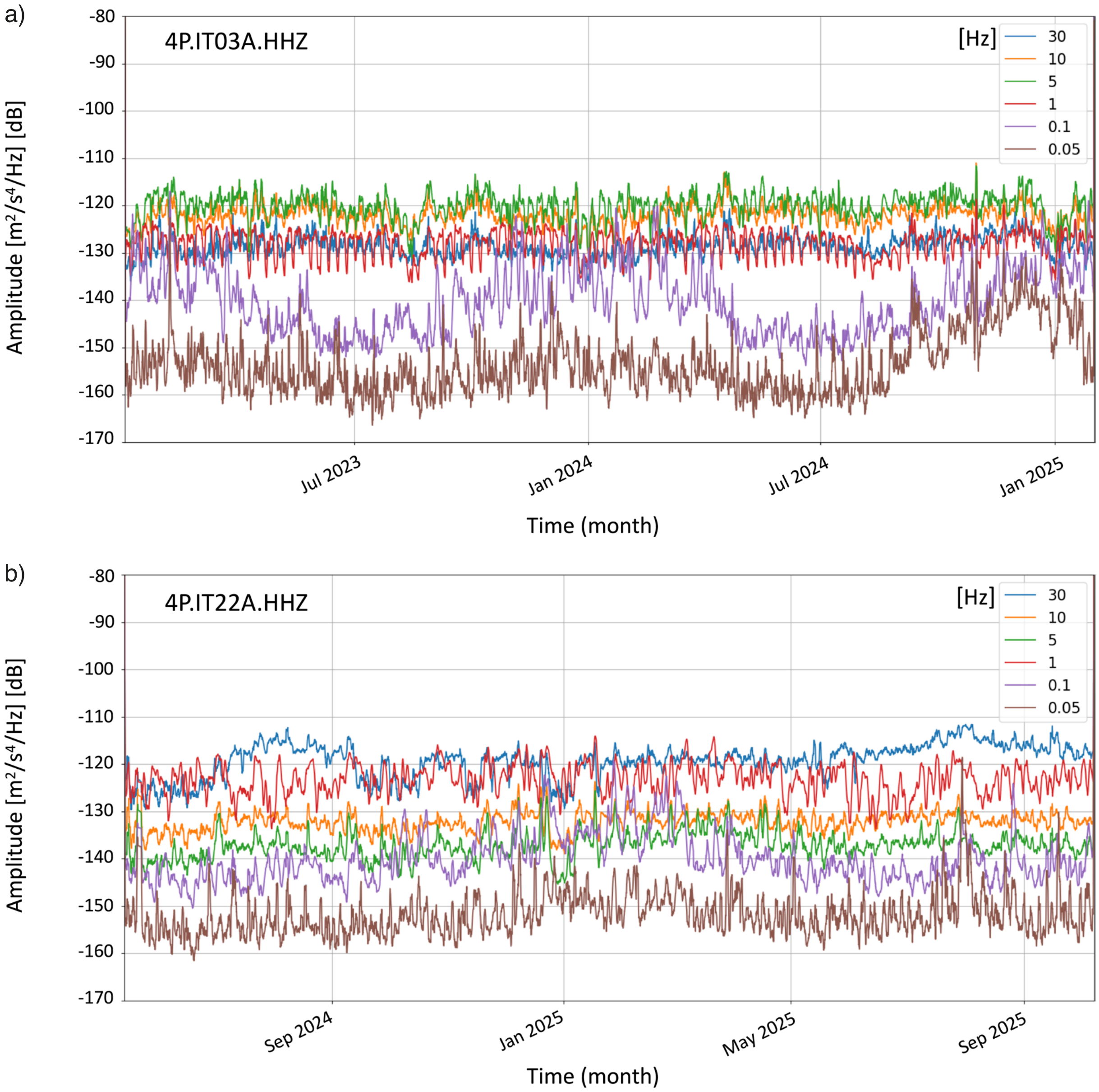

Figure 6. Temporal evolution of the median power spectral density (PSD) for two 4P stations: (a) IT03A, located in Tricerro, in the western Po Plain, and (b) IT22A, located in Pula, Sardinia. Each plot presents the 24-hour running mean of the PSD median amplitude at different frequencies: 0.0333 s (30 Hz, blue), 0.1 s (10 Hz, orange), 0.2 s (5 Hz, green), 1 s (1 Hz, red), 10 s (0.1 Hz, purple), and 20 s (0.05 Hz, brown). The time span differs between the two stations: IT03A covers the period from 01/01/2023 to 31/01/2025, while IT22A spans from 14/05/2024 to 10/10/2025.

at station IT22A in Sardinia, the weekdays-weekend contrast is not observed which is mainly explained with the low anthropogenic noise in the region. The seasonal modulation in the long-period bands is weakly visible. Further analysis indicates that this behavior is not due to the absence of seasonal variations in Sardinia, which are clearly visible at the nearby MN.SENA MedNet station (located in the Sos Enattos mine and equipped with a Trillium 360s), but rather to the relatively high long-period noise at IT22A, likely related to installation/site conditions and sensor characteristics.

3.2 Data availability and real time transmission

As of today, all the 17 stations are integrated into the daily standard reviewed event detection procedures of INGV (Margheriti et al., 2021), and their data are freely available through EIDA (www.orfeus-eu.org/data/eida/). We deliberately chose not to impose any data embargo both to ensure the immediate use of these data within the Italian earthquake alert system and to fulfill the general open data policy of INGV, in line with international recommendations (e.g. IAGA, IASPEI, EPOS). The integration into the real-time monitoring network offers several advantages: it enables continuous verification of data flow, rapid detection of station issues (such as power interruption due to storms, anomalous noise sources, or theft). The operational status of the stations is primarily overseen by the INGV Surveillance Room in Rome (Margheriti et al., 2021), which operates 24/7 and promptly notifies the network manager whenever a station goes offline. For solar-powered sites, we have implemented a dedicated internal tool to monitor power and network connectivity in real time, facilitating early detection of issues related to batteries or routers. Additionally, the 4P stations are integrated into the INGV Strong Motion Data Portal (ISMD, https://ismd.mi.ingv.it/, Massa et al., 2022), which, among other functionalities, provides real-time tracking of Power Spectral Density (PPSD) levels across fixed frequency ranges.

The data availability of the 4P stations exceeds 85%. Gaps in data are addressed by manually retrieving recordings and archiving them in the database. However, large gaps – mainly due to power supply interruption or issues with sensor or digitizer – are unfortunately not recoverable.

3.3 Network detection magnitude

The AdriaArray network has been specifically designed to fill critical gaps in the permanent broadband seismic coverage across Europe. Although its primary aim was not to lower the minimum detection magnitude, it is nonetheless instructive to evaluate the impact of the 17 newly deployed temporary stations on the Italian network detection capability. In this analysis we examine the variation in the detection magnitude distribution before and after the AdriaArray deployment. For simplicity, we neglect the accelerometers not collocated with velocimeters and focus only on the velocimetric stations (active between 2022 and 2025) equipped with channels HH* and EH*. We apply the method proposed by Marzorati and Cattaneo (2016) that estimates the spatial variability of the minimum detectable magnitude by comparing the average noise levels recorded at each station with a synthetic ground motion spectrum. This synthetic spectrum is generated using the ω-square source model (Brune, 1970), simulating earthquakes distributed on a regular grid with 1 km spacing inside the core of the network and 5 km spacing in the surrounding area. Earthquake moment magnitudes range from 1.5 to 4.5, with increments of 0.1. The source spectra are propagated to each station assuming a geometrical spreading factor of 1/R. An event is considered detectable when the signal-to-noise ratio, computed within the 1-30 Hz frequency band, exceeds 20 at a minimum of five stations. The mean noise amplitude at each station is calculated as an average (A_{PSD}) of the PSD values (in dB) over the frequency range of interest (f_{AV}), then converted to m/s using: $A = \frac{10^{\frac{A_{PSD}}{20}}}{2\pi\, f_{AV}}$. Our results show (Fig. 7c) that the new AdriaArray stations lower the detection magnitude by approximately 0.3-0.4 in Sardinia, especially in the northern and eastern areas, while in the Po Plain the reduction is more modest (about 0.2 in the northwest). This smaller improvement is mainly due to the higher seismic noise level in the region, which directly impacts the signal-to-noise ratio and hence the detection threshold at each site. Although it could also be possible to estimate the temporal variation of the detection capability by incorporating noise levels at different times (e.g. day vs. night, weekdays vs. weekends) and accounting for the operational status of stations during those periods, this analysis goes beyond the purpose of the present study.

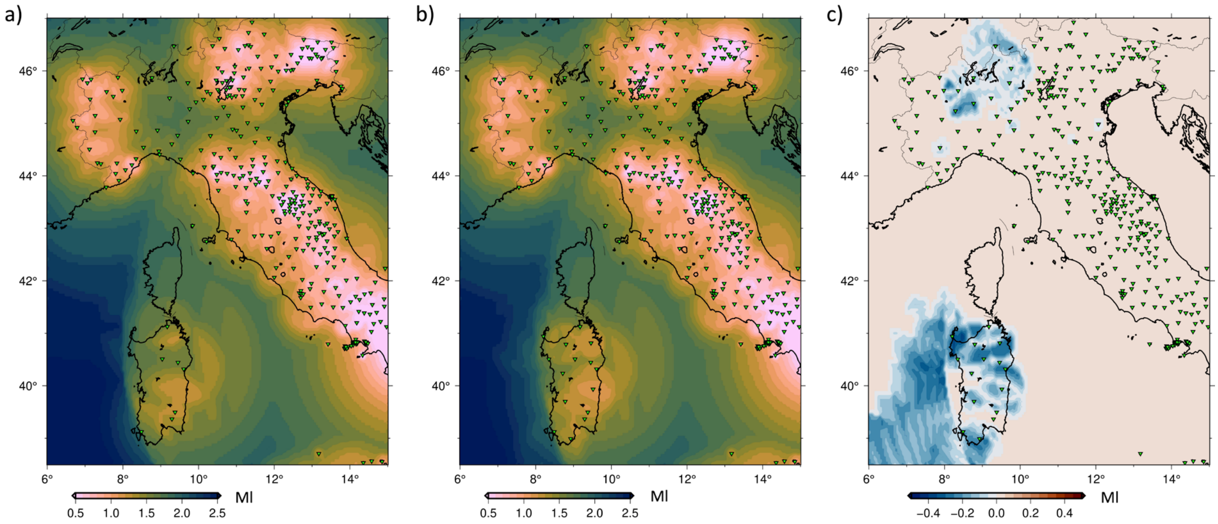

Figure 7. Estimated spatial variability of the minimum detectable local magnitude (Ml) by following the approach of Marzorati and Cattaneo (2016) considering the velocimetric stations (channel HH* and EH*) installed in Italy between 2022 and 2025 a) without the 4P network stations and b) including the 4P AdriaArray network. In c) the differences between (b) and (a) is shown.

4. Comparison of earthquake recordings

The noise performance of the deployed stations enables the clear recording of both local (Figs. 8 and 9) and teleseismic events (Fig. 10), even at sites with elevated ambient noise. As an illustrative example, Fig. 8 shows the waveform of a local event (Ml 3.5) that occurred near Finale Emilia on 15/01/2025 (https://terremoti.ingv.it/). We present waveforms (Figs. 8a-b-c-d-e, center panel) recorded by five stations – two permanent (IV, INGV Seismological Data Centre, 1997) and three temporary (4P) – as well as eight minutes of pre-event noise (Figs. 8a-b-c-d-e, top panel) and the spectral comparison between the earthquake and noise windows (Figs. 8a-b-c-d-e, bottom panel). Clear P-phase arrivals are observed at the nearby stations (PRMA, ZCCA, IT09A), whereas they are less distinct at the noisier IT08A station and at the more distant IT03A station. In these latter cases, the event spectrum exceeds the noise spectrum only within the 0.5-2 Hz frequency range, indicating that this frequency band propagates efficiently within the Po Basin and is less affected by attenuation for small- to moderate-magnitude events. Additionally, the waveforms exhibit long durations, a characteristic signature of seismic wave propagation in deep sedimentary basins (e.g. Molinari et al., 2015).

In Fig. 9 we show the waveform recorded by the Sardinian stations of a Ml 3.3 event that occurred in the Tyrrhenian Sea on 30/08/2024 (https://terremoti.ingv.it/). The waveforms are shown for one permanent station, MN.SENA (MedNet project partner institutions, 1988; Pondrelli et al., 2020) and four temporary ones (4P). The seismic phases are clearer than in the Po Plain event also at ~210 km distance (IT22A). The event spectrum exceeds the noise level for frequencies higher than 0.2-0.5 Hz depending on the epicentral distance with the exception of the IT23A that exhibits a high noise level for frequencies higher than 10 Hz and the event spectrum exceeds the noise only within the 0.9-10 Hz frequency range.

Figure 10 shows data recorded by the functioning 4P stations for the Mw 7.4 event that occurred in Chile (depth: 127.3 km) on July 19 2024 at 01:50:48 (UTC) (USGS, https://earthquake.usgs.gov/). The waveforms have been corrected for the instrument response and filtered using a Butterworth bandpass filter (four poles, zero phase) in the 10-125 s period range. Clear phase arrivals can be identified, demonstrating that the data can be used for earthquake location and for many of the AdriaArray scientific purposes.

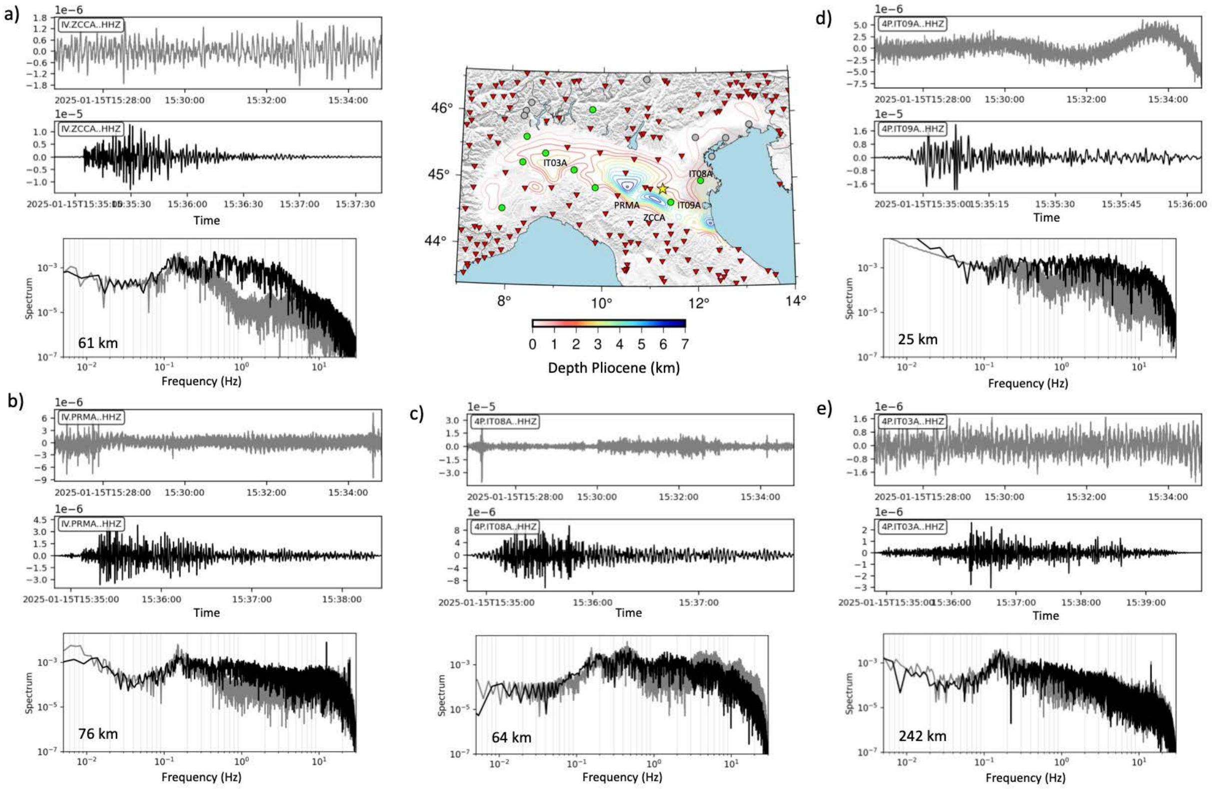

Figure 8. Data recorded by two IV (INGV Seismological Data Centre, 1997) stations – (a) ZCCA and (b) PRMA – and three 4P stations, (c) IT08A, (d) IT09A and (e) IT03A, for the ML 3.5 event occurred near Finale Emilia on 15/01/2025 at 15:34:49 UTC. Each panel shows (top) in gray the noise recorded 8 minutes before the event; (middle) in black the event waveform filtered with a bandpass filtered with corner frequencies of 0.4 Hz and 2 Hz; (bottom) the comparison between the spectrum of the two signals not filtered (gray and black for the noise and the event accordingly). The map shows the epicenter location (yellow star), the permanent stations (red triangles), the 4P stations (green dots) and the iso-depth of the Pliocene sediments according to Molinari et al. (2015).

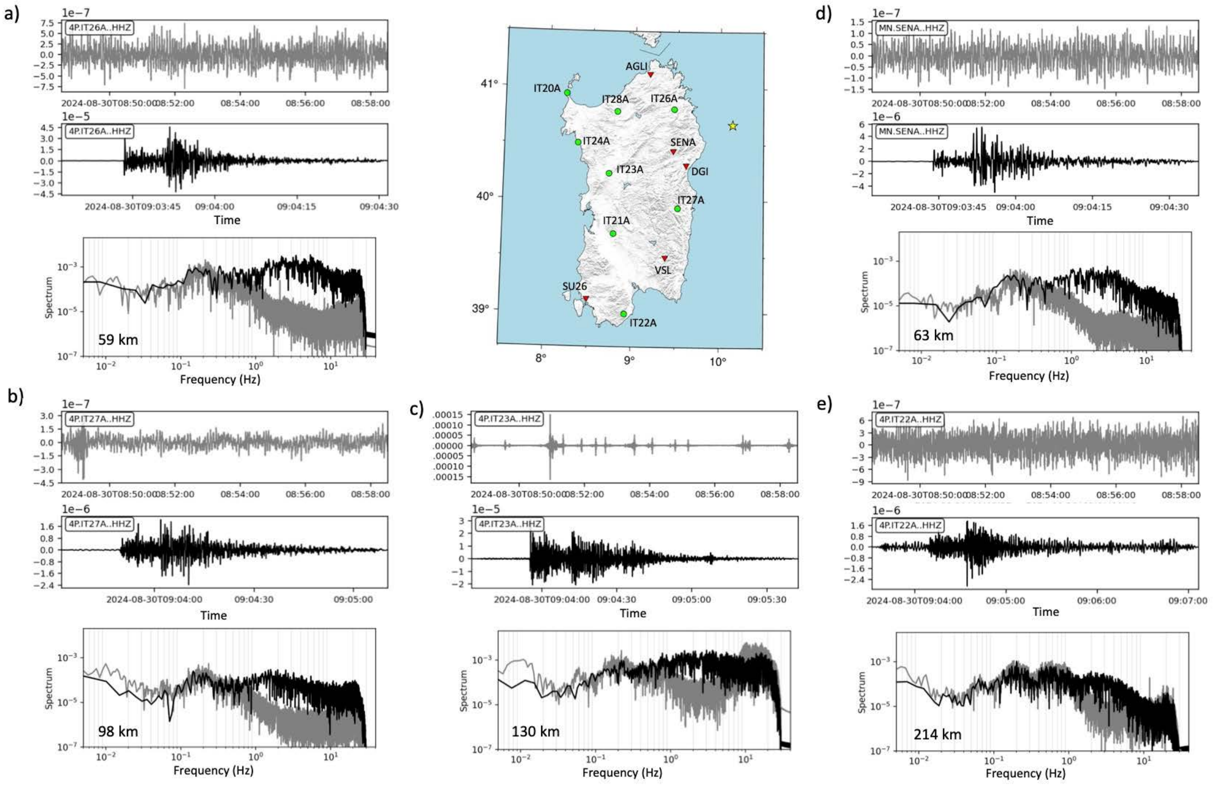

Figure 9. Data recorded by d) one MN station SENA (MedNet project partner institutions, 1988) and four 4P stations, (a) IT26A, (b) IT27A, (c) IT23A and (e) IT22A, for the event occurred in the Tyrrhenian Sea on 30/08/2024 at 09:03:32 with Ml 3.3. Each panel shows (top) in gray the noise recorded 10 minutes before the event; (middle) in black the event waveform filtered with a bandpass filtered with corner frequencies of 0.4 Hz and 10 Hz; (bottom) the comparison between the spectrum of the two signals not filtered (gray and black for the noise and the event accordingly) The map shows the epicenter location (yellow star), the permanent stations (red triangles) and the 4P stations (green dots).

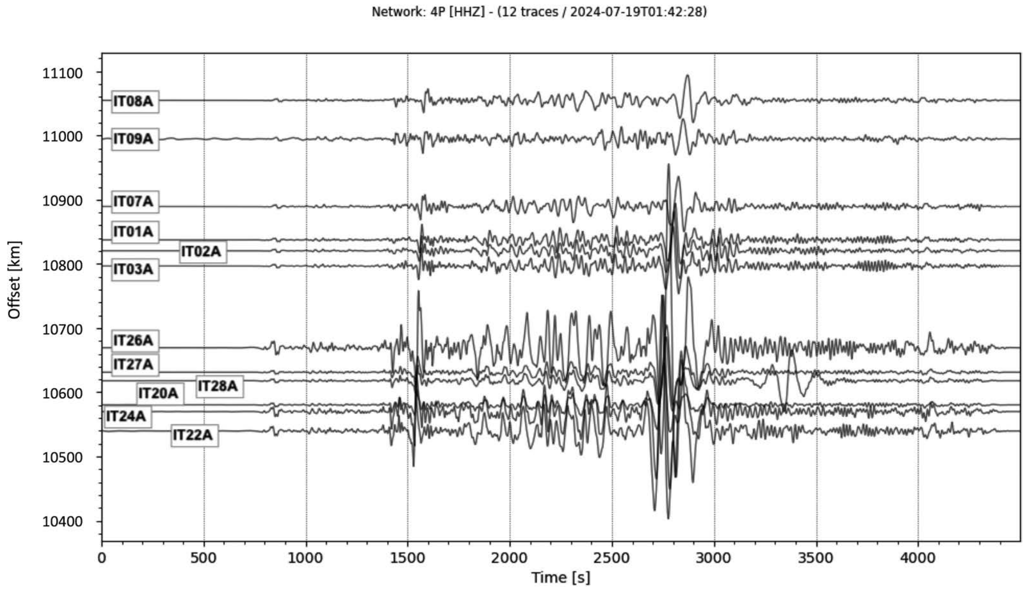

Figure 10. Data recorded by the functioning 4P stations for the Mw 7.4 event occurred in Chile (location: 23.079S, 67.840W, depth: 127.3 km) on 19 of July 2024 at 01:50:48 (UTC) (USGS, https://earthquake.usgs.gov/). The waveforms have been corrected for the instrument response and filtered using a Butterworth bandpass filter in the 10-125 s period range.

5. Conclusions

This work details the contribution of the 4P network to the AdriaArray Initiative, focusing on the deployment and operation of 17 temporary broadband stations in the challenging regions of the Po Plain and Sardinia. Through careful site selection adhering to high-quality standards and the implementation of optimized station configurations, we have successfully addressed critical gaps in Italy's permanent broadband seismic coverage, thereby achieving uniform spatial sampling essential for AdriaArray's objectives.

Our analysis of the noise characteristics and network performance confirms the acquisition of high-quality seismic data, generally exhibiting noise levels below the New High Noise Model (NHNM). We have characterized the diverse seismic noise environment across the deployment areas, identifying influences from anthropogenic activity, regional geology, and sensor types. The network's operational success is further highlighted by its data availability exceeding 85%, its integration into INGV's real-time monitoring systems, and adherence to an open data policy.

The integration of the 4P stations has enhanced the Italian seismic network's detection capabilities. Our results show a reduction in the minimum detectable magnitude by approximately 0.3-0.4 in Sardinia and 0.2 in the Po Plain. In particular, Sardinia has never before been equipped with real-time seismic monitoring mainly due to its low seismicity. A comparable seismic experiment in Sardinia was the LISARD deployment in 2017 (Magrini et al., 2020); however, those data were not available in real-time and are not currently accessible through EIDA. Seismicity in Sardinia is indeed very low, with most of the detected events attributable to quarry-blasts. With the AdriaArray network we have the opportunity to quantify its quietness. Nevertheless, we were able to detect a few seismic events for which the 4P stations provided crucial data to constrain the earthquake locations. We emphasize the importance of monitoring this "quiet" region with high-quality sensors, particularly in view of the possible selection of Sardinia – and specifically the Sos Enattos area in the northeast – as the site for the Einstein Telescope (e.g. Di Giovanni et al., 2020; Naticchioni et al., 2024). Our observations underline the critical importance of deploying high-sensitivity, very broadband sensors for advanced long-period seismology and deep Earth imaging. These high-quality, openly accessible data products are fundamental for advancing high-resolution tomographic studies, refining our understanding of the complex Mediterranean geodynamics, and improving seismic hazard assessments.

Data availability statement. Waveform data from all AdriaArray Seismic Network stations is available through EIDA hjhttp://www.orfeus-eu. org/eida/). The 4P stations are hosted by the INGV-IEDA node.

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Figures have been prepared using the Generic Mapping tools (Wessel et al., 2019) and Obspy (Krischer et al., 2015), and are made using perceptually uniform colormaps (Crameri, 2018, Crameri et al., 2020).

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