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AdriaArray in Albania: Collaborative Deployment, Station Characterization, and Data Integration

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Abstract

This study assesses the deployment, integration, and initial performance of broadband seismic stations in Albania under the AdriaArray initiative. As part of the German Seismological Broadband Array (DSEBRA) project, nine stations were installed to enhance seismic monitoring, improve event detection, and refine data quality. Their integration into the Albanian Seismological Network allows for a systematic evaluation of site effects, noise characteristics, and travel time residuals. Horizontal-to-vertical spectral ratio analysis reveals strong site-dependent variability, with soft-soil sites (e.g., AL07A, AL08A) exhibiting high amplification ($A_0 > 4.0$) and low fundamental frequencies ($f_0 < 1.0$ Hz), while bedrock stations (e.g., AL06A, KKS) show higher fundamental frequencies ($f_0 > 10$ Hz) and reduced amplification ($A_0 < 2.5$). Probabilistic Power Spectral Density analysis highlights seasonal noise fluctuations, with wintertime increases at urban and coastal sites and persistent low-frequency noise exceeding-120 dB at certain locations. Travel-time residuals confirm that bedrock stations (e.g., AL01A, AL03A, AL05A) provide stable phase arrivals, while urban sites show greater scatter, particularly for smaller magnitude earthquakes. The densified network enhances waveform resolution and improves seismic event location accuracy, directly contributing to real-time moment tensor solutions. The DSEBRA's stations accounted for 187 of 289 analyzed moment tensor events, with AL05A and AL08A yielding the highest number of high-quality solutions. These results reinforce the role of uniform instrumentation and regional collaboration in advancing seismic monitoring. The findings establish key benchmarks for the operational quality of AdriaArray stations in Albania, emphasizing the need for further site characterization, noise mitigation at urban sites, and refined velocity models. Continued regional cooperation remains essential for improving earthquake monitoring and geodynamic research in the Adria microplate region.

Keywords: Broadband seismic stations; Site response; Seismic noise; Travel time residuals; Moment tensor solutions

1. Introduction

The Mw 6.4 Durrës earthquake on November 26, 2019, challenged previous interpretations of seismicity in the northern Outer Albanides (Fig. 1a), revealing the influence of deep-seated thrust structures in regional seismogenesis (Teloni et al., 2021; Matraku et al., 2023). Traditionally, seismic activity in western Albania was considered shallow, primarily associated with compressional structures within the sedimentary cover (Bega and Soto, 2017; Aliaj, 2000; Aliaj, 2006; Aliaj et al., 2010; Muço, 1993; Muço and Puka, 1993; Muço, 1998; Copley et al., 2009). However, depth estimates of the Durrës earthquake, ranging from 20 to 40 km, reported by the European-Mediterranean Seismological Centre (EMSC), the United States Geological Survey (USGS), the German Research Centre for Geosciences (GFZ), and the Institute of Geosciences at the Polytechnic University of Tirana (IGEO-PUT), along with aftershock distribution, geodetic data, and the observation of slow slip events following the mainshock, suggest a blind thrust at depth, linked to crustal ramp-dominated thrusting at the Adria-Eurasia boundary. The Durrës earthquake also exposed critical gaps in Albania's seismic monitoring network, where only six out of eight broadband stations and a partially functioning accelerometric network were operational at the time, limiting near-field data acquisition and increasing uncertainties, mainly regarding the focal depths of the mainshock and the aftershocks, and rupture characterization. These challenges highlight the need for improved national and regional monitoring, reinforcing the motivation behind initiatives such as AdriaArray to enhance seismic observations and refine geodynamic models.

Despite these uncertainties, the Durrës earthquake's focal mechanism consistently indicated reverse faulting, reflecting compressive tectonic stresses at the collisional boundary between the Adria and Eurasian plates. Ganas et al. (2020) identified a fault plane solution with a strike of 346°, a dip of 23°, and a rake of 90°, consistent with a thrust fault. Papadopoulos et al. (2020) reported similar parameters with a strike of 345°, dip of 22°, and rake of 99°. Dushi and Havskov (2023) further corroborated this interpretation, emphasizing the influence of intricate crustal structures on the regional seismicity.

The geodynamic significance of deep-seated structures along the eastern margin of the Adria microplate was underscored by the 2019 Durrës earthquake, challenging prior assumptions that these structures exhibited minimal seismic activity. Recent studies (Menichelli et al., 2025) have demonstrated their potential to generate significant earthquakes, emphasizing their critical role within the broader tectonic framework. Situated along the active Adria-Eurasia collision boundary, Albania's geodynamic setting is characterized by a complex interplay of compressive forces, extensional tectonics, and slow-slip phenomena. Notably, Matraku et al. (2023) identified slow-slip events following the Durrës earthquake, highlighting the coexistence of seismic and aseismic deformation processes in the region. The Adria microplate's northeastward convergence at 4-6 mm/yr drives ongoing deformation within the Albanides, a key segment of the Mediterranean orogeny.

In response to the earthquake, the Albanian Earthquake Aftershock Campaign (AlbACa) initiated the first dense mobile seismic deployment, which provided invaluable aftershock data, reinforcing the necessity of high-resolution network coverage for precise seismic characterization (Schurr et al., 2020; Dushi et al., 2020). Recognizing these challenges, Albania has undertaken substantial initiatives to improve seismic monitoring. The Resilience Strengthening in Albania (RESEAL) project led to the permanent installation of ten seismic stations, significantly enhancing the operational capacity of Albania's seismic network (United Nations Development Program, 2024).

Additionally, IGEO, Albania's national geoscience research institute, has joined the Adria-Array initiative, a multinational effort to densify seismic station coverage and develop uniform datasets for multidisciplinary research on geodynamics, tectonics, and seismic hazards (Kolínský et al., 2024). The Adria-Array framework promotes collaborative research through the deployment of mobile broadband pools, the integration of temporary networks like the Albanian Tectonics of Continental Subduction (ANTICS) project (Agurto-Detzel et al., 2024), and a commitment to FAIR principles (Findable, Accessible, Interoperable, and Reusable) in data sharing.

The German Seismological Broadband Array (DSEBRA; Deutsches Seismologisches Breitbandarray), coordinated by Ludwig Maximilian University of Munich (LMU) and funded by the German Research Foundation (DFG), deployed 19 broadband stations across Kosovo, Montenegro, and Albania beginning in 2022 as part of the Adria-Array initiative (Schlömer et al., 2025). Fully operational since mid-2023, these stations significantly enhance seismic monitoring capacity in the region. IGEO's early and modest contribution during the deployment and integration phase provided essential local support and contributed to the establishment of initial scientific cooperation within the AdriaArray framework. This cooperation supports the development of future joint research activities and sustained open-access data sharing, in accordance with the initiative's scientific objectives. This paper evaluates the early operational performance and data reliability of the Albanian seismic network (Fig. 1b) within the AdriaArray framework, analyzing data collected between April 2023 and December 2024 to assess its contribution to regional seismic monitoring.

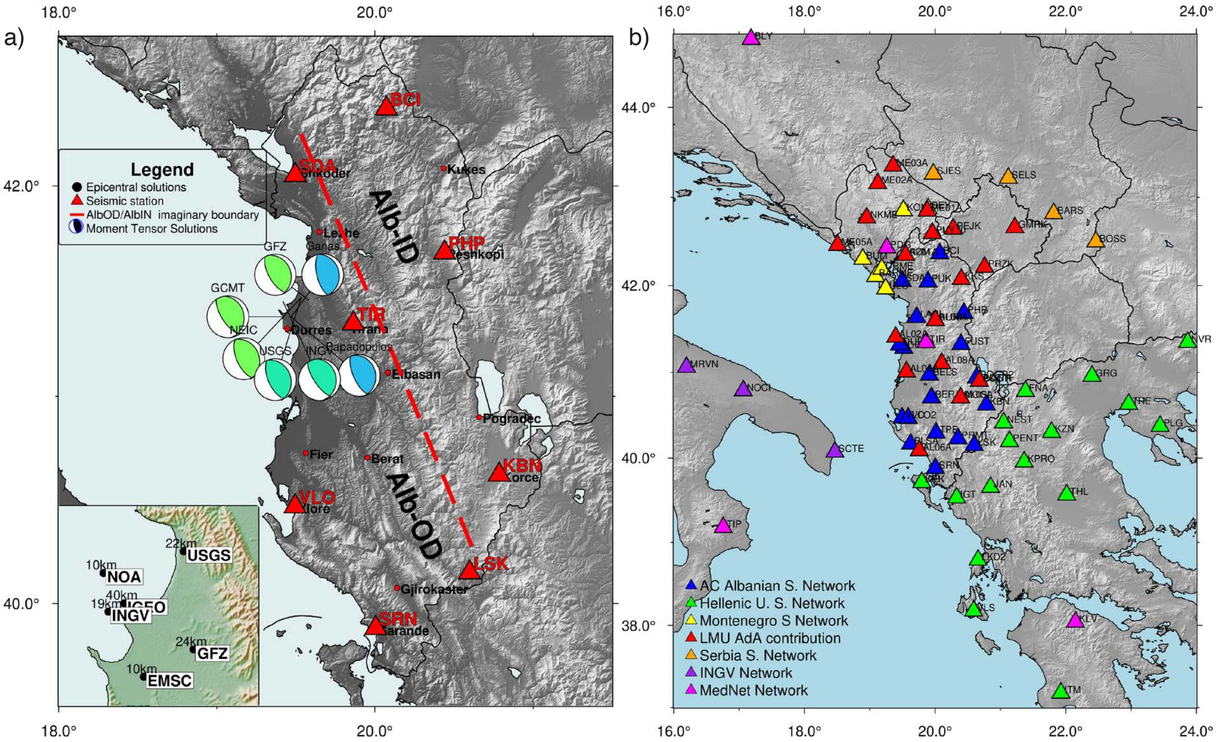


Figure 1. (a) Schematic representation of the outer and inner tectonic domains in Albania, together with the reported hypocenters of the 26 November 2019 Durrës earthquake (Mw 6.4) and its focal mechanism, as documented in referenced studies. The map also shows the operational seismic network at that time, highlighting the sparse station coverage during the event; (b) Current seismic network configuration, including permanent Albanian stations, regional seismic stations, the Hellenic Unified Seismic Network (HUSN; Evangelidis et al., 2021), the Montenegro Seismic Network (MNE; FDSN, Ahern et al., 2019), the Serbian Seismic Network (SRB; FDSN, Ahern et al., 2019), the National Institute of Geophysics and Volcanology (INGV; FDSN, Ahern et al., 2019), and the Euro-Mediterranean Broadband Seismic Network (MEDNET; FDSN, Ahern et al., 2019), accessed through cooperative data-exchange agreements, as well as the recently deployed DSEBRA broadband stations in Albania, Montenegro, and Kosovo.

By analyzing travel time residuals, Probabilistic Power Spectral Density (PPSD) metrics, and site characteristics (e.g., Horizontal-to-Vertical Spectral Ratio (HVSR) results and geological data), this study provides an initial assessment of station performance based on the available data.

2. Deployment of AdriaArray stations in Albania

2.1 Overview of the deployment in Albania

Between 2022 and 2023, nine broadband seismic stations were deployed in Albania (Table 1) under the DSEBRA project as part of the AdriaArray initiative (Schlömer et al., 2025). This deployment enhances seismic monitoring capabilities, improves spatial coverage, and supports the detection and characterization of seismic events. The stations entered their initial operational phase in 2023 and are actively contributing to data collection and regional monitoring. Each station is equipped with a Nanometrics Trillium Horizon 120 s broadband seismometer and a Nanometrics Centaur 24-bit data logger. A GA-88P GPS antenna provides precise timing and location data, while a Teltonika RUT955 mobile router with a 4G LTE antenna enables real-time data transmission with latencies below 3 seconds (Schlömer et al., 2025).

This deployment is a collaborative effort between the Ludwig Maximilian University (LMU) in Munich and the Institute of Geosciences (IGEO), the national research center for Geosciences in Albania. The stations are fully integrated into the Albanian Broadband Seismic Network and contribute to ongoing seismic monitoring. Data and metadata from the nine LMU-operated stations are available in near real-time via the European Integrated Data Archive (EIDA) (Strollo et al., 2021), which also includes stations in Kosovo and Montenegro managed by the LMU node (Schlömer et al., 2025). Access is provided through SeedLink for real-time monitoring and FDSN web services for archived data, subject to a two-year embargo and limited to AdriaArray members. Authentication is securely handled via the EIDA Authentication Service, enabling authorized cross-node access.

Table 1. Locations, Site Attributes, and Access Conditions for the AdriaArray Stations in Albania.

Station	Location	Lat (°)	Lon (°)	Elev (m)	Installation Site	Access
AL01A	Razëm, Malësi e Madhe	42.3463	19.5486	1168	Bedrock-based seismic station	Mountainous region, accessed via Razëm-Rrapsh road
AL02A	Kepi i Palit, Durrës	41.4085	19.3963	6.2	Military base	Controlled access near a military zone
AL03A	Komsi, Burrel	41.6015	20.0047	337	Bedrock-based seismic station	Accessible via SH37
AL04A	Divjakë, Fier	41.0072	19.5617	71.4	City water deposit	Local roads in Divjakë
AL05A	Moglicë, Maliq, Korçë	40.7054	20.3916	532	Bedrock-based seismic station	Moderate elevation, accessible via SH71
AL06A	Himarë, Vlorë	40.0890	19.7582	129	City water deposit	Accessible via Arjileo Street
AL07A	Pogradec, Korçë	40.8996	20.6789	754	Bedrock-based seismic station	Accessible via local roads
AL08A	Elbasan	41.1050	20.1024	243	City water deposit	Accessible via Mehmet Bebeti Street
KKS	Kukës	42.0730	20.4017	399	Bedrock-based seismic station	Accessible via Drini i Zi

After more than a year in operation, the stations are continuously monitored for functionality and technical performance. Quality control of recorded seismic signals and waveform data is conducted at LMU Munich, with additional verification at the Albanian National Seismic Monitoring Center (ANSMC). This two-tiered quality assurance process ensures compliance with international seismic observation standards and aligns with the AdriaArray requirements.

The deployment of these stations has contributed to the densification of the regional broadband seismic network, improving seismic coverage in Albania and surrounding areas. Once integrated into the Albanian Seismic Network (AC), they also support local seismic monitoring by:

- Enhancing earthquake detection across Albania with an improved lower magnitude detection threshold.
- Providing higher-resolution broadband data for real-time seismic analysis.
- Contributing to AdriaArray research, supporting studies on the tectonics of the Adria contact zone, which includes different tectonic settings, among them the continental collision system between Adria and Eurasia, comprising the Albanian region.

Additionally, incorporating these stations into the routine seismic event location workflow of AC has improved event location accuracy, leading to more reliable seismic characterizations of the region.

2.2 IGEO's contribution and Station Maintenance

The Department of Seismology (DS) of the Institute of Geosciences (IGEO) has been central to the deployment and maintenance of the DSEBRA's seismic stations in Albania, providing comprehensive logistical and technical support. As part of its responsibilities, the Department facilitated the planning process, ensured site availability, and secured governmental support for station installations. In addition, DS managed the procurement and contracting of mobile data SIM cards for data transmission and enabled SMS-based router control for the stations located within Albania.

The installation of the DSEBRA stations was conducted collaboratively, with technical oversight from the LMU engineering team and remote support from LMU colleagues. The IGEO field team provided on-site assistance, including VPN configurations, station metadata updates, and data-sharing setup. This coordinated effort ensured the seamless integration of the stations into the broader seismic monitoring framework.

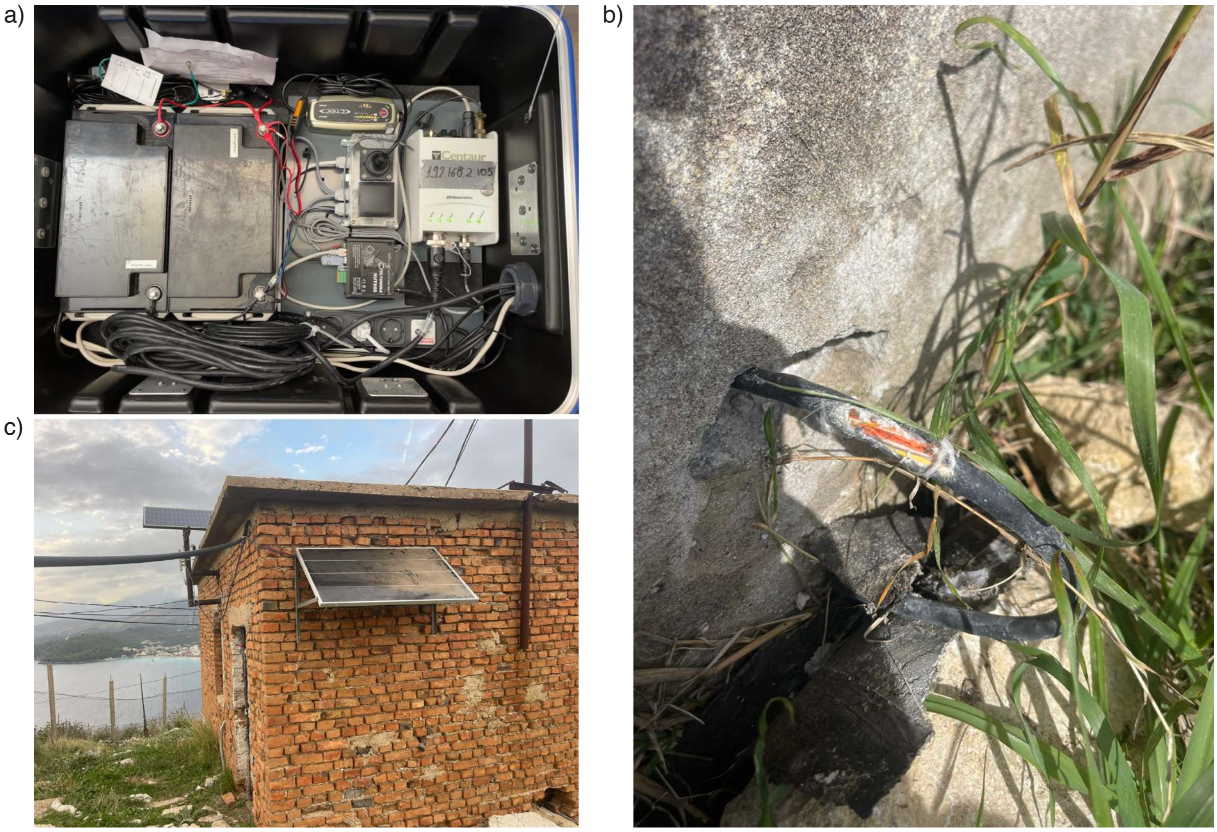


Figure 2. Maintenance challenges and solutions at DSEBRA stations in Albania: power socket repairs at AL02A, signal cable 139 replacement at AL04A, and solar panel installation at AL06A to address lightning-related issues.

The functionality of all DSEBRA stations has been continuously monitored by IGEO, addressing technical challenges in collaboration with LMU experts. Several issues have been resolved on-site by the IGEO team. At station AL01A in Razëm, Malësi e Madhe, both the battery charger and router charger failed due to a power surge or lightning strike. These components were replaced, restoring the station's full operational capacity. At station AL02A in Kepi i Palit, Durrës, a power outage at the hosting military base disrupted data transmission for several days (Fig. 2a). The IGEO team diagnosed the issue on-site, repairing the faulty power socket and resuming normal operations. At station AL04A in Divjakë, Fier, a faulty signal on one component was due to damage caused by rodents chewing the signal cable (Fig. 2b). The cable was replaced using equipment provided by LMU, restoring data integrity.

Similar challenges were addressed at other stations. At station AL05A in Moglicë, Maliq, frequent transmission interruptions occurred early in the installation phase, likely due to issues with the Power Box. The problem was resolved by using an external router charger. Additionally, a faulty memory card was replaced, and the station's functionality was fully restored. At station AL06A in Himarë, Vlorë, power supply issues posed significant challenges. A lightning strike damaged the battery charger, necessitating its replacement alongside modifications to the power supply. The station's location on a hill in a water deposit settlement made it prone to such discharges. To ensure uninterrupted operation, the station was equipped with a solar panel and an extended battery system, providing a reliable and sustainable power source (Fig. 2c).

The reliable operation of all stations has been achieved through a careful site preparation, consistent supervision, and coordinated maintenance. The collaboration between IGEO and LMU has contributed to the management and long-term operation of the broadband seismic station network in the Albanian deployment as part of the AdriaArray framework.

2.3 Integration of AdriaArray Stations into the Albanian Seismic Network

The integration of DSEBRA seismic stations as part of the broadband backbone of the Albanian Digital Seismic Network (AC) has proven instrumental in enabling remote access and control of DSEBRA stations in coordination with the LMU team, integrating routine data quality checks and parametric data, and densifying the Albanian seismic network to improve regional coverage and detection capabilities.

Over a period of joint operation, these enhancements have significantly expanded the network's operational capabilities, contributing also to the advancement of real-time earthquake detection, moment tensor solutions, and SHAKEMAP generation. Combined with AC's existing twelve broadband stations, these additions have further strengthened the detection and analysis of seismic activity, supported by a suite of specialized software systems (Fig. 3).

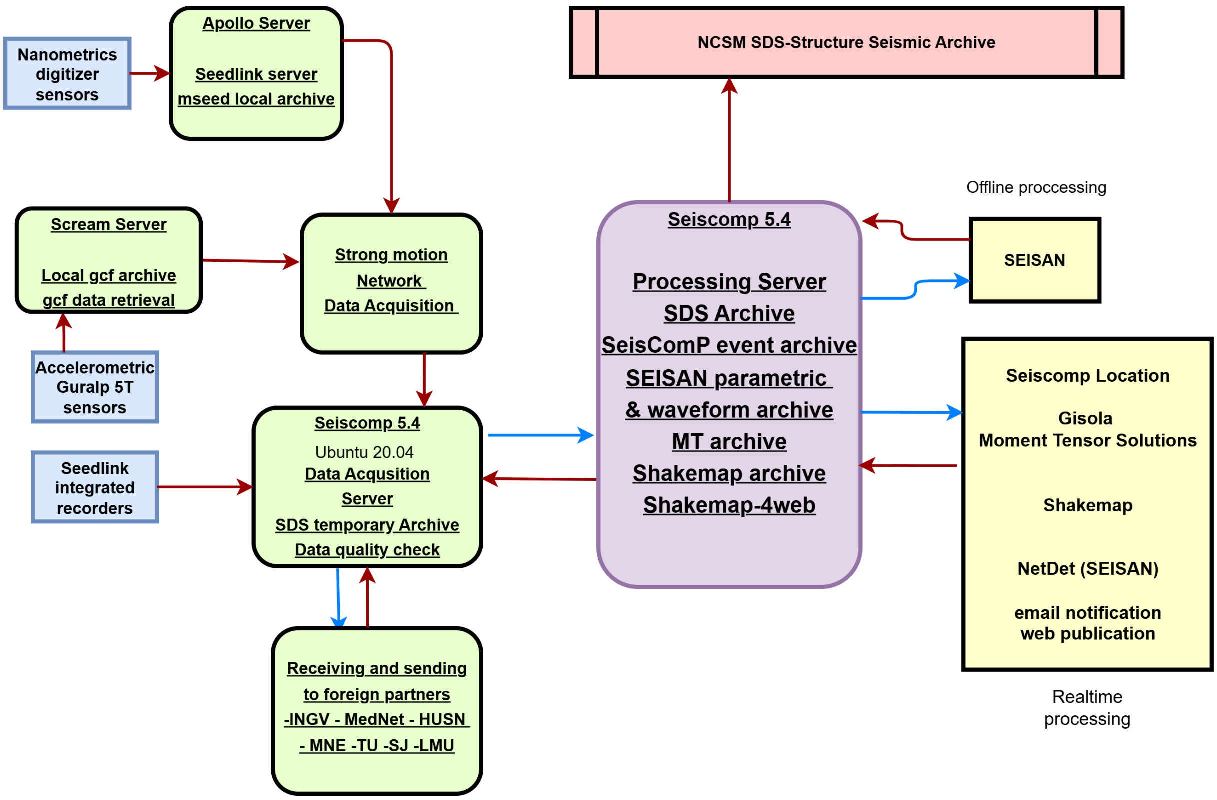


Figure 3. IGEO's real time seismic monitoring and earthquake detection system scheme.

The SeisComP system (Helmholtz Centre Potsdam, 2022) serves as the primary platform for real-time seismic data acquisition and processing at the Albanian National Seismic Monitoring Center (ANSMC). Automatic earthquake detection and location is performed using the SCAutoLoc module, which provides rapid preliminary solutions for seismic events (M > 2.0). Complementing this system, the NETDET routine within SEISAN (Havskov et al., 2020) offers an additional layer of automatic detection by scanning the SeisComP Data Structure (SDS) archive. The SDS archive is a standardized directory structure for waveform data, organized by year, network, station, and channel, and is automatically generated by SeisComP. The NETDET routine has demonstrated superior sensitivity in detecting a larger number of events, particularly those of lower magnitudes, with thresholds approaching M < 1.0. This capability proves especially valuable in the Albanian context, where a high frequency of small-magnitude earthquakes plays a key role in delineating active faults and characterizing ongoing seismotectonic processes. The integration of the DSEBRA stations into both SeisComP and SEISAN workflows has further enhanced overall detection performance, improving event localization accuracy and enabling a more comprehensive analysis of regional seismicity (Fig. 4).

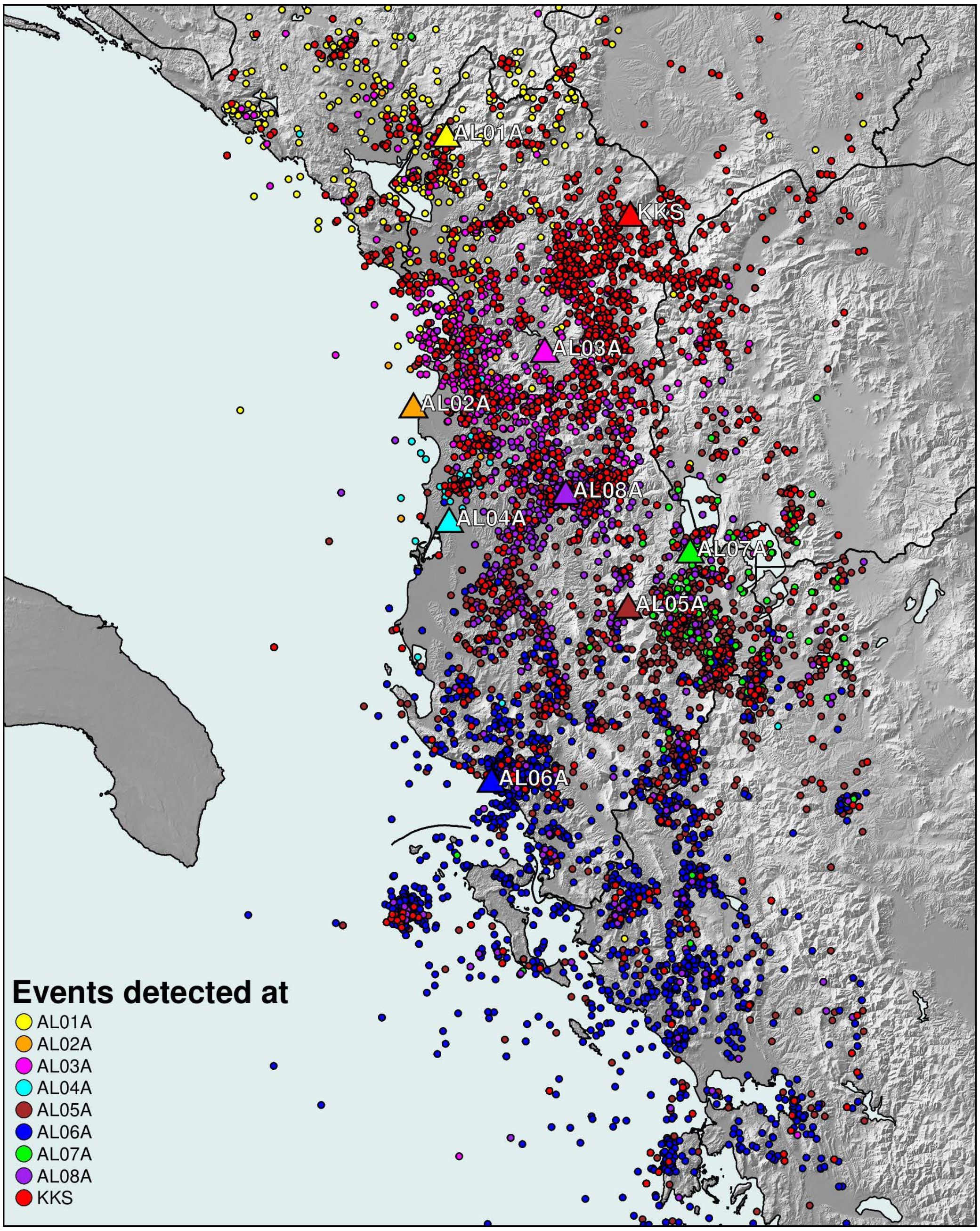


Figure 4. Spatial distribution of seismicity (April 2023-December 2024), with epicenters color-coded by individual AdriaArray stations based on filtered sub-catalogs. Although each event may be recorded by multiple stations, coloring reflects per-station detection subsets, determined by distance and magnitude-dependent sensitivity.

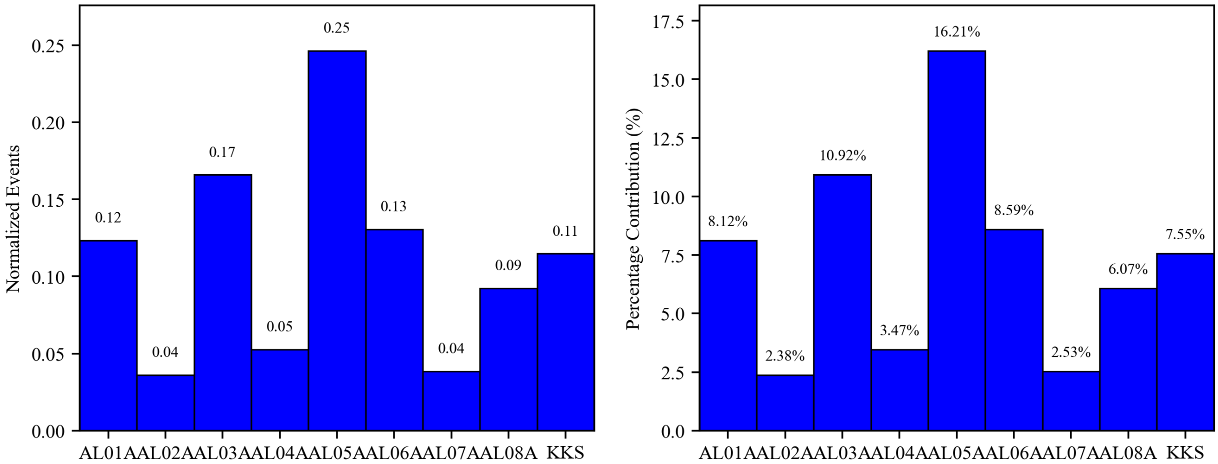


Figure 5. Contribution of AdriaArray Stations to Seismic Event Detection: Normalized Distribution and Percentage of Total Albanian Network Events.

Since April 2023, the AdriaArray broadband temporary network in Albania – now integrated into national and regional monitoring systems – has contributed to the detection of 13,045 local earthquakes, corresponding to approximately 58% of the 22,377 total events recorded by the Albanian Seismic Network within the defined region (38.5°-43°N, 18.5°-21.5°E). Among the AdriaArray stations, AL05A stands out for its performance, accounting for around 27% of all detections (3,628 earthquakes) and recording 6,426 seismic phases (both P and S). In contrast, AL02A recorded the fewest, with 532 events and 816 phases, contributing only about 4% of the total. The normalized distribution of earthquakes among the AdriaArray stations, as shown in Fig. 5, is presented as a histogram that reflects the relative contribution of each station to the total number of detected local events. This visualization highlights AL05A as the most productive station in terms of recorded seismic activity. These variations underscore the different roles played by individual stations within the temporary network and their critical importance in improving the spatial resolution and completeness of regional seismic monitoring.

In addition to routine detection, real-time moment tensor (MT) solutions are calculated using GISOLA (Triantafyllis et al., 2022), based on SeisComP-detected events. Since the installation of the DSEBRA stations across Albania, Kosovo, and Montenegro in April 2023, IGEO has produced 870 MT solutions out of 1,175 total solutions, most of which are automatic. The DSEBRA network alone contributed to 351 of the 504 analyzed solutions (Fig. 6), confirming its significant impact on the quality and quantity of real-time moment tensor analysis in the AdriaArray region.

Among the high-quality moment tensor (MT) solutions during this period, both automatic and revised, DSEBRA stations deployed in Albania provided usable waveform data for 82 out of 105 such events, corresponding to 187 out of 289 earthquakes located within the Albanian territory (38.5°-43.0°N, 18.5°-21.5°E). In these cases, the waveforms recorded by the DSEBRA stations were incorporated into the inversion process, having met the necessary quality criteria. Station-specific participation varied, with AL05A, AL08A, and AL07A more frequently involved in high-quality solutions. AL05A contributed data to 73 events (including 27 high-quality solutions), AL08A to 95 events (29 high-quality), and AL07A to 77 events (25 high-quality). This may reflect how installation conditions and signal quality influence the robustness and azimuthal coverage of MT solutions. In addition, the DSEBRA stations located in Kosovo and Montenegro contributed data to 305 regional moment tensor inversions (Fig. 6), of which 57 were classified as high quality according to the GISOLA criteria (Triantafyllis et al., 2022).

The ShakeMap service represents a recent advancement at ANSMC, utilizing ShakeMap V4.0 (Worden et al., 2018) to generate parametric and visualization products for ground shaking, including intensity (MMI), Peak Ground Acceleration (PGA), Peak Ground Velocity (PGV), and Displacement (PGD) for earthquakes in Albania and surrounding areas. Critical input parameters and waveform data are seamlessly obtained through the SCWFParam module, ensuring rapid ground shaking information. The integration of DSEBRA stations has further enhanced the robustness of this service. The M4.3 earthquake on January 24, 2025, in northwestern Albania, represents a clear demonstration of the system's operational efficiency and its capability for near real-time ground shaking assessment. The event, promptly processed and visualized through ShakeMap (Fig. 7), highlights the effectiveness

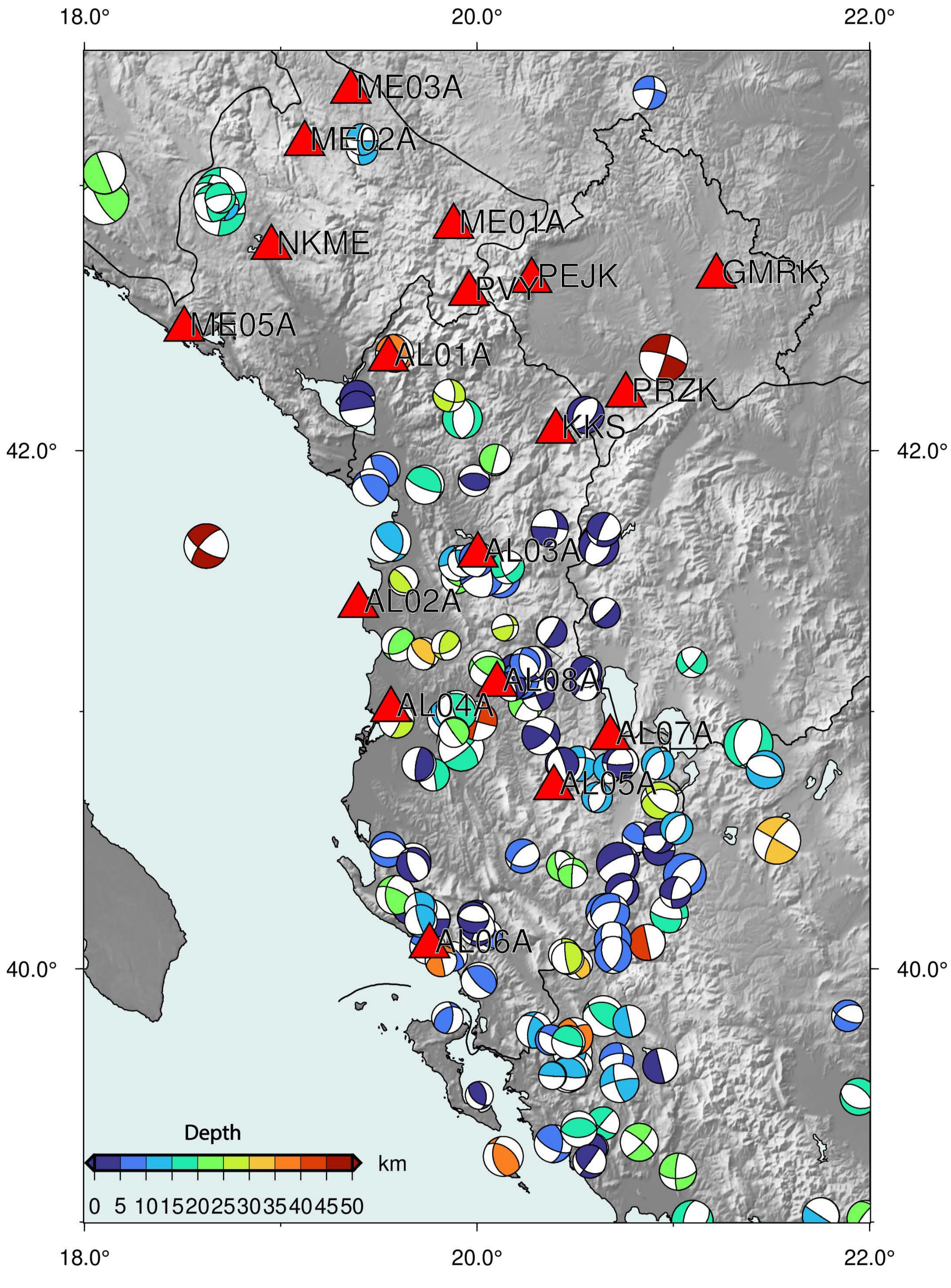


Figure 6. Real time moment tensor (MT) solutions and their spatial distribution, from the real time system, utilizing GISOLA 192 software.

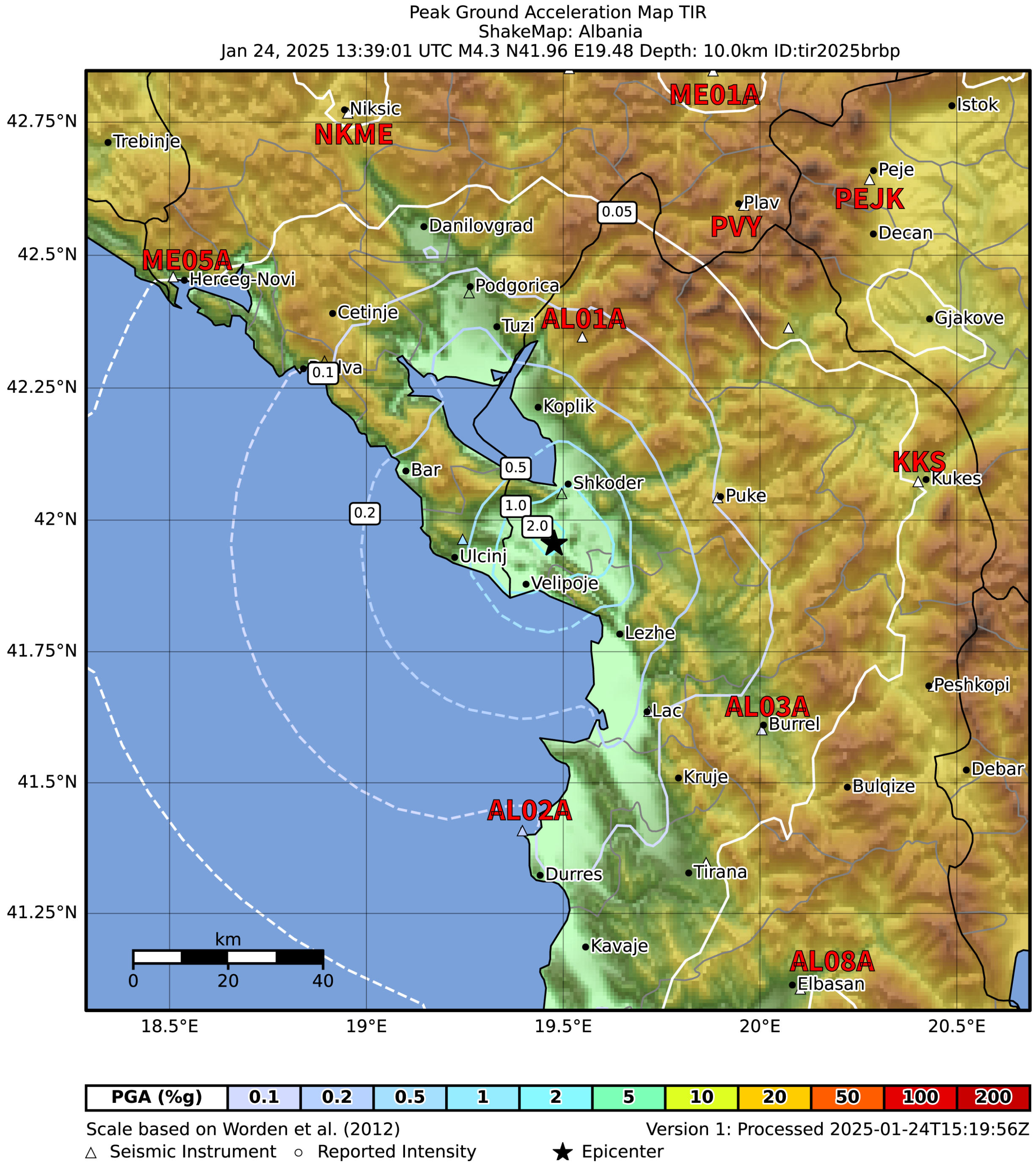


Figure 7. ShakeMap solutions were obtained in real time from the Albanian ANSMC using waveform data from the integrated seismic network, which includes permanent Albanian stations, regional seismic stations provided through cooperative data-exchange agreements, and DSEBRA stations deployed in Albania, Montenegro, and Kosovo.

of the seismic network in providing rapid and reliable information. The AdriaArray stations, particularly AL05A, AL02A, AL03A, and AL04A, played a crucial role in enhancing the accuracy of the shaking estimates, ensuring a more comprehensive representation of ground motion distribution.

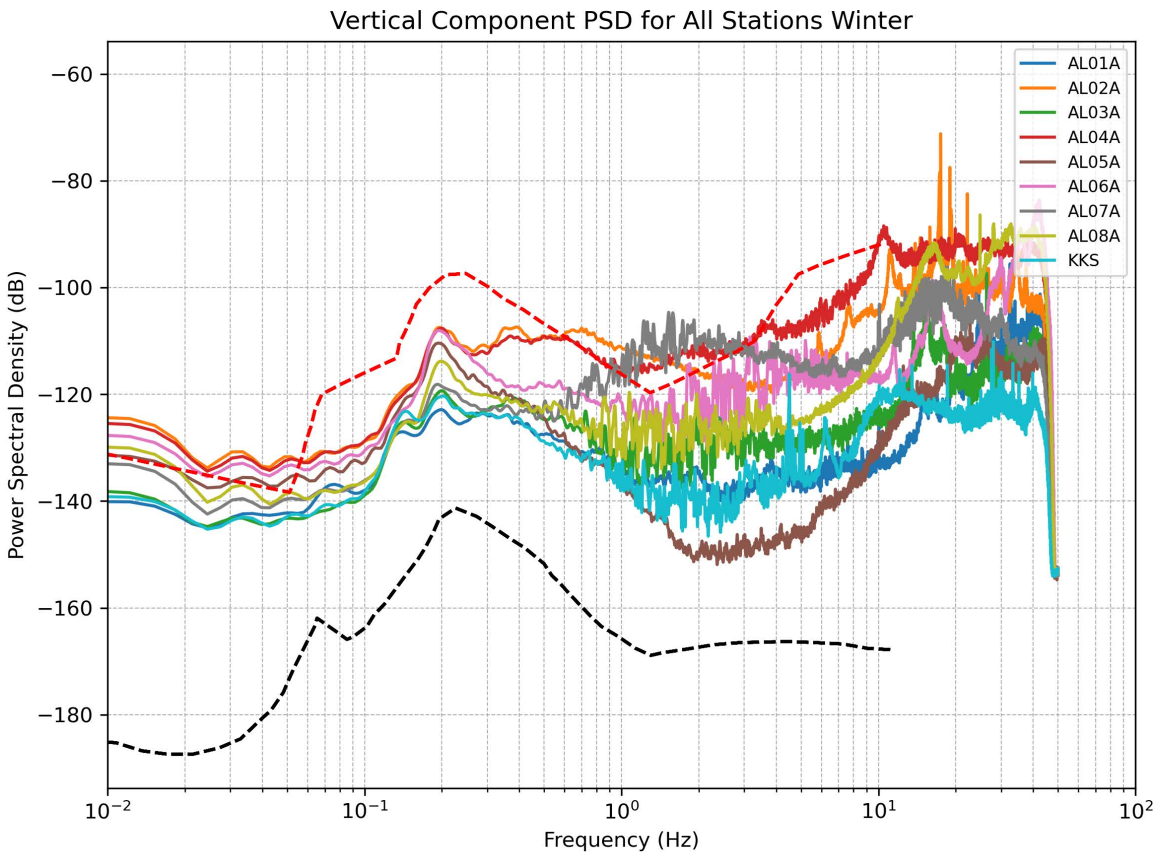
3. AdriaArray station performance, in Albania

3.1 PPSD analysis and Stations noise conditions

The Probabilistic Power Spectral Density (PPSD) method (McNamara and Buland, 2004; Peterson, 1993) was applied to evaluate the ambient seismic noise conditions at the DSEBRA broadband stations. Continuous waveform data from January 2023 to December 2024 were processed using the ObsPy PPSD implementation (Krischer et al., 2015). Preprocessing included detrending, demeaning, and applying a 5% cosine taper to each trace, followed by removal of the full instrument response (sensor and digitizer) to obtain ground velocity in physical units. Data gaps shorter than 10 s were interpolated, while records with longer gaps were excluded from the analysis. The corrected waveforms were segmented into 360 s windows with 50% overlap, Fourier-transformed, and smoothed using a 1/8-octave bandwidth. PPSD distributions were computed separately for the vertical (Z), north-south (N), and east-west (E) components, and compared against the New High Noise Model (NHNM) and New Low Noise Model (NLNM) benchmarks (Peterson, 1993). To explore seasonal variations, two representative days of the year were selected following Boese et al. (2015): the 61st day (early March, late winter/early spring) and the 214th day (early August, summer). For each station, percentile curves (5th, 50th, and 95th) were calculated for all available data and for the selected seasonal days (Fig. 8).

Results reveal clear site-to-site variability in noise levels, reflecting differences in geological setting, environmental exposure, and anthropogenic influence. Stations on bedrock or in remote-location settings (i.e., far from major urban centers, transportation corridors, industrial activity, or other significant noise sources-e.g., AL01A, AL05A, KKS) maintain noise levels well within the NHNM-NLNM bounds. AL01A shows stable spectra, with early March low-frequency (0.140.50 Hz) medians between-135.0 and-125.0 dB and minimal seasonal variation. AL05A exhibits similar stability, with both summer and early March levels rarely deviating by more than 5.0 dB from the NLNM in the microseism band. KKS maintains a consistently low noise floor, with horizontal-vertical differences below 5.0 dB across the DF microseism range. Moderately noisy stations display more evident seasonal shifts: AL03A presents median horizontal noise increases of ~10.0 dB at 0.20-0.33 Hz (3.0-5.0 s) during early March, reaching-120.0 dB; AL06A shows similar behaviour, with up to 8.0 dB seasonal changes in the same band; AL04A experiences high horizontal low-frequency noise, surpassing-115.0 dB in some intervals, and showing a consistent 5.0-10.0 dB horizontal-vertical difference in the DF range; AL07A follows a similar pattern, with amplified horizontal low-frequency components exceeding-110.0 dB in colder months.

Noisiest stations include AL02A and AL08A, both affected by strong environmental or anthropogenic noise. AL02A records early March low-frequency horizontal amplitudes exceeding-120.0 dB and summer high-frequency (>1.00 Hz) values surpassing-110.0 dB AL08A shows pronounced low-frequency variations, frequently breaching the NHNM in the 0.14-0.25 Hz band (4.0-7.0 s), with early March medians reaching-118.0 dB. Seasonal peak shifts are common across the network, with the dominant period moving from ~2.0 s (0.50 Hz) in summer to ~3.0 s (0.33 Hz) in early March, accompanied by amplitude variations from-130.0 to-120.0 dB. Stations on sedimentary sites (e.g., AL04A, AL07A) consistently record 5.0-10.0 dB stronger horizontal noise than vertical in the DF range, confirming microseism amplification by soft sediments, while coastal and urban stations (e.g., AL02A, AL04A, AL08A) show elevated noise above 1.00 Hz during summer, indicating strong anthropogenic influence.



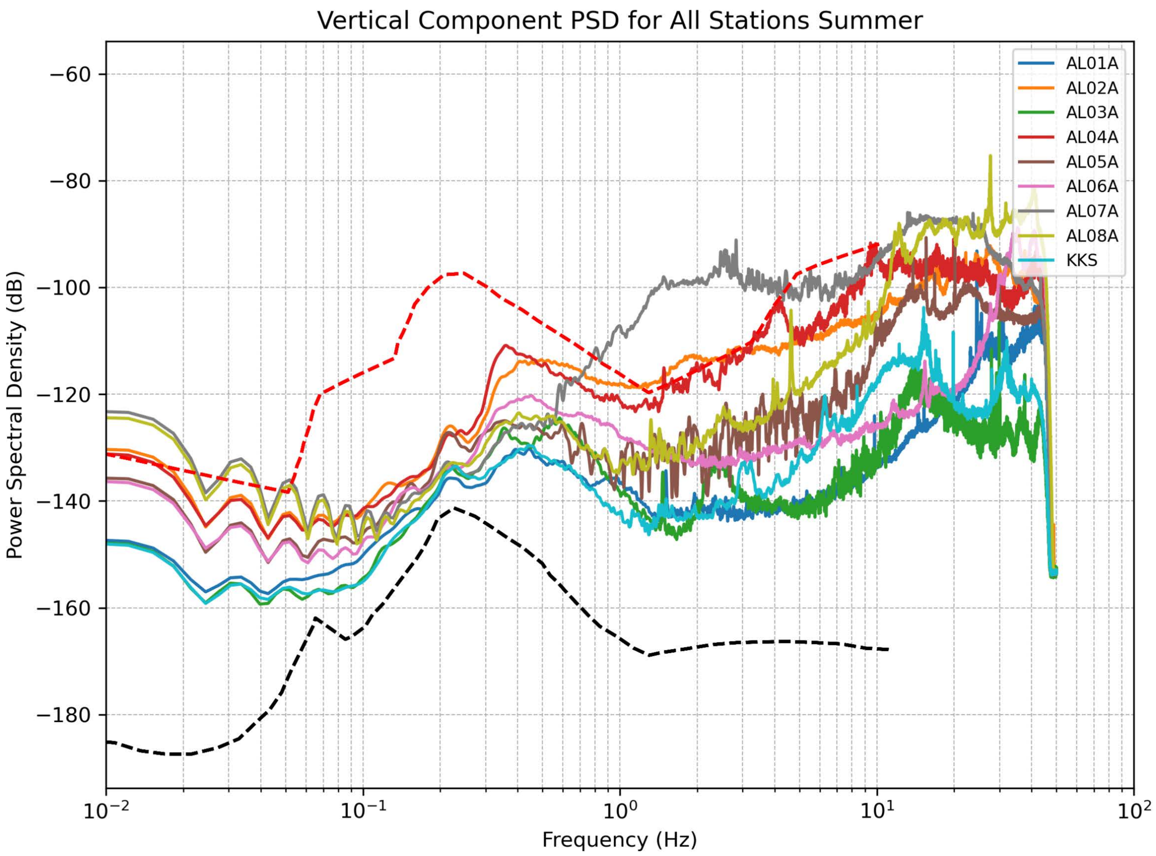


Figure 8. Probabilistic Power Spectral Density (PPSD) comparison for the vertical component of all stations. The upper plot corresponds to winter conditions, while the lower plot corresponds to summer conditions. The dotted curves represent the international reference models for seismic noise levels: Peterson's Low-Noise Model (LNM, black) and High-Noise Model (HNM, red).

3.2 Site effect

To assess the preliminary site and signal quality of the DSEBRA broadband seismic stations in Albania, the Horizontal-to-Vertical Spectral Ratio (HVSR) technique, originally introduced by Nakamura (1989), was applied. This method has been widely used to identify site resonance properties in seismology and has been applied in various seismic network studies (Gosar, 2017; Ávila-Barrientos and Castro, 2016). The analysis focused on determining the fundamental frequency (f_0) and amplification factor (A_0) of ambient seismic noise at each site, as indicators of potential site-effects. Measurements were performed at 04:00 and 22:00 local time to evaluate any influence of varying ambient noise conditions, particularly human-induced noise, on the HVSR results. These values were then applied to support the site classification based on the site geology (Aliaj et al., 2001; Xhomo et al., 2002; Bega and Soto, 2017; Muceku et al., 2021), to which the Vs_{30} range was assigned according to Eurocode 8 classification (Table 2).

Data processing of the ambient seismic noise records was carried out using the HVSRpy software (Vantassel, 2020), which implements the original Nakamura method in a fully scriptable Python workflow. This approach was preferred over GEOPSY (Wathelet, 2008) because it allows direct integration into Python-based seismic network processing routines, avoids GUI-based manual steps, and is better suited for operational stations where the aim is to evaluate preliminary signal quality rather than perform a full SESAME Project (2004)-compliant site characterization. GEOPSY offers advanced statistical analysis and standard-based classification following SESAME guidelines, but these were not the primary objectives of this study, as the sites are already installed and operational.

The HVSRpy preprocessing included detrending each trace by removing its mean value, applying 30 s time windows with a Tukey taper (0.01), and orienting the horizontal components to 0° from north. No bandpass filter was applied at this stage. The spectral analysis used Konno-Ohmachi smoothing (bandwidth = 40, dimensionless) to reduce spectral fluctuations while preserving sharp peaks. Center frequencies ranged from 0.2 to 50 Hz, spaced logarithmically (200 points). A frequency-domain window rejection procedure (n = 2) was applied to remove windows with unstable spectra. This configuration ensured stable HVSR curves for identifying f_0 and A_0 values relevant to operational station quality control and preliminary site response assessment.

Table 2. Characteristics for AdriaArray Stations in Albania.

Station	f_0 (Hz)	A_0 (Amplification)	Site Classification (EC8)	Vs30 (m/s)	Site Geology
AL01A	21.155	5.827	Class B (Stiff Soil/ Weathered Rock)	**360-800**	Pleistocene fluvioglacial deposits (Qp)
AL02A	4.73	3.56	Class B (Stiff Soil)	**360-800**	Tortonian (Miocene) deposits (N13t)
AL03A	12.15	6.07	Class B (Stiff Soil/ Weathered Rock)	**360-800**	Pliocene deposits (N2)
AL04A	0.62	3.93	Class C to D (Soft Soil)	**<180**	Lower Pliocene (Helmas Formation) deposits (N2-1h)
AL05A	20.577	6.362	Class B (Stiff Soil/ Weathered Rock)	**360-800**	Middle Eocene flysch (Pg22)
AL06A	11.71	4.64	Class A (Rock)	**>800**	Upper Cretaceous limestones (Cr2)
AL07A	0.53	5.38	Class D (Very Soft Soil)	**<180**	Pleistocene alluvial, proluvial, and lacustrine deposits (Qp)
AL08A	0.62	3.15	Class C to D (Soft Soil)	**<180**	Lower Oligocene flysch (Pg31)
KKS	9.22	3.90	Class A (Rock)	**>800**	Lower Cretaceous flysch (Cr1)

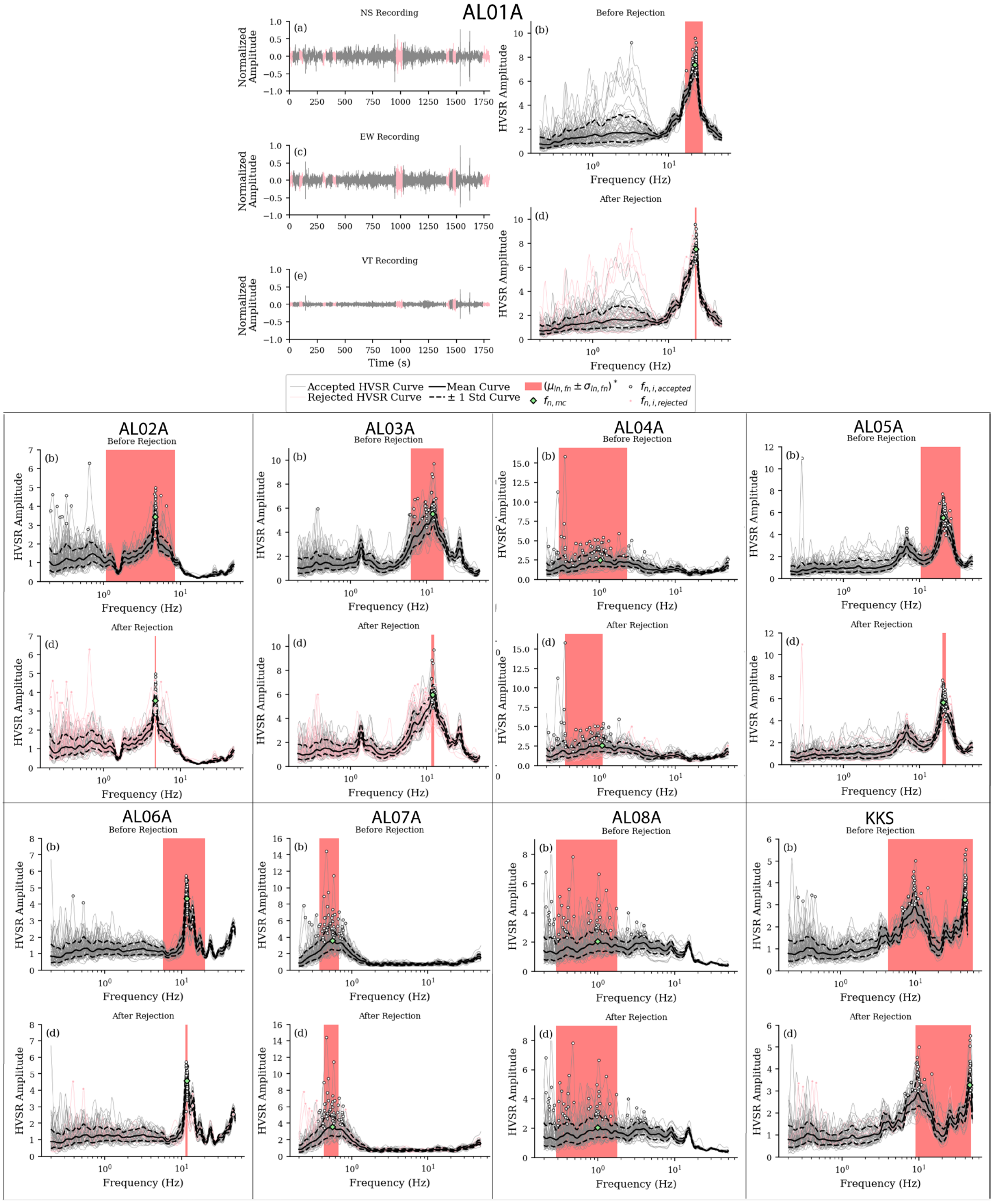


Figure 9. HVSR results for AdriaArray stations showing fundamental frequency (f_0) and amplification (A_0) for site classification. Station AL01A is shown in a zoomed, detailed layout to illustrate the full HVSRPy output (recordings and HVSR curves before/after rejection), while other stations are presented in a condensed format for comparison. Accepted curves are in black, rejected in gray, with the red band marking the frequency range for f_0 estimation.

The AdriaArray seismic stations in Albania are distributed across diverse geological settings (Fig. 10), which influence their expected seismic response characteristics. The observed amplification factors (A_0) and fundamental frequencies (f_0) (Table 2) are examined to identify potential dependency patterns between site resonance characteristics and the underlying geological formations. Stations located on soft soil deposits, such as AL07A and AL08A, tend to present higher amplification values ($A_0 > 4.0$), indicative of increased susceptibility to ground

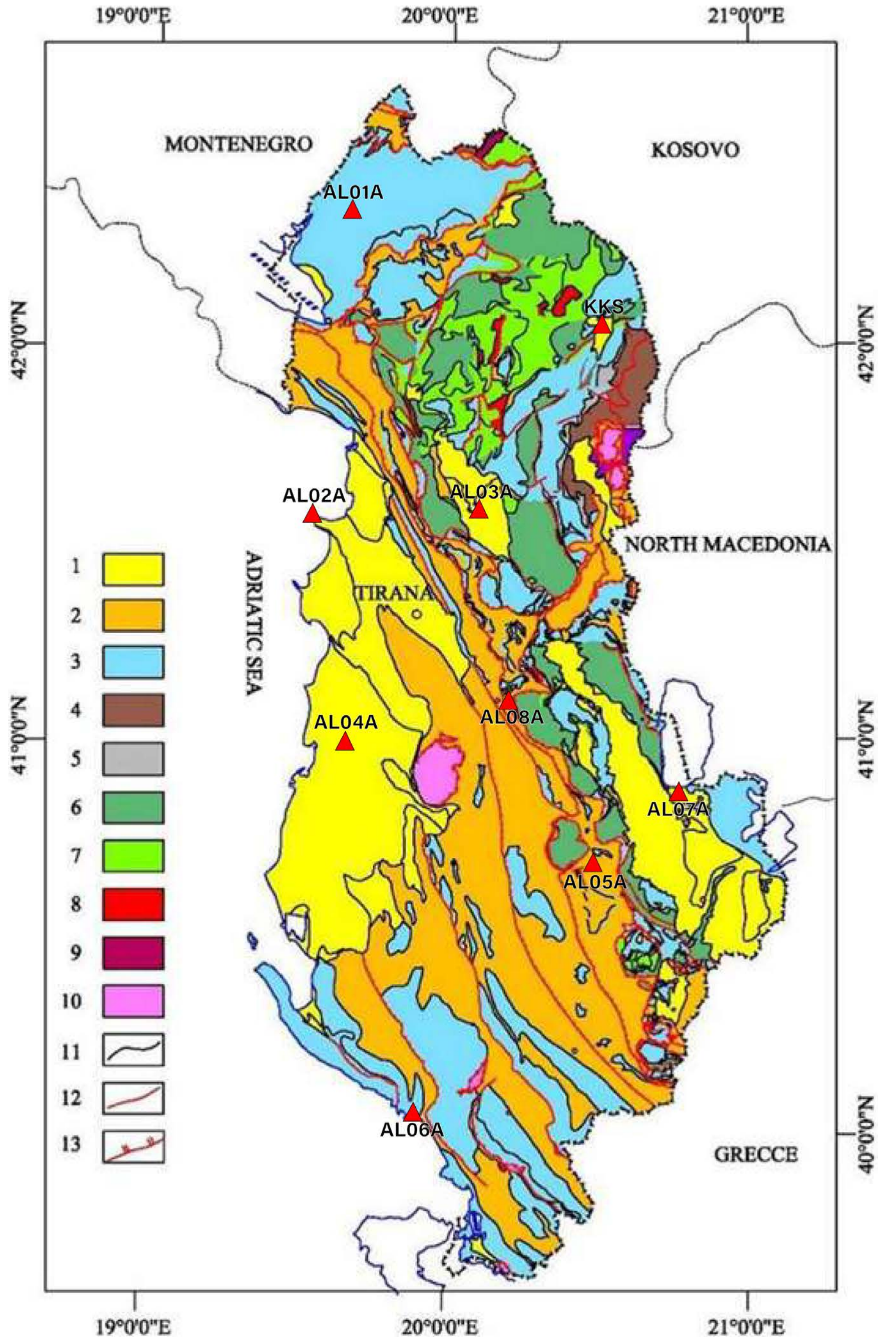


Figure 10. Geological classification of recording sites: (1) Molasse, (2) Flysch, (3) Limestone, (4) Shale, (5) Schist, (6) Intrusive rocks, (7) Volcanic rocks, (8) Plagiogranite, (9) Granite, (10) Gypsum. Structural features include: (11) Lithologic boundaries, (12) Tectonic faults, and (13) Thrust faults (Muceku et al., 2021). Seismic stations are represented by triangles with station codes.

motion amplification, whereas stations situated on rock formations, such as AL06A and KKS, generally exhibit low amplification values ($A_0 < 2.5$), consistent with Vs30 values assigned according to the Eurocode 8 classification for rock sites and with the reduced seismic wave amplification typical of this lithology. Moderate amplification ($2.5 \leq A_0 \leq 3.9$) is generally associated with stiff soil or weathered rock, while very high amplification ($A_0 > 6.0$), although rare, may occur at sites such as AL01A and AL05A where localized geological conditions enhance resonance effects. Rock sites are expected to present high f_0 values (>10 Hz) and low to moderate A_0 values (<4.0), although some stations, such as AL01A, AL03A, and AL05A, display unexpectedly high or very high A_0 values, suggesting possible localized amplification; conversely, soft soil sites typically present low f_0 values (<1.0 Hz) and high or very high A_0 values (>4.0), reflecting the enhanced seismic wave amplification potential of unconsolidated deposits.

To avoid ambiguity and ensure consistency with previous studies (SESAME, 2004; Parolai et al., 2004; Mucciarelli and Gallipoli, 2006), f_0 and A_0 were classified using explicit numeric thresholds tailored to this dataset. For f_0, values below 1.0 Hz (low) indicate thicker or deeper soft sediments, values between 1.0 and 10 Hz (intermediate) represent transitional impedance contrasts, and values above 10 Hz (high) correspond to shallower, stiffer layers or weathered rock. For A_0, values below 2.5 are considered low, between 2.5 and 3.9 moderate, between 4.0 and 6.0 high, and above 6.0 very high. The range of f_0 values provides further insight into the resonance behavior of each site: high values (>10 Hz), as observed at AL01A and AL05A, indicate a shallow impedance contrast typical of stiffer soil or weathered rock; intermediate values (1.0-10 Hz) correspond to transitional site conditions; and low values (<1.0 Hz), such as those found at AL04A and AL07A, suggest thicker sedimentary sequences capable of prolonging earthquake shaking.

Site classification followed Eurocode 8 (EC8) Vs30 bins: Class A (rock, Vs30 > 800 m/s), Class B (stiff soil/weathered rock, 360-800 m/s), Class C (soft soil, 180-360 m/s), and Class D (very soft soil, <180 m/s). The classification in Table 2 integrates geological formations and HVSR parameters (Fig. 9) to characterize site conditions, enabling a clear distinction between rock and stiff soil sites and soft sedimentary environments. These results support the use of HVSR-derived parameters as a first-order site characterization tool, to be complemented by direct geophysical surveys to refine the representative Vs30 (m/s) values, which is currently in progress.

3.3 Travel Times Residuals and Data Quality Assessment

Following the analysis of site effects using HVSR and geological data, as well as the evaluation of noise characteristics through PPSD, we examines travel time residuals to assess the performance of the AdriaArray broadband stations in Albania. The analysis is based on parametric data accumulated since their installation, with a focus on evaluating station accuracy, velocity model consistency, and site-specific biases. Given that the DSEBRA stations are integrated into the routine processing of the Albanian Seismological Network (AC), their travel time residuals provide essential insight into waveform consistency and potential deviations linked to site conditions, instrumentation, and regional wave propagation effects.

The dataset consists of seismic events recorded since the deployment of AdriaArray stations in Albania, processed under routine procedures used for national and regional seismic monitoring. The impact of network densification is assessed by examining residual distributions in relation to stations, geological setting, and noise conditions. The uniform instrumentation across all stations enables direct comparison of travel time residuals, minimizing potential discrepancies caused by sensor variability. In addition to improving event detection and location accuracy, the integration of these stations provides valuable data for refining seismic velocity models, particularly in regions of complex tectonic structure such as the Dinarides-Hellenides transition through the Albanides (Dushi and Havskov, 2023).

Travel time residuals were analyzed using the TTPLOT routine in SEISAN (Havskov et al., 2021), evaluating residuals as a function of time, distance, and magnitude (Fig. 11).

The results indicate that stations installed on stable bedrock formations yield well-constrained residuals, suggesting a lower degree of site-related phase arrival perturbation. Stations AL01A (Razëm), AL03A (Komsi), AL05A (Moglicë), AL07A (Pogradec), and KKS (Kukës) exhibit narrow residual distributions across event distances and magnitudes, reinforcing their reliability for seismic phase arrival analysis. The consistent travel time behavior at these sites confirms their suitability for regional seismic studies, particularly in refining wave propagation characteristics and velocity model adjustments.

Conversely, stations located in urban, infrastructural, or soft sedimentary environments, such as AL04A (Divjakë), AL06A (Himarë), and AL08A (Elbasan), exhibit greater scatter (Lin et al., 2010) in residuals, particularly for lower-magnitude events. This variability suggests increased susceptibility to localized site effects and anthropogenic noise, which can affect waveform clarity and phase picking accuracy. Despite these site-induced variations, residuals for larger-magnitude events remain consistent, indicating that the instrumentation and processing methodologies effectively mitigate external disturbances when signal amplitudes are sufficiently high.

Station AL02A (Kepi i Palit), situated near a military base, presents a distinct case where controlled access and a coastal setting introduce specific operational conditions. While minor residual variations are observed as a function of distance, overall data quality remains high, benefitting from effective noise control measures.

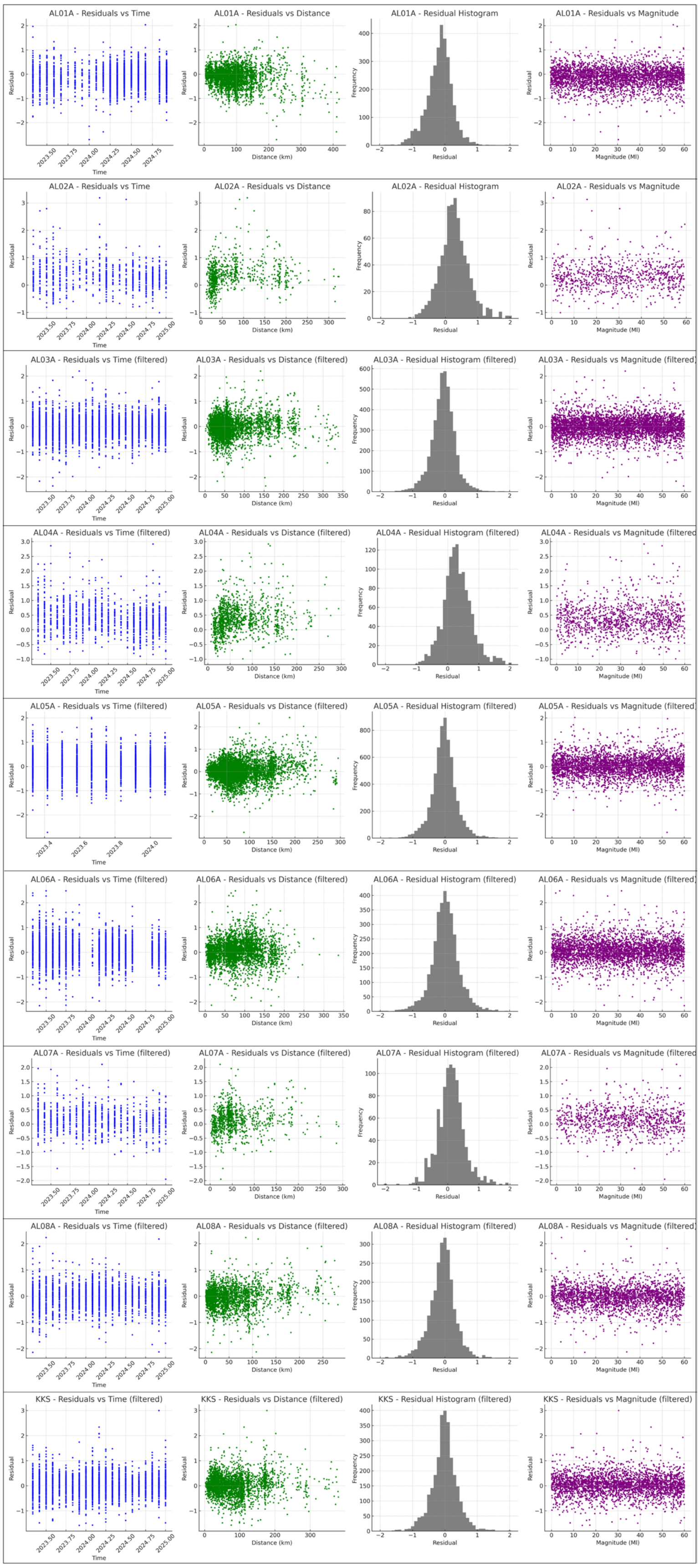


Figure 11. Data statistical quality check for the AdriaArray temporary seismic stations installed across Albania, showing the variation of the travel time residuals, picked automatically and double checked manually, with time, distance and magnitude, as well as their most probable occurrence, from the frequency distribution histogram, correspondingly for each of the AL01A to AL08A seismic stations.

Temporal analysis of residuals across all stations reveals no systematic biases, indicating stable operation and well-maintained instrumentation throughout the deployment period. Distance-dependent residual distributions suggest that the velocity model used for routine processing aligns well with regional wave propagation characteristics, particularly at bedrock sites (Dushi and Havskov, 2023). Magnitude-based analysis further confirms that larger seismic events produce well-constrained residuals across all stations, whereas smaller events exhibit increased scatter, particularly at sites with significant anthropogenic influence.

The results highlight the critical role of site conditions in determining station performance. Stations installed on bedrock or in isolated regions, such as AL01A, AL03A, AL05A, AL07A, and KKS, maintain stable residual distributions, whereas those in urban and soft sedimentary environments show increased variability due to site effects. Nonetheless, all AdriaArray stations in Albania demonstrate overall satisfactory performance, supporting their integration into regional seismic monitoring and data processing workflows.

The results, although time limited and preliminary, confirm that the broadband stations contribute to the quality and resolution of seismic observations in Albania. Further refinements, particularly in noise mitigation at urban sites and velocity model optimization, are necessary to enhance network performance.

4. Discussion and outlook

This work reflects the IGEO's active contribution during the deployment campaign of the DSEBRA broadband seismic stations in Albania, within the AdriaArray initiative. It further describes the new station integration and operation with the Albanian Seismological Network (AC), providing enhanced coverage also for local and regional seismic monitoring. A post-installation quality check is presented, following well-accepted procedures that combine analyses of site conditions, seismic noise level, and travel time residuals. Techniques such as HVSR and PPSD were employed to obtain insights into station-specific performance, network-wide patterns, and the potential for iterative improvements. The recording and overall data quality of the DSEBRA stations deployed in Albania are notably influenced by local site effects. Analysis using the HVSR-based site characterization method described in subsection 3.1, implemented with the HVSRPy routine, revealed a consistent relationship between the measured amplification factors (A_0), fundamental frequencies (f_0), and the underlying geological conditions. Stations located on soft soil deposits, such as AL07A and AL08A, displayed high to very high amplification values (A_0 between 4.2 and 6.8) and low fundamental frequencies (f_0 between 0.7 and 0.9 Hz), indicative of thick unconsolidated sediments with a high potential for seismic wave amplification. In contrast, stations installed on rock formations, including AL06A and KKS, showed low amplification factors (A_0 between 1.8 and 2.3) and high fundamental frequencies (f_0 between 10.5 and 12.4 Hz), consistent with high near-surface shear-wave velocities and reduced susceptibility to ground motion amplification.

Intermediate conditions were observed at stations underlain by stiff soils or weathered rock, where A_0 values ranged from 2.6 to 3.8 and f_0 values from 2.5 to 7.8 Hz, reflecting transitional impedance contrasts. However, certain stations classified geologically as stiff soil or rock, such as AL01A, AL03A, and AL05A, exhibited unexpectedly high amplification factors (A_0 between 4.5 and 5.7) despite higher fundamental frequencies, suggesting localized variations such as weathered bedrock layers or thin surficial sedimentary deposits enhancing resonance effects. These results are in agreement with the Eurocode 8 site classification based on Vs30 values, where Class A (rock) and Class B (stiff soil/weathered rock) correspond to higher f_0 and lower A_0, while Class C and D sites are associated with lower f_0 and higher A_0.

Overall, the observed distribution of A_0 and f_0 values across the network supports the classification derived from geological mapping and Vs30 estimates, confirming the sensitivity of site response to local subsurface conditions. These findings underline the importance of incorporating direct on-site geophysical surveys to refine Vs30 measurements at each station, thereby improving the accuracy of site effect estimates and ensuring high-quality data for subsequent scientific analyses within the AdriaArray initiative.

The PPSD results show that noise performance across the DSEBRA network is strongly controlled by geology, distance from noise sources, and environmental forcing. Remote bedrock stations such as AL01A, AL05A, and KKS offer the quietest conditions, with medians well within the NHNM-NLNM range throughout the year and only minor seasonal fluctuations, likely related to atmospheric or microclimatic variations. Seasonal modulation of the double-frequency (DF) microseisms is clearly expressed in several stations, with shorter-period peaks (~1.5-3.0 s; 0.33-0.67 Hz) tied to the Ionian Sea and longer-period peaks (~4.0-7.0 s; 0.14-0.25 Hz) linked to more distant sources such as the North Sea (Longuet-Higgins, 1950; Hasselmann, 1963; Schlömer et al., 2025). Coastal and near-coastal sites respond more strongly to these seasonal changes, reflecting the enhanced coupling of oceanic swell energy during storm seasons.

Stations on soft sediments, particularly AL04A and AL07A, exhibit marked amplification of DF microseisms, consistent with established site-effect observations (SESAME, 2004; Mucciarelli and Gallipoli, 2006), while urban and coastal stations such as AL02A and AL08A show sustained high-frequency noise during summer, reflecting the influence of human activity. These patterns align with regional trends reported by Schlömer et al. (2025) for the AdriaArray network and highlight the importance of considering both natural and anthropogenic noise sources when evaluating station performance. Improving vault shielding, introducing physical barriers, or optimizing station siting within the same geological unit could mitigate dominant noise sources, particularly for the noisiest sites (Zürn et al., 2007).

Travel time residuals across the stations highlight the compatibility of the current velocity model (Dushi and Havskov, 2023) with observed seismic wave propagation. Stations in geologically stable or remote settings (e.g., AL01A, AL03A, AL05A, AL07A, KKS) exhibit tightly distributed residuals, as well described in Section 3.3, underscoring good-quality data acquisition and strong parametric reliability. In contrast, urban, infrastructural, and soft-soil sites (e.g., AL04A, AL06A, AL08A) show greater scatter at smaller magnitudes, likely tied to ambient noise, but remain consistent at larger magnitudes, suggesting robust instrumentation and effective data processing. Notably, the AL08A station shows increased scattering in low-magnitude arrivals, which is not solely attributed to path effects in soft sediments, but also to high background noise conditions that reduce STA/LTA contrast, increasing the chance of mis-picking or undetected onsets. Despite this, residuals for moderate-to-large events remain tightly grouped, confirming the robustness of performance at AL08A and other similar sites. The temporal stability of residuals across all stations indicates well-maintained equipment and no systematic biases, while distance-dependent patterns confirm that the velocity model adequately reflects regional structure. One of the most important scientific contributions, aligning with the AdriaArray objectives, is the application of newly acquired waveform data to produce reliable, well-distributed, and high-quality moment tensor (MT) solutions. The DSEBRA stations in Albania provided usable waveform data for 82 out of 105 high-quality MT events, corresponding to 187 out of 289 analyzed earthquakes within Albanian territory. In these cases, DSEBRA waveforms met the quality criteria for inclusion in the inversion process. Station-specific participation varied, with AL05A, AL08A, and AL07A standing out in both the number of total and high-quality solutions, contributing respectively to 73 events (27 high-quality), 95 events (29 high-quality), and 77 events (25 high-quality). In addition, combined stations in Kosovo and Montenegro contributed to 305 regional MT inversions, of which 57 were classified as high quality, thereby reinforcing the significance of cross-border collaboration for AdriaArray deployments.Overall, DSEBRA's integration with the AC has yielded valuable gains in seismic monitoring coverage and data quality, ensuring improved resolution of seismic wavefields and more accurate characterization of seismic events in Albania and the broader Adria region. Nonetheless, further refinements are warranted. Stations with persistently high anthropogenic or seasonal noise may benefit from additional mitigation strategies, such as improved shielding or site relocation, while velocity models can be refined by incorporating updated near-surface constraints and inter-station correlations. Given the success of joint deployments in Albania, Kosovo, and Montenegro, continued regional collaboration under the AdriaArray umbrella remains pivotal for advancing research on the geodynamics, active tectonics and seismicity of the Adria region, refining event location accuracy, and deepening our understanding of the complex tectonic regime, especially in the Balkan area.

5. Conclusions

Our study evaluates the operational performance and data quality of the broadband seismic stations deployed in Albania under the AdriaArray initiative. The integration of DSEBRA stations into the Albanian Seismological Network (AC) has improved seismic monitoring, enhancing event detection and characterization. Key findings highlight the following:

- Local geology strongly influences station performance. Soft sediment sites exhibit larger wave amplification, while bedrock stations provide more stable recordings. Direct Vs30 measurements are recommended to refine site classifications and improve site characterization.

- Seasonal and environmental factors affect noise levels, with bedrock sites maintaining lower noise floors and urban/coastal stations experiencing higher low-frequency noise in winter. Patterns in DF microseisms align with previous studies, confirming ocean wave influences, while anthropogenic noise is more pronounced in summer.
- Stations on stable geological formations show well-clustered travel time residuals, contributing to accurate phase arrival times and robust velocity model calibration. Urban and soft-soil sites exhibit greater residual scatter, particularly for smaller magnitudes, but remain stable for larger events. The newly installed stations have enhanced waveform resolution and improved moment tensor solutions, contributing to higher-quality source parameter estimations within the AdriaArray initiative.
- Stations such as AL01A (Razëm), AL03A (Komsi), AL05A (Moglicë), AL07A (Pogradec), and KKS (Kukësi) demonstrate stable performance and high data reliability, benefiting from favorable site conditions. In contrast, AL02A (Kepi i Palit), AL04A (Divjakë), AL06A (Himarë), and AL08A (Elbasan) are more affected by anthropogenic noise and environmental factors. Additional shielding, improved noise mitigation strategies, or site adjustments could enhance data quality at these locations.

These findings provide benchmarks for the continued optimization of the AdriaArray deployment, ensuring high-quality data acquisition and reliable seismic observations.

Data availability statement. Data can be downloaded at: https://instituteofgeosciencesalban-my.sharepoint.com/:f:/g/personal/b_rama_geo_edu_al/Ek54fdx08IBIj7T6dA42A9QBdWMTjzq2PG3l3f0Go8BtZg?e=dA9Tq0.

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