MULTI-PROBE ANALYSIS OF THE MARINE SOUNDSCAPE: APPROACHES AND RESULTS FROM THE VONGOLA PROJECT

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Abstract

The VONGOLA project (Visual and nOise-eNhanced AI Analysis for Marine Biodiversity MonitorinG, Observation and LeArning), led by CSFNSM, developed approaches for monitoring biodiversity and evaluating human interference in marine ecosystems. A monitoring network integrated technologies for deep-sea and shallow-water environments. One task enabled the first permanent Distributed Acoustic Sensing (DAS) system in the Mediterranean Sea, operated off Catania through an INFN-LNS electro-optical cable. Another task established two shallow-water multi-probe observatories: a cabled station at NOEL in the Messina Strait and an autonomous station in the Plemmirio Marine Protected Area. This contribution presents an overview of the VONGOLA network and its capability for analysis of the marine soundscape. NOEL observations acquired between July and September 2025 show recurrent day–night variability, with higher and more variable low-frequency levels during daytime, compatible with stronger anthropogenic activity, and a more regular high-frequency enhancement during night-time, compatible with biological activity. The comparison between July and September reveals an increase of up to 8 dB in the upper part of the analyzed spectrum. Although its origin cannot be attributed to a single source, this trend demonstrates the value of continuous monitoring for detecting changes in coastal acoustic conditions and supporting assessments of acoustic Good Environmental Status.

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1. Introduction

The marine soundscape is composed of signals produced by biological activity, human operations and geophysical processes. Its description is fundamental for monitoring marine ecosystems and for evaluating the effects of anthropogenic noise on marine life. Commercial shipping represents one of the main sources of continuous low-frequency underwater noise, generated by engines, onboard machinery, propellers and cavitation [1], [2]. Biological sources include sounds produced by marine invertebrates and cetaceans, including dolphins and sperm whales. Fin whales (*Balaenoptera physalus*) produce characteristic low-frequency calls around 20 Hz [3]. Earthquakes and other geophysical phenomena can also generate signals that propagate over large marine areas and interact with submarine infrastructures [4], [5], [6].

Passive Acoustic Monitoring (PAM) provides a non-invasive approach for observing the underwater acoustic environment over extended periods.

The environmental relevance of underwater-noise monitoring is recognised by Descriptor 11 of the European Marine Strategy Framework Directive. In particular, European monitoring guidelines consider continuous low-frequency anthropogenic noise, including the 1/3-octave bands centred at 63 and 125 Hz [7], [8].

Within this framework, the VONGOLA project (Visual and nOise-eNhanced AI Analysis for Marine Biodiversity MonitorinG, Observation and LeArning) was developed to integrate complementary observations acquired at different spatial scales and under different deployment conditions [9], [10]. The project combines

fixed-point acoustic measurements, distributed fibre sensing and contextual information to support the interpretation of biological, anthropogenic and geophysical contributions to marine soundscapes. Processed acoustic products are organised through harmonised procedures and integrated into the ITINERIS Ocean Sound infrastructure [11].
This contribution describes the VONGOLA monitoring and processing framework and presents the NOEL station as a preliminary case study. The aim is to show how multi-day calibrated SPL products can reveal recurrent day–night variability and changes in coastal acoustic conditions, while providing a basis for future comparisons among monitoring sites.

2. The VONGOLA Multi-Site and Multi-Probe Monitoring Network

The VONGOLA project (Visual and nOise-eNhanced AI Analysis for Marine Biodiversity MonitorinG, Observation and LeArning), coordinated by the Centro Siciliano di Fisica Nucleare e di Struttura della Materia (CSFNSM) within the framework of PNRR-funded initiatives, aims to develop innovative techniques for monitoring marine biodiversity and assessing anthropogenic impacts on marine ecosystems. Particular attention is devoted to underwater noise pollution and to the observation of signals of biological, anthropogenic and geophysical origin. To address these objectives, the project combines artificial intelligence methods, acoustic sensing technologies, underwater video observations and multiparametric monitoring systems [9], [10].
The VONGOLA monitoring framework is organised as a multi-site and multi-probe network extending from coastal environments to the deep sea. It combines fixed-point acoustic-pressure measurements acquired by conventional hydrophones with spatially distributed strain measurements obtained through Distributed Acoustic Sensing (DAS). Visual systems, environmental probes and AIS receivers provide complementary information for interpreting biological, anthropogenic and geophysical acoustic events. The main installations considered in this contribution are located along the eastern coast of Sicily and are shown schematically in Fig. 1. A network of AIS receiving stations covering the Western Ionian Sea complements the acoustic monitoring systems by providing vessel positions, trajectories and navigation information. When temporally aligned with the acoustic observations, these data can support the association of detected signals with individual vessel passages and the investigation of ship-related contributions to the marine soundscape. An example of the available vessel-traffic information is shown in Fig. 2.

2.1. Shallow-Water Multi-Probe Observatories

Two shallow-water observatories were developed within VONGOLA to extend the monitoring activity to coastal environments: the cabled NOEL station in the Strait of Messina and the autonomous station deployed in the Plemmirio Marine Protected Area. Both observatories are equipped with an Ocean Sonics icListen hydrophone, a visual monitoring system and an environmental probe. Their acquisition and data-management strategies differ according to the characteristics of their deployment sites [10].

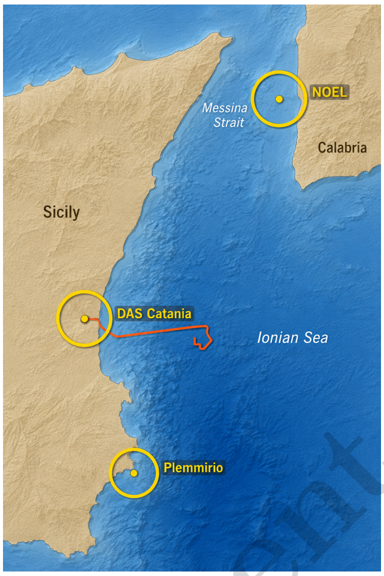

Figure 1: Schematic geographical overview of the main VONGOLA monitoring sites along the eastern coast of Sicily.

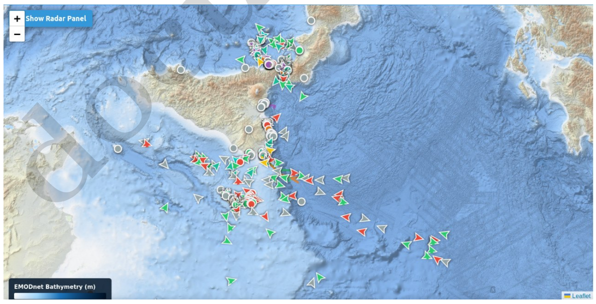

Figure 2: Snapshot of the AIS monitoring interface covering the maritime area around Sicily, displayed over an EMODnet bathymetric basemap. The symbols indicate AIS-reported vessel positions and approximate headings.

2.1.1. NOEL cabled station

The NOEL observatory was deployed at the Natural Ocean Engineering Laboratory in the Strait of Messina as the first cabled hydrophone station installed in the area. The station was connected to shore through a combined power-and-Ethernet cable, enabling continuous power supply, remote control and access to the acquired data. The underwater station was built around a protective sphere housing the control computer, the Ethernet communication system and the electronics required to operate the external instruments [10].
The main acoustic sensor was an Ocean Sonics icListen high-frequency hydrophone. The hydrophone gener-

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ated `.wav` and `.txt` files, divided into three-minute segments per hour. Completed files were transferred through an SSH connection to the shore computer for storage and subsequent processing.

A Raspberry Pi 3B+ acted as the local control unit and operated as an HTTP server through software automatically launched at system start-up. It managed the power state of the instruments and handled communication with the environmental setup. An internal Ethernet switch connected the Raspberry Pi, the hydrophone and an IP camera, allowing the different components to be remotely accessed through the cabled network.

Visual observations were provided by a Tapo C202 IP camera, which transmitted a real-time RTSP video stream and supported periodic video recordings.

The original configuration also included an Idronaut multiparametric CTD probe for monitoring the main physical and chemical properties of the water column. The measurements were acquired through the Raspberry Pi and transferred to the shore-based monitoring system. Following the initial monitoring campaign, the station was recovered and is currently being upgraded by replacing the CTD acquisition chain with a sound velocimeter. The upgraded configuration is intended to provide direct sound-speed measurements for the interpretation of acoustic propagation and signal arrival times.

2.1.2. Plemmirio autonomous station

The second observatory was deployed in the Plemmirio Marine Protected Area, where the environmental conditions did not allow the deployment of a permanent cabled connection. This station therefore operated autonomously using internal batteries and local storage. Acoustic, visual and environmental data were recorded according to predefined acquisition cycles and retrieved after recovery of the observatory.

2.2. Distributed Acoustic Sensing System

Within the VONGOLA project, a Distributed Acoustic Sensing (DAS) interrogator was installed on the INFN-LNS submarine optical-fibre infrastructure offshore Catania, providing spatially distributed observations along the submarine cable [9], [10]. Further details on the DAS system are reported by Idrissi et al. [12].

3. Data Processing and Preliminary Observations

Hydrophone recordings acquired within the VONGOLA network are processed through a workflow in order to produce calibrated and standardized acoustic data. Raw hydrophone data are first converted into calibrated `SIG.h5` files, where the pressure time series is stored in μPa together with station metadata such as sampling rate, hydrophone sensitivity, ADC parameters, deployment information and geographic position.

The calibrated signals are then processed separately for the low-frequency and high-frequency ranges. Power spectral density (PSD) spectrograms are computed using Hamming-windowed FFT segments with 50% overlap, while SPL values, expressed in dB re 1 μPa, are obtained by integrating the spectral energy over 1/3-octave bands. For each recording, the workflow produces PSD spectrograms together with band-wise SPL statistics, including the mean and selected percentiles [13]. The resulting products are saved in HDF5 files with standardized metadata and are integrated into the ITINERIS Ocean Sound data infrastructure, where they are made accessible through the INFN-LNS ERDDAP server [11].

3.1. NOEL Case Study: Temporal and Spectral Soundscape Variability

As a preliminary case study, the analysis focuses on a selected subset of the SPL products acquired at the NOEL station between July and September 2025. The case study is organised into two complementary analyses. The first investigates recurrent day–night variability in selected low-frequency (LF) and high-frequency (HF) ranges, with particular attention to daytime anthropogenic contributions and night-time biological activity. The second compares the spectral SPL distributions measured in July and September to identify changes in the acoustic conditions of the site over the observation period.

For each valid recording, SPL values in the selected frequency range were summed on a linear-energy scale at each time step, and the median over time was then calculated. The resulting value was assigned to the corresponding acquisition date and local hour. The analysis considered the 63–800 Hz range for the LF contribution and the 4–80 kHz range for the HF contribution. Local sunrise and sunset times were superimposed to support the interpretation of the resulting day–night patterns. The LF and HF distributions are shown separately in Figs. 3 and 4.

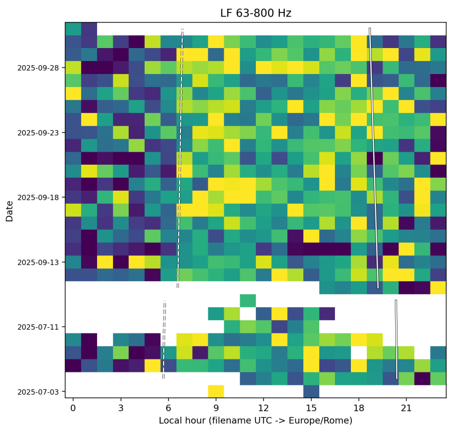

Figure 3: Day–night variability of the band-integrated SPL measured at NOEL between July and September 2025 in the 63–800 Hz LF range. Median values are shown as a function of acquisition date and local hour. Local sunrise and sunset times are superimposed, while white cells correspond to unavailable data.

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Figure 3 shows generally higher and more variable LF levels during daytime hours. This behaviour is compatible with stronger contributions from vessel traffic and other local anthropogenic activities during the day, although individual acoustic events were not associated with specific sources in this analysis.

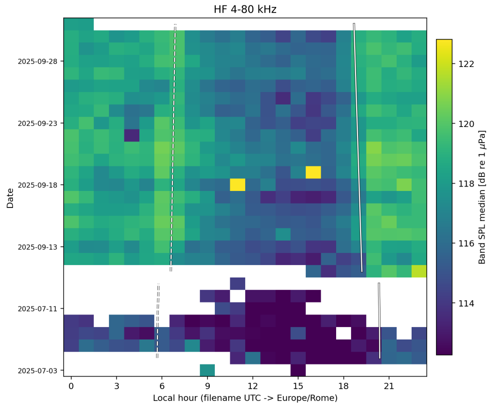

Figure 4: Day–night variability of the band-integrated SPL measured at NOEL between July and September 2025 in the 4–80 kHz HF range. Median values are shown as a function of acquisition date and local hour. Local sunrise and sunset times are superimposed, while white cells correspond to unavailable data.

The HF distribution in Fig. 4 exhibits a more regular enhancement during night-time hours and around the transitions between daylight and darkness. This pattern is compatible with biological acoustic activity, including sounds produced by snapping shrimps.

A second analysis compared the SPL spectra recorded in July and September. First, each valid recording was reduced to a single spectrum by calculating the median SPL over time for every 1/3-octave band. The resulting spectra were then separated by month. For each frequency band, the median across all recordings was calculated separately for July and September, together with the interval between the 25th and 75th percentiles. The resulting monthly spectral distributions are shown in Fig. 5.

The median spectra of the analysed July and September subsets are nearly coincident up to approximately 5 kHz. A divergence begins to emerge at approximately 6.3 kHz and becomes progressively more pronounced above 8–10 kHz.

Railway works were known to have taken place at the nearby railway station, located only a few hundred metres from the NOEL observatory, during the observation period. Although these activities represent a plausible local anthropogenic contribution to the observed increase, their temporal overlap with the analysed acoustic intervals could not be verified. Other possible factors include variations in biological activity, meteorological conditions and additional local anthropogenic sources. The result is therefore interpreted as evidence of a change in the acoustic conditions of the site between July and September.

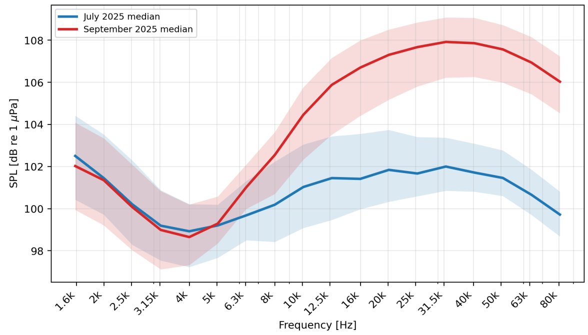

Figure 5: Comparison of the NOEL SPL spectra for July and September 2025 over the 1.6–80 kHz range. The July and September subsets include 93 and 466 valid recordings, respectively, distributed over 8 acquisition days in July and 20 acquisition days in September. For each 1/3-octave band, solid lines show the monthly median across valid recordings, after calculating the temporal median within each recording. Shaded regions indicate the corresponding 25th–75th percentile range.

Although the observed increase is limited to approximately 8 dB, its coherent development across several adjacent high-frequency bands highlights the importance of continuous acoustic monitoring for detecting moderate changes in coastal soundscape conditions. Long-term observations are necessary to distinguish persistent trends from short-term variability and to support the assessment of acoustic Good Environmental Status (GES).

For comparison with the NOEL results, a preliminary spectral reference was also derived for the Plemmirio autonomous station. The available dataset consists of nine paired LF and HF intervals acquired on 1 October 2025 between 14:30 and 18:35 local time. For each interval, the temporal median SPL was calculated separately in each 1/3-octave band, and the median and interquartile range were then evaluated across the nine intervals. As shown in Fig. 6, the LF product covers the 16–800 Hz range, whereas the HF product is presented from 1 to 64 kHz.

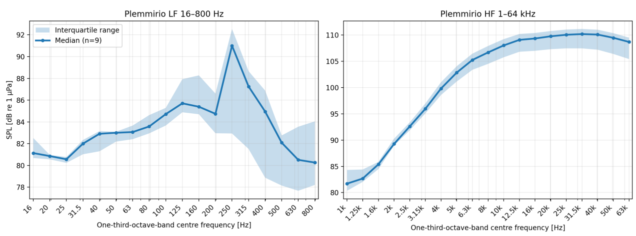

Figure 6: Preliminary spectral SPL distributions obtained at the Plemmirio autonomous station from nine intervals acquired on 1 October 2025. For each interval, the temporal median was calculated in every 1/3-octave band. Solid lines show the median across the available intervals, while shaded regions indicate the corresponding interquartile range. The LF and HF products are shown over 16–800 Hz and 1–64 kHz, respectively.

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Limited by the limited temporal coverage, the resulting spectra provide a preliminary descriptive reference for Plemmirio rather than a temporal characterisation equivalent to the multi-day NOEL analysis.
Figure 7 compares two time–frequency maps of 1/3-octave-band SPL obtained from acquisitions recorded at the same local hour, one in July and one in September. The latter shows higher SPL values above approximately 8 kHz, consistent with the monthly spectral distributions shown in Fig. 5.

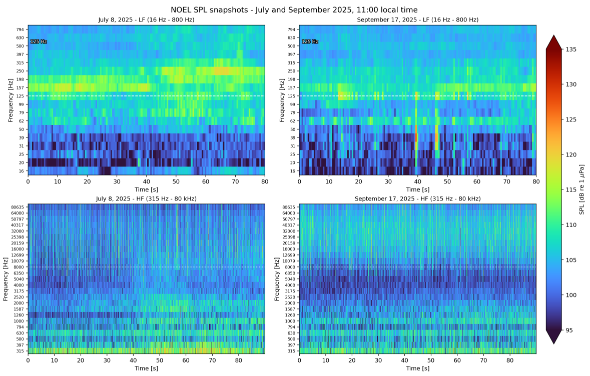

Figure 7: Time–frequency maps of the 1/3-octave-band SPL acquired at NOEL on 8 July and 17 September 2025 at approximately 11:00 local time. The LF and HF products are displayed using the same SPL colour scale.

Another acquisition showing features compatible with ship-related acoustic contributions is presented in Fig. 8. The LF map shows a persistent enhancement in the 1/3-octave band centred at 125 Hz. Additional time–frequency structures are visible in the HF range over the same observation interval.

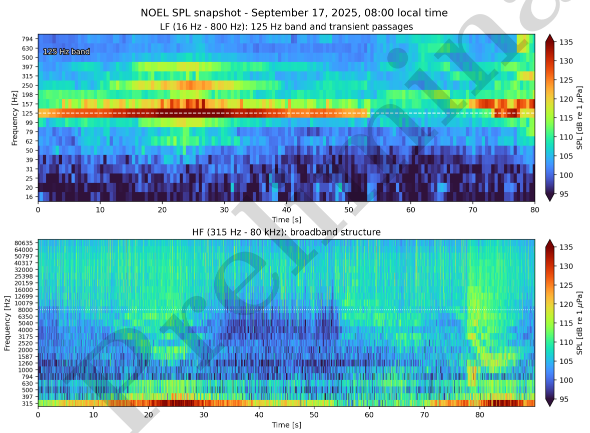

Figure 8: Time–frequency maps of the 1/3-octave-band SPL acquired at the NOEL station on 17 September 2025 at 08:00 local time. The LF panel shows a persistent increase around the 125 Hz band together with several transient increases, while the HF panel displays additional time–frequency structures over the same acquisition interval. These features are compatible with ship-related acoustic contributions.

The interpretation is based on the acoustic characteristics of the observed signal. The AIS receiving infrastructure included in the VONGOLA monitoring framework will support future associations between such features and vessel positions, trajectories and navigation information, allowing the identification of individual ship passages.

3.2. Automated Analysis and Future Developments

The standardized spectrograms and statistical acoustic products generated by the processing workflow also provide suitable inputs for automated analysis methods. Building on existing automated-analysis strategies [13], future developments will investigate machine-learning-based procedures for detecting and classifying acoustic events within long-term hydrophone and DAS datasets. The integration of these methods with temporally synchronized AIS and environmental information may support source attribution, reduce the amount of data requiring manual inspection and facilitate the identification of recurrent acoustic patterns.

4. Conclusions

The VONGOLA project provides a multi-probe framework for monitoring marine soundscapes in deep-sea and shallow-water environments. The network combines conventional hydrophones, Distributed Acoustic Sensing, AIS receiving systems, visual observations and environmental probes, providing complementary information over different spatial and temporal scales.
The preliminary NOEL case study demonstrates how calibrated SPL products acquired over extended periods can be used to investigate both recurrent daily patterns and changes in the acoustic conditions of a coastal site. The low-frequency range exhibits generally higher and more variable levels during daytime hours, consistent with stronger contributions from vessel traffic and other local anthropogenic activities. Conversely, the high-frequency range shows a more regular night-time enhancement compatible with biological activity, including sounds produced by snapping shrimps.
The comparison between July and September 2025 reveals an increase in the high-frequency acoustic background during September, beginning at approximately 6.3–8 kHz. Railway works were known to have taken place at the nearby railway station during the observation period, but their temporal overlap with the analysed acoustic intervals could not be verified. Biological activity, meteorological conditions and other local anthropogenic sources may also have contributed. The result is therefore interpreted as evidence of a change in the acoustic conditions of the site rather than as an attribution to a single source.
Future work will strengthen the integration of hydrophone data with AIS, environmental, visual and operational information. The AIS receiving infrastructure will support more robust associations between detected acoustic events and vessel positions and trajectories. Automated detection and classifica-

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tion procedures will also be developed to facilitate the analysis of the large volume of data generated by the VONGOLA network and to improve the attribution of biological and anthropogenic acoustic sources.

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