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ACOUSTIC CHARACTERIZATION OF PANAREA'S HYDROTHERMAL SYSTEM

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ABSTRACT

This study explores the underwater soundscape of the Mediterranean's most intense hydrothermal system, located in the waters of Panarea, Aeolian archipelago (Italy). Funded by the IPANEMA project, the research employed an array of four synchronized hydrophones to analyze acoustic data. The underwater noise was monitored across a broad frequency range to identify and characterize primary noise sources, including CO2 bubble emissions from fumaroles, ship noise, and weather phenomena. Positioned at a depth of 24 meters near active volcanic fumaroles emitting carbon dioxide (CO2), the acoustic array was used to investigate the intensity and dynamics of these noise sources and their potential correlation with volcanic activity. The analysis focused on identifying temporal patterns of Sound Pressure Levels (SPLs) on both small and large scales and correlating them with the site's hydrothermal activity. This work highlights the importance of passive acoustic monitoring for understanding underwater noise and its impact on sensitive marine environments influenced by both human activities and natural phenomena.

Keywords: *underwater acoustics, hydrotermal system, CO2, soundscape, IPANEMA project*

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1. INTRODUCTION

The European Carbon Dioxide Capture and Storage Laboratory (ECCSEL-ERIC) is a distributed, pan-European research infrastructure that integrates the leading laboratories across Europe focused on CO2 Capture and Storage (CCS). The ECCSEL-ERIC primary goal is to mitigate artificial CO2 emissions and combat climate change [1]. In the framework of ECCSEL-ERIC activities the IPANEMA (Implementation PAnarea Natural laboratory of ECCSEL and MArine observatory) project aims to establish the ECCSEL NatLab-Italy laboratory [2]. The IPANEMA project, involving Istituto Nazionale di Oceanografia e di Geofisica Sperimentale (OGS), Istituto Nazionale di Geofisica e Vulcanologia (INGV), and Istituto Nazionale di Fisica Nucleare (INFN), focuses on creating a network of tools to monitor and study natural CO2 emissions, primarily resulting from volcanic activity in the Mediterranean region, with a particular emphasis on the Aeolian Islands and the Ionian Sea. Studies on underwater acoustic techniques to monitor CO2 emissions are conducting in two sites. One site is located in shallow waters off Panarea in the Aeolian Islands (IPANEMA-Panarea), and the other is situated in deep waters at a depth of 2100 meters in the Gulf of Catania (IPANEMA-Catania), in the Western Ionian Sea. This work presents the first acoustic measurements acquired at the hydrothermal site of Panarea at a depth of 24 m [3].

2. THE IPANEMA-PANAREA ACOUSTIC ARRAY

The study area identified for investigating CO2 emissions in shallow waters at the Aeolian Islands is the hydrothermal complex of Panarea Island. At a depth of 24 meters, an autonomous acoustic array has been deployed, consisting of four broadband hydrophones (model Ocean Sonics IcListen Smart Hydrophone), each equipped with internal 497 GB memory cards. One of the primary objectives of the array is to develop techniques for detecting CO2 sources using acoustic methods. Accurate localization of CO2 emissions through acoustic techniques (multi-lateration, beamforming, cross-spectrum methods) requires the synchronization of the four hydrophones. This synchronization was achieved by designating the internal clock of one acoustic sensor as the master clock for the other sensors. The acoustic array is powered by a 408 Ah battery pack. The system is designed to allow for the periodic replacement of the battery pack and hydrophones, while keeping the mechanical structure that houses them on the seabed

3. ACOUSTIC DATA ACQUISITION AND ANALYSIS

Acoustic data was acquired from four hydrophones at a sampling frequency of 128 kHz and a dynamic range of 24 bits, with a duty cycle of 5 consecutive minutes every hour. This setup enabled the measurement of acoustic noise in the study area up to frequencies of 64 kHz. The chosen sampling frequency allows for comprehensive monitoring of the underwater acoustic environment, covering geophysical phenomena (e.g., CO2 emissions, earthquakes), biological activities (e.g., fish and cetacean vocalizations), atmospheric conditions (e.g., wind, rain), and anthropogenic noise (e.g., ship traffic and recreational boats).

Data analysis is performed offline after hydrophones' data recovery. Sound Pressure Level (SPL) measurements in 1/3 octave bands are computed automatically in a Python environemnt using the analysis approach described in [4]. For each 5-minute acquisition, the spectrogram is calculated using 2048-point Fourier transforms with Hamming windows of equal length and a 50% overlap. From the Power Spectral Density (PSD) values obtained in the spectrogram, mean SPL values in 1/3 octave bands and their 50th, 90th, 95th, 98th, and 99th percentiles are calculated.

Two different analysis pipelines are conducted in parallel. The first pipeline analyzes raw files sampled at 128 kHz, allowing for SPL measurements at frequencies above 125 Hz. The second pipeline analyzes the same files resampled at 2 kHz, lowering the minimum valid frequency to 2 Hz while maintaining the same number of Fourier transforms points. This approach enables the assessment of soundscape variability even on small temporal scales of a few minutes.

Additionally, the intensity and direction of the acoustic field are computed up to a maximum frequency of 400 Hz using cross-spectrum methods [5]. Figure 1 reports, as an example, the direction of the acoustic intensity vector during the passage of a vessel near the IPANEMA-Panarea array. The top panel shows the PSD of the acoustic signals recorded by one of the hydrophones in the array, displayed as a spectrogram. The middle panel shows the azimuthal directions of the acoustic intensity vector for each bin of the spectrogram, corresponding to the same time and frequency intervals. Similarly, the bottom panel shows the corresponding elevation directions of the acoustic intensity vector.

4. ACOUSTIC MONITORING OF CO2 EMISSIONS

The primary goal of the IPANEMA project is to monitor CO2 emissions in marine environments from hydrothermal vents. Acoustic measurements are aimed at estimating emitted flow rates, developing techniques for source identification through acoustic methods, and estimating bubble sizes based on their acoustic spectrum.

The station was positioned at a depth of 24 meters, a few meters away from an intense CO2 source. Figure 2 reports a 13 days long spectrogram of the noise acquired by the station from May 10, 2023 to May 22, 2023. The spectrogram was obtained by calculating the median values of the PSD over the 5-minutes long files acquired every hour. The increase of PSD at low frequencies from 10 May 2023 to 22 May 2023 is most likely associated with volcanic activity from the nearby Stromboli volcano, as reported in [6] [7]. The dashed black line delimits the frequency bands analyzed using the two analysis pipelines described in Section 3.

The noise measured by the IPANEMA-Panarea acoustic array is largely correlated with the geophysical activities of the area, particularly the variations in emissions from the nearby source. The study area is located in a highly active volcanic zone near the Stromboli volcano, resulting in a dataset that includes numerous

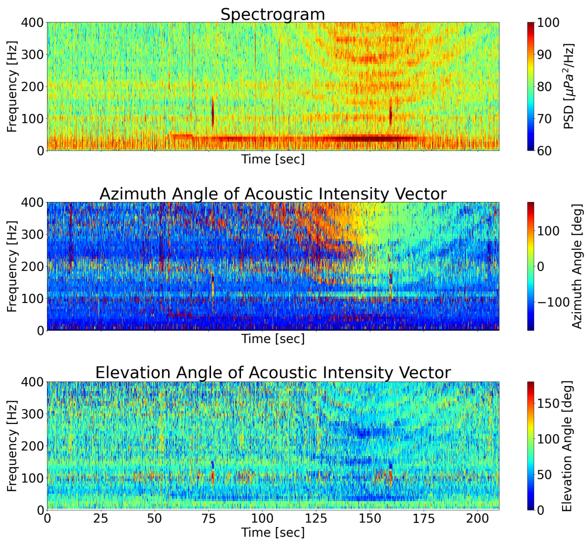

Figure 1. Top panel: Power Spectral Density (PSD) of the acoustic signals recorded by one of the hydrophones in the IPANEMA-Panarea array, displayed as a spectrogram during the passage of a vessel near the array. Middle panel: Corresponding azimuthal directions of the acoustic intensity vector. Bottom panel: Corresponding elevation directions of the acoustic intensity vector.

low-frequency events (a few Hz) related to seismic activity. The area is also frequented by numerous recreational boats. The array measurements enable the identification of noise generated by the boats and the use of this information to estimate the impact of marine traffic on the marine environment.

Figure 3 reports SPL measurements in the 63 Hz centered one-third octave band over the same analysed time window. The figure includes mean values, median, and the 90th, 95th, 98th, and 99th percentiles of the SPL values calculated within each 5-minute data acquisition. The graph clearly shows variations in SPL that follow a periodic pattern with a semi-diurnal periodicity. This suggests that the noise produced in this frequency band is modulated by tidal actions. The SPL in this frequency band is also good indicator for both the presence of boats and the monitoring of volcanic phenomena in the area.

In the kHz frequency range in submarine hydrothermal areas, most of the energetic radiated noise is produced by gas bubbles, due to the volume oscillation motion of

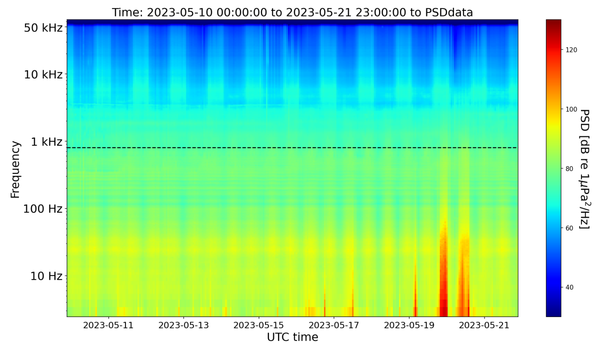

Figure 2. Spectrogram of the acoustic noise at the Panarea site from May 10, 2023 to May 22, 2023. The dashed black line delimits the frequency bands analyzed using the low frequency and high frequency analysis pipelines.

the bubbles' walls after their formation at the vents [8]. Figure 4 shows the SPL values measured within the same time window in the one-third octave frequency band centered at 5 kHz, corresponding to the breathing noise produced by bubbles with a diameter on the order of millimeters.

Unlike the SPL in the third-octave band centered at 63 Hz shown in Figure 3, the SPL calculated in the third-octave band centered at 5 kHz follows a diurnal periodicity. A correlation between hydrothermal activity and tidal phenomena has also been observed in other hydrothermal areas around the world. The impact of tidal forces on venting temperature has been reported in [9].

5. CONCLUSIONS

Acoustic monitoring of hydrothermal areas offers an innovative and complementary approach to traditional methods, which primarily rely on geochemical measurements and fluid temperature assessments. The acoustic noise generated by emissions from vents enables the monitoring of flow variability and bubble size, as well as the identification of source locations on the seabed through tracking techniques. Preliminary long-term SPL measurements have revealed distinct diurnal and semidiurnal patterns, indicating that the gas release mechanism in water is influenced by tidal effects.

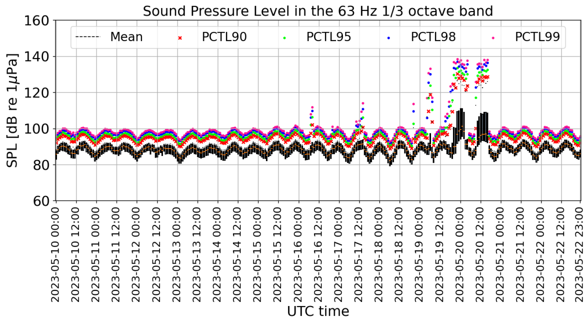

Figure 3. Time series of Sound Pressure Level values in the 63 Hz third-octave band over 13 days, acquired with a duty cycle of 5 minutes per hour. The figure shows the mean values, median values, and the 90th, 95th, 98th, and 99th percentiles.

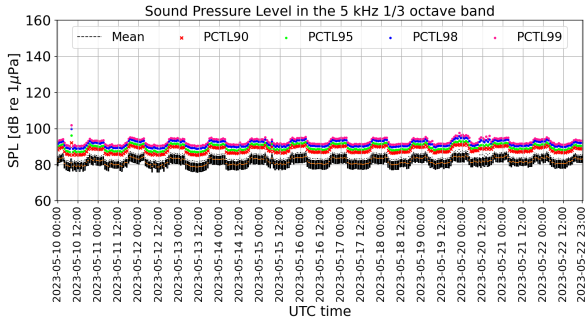

Figure 4. Time series of Sound Pressure Level values in the 5 kHz third-octave band over 13 days, acquired with a duty cycle of 5 minutes per hour. The figure shows the mean values, median values, and the 90th, 95th, 98th, and 99th percentiles.

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