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The IPANEMA Project: Underwater Acoustic Structure for Volcanic Activity and Natural CO_2 Emissions Monitoring †

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Abstract: Carbon dioxide produced by human activities (i.e., use of fossil fuels, deforestation, and livestock farming) is the main greenhouse gas causing global warming. In 2020, the concentration in the atmosphere exceeded the pre-industrial level by 48% (before 1750). The study of natural CO_2 (carbon dioxide) emissions due to volcanic activity through innovative measurement techniques is the main goal of the IPANEMA project. These studies are both essential for the evaluation of natural CO_2 emissions and for the development of future carbon capture and storage in underground geological formations to ensure that there are no leaks from the storage sites. Through the installation of two underwater acoustic stations, i.e., one in Panarea and one in the Gulf of Catania, we want to investigate techniques for estimating the flux of CO_2 emitted by natural sources, locating emission sources, and, in general, monitoring volcanic activity.

Keywords: underwater acoustics; monitoring; carbon dioxide; volcanic activity; Panarea; Catania

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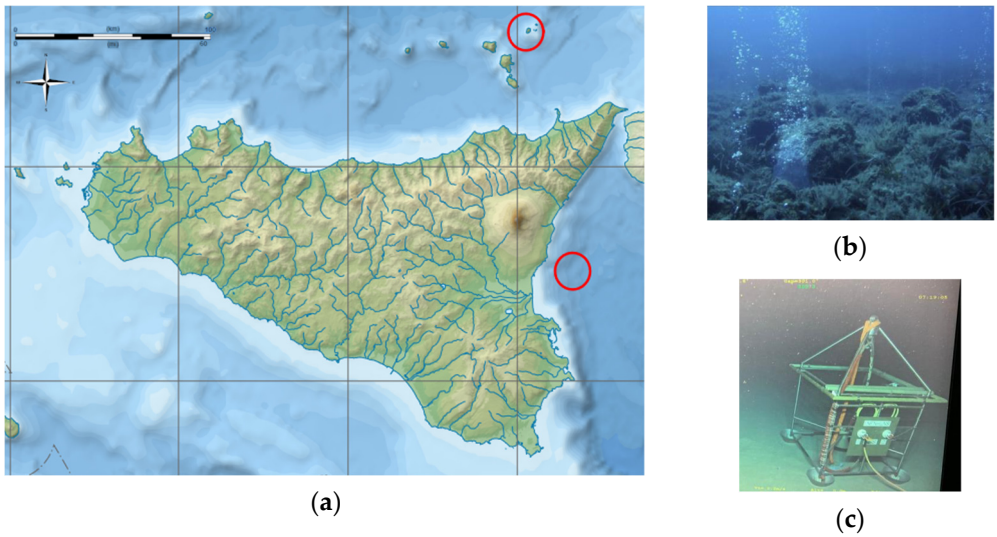
1. Introduction

The European Carbon Dioxide Capture and Storage Laboratory (ECCSEL-ERIC) is a distributed pan-European research infrastructure that connects the main existing laboratories in Europe working on CO_2 capture and storage (CCS). The IPANEMA project provides for the implementation of the ECCSEL NatLab-Italy laboratory and involves OGS (National Institute of Oceanography and Experimental Geophysics), INGV (National Institute of Geophysics and Volcanology), and INFN (National Institute for Nuclear Physics). The goal is the creation of a network of tools for monitoring and studying natural CO_2 emissions, mainly due to the volcanic activity present in the Mediterranean area, with particular attention to the Aeolian Islands and the Ionian Sea.

The IPANEMA project is conducted in two different geographical areas of Sicily (see Figure 1). On the one hand, an autonomous station will be installed on Panarea Island, and on the other hand, another seafloor observatory will be connected to the onshore in the Gulf of Catania.



(**a**) (**b**) (**c**)

Figure 1. (**a**) The two study sites of the IPANEMA project: the location for the Panarea observatory in the Aeolian Islands (North-East Sicily) and the location for the observatory in the Gulf of Catania, at the end of the Test Site cable (East Sicily). (**b**) Active tectonic faults that form an extensive CO_2-emitting fumarolic field in Panarea. (**c**) Deep underwater multidisciplinary laboratory since 2005 in the Gulf of Catania.

1.1. Panarea Island Observatory

The first study area, in the shallow waters of Panarea (24 m depth), is part of a large quiescent submarine strato-volcano, characterized by active tectonic faults that form an extensive CO_2-emitting fumarolic field. Fumaroles are underwater openings on the seabed that allow the escape of high-temperature gases. They are typical of volcanic and geothermal areas and represent an important source of information on the volcanic activity of the area to which they are closely related. This site has therefore already been chosen by OGS to investigate the effects of an increase in carbon dioxide on the biogeochemical and ecological functions of the marine ecosystem. The study of natural CO_2 emissions in Panarea represents an optimal "test bench" for analyzing CO_2 storage monitoring and control methods. Among several proposed techniques to reduce CO_2 concentration in the atmosphere, there is carbon capture and storage (CCS), which allows for the removal of CO_2 from the atmosphere and its permanent storage under the Earth's surface. Monitoring of CO_2 storage is a fundamental phase that guarantees the safety and sustainability of this methodology and consists of checking that there are no leaks from the storage site. In this context, underwater acoustics represent a non-invasive and efficient method to monitor CO_2 emissions in the marine environment from underground sources [1–6]. In the framework of the IPANEMA project, an autonomous observatory hosting a four-hydrophone acoustic array will be installed off Panarea coasts, aiming at the development of acoustic techniques for bubble localization and the measurement of the CO_2 flux.

1.2. Gulf of Catania Observatory

The second study area is located in the Gulf of Catania (25 km east off the coast at a depth of 2050 m), where a deep underwater multidisciplinary laboratory has been operative since 2005. The site serves the OnDE, SMO, SN 1, and FOCUS-ERC experiments [7–10]. The area is suitable for the study of numerous natural hazards due to its high seismicity and the presence of the Etna volcano, whose roots sink down to the seafloor. In this area, the possible presence of acoustic signals (tremors and cracks) related to the volcanic activity of Etna will be investigated.

2. The Underwater Stations

The Panarea shallow water site will be acoustically monitored by an array of four large-bandwidth hydrophones (model Ocean Sonics IcListen Smart Hydrophone) fed by a battery pack. In order to locate CO_2 emissions acoustically, the four hydrophones are time-synchronized. Time synchronization has been obtained by using the internal clock of one of the acoustic sensors as a master clock for the other sensors. Synchronization was tested and verified during tests on the dry bench. From considerations on the internal memory capacity of the hydrophones (497 GB), on the electrical consumption of the sensor, and on the energy capacity of the battery pack (408 Ah), a data-taking mode that provides 6-min recordings every hour was set. For the first measurement campaign, acoustic data are acquired with a sampling frequency of 128 kHz. This choice guarantees the acoustic monitoring of the study area for about 6 months. Given the shallow depth at which the Panarea station is located, it was deemed necessary to create a protective structure to safeguard the instrumentation from wave and atmospheric phenomena and from fishing activities. This structure, designed at the INFN-LNS, consists of a fixed part to be anchored to the seabed and a removable part that houses the sensors and battery pack and will be cyclically replaced at the end of each data collection period. The battery pack that powers the hydrophones is placed inside a bentosphere that has been subjected to a vacuum leak test. The hydrophones are fixed on supports whose respective distances are 1 m (see Figure 2).

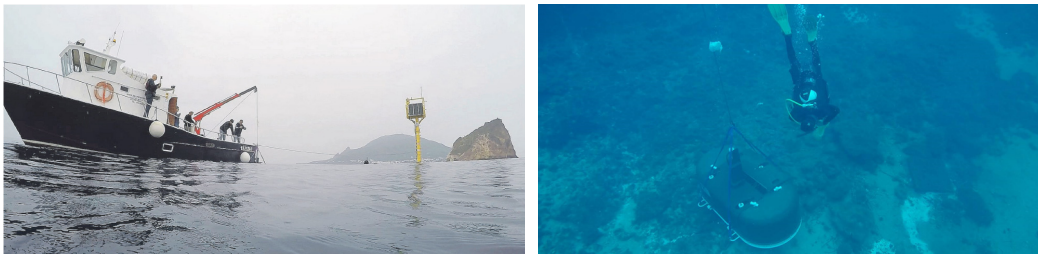


(**a**) (**b**) (**c**)

(**d**)

Figure 2. Panarea acoustic station during the mechanical assembly phase: (**a**) the commercial hydrophone forming the array, (**b**) the battery pack, (**c**) the IPANEMA station with the open deck, and (**d**) the IPANEMA station with the closed deck where the four hydrophones are shown.

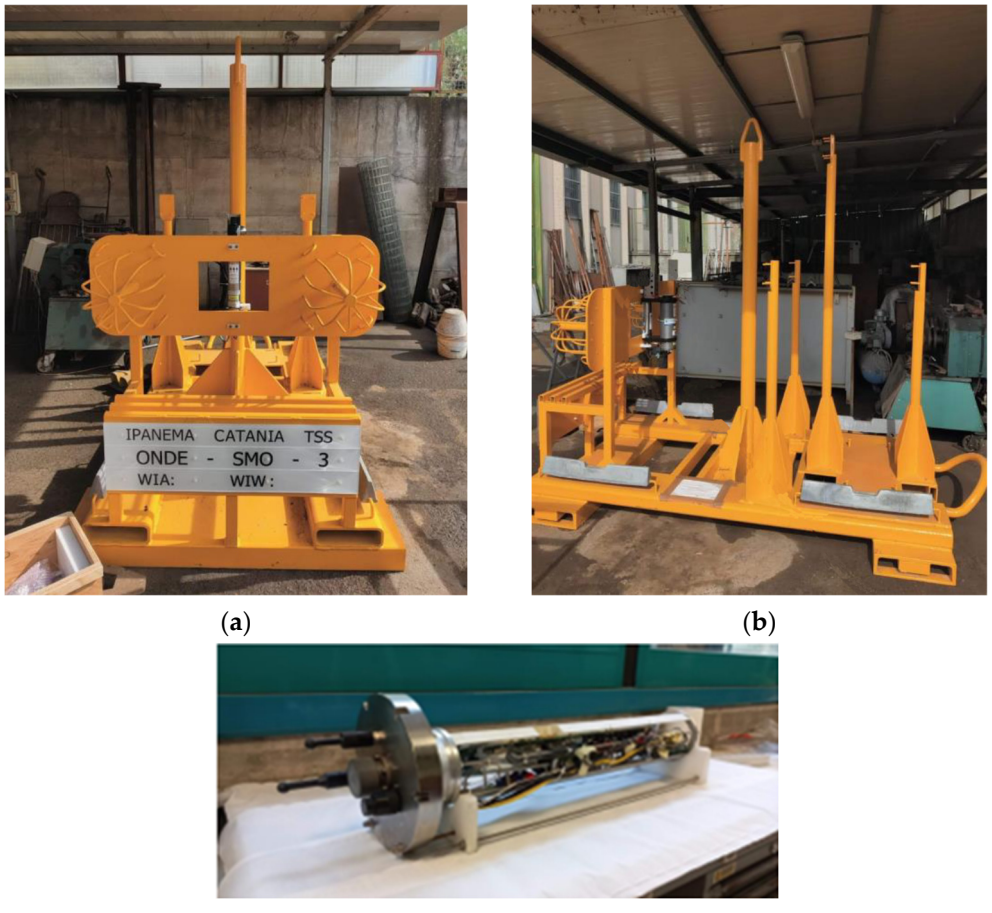
On 9th May 2023, the installation of the Panarea acoustic station was completed in an area rich in submerged hydrothermal springs where the INGV has a monitoring site (see Figure 3). After six months, the removable part will be replaced by an identical one, while continuing to collect data without big lost chunks and being able to download the data taken. This will allow the start of the analysis of the months already recorded, checking the data, and testing the analysis algorithms to automate future deployments.



(**a**) (**b**)

Figure 3. Panarea acoustic station during its first deployment: (**a**) a crane boat submerging the station in water; and (**b**) a submerged diver releasing the station from the crane.

The study area in the Gulf of Catania will be monitored by a cabled underwater acoustic array consisting of four hydrophones and oceanographic instrumentation for the measurement of the main seawater parameters, such as pressure, conductivity, temperature, depth, dissolved oxygen, salinity, and pH (see Figure 4).



(**a**) (**b**)

(**c**)

Figure 4. The IPANEMA Catania station: (**a**) the mechanical frame (front view), (**b**) the mechanical frame (side view), and (**c**) the electronics container.

Hydrophones having a sensitivity variation as a function of the depth better than 1 dB (model SMID TR-401) were selected for the Catania deep sea study area. They are installed at the vertices of a tetrahedron with an edge of 1 m. All acoustic sensors and oceanographic instrumentation are Global Positioning System (GPS) time-synchronized. Data transmission takes place through optical fibers, and all data is streamed in real-time to shore, which will allow for their analysis at the same time. The deployment of the Catania acoustic station is foreseen in spring/summer 2024.

3. The Data Analysis

The effectiveness of passive acoustic monitoring techniques in the context of a controlled CO_2 gas release experiment was demonstrated in the QICS (Quantifying and Monitoring Potential Ecosystem Impacts of Geological Carbon Storage) project conducted off the west coast of Scotland [1]. Further studies conducted in the North Sea have demonstrated the possibility of determining the diameter of CO_2 bubbles acoustically and estimating their position using beamforming techniques [2,3]. Passive acoustic has also been applied to the monitoring of natural gas seeps [4–6].

Bibliographic research has revealed the presence of various scientific works dedicated to the study of the fumaroles of Panarea using acoustic methodologies. In [5], the variations in the flow of CO_2 and the presence of any anomalies were studied, and in [6], an approach to quantifying bubble size and gas flux was developed.

The primary goal of the research in Panarea is the size estimation of the bubbles starting from their acoustic spectrum, thus making it possible to determine the flow of gas emitted. Size estimation of the CO_2 bubbles can be carried out using the Minnaert formula [11], which correlates its fundamental peak frequency with its radius r and the environmental pressure P (see Equation (1)).

$$f = \frac{1}{2\pi r\sqrt{\frac{3P\gamma}{\rho}}} \quad (1)$$

where γ is the ratio of gas-specific heat at constant pressure and volume, and ρ is the water density.

This formula is only suitable for cases where the rate of bubble generation is low and it is possible to detect bubble signals automatically from ambient background noise. Instead, in the case of high gas flux conditions, sounds will appear as a continuous, stationary random process, and it will be necessary to apply the inversion method to the measured acoustic spectrum [2,6].

The gas flux estimate is derived from the Probability Density Function (PDF) of the bubble equilibrium radius, considering acoustic propagation to determine the acoustic range. Isolated CO_2 emissions will be tracked acoustically by using multi-lateration techniques based on the difference in the times of arrival of the sound to the sensors. Continuous emissions will be located through beamforming and cross-spectrum methods [3].

4. Conclusions and Next Steps

The IPANEMA project aims to study the natural emissions of carbon dioxide in the Mediterranean region due to volcanic activity. The project is part of ECCSEL-ERIC, which has a broader purpose of monitoring artificial CO_2 emissions to combat climate change and testing the feasibility of carbon capture and storage techniques. During this project, two underwater stations have been designed for underwater data recording: Panarea, an autonomous station replaceable every 6 months, and Catania, a station connected and fully controlled from onshore.

As a start to the installation phase, the Panarea station has already been deployed and is operational. It is planned to periodically replace the hydrophones and the battery pack (a removable pack from the base). After that, efforts will be made to retrieve the already

collected data and analyze it with the aim of quantifying the emitted carbon dioxide flux and the location of the fumaroles.

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