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ADVANCES IN OPTOACOUSTIC TECHNOLOGIES FOR MONITORING THE IONIAN SEA

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ABSTRACT

Fiber-optic monitoring technologies have gained significant relevance in recent years, particularly in geophysical and acoustic sensing applications. The FOCUS project has extended an existing 28 km submarine optoelectric cable near Catania, reaching depths of down to 2100 meters. This extension, which spans 6 km, incorporates two optical fibers: one with a triple loop connected to a BOTDR (Brillouin Optical Time Domain Reflectometer) for geophysical surveys, and the other with a double loop recently connected to a DAS (Distributed Acoustic Sensing) system for acoustic measurements provided by the VONGOLA project. The DAS installation enables continuous monitoring of underwater acoustic events and seismic activity in a unique environment influenced by the proximity to Mount Etna and the port of Catania. Together with the IPANEMA-CT acoustic observatory in the same location, this setup creates a powerful, multi-instrumentation monitoring system. This proceeding presents these three projects, shows a data acquisition of each, and explores the potential for joint detection of events. Furthermore, it analyzes the recording of an earthquake by the DAS and the calibrated hydrophones and discusses the possibility of using the hydrophones as a reference to calibrate DAS data. For these reasons, the Catania cable offers an ideal environment for developing and testing monitoring algorithms and new technologies in the Ionian Sea.

Keywords: *monitoring, optoacoustic technologies, Distributed Acoustic Sensing, FOCUS project, IPANEMA Project, VONGOLA Project*

1. INTRODUCTION

The multidisciplinary laboratory at the port of Catania (Sicily) is managed by the Istituto Nazionale di Fisica Nucleare—-Laboratori Nazionali del Sud (INFN—-LNS). This facility is connected to an advanced deep-sea MEOC (Main Electro-Optical Cable), which extends to a depth of 2100 meters across the North Alfeo fault, reaching up to 29 km offshore. Its location, along with its proximity to Mount Etna, makes this laboratory a key site for various types of studies. The MEOC cable, with its advanced sensing capabilities, provides critical infrastructure for continuous data collection from connected sen-

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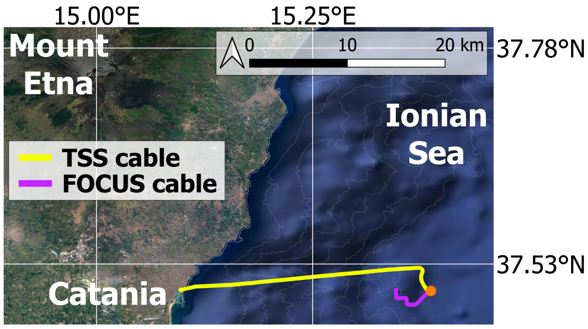

Figure 1. Map showing the locations of the TSS and FOCUS cables. The orange dot marks the location of IPANEMA-CT acoustic observatory.

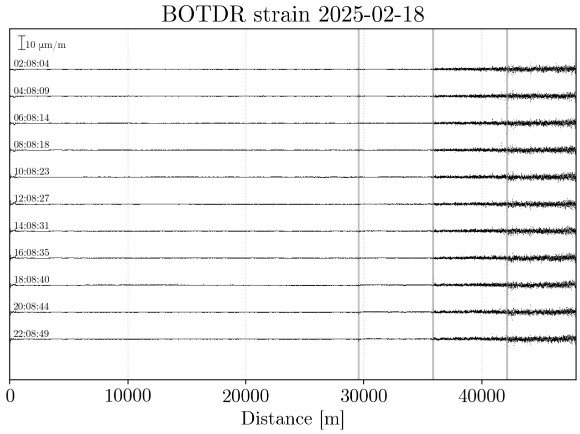

Figure 2. Strain measurements every two hours from the FOCUS BOTDR on 18 February 2025. The vertical lines represent the different connections (TSS cable and fibers of the FOCUS cable).

sors, as it contains 10 internal optical fibers.

The MEOC is deployed in an easterly direction from the port of Catania, and is divided into two branches – each branch is approximately 3 km in length. The two branches extend in slightly northern and southern directions. The first section of the cable, about 1.5 km long, is above water, followed by an approximately 25 km underwater section on the seabed. The northern branch, known as Test Site North (TSN), houses four of the optical fibers, which are currently managed by the Istituto Nazionale di Geofisica e Vulcanologia (INGV). The southern branch, called Test Site South (TSS), carries the remaining six fibers. In this proceeding, only the portion of the cable that operates the TSS will be discussed, therefore, the entire cable will be referred to as the TSS cable.

At the end of the TSS cable at 2100 m depth, a termination frame facilitates the connection of the instrumentation to each of its fibers. The FOCUS project, detailed in section 2, has installed a 6.4 km cable extension for two of these fibers (see Figure 1). The IPANEMA project, discussed in section 3, utilizes two of the TSS cable fibers. Finally, section 4 will cover the VONGOLA project, which also uses one of the TSS cable fibers connected to the FOCUS extension.

2. THE FOCUS PROJECT – BOTDR TECHNOLOGY

The FOCUS (Fiber Optic Cable Use for Seafloor) project, led by Centre National de la Recherche Scientifique (CNRS), involved the installation of a new cable connected to the TSS cable, utilizing two of its fibers. This extension, known as the FOCUS cable, increases the MEOC length to 35.9 km as of October 2022. The FOCUS cable was deployed in a zigzag pattern, crossing the mapped North Alfeo fault at four points (buried 20 cm deep where the terrain and seafloor conditions permitted). It contains three tightly bundled fibers in the core and two loose fibers within a small steel tube in the shield layer. These fibers are connected in both double and triple loop configurations. Specifically, one incoming fiber through the TSS first passes through a tightly bundled fiber, and then is routed through a loose fiber on its return path (double loop). The other TSS fiber begins by passing through the loose fiber and then follows the path of the other two tightly bundled fibers (triple loop) [1].

This project also includes the installation of a Brillouin Optical Time Domain Reflectometer (BOTDR) that interrogates the fiber of the FOCUS cable with a triple loop, covering about 48.6 km. The system is used to test the application of laser reflectometry for detecting long-term static strain on the seafloor. It operates by sending a pulse of light through the fiber and analyzing the backscattered light resulting from interactions between the light and the vibrations in the fiber's crystalline lattice. The Brillouin frequency shift, which varies with strain and temperature, is then used to determine the precise location and magnitude of these changes along the fiber's length [2]. This system continuously stores analyzed data in 2-hour files. Figure 2 shows the strain measured by the BOTDR over a day. As indicated by the scale in the top left corner, no significant deformation (above 10 microdeformations) is observed on this particular day.

In 2023 and 2024, preliminary measurement campaigns of the TSS and FOCUS cables using Distributed Acoustic Sensing (DAS) technology were conducted in collaboration with the Institut Français de Recherche pour l'Exploitation de la Mer (IFREMER) [3]. The successful joint operation led to the decision to permanently install a DAS at this site as part of the VONGOLA project, as discussed in section 4.

3. THE IPANEMA PROJECT – HYDROPHONE PHASED ARRAY

The IPANEMA (Implementation PAnarea Natural laboratory of ECCSEL and MArine observatory) project, led by Istituto Nazionale di Oceanografia e di Geofisica Sperimentale (OGS), built two arrays of four hydrophones: one autonomous array for shallow waters offshore Panarea Island (Eolian Archipelago), and one cabled array to monitor the Gulf of Catania (IPANEMA-CT). The latter also includes oceanographic instrumentation for measuring key seawater parameters, such as pressure, conductivity, temperature, depth, dissolved oxygen, salinity, and pH [4].

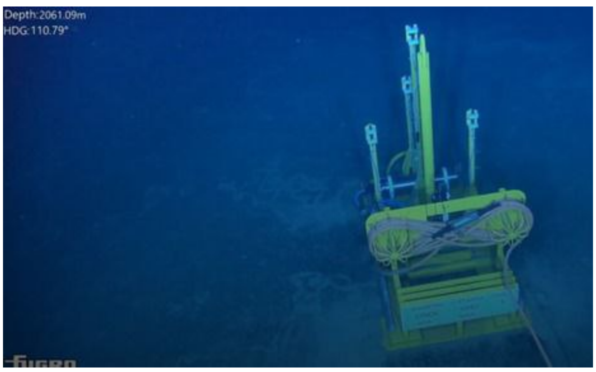

Figure 3. Screenshots of the FRUGRO ROV during the installation of the IPANEMA-CT acoustic observatory. The image shows the four hydrophones of the frame arranged in a tetrahedral configuration, with a depth exceeding 2060 m.

In October 2024, the deep-sea acoustic observatory called IPANEMA-CT was deployed and connected to two fibers of the TSS cable, approximately 29 km offshore at a depth of 2100 meters (see Figure 3), in the same location as the previous hydrophone phase array NEMO-OνDE (2005-2006) and SMO-OνDE-2 (2017-2021) [5], marked by an orange dot in Figure 1. The oceanic sensor installed in IPANEMA-CT is the SeapHOx™ V2 by Sea-Bird Scientific. The hydrophones used are SMID TR-401 models (the same as those used in SMO-OνDE-2, but with a ground guard ring), arranged in a tetrahedral pyramidal shape with a 1-meter distance between each. They are equipped with a high-resolution 32-bit Analog-to-Digital Converter (ADC). These omnidirectional hydrophones have a Received Voltage Response (RVR) of approximately -172 ± 3 dB re 1 V/μPa in the 10 Hz – 70 kHz frequency range. The data is synchronized by a GPS clock and continuously transmitted to shore with a sampling frequency (f_s) of 192 kHz.

4. THE VONGOLA PROJECT – DAS TECHNOLOGY

The VONGOLA (Visual and Noise-enhanced AI Analysis for Marine Biodiversity Monitoring, Observation, and Learning) project, led by Centro Siciliano di Fisica Nucleare e Struttura della Materia (CSFNSM), aims to monitor marine biodiversity in the Mediterranean Sea using non-invasive technologies. In January 2025, the CSFNSM connected its DAS (Distributed Acoustic Sensing) prototype system to the second available fiber with the double loop in the FOCUS cable, extending up to 42.2 km [6]. DAS is a novel technology that uses standard optical fiber as a sensor to detect and measure vibrations or acoustic signals along its length. It works by sending a laser pulse through the fiber and analyzing the backscattered light. Changes in the light's characteristics, due to strain or temperature variations, are used to detect and locate acoustic events or disturbances in real time [2]. This technology is powerful because it creates an array of virtual receivers along the cable, recording raw signals from each point [6]. It is particularly effective for detecting low-frequency sounds, as it can capture subtle vibrations along fiber-optic cables, which are highly sensitive to these types of waves. Vessels and seismic events, for example, generate low-frequency sounds (65–125 Hz for vessels and below 40 Hz for seismic events), which can propagate over long distances. DAS can detect these long-range signals, making it an invaluable tool for monitoring both anthropogenic noise and geophysical activities.

The VONGOLA DAS has started operating at a f_s of 2 kHz with a channel spacing of about 5.1 meters.

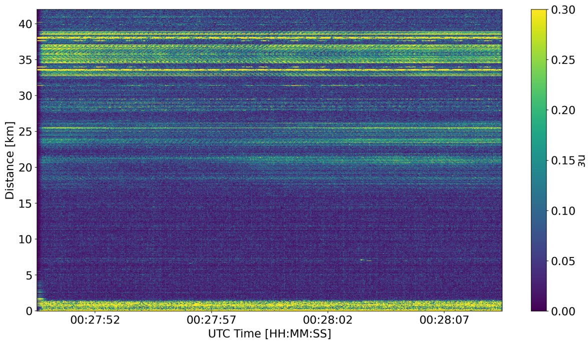

Figure 4. Nano-strain (nϵ) DAS data filtered between 15 and 45 Hz over 20 seconds of measurement, recorded on 26 January 2025. It highlights the passage of a vessel near the 21.2 km point of the cable, which is distinctly observed in both the TSS and FOCUS sections. Its time resolution is 1 s, and the distance resolution is 51.07 m.

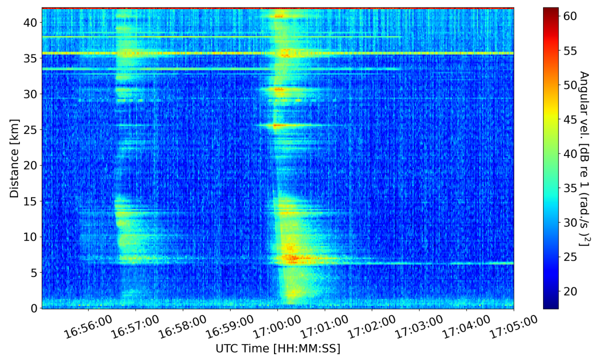

Figure 5. DAS data filtered between 1 and 25 Hz over 10 minutes of measurement, recorded on 18 February 2025. It highlights an earthquake. Its time resolution is 1 s, and the distance resolution is 200 m.

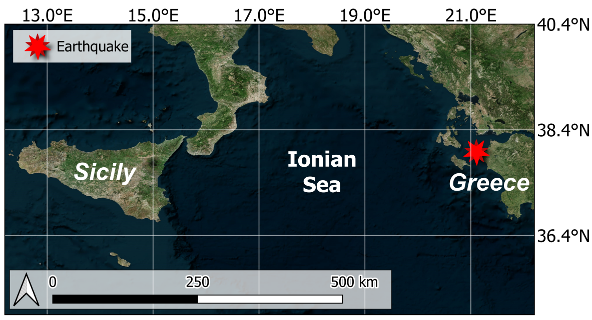

Figure 6. Map showing the location of the mb 5.1 earthquake that occurred on 18 February 2025 at 16:54:34 (UTC) off the Greek Ionian Coast, 507 km away from the IPANEMA-CT position.

Figure 4 shows an example of a measurement in which the presence of a vessel is visible, marked by hyperbolic curves in the 17–25 km and 32–39 km sections of the interrogated fiber. The data was filtered between 15 and 45 Hz using an 8th–order Butterworth pass-band filter [6].

In Figure 4, the signal is more prominent in the FOCUS cable than in the 20–25 km range (the closest points to the vessel) of the TSS cable. This is because DAS technology is more sensitive to signals propagating parallel to the cable, as observed in the FOCUS section (at distances of 35–37 km), than to those propagating nearly perpendicular to it, as seen in the 20–25 km section of the TSS cable [6].

Seismic phenomena, such as earthquakes, are also clearly evident in DAS measurements. For example, Figure 5 shows a recording of a distant earthquake, clearly showing the Primary (P), Secondary (S), and Tertiary (T) waves.

Analyzing the Figure 5 related to the detected earthquake event, it was determined that the signal was received at 16:55:49 (UTC). This is consistent with a magnitude mb 5.1 earthquake that occurred 507.045 km away at 16:54:34 (UTC) [7], as shown in Figure 6. It occurred 75 seconds earlier, this time difference corresponds to an estimated P–wave seismic velocity of 6.76 km/s (a more detailed study is needed to determine a better approximation).

5. GEOPHYSICAL EVENT ANALYSIS

Figure 5 presents an earthquake recorded in the DAS data. As expected, this event is not visible in Figure 2 from the BOTDR data, as it primarily detects high-frequency strain changes. However, the IPANEMA-CT hydrophones have successfully recorded the event. This allowed the collection of the raw signal from one of them, as well as from two points on the DAS, one before and one after the hydrophone phased array: the 28.0 km point on the TSS cable and the 30.6 km point on the loose fiber section of the FOCUS cable. Since earthquakes generate low-frequency signals (below 50 Hz), these three signals were decimated

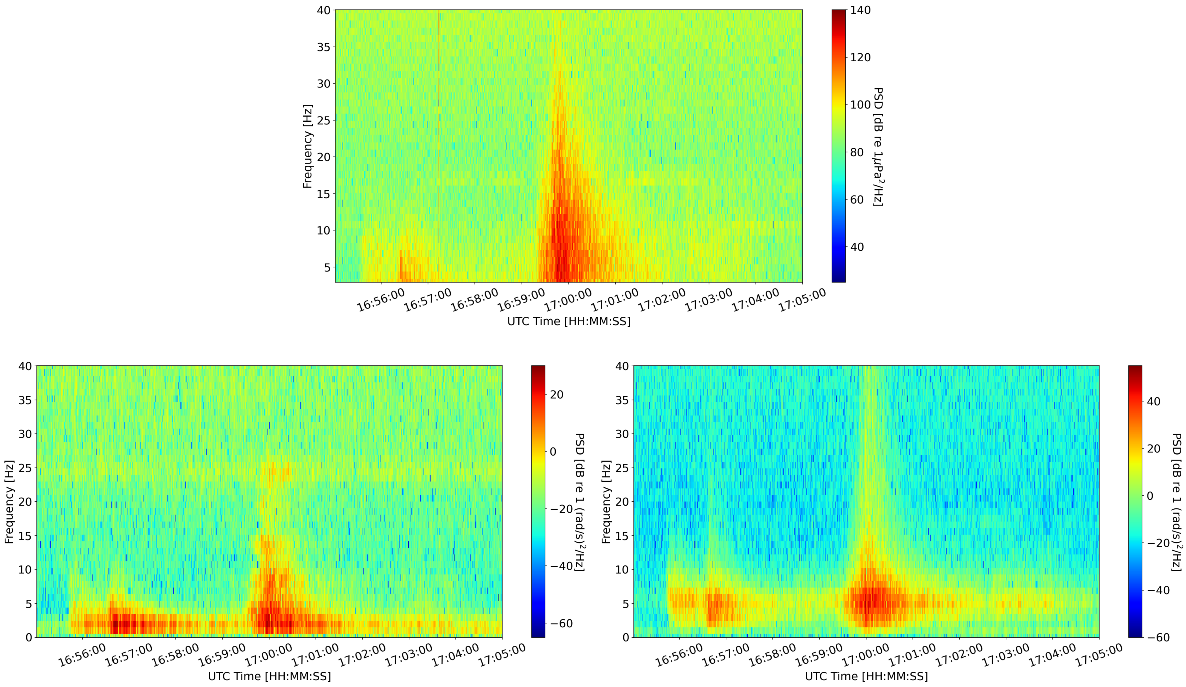

Figure 7. 2048-point NFFT spectrograms of decimated signals with a f_s of 2 kHz. A zoom-in between 0 and 40 Hz is applied. (*Top*) Acoustic data from a hydrophone at the IPANEMA-CT acoustic observatory. (*Bottom left*) The recorded signal by a DAS point in the TSS cable section. (*Bottom right*) The recorded signal by a DAS point in the FOCUS cable section.

to a f_s of 2 kHz, and their spectrogram is presented in Figure 7.

Figure 7 shows that both technologies are able to detect the same earthquake. As expected, the P and S waves, which propagate through solid media, are more sensitively detected by the DAS. The hydrophone detects these seismic waves indirectly through the vibrations they cause in the surrounding water and IPANEMA-CT frame, though with less clarity. In contrast, the T wave, which is an acoustic signal, is more intensely perceived by the hydrophone, where it is clearly distinguishable. This opens up the possibility of studying the estimation of the magnitude of nearby earthquakes, as demonstrated in previous studies [8].

One of the main challenges of DAS technology is calibrating its raw data, which depends on the characteristics of the fiber it interrogates. These characteristics must be well understood, as they are influenced by factors such as the bathymetry of the cable, whether it is suspended, laid on the seabed, or buried; its reinforcement; and other physical conditions. Events like the one observed in this study can be used to calibrate DAS signals or, at the very least, to characterize the cable section points close to the hydrophone phased array, as has been done in previous studies using air-gun shots from a ship [9]. This is possible with the technology in the INFN-LNS cable. By applying the Power Spectral Density (PSD) mean between the frequencies from 0 to 40 Hz in Figure 7 spectrograms and removing the offset to set the minimum dB to 0, the comparability between the technologies becomes evident in Figure 8. The P, S, and T waves are clearly visible in all three datasets, with their different arrival times and sensitivities depending on the receiver. In this case, the offsets applied are a 19.7 dB deviation for the DAS data on the FOCUS cable, a 23.1 dB offset for the DAS data on the TSS cable, and a -82.0 dB offset for the IPANEMA-CT data. Thus, the idea would be to calibrate these sections of the cable interrogated by the DAS and to obtain a trans-

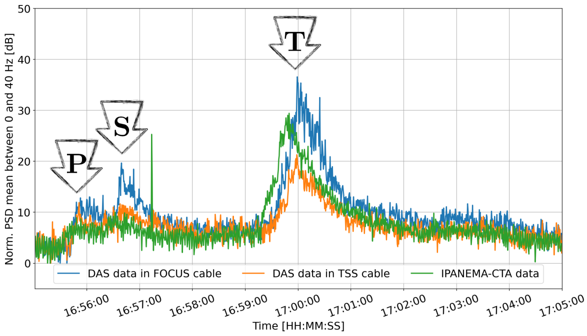

Figure 8. Mean PSD calculated between 0 and 40 Hz from the spectrograms of the IPANEMA-CT hydrophone, the DAS point at 28.0 km (TSS cable section), and the DAS point at 30.6 km (FOCUS cable section). These PSDs have been shifted (normalized individually) such that their minimum value is set to 0 dB, facilitating visual comparison. The occurrence of the P, S, and T waves from the earthquake is indicated by the three arrows.

formation of these data to pressure, as received by a calibrated hydrophone.

6. CONCLUSIONS

This proceeding has presented the three projects currently conducting experiments using the TSS cable, highlighting the great scientific and technological potential of the INFN-LNS research facility. It houses three distinct technologies -BOTDR (FOCUS project), DAS (VONGOLA project), and a hydrophone phased array (IPANEMA project)- all synchronized and continuously collecting data. It is also worth mentioning that the INFN-LNS has an Automatic Identification System (AIS) antenna to vessel tracks in the area. All of this represents a unique long-term monitoring system in the Mediterranean Sea, where different types of instrumentation can be tested for marine science applications. The combination of these technologies, connected to the same cable and monitoring the same environment, provides rich and diverse data, offering significant insights into marine research.

Moreover, the infrastructure is strategically located near the Port of Catania, making it ideal for monitoring anthropogenic noise produced by vessels, utilizing both hydrophones and DAS. This is also an excellent choice for bioacoustic studies, particularly for detecting whale notes, where hydrophone data can complement DAS data. Additionally, the site offers a valuable opportunity for seismic event monitoring, an especially important capability given its proximity to Mount Etna and the fact that the cable crosses the North Alfeo fault.

The potential of the infrastructure deployed and connected to the TSS cable is evident in its ability to integrate these technologies. By placing calibrated hydrophones, such as those used in the IPANEMA-CT acoustic observatory, in close proximity to the cable interrogated by the DAS, it becomes possible to calibrate DAS data and even estimate the magnitude of seismic events from these collected data. While this will require time and the development of an efficient method for gathering sufficient statistics, the prospect of calibrating and cross-validating these data sets opens up a promising avenue for future research.

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