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THE ITALIAN OCEAN SOUND MONITORING SUB-SYSTEM FOR THE ITALIAN INTEGRATED ENVIRONMENTAL RESEARCH INFRASTRUCTURES SYSTEM (ITINERIS) PROJECT

Simone Sanfilippo[1*] **Danilo Bonanno**[1] **Letizia S. Di Mauro**[1]
Dídac Diego-Tortosa[1] **Abdelghani Idrissi**[1] **Giorgio Riccobene**[1,2] **Salvatore Viola**[1,2]
[1] Laboratori Nazionali del Sud (LNS), Istituto Nazionale di Fisica Nucleare (INFN). Catania, Italy.
[2] Centro Siciliano di Fisica Nucleare e Struttura della Materia (CSFNSM). Catania, Italy.

ABSTRACT

The aim of the Italian Integrated Environmental Research Infrastructures System (ITINERIS) project, is to establish the Italian Hub of Research Infrastructures within the environmental scientific domain. ITINERIS will create a flexible system to collect and store, for the first time in a national integrated system, ocean data and metadata and make them available for the entire scientific community (FAIR principles). Laboratori Nazionali del Sud (LNS) of Istituto Nazionale di Fisica Nucleare (INFN) coordinates the design and operation of a deep-sea Junction Box (JB) installed at the Portopalo di Capo Passero site, Italy, at a depth of about 3450 m. The JB hosts a broadband hydrophone whose data are continuously streamed to shore and analysed. Two JBs are in operation since October 2024 and their hydrophones' data are continuously recorded. LNS is also leading the implementation of the Ocean Sound sub-system, part of the Italian Ocean Data Portal developed under the ITINERIS project. Acoustic data from LNS JBs are now released in the project trough an ERDDAP server. In this contribution, an overview of the project is discussed and a preliminary analysis on ambient noise monitoring will be also presented.

Keywords: *ITINERIS, ocean sound, underwater acoustics, Sound Pressure Level analysis*

**Corresponding author*: *sanfilippo@lns.infn.it.*

1. INTRODUCTION

Sound is vital for many marine species due to its efficient transmission in water, facilitating communication, navigation, and predator-prey detection. However, increasing human activities have introduced significant anthropogenic noise, disrupting marine ecosystems [1]. Major sources include shipping, seismic surveys, military sonar, and coastal infrastructure, with fish and marine mammals being particularly affected. Noise can alter behavior, induce stress, impair communication, and, in extreme cases, cause mortality. Commercial shipping is the primary contributor, generating continuous low-frequency noise (up to hundreds of Hz) through mechanical vibrations, propeller cavitation, and hull movement, overlapping with marine species' hearing ranges [2]. Ambient noise levels have risen globally, with some areas experiencing increases of nearly 3 dB per decade [1]. Seismic airguns, used for hydrocarbon exploration, emit high-intensity, low-frequency pulses (less than 150 Hz) exceeding 250 dB re 1 μPa, affecting vast marine areas [3]. Ocean sound monitoring is crucial for safety, security, disaster prevention, marine spatial planning, ecosystem health, and climate change studies. Recognizing its importance, the Marine Strategy Framework Directive (MSFD) (Art. 3, point 8; Annex III, Table 2) mandates its inclusion among environmental variables to assess ocean health [4].
Despite international efforts, the lack of standardized protocols for collecting, analyzing, and sharing ocean sound data remains a major challenge. Given its high spatial and temporal variability, an effective measurement plan should address: i) measurement type (pressure or parti-

cle motion), ii) detector location, iii) directivity and sensitivity, iv) sampling and resolution, v) recording duration, and vi) acquisition intervals. However, inconsistencies in sensor specifications, calibration, depth, location, sampling frequency, and data formats complicate data integration. Additionally, the absence of common analysis frameworks and unified metadata standards hinders the establishment of a shared system at national and international levels. Further restrictions arise from data embargoes, often imposed to protect sensitive or strategic information, limiting accessibility and sharing.

In this context, the Italian Integrated Environmental Research Infrastructures System (ITINERIS) project [5], funded through Italy's National Recovery and Resilience Plan (PNRR), aims to create a unified national framework for marine data, ensuring traceability, accessibility, interoperability, and compliance with FAIR principles [6]. Within ITINERIS, the Ocean Sound Sub-System (OS-SS), part of the ITalian Integrated Ocean Observing System (IT-IOOS), will establish for the first time a national-level integrated platform with standardized procedures, guidelines, and tools for collecting, analyzing, and sharing ocean sound data in accordance with best practices.

2. THE ITALIAN OCEAN SOUND SUB-SYSTEM

The main purpose of the Ocean Sound sub-system is to expand the accessibility and usability of acoustic data in marine environment for multiple applications, like monitoring acoustic pollution, search for soniferous marine species, identifying surface and underwater vehicles, and studying geological events like earthquakes. This initiative will also define and disseminate a set of recommendations and best practices for collecting, analyzing, and distributing ocean sound data among all the Research Infrastructures (RIs) operating acoustic devices in Italian waters. Furthermore, the OS-SS is transversal, providing services and information from/to multiple IT-IOOS RIs for the production of ocean sound data and time series from recorded raw acoustic data.

To ensure data transparency, each dataset produced by ITINERIS RIs will be accompanied by a corresponding metadata set. Metadata play a key role by providing the contextual details required to interpret primary data, including information such as time, location, and collection methods. This contextualization is crucial for ensuring the reproducibility of scientific results, forming a fundamental pillar of scientific advancement. Furthermore, metadata are essential for aligning and comparing datasets from various studies, particularly in environmental and oceanographic research, where data stem from diverse sources and methodologies. By harmonizing these datasets, metadata enable meaningful comparisons and comprehensive analyses. They are also vital for long-term data preservation and usability, ensuring future researchers can access and comprehend information despite evolving technologies and personnel turnover.

Utilizing extensive expertise in deep-sea acoustic systems and data analysis, the Laboratori Nazionali del Sud (LNS) of the Istituto Nazionale di Fisica Nucleare (INFN) is leveraging its role within ITINERIS and IT-IOOS to promote interdisciplinary research in environmental sciences. Specifically, INFN - LNS has a dual objective: designing and deploying a new underwater Junction Box (JB) at the infrastructure of Portopalo di Capo Passero, Italy, at a depth of approximately 3450 meters, and, on the other hand, develop and maintain the OS-SS of the IT-IOOS. LNS has already designed and successfully operates a network of 5 prototype JBs at this depth. Each JB enables the connection of over 10 observatories to the mainland and incorporates acoustic sensors. These sensors facilitate the creation of a phased array on the seafloor, allowing for the efficient collection, storage, and near real-time processing of acoustic data. This acoustic system primarily supports research in bioacoustics, geophysics, and vessel noise monitoring. Additionally, the collected data enhance the positioning system of the KM3NeT Neutrino Telescope [7] research infrastructure and further advancements in acoustic neutrino detection.

2.1 The Capo Passero INFN infrastructure

The Capo Passero site (figure 1), operated by INFN - LNS, is a cabled multipurpose subsea infrastructure supporting various projects and experiments. It features a phased array of hydrophones installed on the seafloor (average depth of 3450 m), located approximately 100 km southeast of Capo Passero. Two Main Electro-Optical Cables (MEOCs) extend from shore. These MEOCs, each nearly 100 km in length, provide power and data transmission for deep-sea observatories. Each cable terminates at a Cable Termination Frame (CTF), which connects to a network of specialized subsea components (JBs, fig. 2) designed to ensure a high-reliability, high-availability, and high-speed data link, along with an uninterrupted power supply for multiparametric deep-sea observatories, requiring precise time synchronization and high data transfer rates. While MEOC-1 supports three JBs, MEOC-2 will accom-

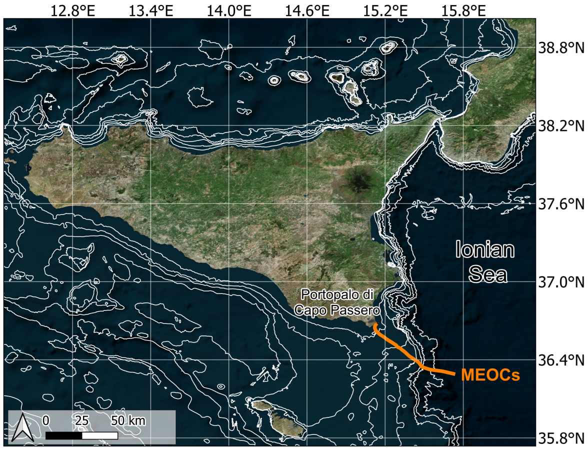

Figure 1. Bathymetric map of the southeastern coast of Sicily, displaying depth contour lines (isolines) that depict the underwater topography of the Ionian Sea. This map integrates satellite imagery with bathymetric data, emphasizing the morphology of the seabed. It also marks the location of the INFN - LNS Portopalo di Capo Passero site and indicates the path of the two MEOCs described in the text.

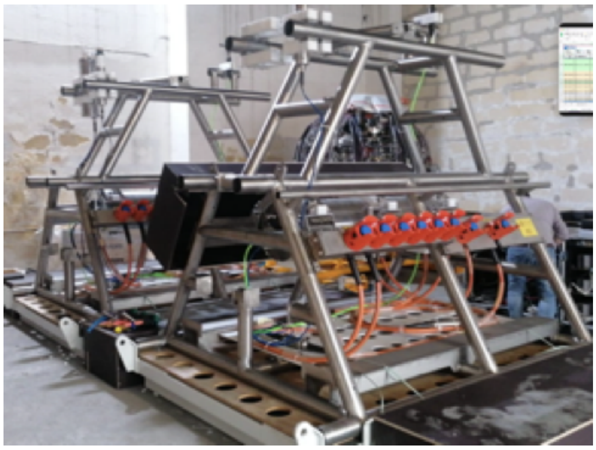

Figure 2. Picture of two Junction Boxes subsea assets in the assembly hall ready to be deployed on the seafloor of the Portopalo site.

modate up to six additional JBs. Each JB serves as a hub, supplying power and data connectivity to oceanographic probes and up to 14 observatories linked through electro-optical jumper cables. For acoustic monitoring, each JB is equipped with at least one hydrophone. This hydrophone (DG0330 from co.l.mar.) is omnidirectional, covering a frequency range from a few Hz to approximately 90 kHz, and operates via two output channels. The signal is processed through two amplifiers: one with a +26 dB gain and the other with a +46 dB gain. These gains allow the detection of both distant/weak and close/strong sources, preventing signal saturation. The high-gain channel has a Received Voltage Response (RVR) of about -156 dB re 1 V/μPa at 1 m. The two audio streams are recorded at 24-bit depth in stereo mode. Each JB incorporates a custom Instrumentation Control Electronics (ICE) board, developed by INFN, which acquires the audio signal and transmits it to shore within the JB's optical data stream. On land, data are stored and distributed to analysis stations. The data can indeed be accessed in native AES/EBU format (for compatibility with standard acoustic tools and software) or in an alternative format that retains acoustic fidelity (24-bit per channel, 195.3 kHz sampling rate, absolute time header).

3. DATA ACQUISITION (DAQ) CHAIN AND HARVESTING STRATEGY

A sketch of the Ocean Sound sub-system is represented in fig. 3. The data flow from the data acquisition to the data dissemination is managed entirely by each PU belonging to the RIs involved in the sub-system. Specifically, each PUs is responsible to harvest raw data, ensure the quality of raw data and the availability of a subset of raw data for checks and reproducibility, controlling the output files and data, archiving data and products and interfacing with the ITINERIS Marine Data Portal. Data are then continuously collected by saving 5-minute raw data files every 5 minutes from hydrophones. This is performed at the Ground Terminal facility (green box in fig. 3) located at the Capo Passero harbor INFN - LNS shore station. Custom data acquisition systems are employed to retrieve the acoustic data stream at the shore station's data center and subsequently transfer the data to dedicated computing services. Hardware and software developed by INFN - LNS enable full remote control of the subsea observatory, with the ability to modify data acquisition settings. Data are initially managed by a Virtual Machine (VM) that checks audio data integrity, verifies recording date and time, confirms data format, and detects missing chunks. Once the data passes these checks, a second VM analyzes them in a Near-Real-Time (NRT) mode. During

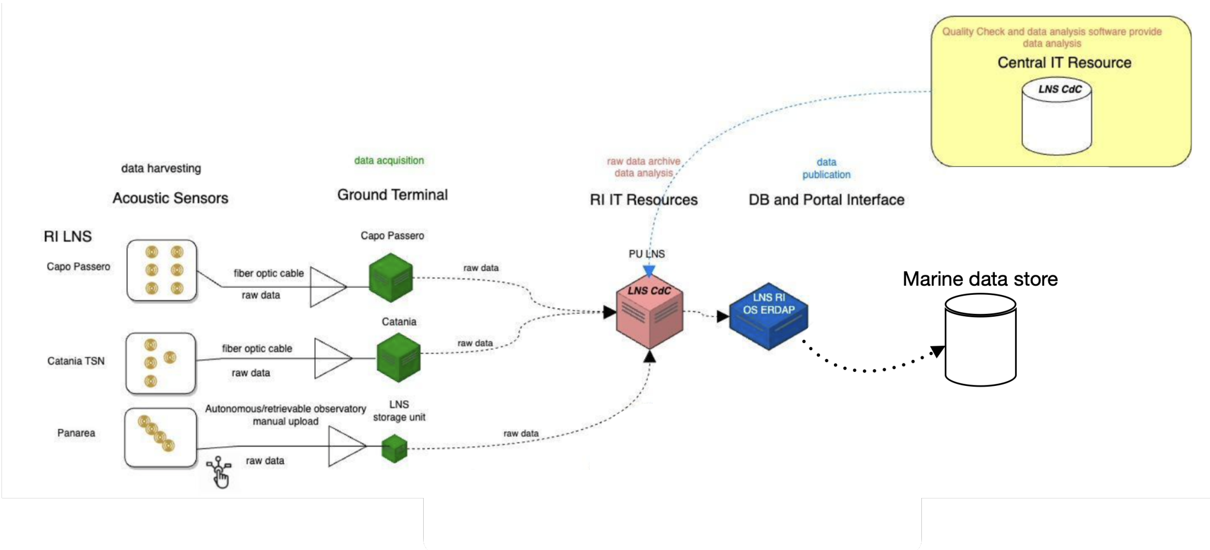

Figure 3. The logic flow of acoustic data generated by the Ocean Sound sub-system is shown. The layout of the system is parallelized in such a way that each RI builds up a proprietary data harvesting and output production chain. The OS-SS management is in charge for distributing/updating analysis codes and perform joint quality controls on output.

this stage, the raw binary files are converted into Hierarchical Data Format (HDF5) with a 6x compression ratio to save disk space (e.g., 5-minute raw recordings occupy around 225 MB at 24-bit depth and 195.3 kHz sampling frequency). Metadata are also generated at this stage and added to the raw file header. Indeed, FAIRness will be ensured through a shared protocol for data analysis and data quality check. In order to make acoustic raw data FAIR, it is essential, following the indications of EMODnet and GOOS on acoustic metadata format, to identify key information to be published together with raw data before any data elaboration. This will ensure quality control and certification of elaborated products.

The DAQ chain concludes with transferring all output data (both raw and analyzed) to permanent storage located in the INFN - LNS data center (labeled as LNS Production Unit (PU) in fig. 3, magenta box). Due to the large size of raw data files and the continuous acquisition process, only a portion of the acoustic data is permanently stored in the data center's digital memory, specifically one raw data HDF5 file per hour (6 GB/day). The remaining raw data is erased weekly after analysis. All processed data and products are also stored in HDF5 format, with their disk space usage being minimal (6 MB/file) compared to the raw data. Additionally, the primary storage system at INFN - LNS is continuously accessed by an ERDDAP (Environmental Research Division's Data Access Program [8]) server (blue box in fig. 3), acting as a bridge between local data and the ITINERIS Marine Data Portal [5]. ERDDAP is a web-based data server enabling users to search, visualize, and download diverse environmental and oceanographic datasets. It provides a unified interface for retrieving data in multiple formats, such as CSV, NetCDF, and JSON, and supports various data types, including time series, gridded datasets, and trajectory data.

3.1 Analysis and preliminary results

A key Essential Ocean Variable (EOV) for describing ocean ambient noise is the Sound Pressure Level (SPL) [9, 10]. When studying noise, averaging the measured data is crucial. This is because sound pressure fluctuates continuously, and an isolated "snapshot" at any given moment cannot reflect the statistical variations. To perform data averaging, the measured signals are segmented into analysis time windows. For each window, the SPL is computed at each analysis frequency (typically for every third-octave band). This process produces a sequence of SPL values for each frequency band, which are then processed to determine average levels and statistical variability. The appropriate window length depends on the characteristics of the data. For instance, sounds at frequencies below a few hundred Hz can travel great distances in deep oceans. Fin whales (*Balaenoptera physalus*) use these frequencies for communication, detectable hundreds of kilometers away [11]. On the other hand, low-frequency sounds from ships propagate equally well, potentially masking whale communications [12]. Projects like NEMO-OνDE [13, 14] and SMO-OνDE-2 [15] recently established a data library with over 2000 hours of recordings in the Ionian sea. This library is valuable for modeling underwater noise at great depths (about 2100 m), studying variations caused by environmental factors, biological sources, and human activity, and detecting cetacean presence [16, 17].

In the scenario presented here, a selection of raw data and SPLs in third-octave frequency bands are calculated and stored for soundscape analysis of the site. Specifically, from the continuous data stream of INFN - LNS audio assets, SPL provides statistical insights into how noise levels vary across frequencies or frequency bands within large samples. This is then used as inputs for algorithms that estimate the sources of sounds, such as vocal animals/cetaceans or anthropogenic activities. During the analysis chain, a set of metadata is also generated and integrated with the initial metadata from the raw file. As a result, the final HDF file includes not only the calculated SPL values (mean and percentiles), but also comprehensive information such as the sampling frequency, time/frequency resolution, time window, and other relevant parameters. In addition, it contains metadata related to the date and time of acquisition, geographical coordinates of the used mooring station, and other technical details, all in accordance with the ISO standards [8].
Considering all of the above, and following the prescription of the MSFD [18, 19], the mean SPL value is calculated alongside the 25th, 50th, 75th, and 95th percentiles for 5-minute intervals in third-octave bands including 63 Hz and 125 Hz bands (primarily cargo ship noise) as reported in fig. 4. The figure shows five-minute spectrograms in third-octave bands as recorded on March 25, 2025 (19:20 UTC) by an hydrophone of the network of the Capo Passero site. Here, an FFT with 2^{16} points and a 50% overlap Hamming window was used. This configuration provides a time resolution of approximately 0.3 seconds and a frequency resolution of about 3 Hz, with a sampling frequency of 195.3 kHz. Several high-frequency signals can be identified, primarily time-varying signatures from acoustic emitters located on the seabed of the

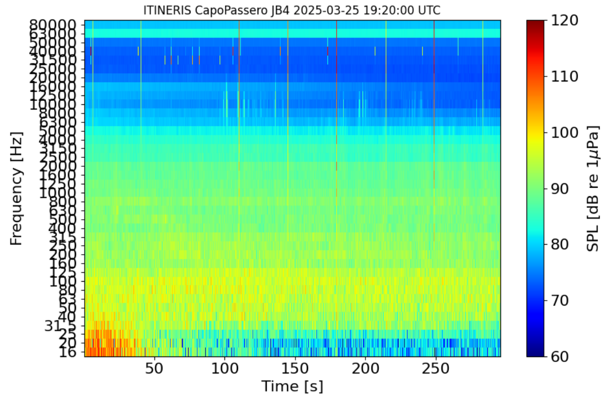

Figure 4. Spectrogram in third-octave bands as was derived from 5 minutes of acoustic recordings at the ITINERIS site on March 25, 2025, at 19:20 UTC captured by the hydrophone aboard one of the JB subsea assets (JB4).

site, which are captured by the hydrophone at frequencies ranging from 20 kHz to 50 kHz. These emitters are acoustic beacons used to triangulate the positions of observatories on the seafloor, and for the acoustic positioning system of the KM3NeT Neutrino Telescope [7]. At lower frequencies, the third-octave bands at 63 Hz and 125 Hz exhibit characteristic diffuse noise from maritime traffic. Preliminary analysis at lower frequency (tens of Hz) also denotes the presence of a transient event most probably related with and earthquake not detected from land instrumentation. Furthermore, a preliminary overview of the site's soundscape over an extended time period is presented in fig. 5, focusing on the two third-octave frequency bands at 63 Hz and 125 Hz. The long-term SPL monitoring data, acquired from the hydrophone at station JB4, shows the mean SPL values for these bands (63 Hz and 125 Hz, left and right plots respectively), over a 112-day period from December 10, 2024, to March 31, 2025 together with a linear fit (red line) just to drive the eyes and two horizontal lines corresponding to maximum value of the ratio (blue dashed line) and minimum one (green). The SPL values derived from the fit suggests a consistent presence of noise from commercial shipping activity in the area, with levels around 90 dB re 1μPa [12]. Finally an SPL' projection histogram is also reported together with the two time series at 63 Hz and 125 Hz, respectively.

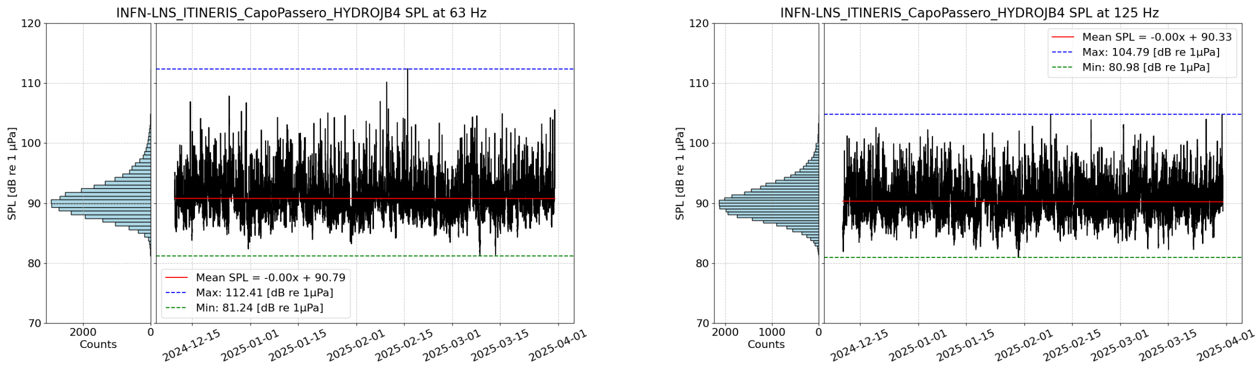

Figure 5. Mean value of SPL in the 63 Hz (left) and 125 Hz (right) third-octave bands as captured by the hydrophone aboard one of the JB subsea assets. It covers a 112-days of ocean sound recordings, taken from December 10, 2024, to March 31, 2025, at the Portopalo di Capo Passero site. The spectrum is predominantly populated by typical emission noise from commercial ships, with a sound level around 90 dB re 1μPa (left-hand side histogram of the two figures). It also displays a linear fit (solid red) and the maximum and minimum SPL' values in dashed blue and dashed green, respectively.

4. CONCLUSIONS

Sound pressure is one of the key variables for the Ocean Sound EOV. It travels through water as compressions and expansions and can be captured, either actively or passively, by underwater hydrophones [9]. This helps answer questions regarding how SPL contributes to soundscapes and the distance of sound sources. Overall, changes in ocean sound levels over time remain poorly characterized in the scientific literature. The lack of regularly sampled, long-term ambient sound data across diverse locations limits our capacity to assess global acoustic trends. This persistent data gap hampers the identification of areas where anthropogenic noise may be increasing, obscures the understanding of contributing sources, and poses challenges for the design and implementation of targeted mitigation strategies.

The analysis strategy proposed in this manuscript is designed as a unique, advanced monitoring tool for underwater noise levels in the framework of the ITINERIS project. Here, ocean sounds are captured by large bandwidth hydrophones installed at the INFN-LNS site of Portopalo di Capo Passero, Italy, facilitating real-time and long-term data collection. As stipulated by the European MSFD, studying SPL in third-octave bands is essential for monitoring ecological status and the effects of anthropogenic noise on marine mammals and other marine life. Within the ITINERIS project, INFN-LNS contributes to the creation of a national database for cataloging and validating acoustic data recorded by various partner research infrastructures, by establishing the so-called Ocean Sound monitoring sub-system. Data quality, especially metadata, is vital as it directly impacts result management, particularly for analyses that need to be comparable and repeatable across different RIs. Therefore, an unified strategy is being developed among the participating entities in the project to establish, for the first time, a national standard for the type and format of result sharing. Since the analysis is primarily conducted locally, data management rules will ensure uniformity and consistency in processing. Each recording is accompanied by a set of metadata in a standardized format, allowing for analysis by all partners, even years later. Such initiatives are essential to support robust scientific assessments and to guide the development of evidence-based policies aimed at achieving Good Environmental Status with respect to underwater noise.

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