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TOWARD FULL IMPLEMENTATION OF THE KM3NeT RESEARCH INFRASTRUCTURE

KM3NeT – INFRADEV 2 – HORIZON – 101079679

Report on the promotion of technology developments

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ABSTRACT

In this report, we summarize the efforts, conducted within the Kilometer Cube Neutrino Telescope (KM3NeT) Collaboration, towards the promotion of technological developments. In particular, KM3NeT is a large Research Infrastructure (RI) comprising a network of deep-sea neutrino

telescopes in the Mediterranean Sea. The requirements for ensuring the reliable operation of the detectors in the challenging environment of the deep sea and for achieving the physics goals of the experiment highlight the need for innovative solutions to the technological problems encountered. Close collaboration with the private sector is therefore essential to guarantee compliance with the KM3NeT standards. Here, we showcase this interchange, giving emphasis on the technological achievements advanced throughout this exchange, and underlining the ways that private companies have benefited from. We also report on workshops that took place between physics researchers, laboratory technicians and company employees, highlighting how private companies improved their knowledge and expertise in building products that are now available in store.

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IV. APPLICATION AREA

This document is a formal deliverable of the Grant Agreement of the project, applicable to all members of the KM3NeT – INFRADEV2 project, beneficiaries and third parties, as well as its collaborating projects.

V. TERMINOLOGY

KM3NeT	Kilometer Cube Neutrino Telescope
RI	Research Infrastructure
CSA	Coordination and Support Actions

ARCA	Astroparticle Research with Cosmics in the Abyss
ORCA	Oscillation Research with Cosmics in the Abyss
NMO	Neutrino Mass Ordering
WP	Working Package
AB	Acoustic Beacon
LBL	Long Baseline
DOM	Digital Optical Module
DU	Detection Unit
APS	Acoustic Positioning System
RAPS	Relative Acoustic Positioning system
LNS	Laboratori Nazionali del Sud
INFN	Istituto Nazionale di Fisica Nucleare
QA/QC	Quality Assurance/Quality control

VI. PROJECT SUMMARY

The Kilometer Cube Neutrino Telescope (KM3NeT) is a large Research Infrastructure (RI) comprising a network of deep-sea neutrino telescopes in the Mediterranean Sea with user ports for Earth and sea science instrumentation. During the EU-funded Design Study (2006-2010) and Preparatory Phase (2008-2012), a cost-effective technology was developed, deep-sea sites were selected and the Collaboration was formed in 2013. This proposal constitutes a second INFRADEV project dedicated to KM3NeT in order to implement an efficient framework for mass production of KM3NeT components, accelerate completion of its construction and provide a sustainable solution for the operation of the RI during ten or more years. Following the appearance of KM3NeT on the 2016 ESFRI Roadmap and in line with the recommendations of the Assessment Expert Group, this project addresses the Coordination and Support Actions (CSA) to prepare a legal entity for KM3NeT, accelerate its implementation, establish open access to the RI and its data and ensure its sustainability by implementing an environment-friendly operation mode and evaluating the Collaboration socio-economic impact.

VII. EXECUTIVE SUMMARY

In this communication, we summarize the knowledge and technology exchange that took place between universities, national laboratories and the private sector, in the context of the KM3NeT experiment. The development of several components essential for the realisation of the KM3NeT detectors was achieved through close cooperation between physicists, technicians and industry partners. Here we showcase this knowledge and expertise exchange, and underline how the private sector has benefited from it. We also report on workshops that were held along the same lines of reasoning.

VIII. TABLE OF CONTENTS

1. Introduction

The Kilometer Cube Neutrino Telescope (KM3NeT) is a large research infrastructure, comprising a network of deep-sea neutrino telescopes deployed in the Mediterranean Sea. It consists of two large-scale detectors:

- The Astroparticle Research with Cosmics in the Abyss (ARCA), and the
- Oscillation Research with Cosmics in the Abyss (ORCA).

The ARCA telescope is constructed for detecting high energy neutrinos from distant astrophysical sources, while ORCA has been designed to study neutrino oscillations and the neutrino mass ordering (NMO). The two detectors share the same design, technology and detector elements, with the distance between detection units optimised for the targeted energy regimes.

During the detector design and construction phases, the need emerged for KM3NeT to develop or modify technological solutions, to meet the specifications required. This work was primarily carried out within collaborating institutes and national laboratories, often in close cooperation with the private sector. The purpose of the INFRADEV2 Working Package (WP) 5.5 is to describe and document items that fall in this latter category. In particular, the aim of WP 5.5 is to showcase the interaction between physicists and private companies, highlighting how the industry has profited through this interchange and how they improved their knowledge and expertise.

The first attempts to install neutrino telescopes in the abyss represented a major technical and technological challenge and contributed significantly to the knowledge and technology transfer to KM3NeT. Within this framework, the ANTARES project provided opportunities for collaboration with companies, resulting in technological advancements from which KM3NeT has benefited. Similarly, several sea-based neutrino telescope projects are planned or under development worldwide, and the expertise gained through interaction with KM3NeT allows European companies to enhance their competitiveness and pursue supply opportunities.

The report on the promotion of technology developments includes the Acoustic Beacons used for the calibration system, which are described in Section 2, the KM3NeT hydrophones in Section 3 and the tripods hosting the acoustic beacons in Section 4. The Tektron battery packs are presented in Section 5 and the Deep Sea Canopus built in collaboration with EXAIL is mentioned in Section 6. The high-reliability acquisition electronics and the qualification and performance assessment of photomultiplier tubes are reported in Sections 7 and 8, respectively, and the knowledge transfer on the integration and testing of optical fibres is outlined in Section 9. Technology forums for discussing with industrial partners on common issues on equipressure and eco-responsibility in underwater exploration are mentioned in Section 10. Furthermore, the outcomes of two workshops that took place in

Catania, between physicists, technicians and company employees are outlined in Section 11. Finally, we report on the presentation of the KM3NeT technology at the Thessaloniki International Fair (TIF) on technology and innovation in Section 12.

2. Acoustic Beacons for KM3NeT

KM3NeT groups involved (University / Research group): IGIC - Universitat Politècnica de València / Physics applied to the detection of astroparticles and intelligent systems

Private company: Mediterráneo Señales Marítimas (MSM)

The project involved the design and manufacturing of the Acoustic Beacons (ABs) for the KM3NeT acoustic positioning calibration system. At the time of the KM3NeT design, identifying suitable marine acoustic transmitters proved challenging, as they had to satisfy all specifications required for the AB of the KM3NeT acoustic positioning system in terms of frequency range, power emission, operating depth, communication, small and precise latency for triggering, power consumption, and life expectancy. To comply with the KM3NeT standards, the AB was designed and developed by the UPV group in collaboration with MSM, combining the expertise in electronics, acoustics mechanics and marine technologies. The MSM company is manufacturing and supplying the product.

The AB (Fig. 1) is a broadband range acoustic emitter (20-50 kHz) able to work at rating depths up to 400 bars in an underwater environment. It provides the emission of short intense signals (Sound Pressure Levels larger than 180 dB per 1 µPa@1m at 34 kHz) and has Long Baseline (LBL) functionality. Each beacon can emit an arbitrary signal pre-defined from shore. The AB is composed of a piezo-ceramic transducer (Fig. 2) and an electronic board (Fig. 3) integrated in a one piece only system by a cylindrical aluminum or titanium vessel. The electronic board is specifically designed to fulfill the positioning system requirements, enabling the transducer communication and the signal emission control and amplification. It has a serial interface communication via RS232 for signal configuration from shore and a trigger line to emit the acoustic signal with a precision better than 1 µs. The system was fully tested and validated (pressure tests, electronics reliability, power consumption, shocks, …) and the acoustic emission has been fully characterized (Fig. 4).

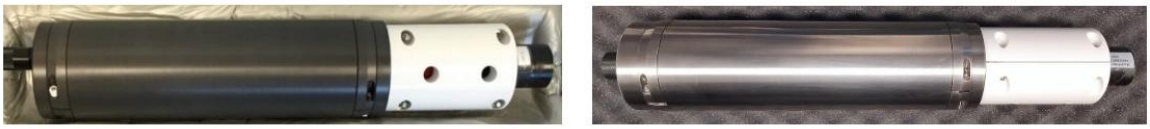


Figure 1: *Picture of the acoustic beacon. left: aluminum vessel; right: titanium vessel.*

Figure 2: *Pictures of the transducer of the acoustic beacon*

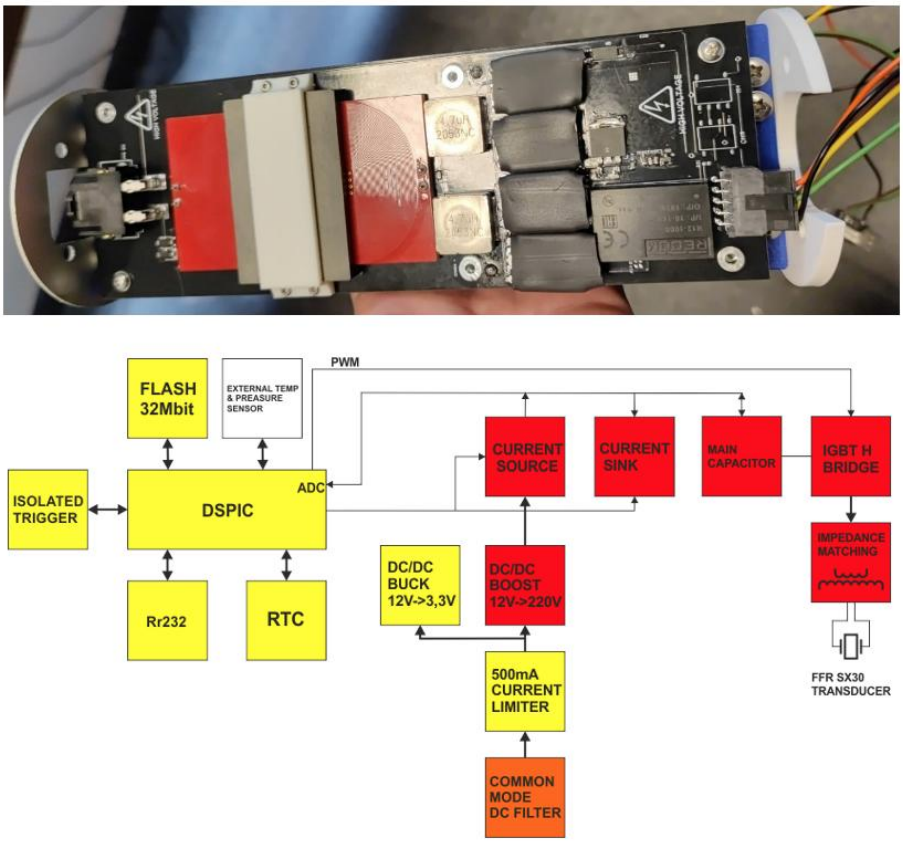


Figure 3: *Picture and block diagram of the acoustic beacon electronics.*

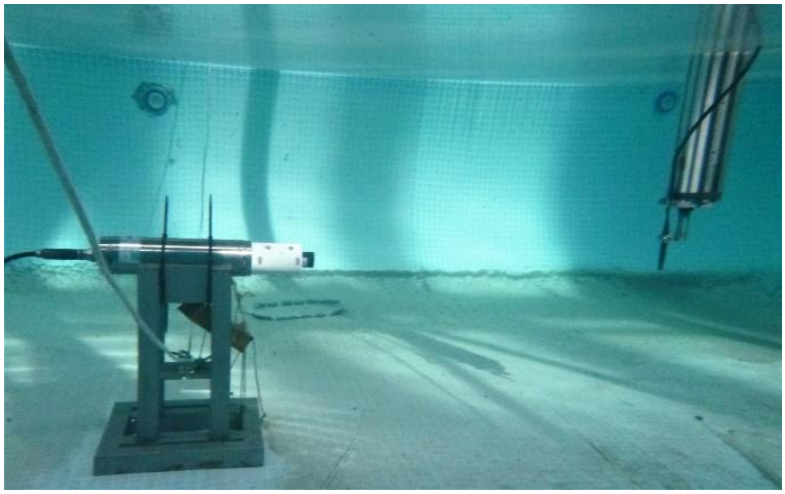


Figure 4: *Picture during the characterization of the AB in the pool at UPV facilities.*

The AB can work as autonomous or connected following the specifications of the KM3NeT experiment (Fig. 5). Both modes of operation are used in KM3NeT and the ABs emit the acoustic signals that are received by the piezoceramic sensors of the Digital Optical Modules (DOMs) of the telescopes forming a special long baseline positioning system. Knowing the position of the emitters, it is possible to monitor the position of the DOMs that are in motion due to the effects of sea currents.

The collaboration was highly synergistic, with each party complementing the other. On one hand the UPV group brings expertise in acoustic transducers for underwater applications, including the electronics, and as they are directly involved in KM3NeT they have a deep understanding of the problem. On the other hand, MSM is a reputable company providing technology and solutions for marine navigation and systems, with expertise in mechanics and marine technologies. Collaboration for the development and supply of the KM3NeT ABs started in 2014, signing an R&D contract for this purpose. Since then, the collaboration has been further strengthened through the signing of additional R&D contracts between MSM and UPV (in 2018, 2021 and 2023) for the AB development and supply to different groups in KM3NeT. The company has derived significant benefits, including the enhancement of its technical expertise, the strengthening of its reputation, and the initiation of related projects and product developments, Ref. [1, 2].

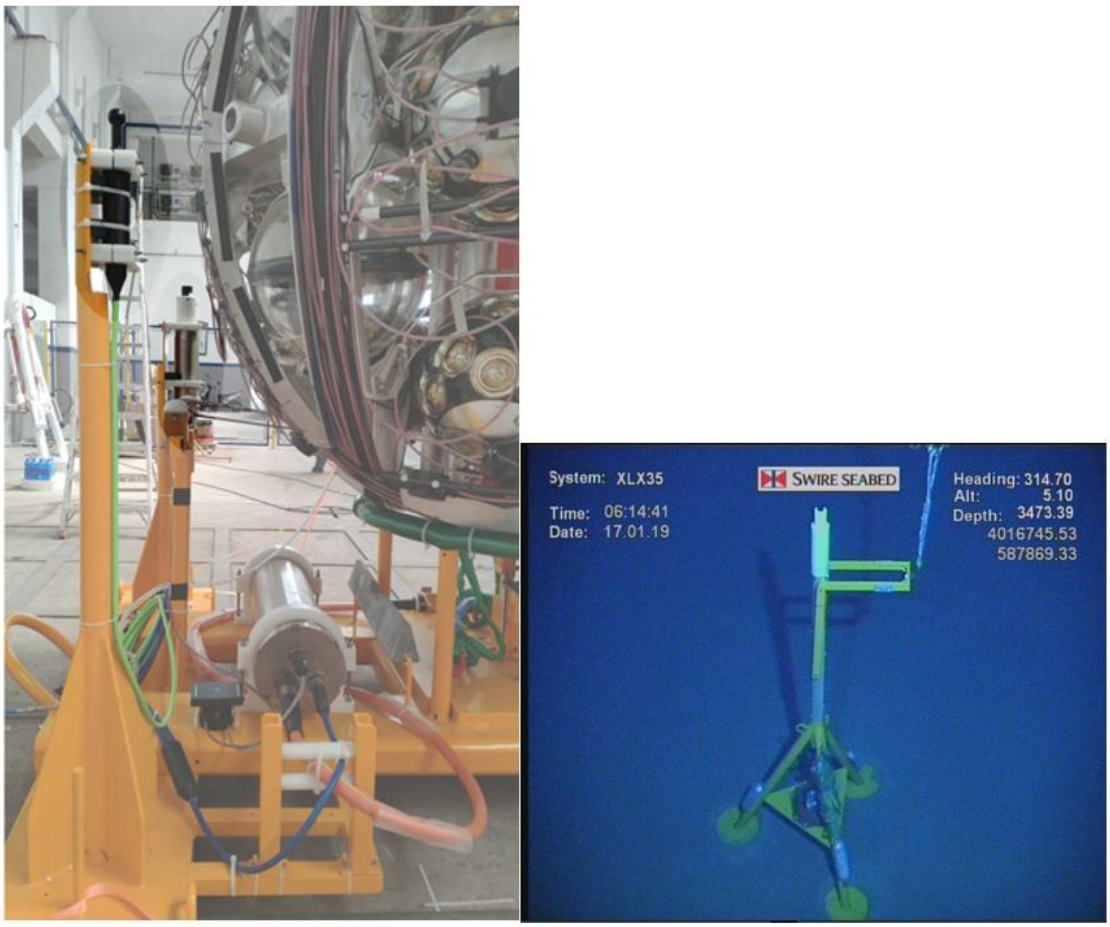


Figure 5: *AB integrated in a KM3NeT detection unit (left). AB deployed as autonomous (right)*

3. Hydrophones

KM3NeT groups involved (University / Research group): Instituto Nazionale di Fisica Nucleare - Laboratori Nazionali del Sud (INFN LNS), AstroParticule & Cosmologie - Université Paris Cité (APC), Instituto de Física Corpuscular (IFIC)

Private company: Co.l.mar and Telesub Lanterna

The hydrophones installed on the bases of the Detection Units (DU), whose primary goal is to provide fixed references for the LBL of the Acoustic Positioning System (APS) of the detector, are provided by Co.l.mar. In 2014 KM3NeT requested a novel technology based on a digital system with two different gain values and standard AES-EBU output to allow flexible interfacing with commercial software tools and boards.

In order to implement a phased array, the collaboration asked for a connection to an external clock synchronized with the detector master clock. High sampling rate 192 kHz and

quantization bit, plus low intrinsic noise and double gain (-156dB re 1V / uPa @ 5kHz and -176dB re 1V / uPa @ 5kHz) make this product unique within the context of deep-sea hydrophone applications. The interaction with the company was directed into three main activities:

- Improvement of reliability of the electronics
- Improvement of mechanics and connections
- Improvement of interfaces and calibrations

The first activity was carried out under a rigorous qualification plan organised by APC, IFIC and INFN, with the objective of improving component quality and resistance to stress tests, eliminating infant mortality. This enabled the company to develop standardized protocols for testing its equipment. An audit was carried out in March 2024 to check advancements and improve quality of storage and manufacturing processes. Moreover, the quality of the documentation improved significantly.

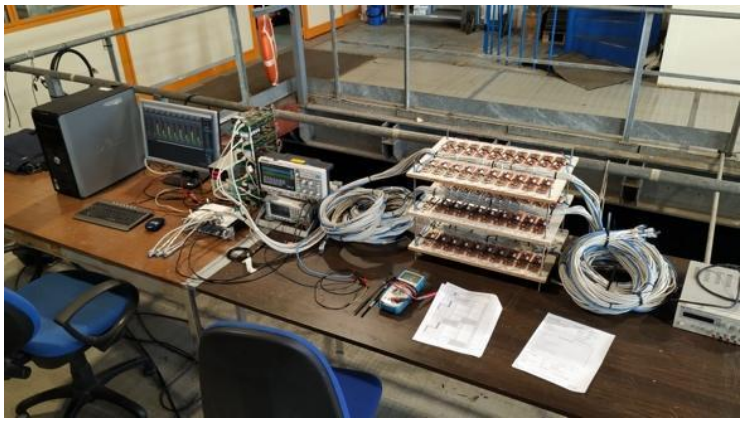


Figure 6: *A picture of the Co.l.mar hydrophone under test.*

For the second task, the company began with a basic hydrophone design using epoxy resin and a stainless steel casing, which demonstrated suboptimal performance. Following the interaction with KM3NeT, the design was thoroughly reviewed and a POM-C envelope was developed. From the point of view of subsea connectors and interfaces, the company suggested the use of titanium connectors in place of the original rubber molded ones originally planned by the collaboration. This contributed to improved reliability and long-term stability of the hydrophones. Collaboration with KM3NeT enabled the company to develop an interface tool to quickly read and power hydrophones.

The project has been advertised by Co.l.mar in [3]. More pictures and information on the Co.l.mar hydrophones, including some further specifications, can be found in the following brochures:

DG1330 Hydrophone

co.l.mar.

The digital hydrophone DG1330 is a cutting-edge device designed by Co.l.mar specifically for integration into the world's largest underwater observatory, the KM3NeT project and installed on ARCA/ORCA neutrino telescopes.

https://www.km3net.org/

Two channels with different gain
Very low self noise on both channels
Wide frequency range
High sensitivity. high dynamic range
24Bit, up to 216 kHz sample rate
External 25MHz digital clock input or internal clock
AES/EBU interface, USB and Analogue outputs.
Non metal body: corrosion proof
Ultra Deep & Long term deployment

www.colmaritalia.it

This hydrophone has been customized to seamlessly interface with INFN electronics, ensuring optimal performance within the project's sophisticated infrastructure.

Our hydrophone, chosen by INFN, is designed for recording acoustic signals up to depths of 3500m, with a lifespan exceeding 20 years. Its external POMC jacket, devoid of metallic components, mitigates galvanic corrosion risks, facilitating prolonged deployments. Featuring an internal stainless steel core, it ensures resistance against hydrostatic pressure, making it ideal for ultra-deep applications.

Following the success and demand generated by the KM3NeT project, this advanced hydrophone is now available for civilian use in stand alone version. It comes equipped with its own receiver featuring two analog outputs with varying gains, offering flexibility in signal processing. Additionally, it boasts a USB output for convenient signal acquisition directly to a laptop or computer.

Another feature of this system is its versatility in power supply. The entire setup, comprising the hydrophone and receiver, can be efficiently powered using a standard mobile battery charger, enhancing its usability and portability for a wide range of applications in underwater monitoring and research.

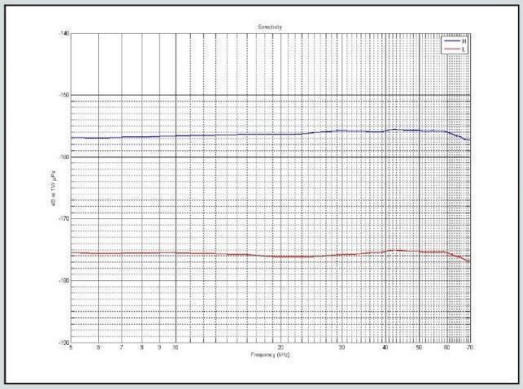
co.l.mar.

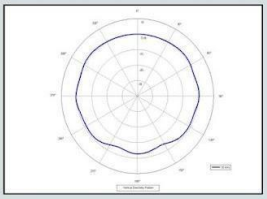
CO.L.MAR. S.r.l. via delle Pianazze, 74 - 19136 La Spezia (Italy)
Tel +39 0187 982590 Fax 943461 P.I.00742150113
e-mail: colmar@colmaritalia.it www.colmaritalia.it

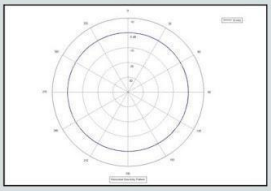
DG1330 Hydrophone

www.colmaritalia.it

Working band:	5-90.000 Hz
High pass filter on preamplifier :	700 Hz (on demand)
CH1 output sensitivity:	-156dB re 1V / uPa @ 5kHz
CH2 output sensitivity:	-176 dB re 1V / uPa @ 5kHz
Directivity :	Spherical - Omnidirectional
Max working depth :	3500 m
Gain @5kHz:	46 dB (CH1), 26dB (CH2)
Equivalent input acoustic noise @5kHz:	34 dB re 1uPa / sqrtHz
Input impedance:	10 MOhm
Hydrophone supply voltage range:	9 -18 Vdc
Current consumption:	100mA @ 12 Vdc
Output:	AES3 protocol
Weight in air:	1600 gr with 4m cable
Body construction:	POMC (stainless steel inner core)
Dimensions:	330 x 52 mm
Receiver power supply (gives 12 Vdc to hydro.)	5Vdc
Receiver outputs:	CH1 and CH2 analogue (BNC), USB digital for PC
Receiver Inputs:	Coax in (stand alone version), RJ45 (INFN version)







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4. Tripods

KM3NeT groups involved (University / Research group): Instituto Nazionale di Fisica Nucleare - Laboratori Nazionali del Sud (INFN LNS), AstroParticule & Cosmologie - Université Paris Cité (APC)

Private company: SAMO S.R.L.

The company SAMO srl provides tripods used in KM3NeT. These are mechanical structures that host the acoustic beacons for the acoustic positioning system long-baseline of KM3NeT used in ARCA and, till 2023, also ORCA. Despite its apparent simplicity the structure requires a special design and construction rules to operate in deep sea for 20 years, with planned recoveries and immediate redeployment every 3 years for refurbishment of scientific payload onboard. Stability and balancing on sea-bottom and during deployment and recovery must be considered both for loading/unloading (in air) deployment/recovery (in water) operations.

SAMO worked with KM3NeT to improve the design of the tripods and to establish best practices for quality assurance and control, such as the use of certified materials, and the application of welding and corrosion protection measures (use of specific painting and anodes) to comply with deep-sea oil-and-gas standards and certifications.

Figure 7: *Pictures of the KM3NeT tripods*

The company benefited from the interaction with the KM3NeT Collaboration, incorporating expertise in deep-sea mechanics and corrosion protection. Thanks to the

acquired expertise the company has become a local reference for research institutes and other scientific companies working in marine environments, providing mechanical structure for both deep sea and shallow water projects.

5. Tektron battery packs

KM3NeT groups involved (University / Research group): Instituto Nazionale di Fisica Nucleare - Laboratori Nazionali del Sud (INFN LNS), Instituto Nazionale di Fisica Nucleare - Sez Catania

Private company: Tektron

Tektron provides the battery packs installed on tripods for the autonomous beacons of the acoustic positioning system of KM3NeT used both for ARCA and ORCA. Battery packs are made with glass housing inside which a set of Lithium Batteries (four planes of four parallels and series, designed to provide 12VDC, for more than 400 Ah) is packed properly to ensure safety and reliability for subsea use. A dedicated wake up board, allows (pre)setting of intervals at which the battery pack can be activated to deliver the requested power provided by the battery core.

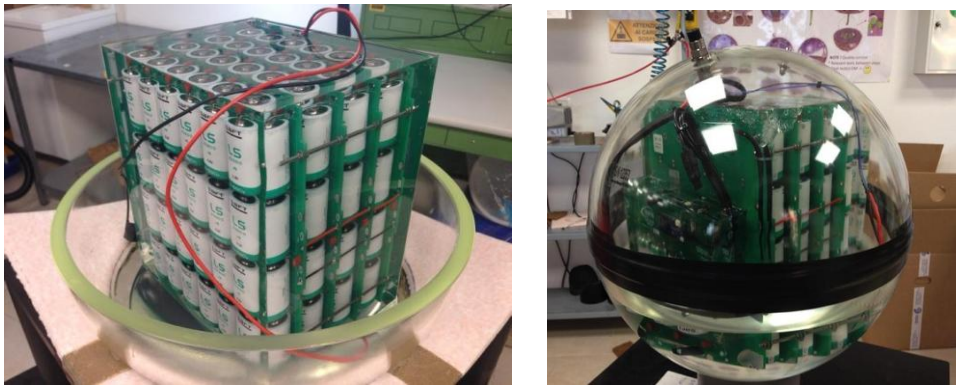

Figure 8: *Pictures of the Tektron battery packs*

Once the technology has been established and first prototypes have been developed, the industrialization of the production process has been refined by a local Sicilian company which today takes care of construction, assembly and test. The company has become a reference for this part of the project and produces today battery packs for a few users in subsea applications. A picture of a battery pack for a different scientific application is shown below:

Figure 9: *Photographs of the Tektron battery packs prepared for another experiment.*

6. Deep Sea Canopus

KM3NeT groups involved (University / Research group): Instituto Nazionale di Fisica Nucleare - Laboratori Nazionali del Sud (INFN LNS)

Private company: EXAIL

KM3NeT currently employs a Relative Acoustic Positioning System (RAPS) that uses a long baseline of acoustic beacons and receivers placed on Detection Units and Junction Boxes. These are powered from shore and synchronized with the detector master clock. Additionally, a subset of 3 to 4 autonomous, battery-powered beacons is used, which are recovered every three years for battery replacement and refurbishment. To enhance the georeferencing of the units for astronomy purposes, KM3NeT needs to recover the position of at least 3, ideally 6, RAPS elements. Consequently, KM3NeT has tasked EXAIL with developing an absolute positioning system for the telescope, incorporating both on-shelf and off-shelf equipment.

For this project, conventional LBL techniques were employed. The Canopus LBL transponder and the Ramses transceiver, both already available on the market, are the main

components of EXAIL's LBL system. A cabled Titanium Canopus transponder, developed specifically for this project, will remain on the junction box for over 20 years, powered externally. The transponder's measurements will be outputted via a serial communication port.

The system will ensure:

- Positioning of any mobile transponder during the deployment phase within the LBL array.
- Positioning of the ROV within the LBL array.
- Real-time monitoring of pressure and baselines between reference autonomous transponders on the seabed, any other mobile transponder, and the cabled transponders on the junction box. Data will be sent to shore through the transponders installed on the junction box.

The specifications of the cabled Titanium Canopus transponder, including its compatibility with existing KM3NeT seafloor assets (Junction Boxes), were discussed in several joint meetings between the KM3NeT Collaboration and EXAIL. These meetings covered various aspects such as mechanical constraints, shell materials, power consumption, inrush current limitations, and communications.

The positions of the elements of the proposed absolute positioning system on the sea floor were also decided in joint meetings, where scientific and technological requirements were analyzed and evaluated within a framework of mutual knowledge exchange and growth.

Thanks to the collaboration with KM3NeT, EXAIL will develop a transponder for an absolute positioning system for the first time, capable of remaining operational for over twenty years. This will be the first time such a system will be operated for such long periods and at a depth of 3,500 meters. The development of a wired system connected to the KM3NeT detector's data transport network ensures that measurements can be constantly monitored remotely. The ability to integrate the results of the system developed by EXAIL with the relative positioning data of KM3NeT also represents an opportunity to refine the reconstruction techniques used and evaluate performance over long time scales.

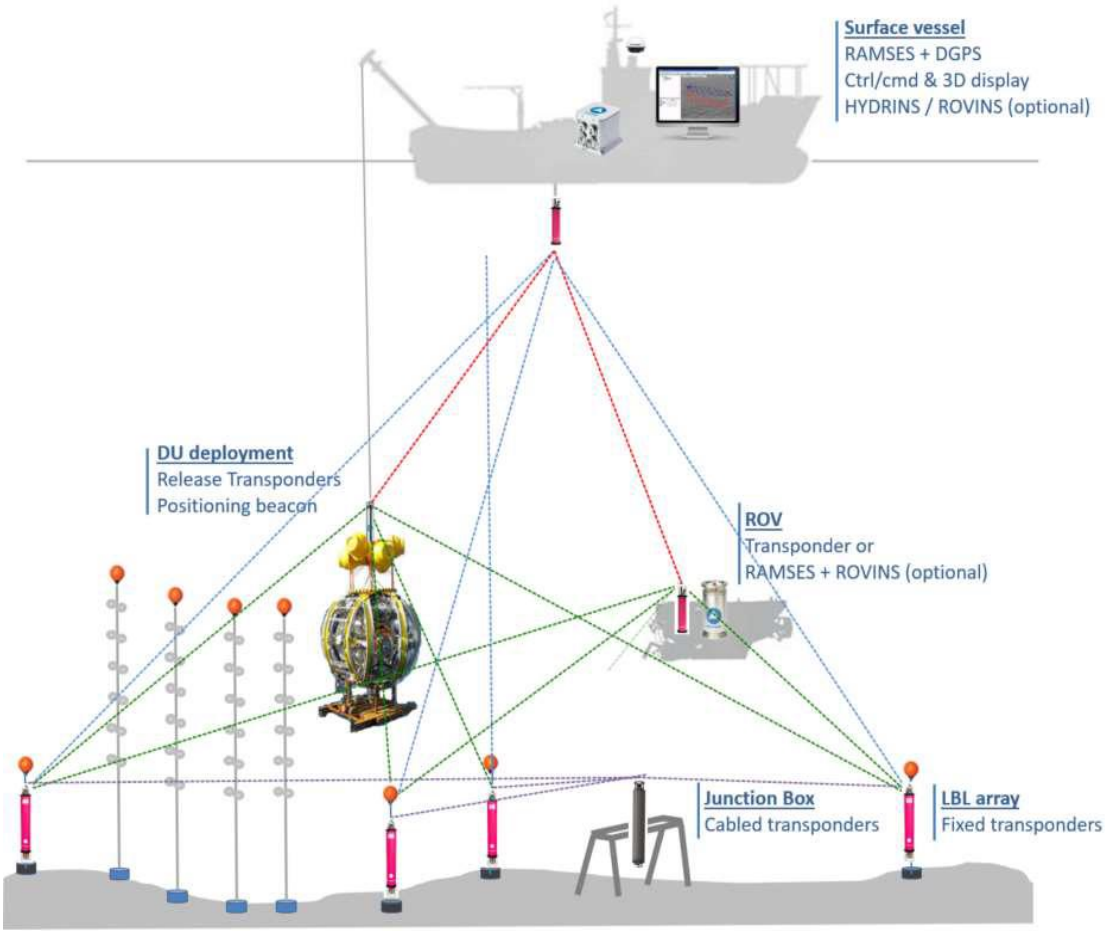

Figure 10: *Schematic of the absolute positioning system co-developed by EXAIL and KM3NeT.*

7. High-reliability acquisition electronics

KM3NeT groups involved (University / Research group): Universitat de València

The KM3NeT deep-sea neutrino telescopes are equipped with more than 10,000 Digital Optical Modules (DOMs). Each DOM houses 31 photomultiplier tubes and sophisticated electronics. The Central Logic Board (CLB) in each DOM manages data acquisition with sub-nanosecond precision via the White Rabbit protocol, while consuming only about 7 W. As the system is designed to operate at extreme depths (2500 m - 3500 m), ensuring reliability is of primary importance. KM3NeT has implemented a comprehensive reliability strategy for the electronics of the ARCA and ORCA detectors, combining FIDES (Reliability, Availability, Maintainability, Safety) analysis, Design for Manufacturability (DfM) optimization, and rigorous Highly Accelerated Life Test (HALT) and Highly Accelerated Stress Screening (HASS) testing.

Produced by several European industries, including the defense and aerospace sectors where product reliability is critical, the FIDES Guide provides a practical tool for controlling and improving reliability throughout a product's lifecycle. KM3NeT employs the FIDES methodology to quantify electronics reliability for deep-sea operation.

Three projects related to enhancing system robustness by solving synchronization issues, monitoring critical parameters and improving reliability are supported either by scientific or knowledge transfer grants to advance the technology readiness level (TRL) of the products, aiming at commercialisation. These projects involve:

- Advancing toward the development of an acquisition module based on ADCs, with sub-nanosecond synchronization provided through the White Rabbit protocol. The project started from the initial development phase, TRL0, and it is expected to reach TRL4. An expansion board providing White Rabbit Functionality is also being developed in its early technological stages, progressing from TRL0 to TRL4.
- Improving the synchronization level achieved by the White Rabbit switch and developing another component, a White Rabbit acquisition node based on TDCs. The goal is to achieve a TRL 8-9 by the end of the project for the TDC-based acquisition node.
- Improving the reliability of the White Rabbit Switch, equipping it with two redundant power supplies that can be hot-swapped (disconnected and connected) while maintaining the switch's functionality, including synchronization at a sub-nanosecond level. Additionally, an improvement of the calibration between the ports of the switch is expected.

Optimizing the reliability and ensuring robustness and long-term performance of the electronics are not only important for the qualification of the KM3NeT acquisition electronics, but also of significant interest to the industrial sector. Feedback from the strategies implemented by KM3NeT has led to significantly lower failure rates in the latest generations of the electronics. Current efforts are directed towards refining reliability models through the integration of operational experience and automating quality control.

8. Qualification and performance assessment of photomultiplier tubes

KM3NeT groups involved (University / Research group): Instituto Nazionale di Fisica Nucleare – Sezione di Napoli (INFN NA)

Private company: Hamamatsu Photonics

The 3-inch R14374-02 photomultiplier tube (PMT) by Hamamatsu is an evolution of the R12199-02 model previously used in the KM3NeT DOMs and was selected as its successor due its enhanced time response and improved photo-detection uniformity. PMTs are the core components of the KM3NeT digital optical modules (DOMs) and thus crucial for the construction of the telescopes, so the qualification and performance assessment of the new PMT model are essential. More than 1000 R14374-02 PMTs were characterized to determine key performance indicators such as: dark count rate, transit time spread (TTS), and spurious pulse rates.

Additionally, a subset of 200 PMTs underwent detailed quantum efficiency (QE) mapping which is essential for accurate Monte Carlo simulations of the detector response.

Custom automated test benches as well as procedures were developed to ensure fast, reproducible, and precise evaluation of such a large batch of sensors. A major challenge involved the need to standardize procedures across several labs, maintain consistency over a multi-year testing campaign, and guarantee compliance with the strict specifications defined by the KM3NeT Collaboration. The improved features of the R14374-02 model are directly reflected in an enhanced timing resolution for track reconstruction, better efficiency calibration for neutrino event simulations and improved homogeneity, minimizing DOM-to-DOM variability in response. Due to its improved performance, this model has become the standard choice for all future lines of the KM3NeT detector, both in the ARCA and ORCA configurations.

A strong collaborating workflow was established between the KM3NeT institutes (in particular INFN and other European labs) and Hamamatsu Photonics, resulting to a deep technical exchange that included:

- Bilateral meetings to define improvements from the R12199-02 to the R14374-02 model held at CAPACITY laboratory in Caserta
- Regular testing updates and review calls during the mass production phase

Hamamatsu Photonics benefited significantly from this collaboration with KM3NeT in several ways:

- Product Development: Feedback from KM3NeT led to optimizations in the R14374-02 tube, including a more uniform photocathode layer deposition and enhanced dynode structure for improved TTS.
- Performance Validation: The KM3NeT test campaign represented an extensive long-term stress test, uncovering subtle issues in early batches and allowing Hamamatsu to refine manufacturing processes.
- Market Reputation: Successful deployment in a high-profile scientific experiment like KM3NeT boosted Hamamatsu's credibility and visibility in the field of deep-sea and high-energy physics instrumentation.

- Internal Expertise: Through repeated interactions with physicists and engineers from KM3NeT, Hamamatsu's staff gained deeper insight into scientific-grade detector requirements, reinforcing their ability to serve similar projects in the future.

9. Integration and testing of optical fibres

KM3NeT groups involved (University / Research group): Instituto Nazionale di Fisica Nucleare – Laboratori Nazionali del Sud (INFN LNS)

Private company: ELMACOM S.R.L.

The company ELMACOM srl situated in Rome, provides the ARCA Junction Box (JB) vessel used in KM3NeT. In particular, each ARCA Junction Box has two Optical -Power Assemblies (OPA) installed in the frame. Each OPA manages seven detection units, resulting in a total of 14 detection units per JB. The collaboration designed the entire optical network and carried out the integration of the first three OPAs at Laboratori Nazionali del Sud.

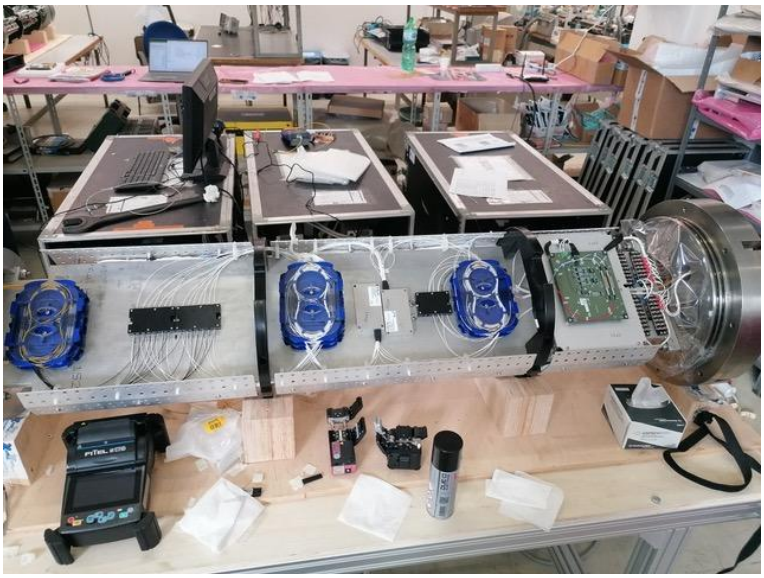

Figure 11: *Picture of the fully implemented optical Junction Box vessel.*

KM3NeT expertise was transferred to the company by Jan-Willem Schmelling and Sara Pulvirenti. Having acquired the necessary expertise to integrate the optical components, the company has become a reference point for this part of the project and now handles the integration of the JB optical network.

Through its interaction with the KM3NeT collaboration, Elmacom acquired expertise in optical splicing and in network testing using dedicated instrumentation, including a Tunable Laser source and an Optical Power Meter.

Figure 12: *Picture during the training provided by KM3NeT experts at Elmacom.*

The expertise acquired enables the company to expand its service portfolio to additional interested customers. For example, after KM3NeT training, Elmacom implemented the integration and testing of the optical part of the underwater station Marine Hazard Project (https://km3net4rr.infn.it/marine-hazard/).

Figure 13: *Optical splicing in the JB vessels at Elmacom.*

10. Equipressure and eco-responsibility technology Forums

CPPM has prioritised the organisation of a technology forum to provide an opportunity for discussion with industrial partners on common issues. Open to scientists, engineers and technicians, the aim of the forum was to share experiences, get feedback, exchange ideas and clarify shared questions. Two themes (one technical and the other cross-disciplinary) were chosen, reflecting the issues shared by the academic and industrial communities:

1. **Equipressure**, presented by Alain Cosquer (CPPM engineer)
2. **Eco-responsibility**, presented by Philippe Lagier (CPPM engineer)

This discussion was held as part of the ‘’Des abysses au cosmos‘’ exhibition, organised by the CPPM and the town hall of La Seyne-sur-Mer from September 15 to October 8, 2023, at the Fort Napoléon, and in which the industrial partners of the CPPM were also represented.

Figure 14: *Equipressure and eco-responsibility technology forums at the CPPM in France.*

The idea for this exhibition, which has attracted more than 1,500 visitors since it opened, arose from a proposal to celebrate the dismantling of the ANTARES experiment, which began almost thirty years ago, at the beginning of neutrino research. At the time, this was one of the

first attempts to install a neutrino telescope in the abyss, which represented a real technical and technological challenge. Although the telescope was dismantled in 2022, the connecting cable and junction box are still at the bottom of the sea. The construction and operation of the detector have enabled the CPPM to capitalize on this experiment from a technical point of view. This feedback has also enabled the development of the KM3NeT second-generation neutrino telescope and the Laboratoire Sous-Marin Provence Méditerranée (LSPM) interdisciplinary underwater platform.

Round table of participants:

Viorel Ciausu	Submarine Systems Unit, Ifremer
Jean-Marie Poye-Bottan	SIMEC Technologies, Orange Marine Submarine Engines department
Stéphan Beurthey	In charge of developing and promoting partnerships, IN2P3/CNRS and CPPM
Sébastien Lacombe	Underwater engineering and marine operations, SnaecO
Christophe Lerouvillois	KM3NeT Design engineer, CPPM
Vincent Bertin	ANTARES and KM3NeT Physicist, CPPM
Damien Dornic	ANTARES and KM3NeT Astrophysicist, CPPM
Evelyne Garçon	Engineer in experimental techniques, CPPM
Carl Gojak	EMSO Observatory, DT INSU/CNRS
Victoria Ciarlet	European Project Manager for KM3NeT-INFRADEV2, CPPM
Stéphane Théraube	LSPM Power Manager, CPPM
Pascale Keller	Instrumentation engineer and LSPM operational manager, CPPM
Guillaume Matte	R&D Engineer, Exail
Charles Rebour	Mechanical engineer, OSEAN
Olivier Philippe	CEO, OSEAN
Hervé Allaire	Founder and CEO, Ship As A Service SAAS/COMEX Marine
Jan Opderbecke	Submarine Systems Unit, Ifremer

Figure 15: *Exhibition stands at the equipressure and eco-responsibility technology forums at the CPPM in France.*

Figure 16: *Exhibition stands at the equipressure and eco-responsibility technology forums at the CPPM in France*

Figure 17: *Exhibition stands at the equipressure and eco-responsibility technology forums at the CPPM in France*

Equipressure

The design of equipressure systems, defined as systems in which pressures are equal and in equilibrium, is affected by various parameters, including the air, the properties of the working fluid, variations in its state parameters, and the deformable or rigid nature of the surrounding medium.

The principles and environmental constraints of equipressure systems were discussed giving emphasis to the methods tested and used for designing closed systems. For the design of the Node, intended to be placed at a depth of 2,500 m for several years, the systems had to withstand a pressure of 250 bar. Unlike what one might imagine, the enclosure was not a 'non-deformable' medium: the aim was to design an elastic medium that could adapt to the pressure of different environments (underwater and outside). At CPPM oil filling is used to create a deformable medium. Selected key topics of the discussion are reported. These include the main points to consider when designing such systems:

- the integrity of the systems during descent and ascent, under safe conditions as the constraints during descent and ascent are not the same; as an example, the Rolex luxury watches are resistant to depths of thousands of metres and fitted with a non-return valve for ascent.
- the conditions under which the equipment will be used, whether it will be in a permanent state (15-year structure at the bottom of the water) or whether it will be lowered and raised regularly.
- managing a system with cinematics, i.e. whether or not it is moving once it has been immersed to great depths.

This was followed by an exchange of experiences among the participants, with each representative presenting how equipressure was applied in their sector and under their unique constraints.

- The experience at the CPPM and the nodes design were discussed, as at the CPPM, the use of equipressure has been successful and has reduced costs.
- SnaecO and conception of Remotely Operated underwater Vehicles (ROV): The experience using equipressure to design a miniature hydraulic compensator with a rolling diaphragm, which was not commercially available, for a small ROV, was shared.
- SIMEC/Orange marine for the design of compensation systems: A presentation was given on the application of equipressure in the design of compensation systems for ROVs. These systems are equipped with position sensors, eliminating the need for a camera to monitor the volume of oil, particularly on moving robots. These sensors give a constant indication of the oil level and identify any leaks.
- La DT NSU et le IODA6000: The IODA6000 was an incubator for measuring the dynamics of oxygen concentration. Lessons learnt from the first instrument, which was made entirely of polycarbonate and in equipressure (including the battery) were discussed and the difficulties encountered for equipressure electronics were detailed.

Eco-responsibility in underwater exploration

Eco-responsibility is a vast subject, difficult to grasp, especially for non professionals trained in the field. The aim of the discussion was to address eco-responsibility in the context of the design and operation of detectors, underwater exploration and marine operations. A collective discussion subsequently took place on a range of issues common to all professionals in these sectors.

The impact of the ANTARES experiment on the marine environment as well as the impact of the main materials used for the detector construction, the sea campaigns for the installation and the technical resources for the production and operation of the detector were addressed. The feedback from ANTARES has been evaluated and has led to improved environmental standards in the design and operation of the KM3NeT detector, i.e. the choice of oil, which is now biodegradable, purchasing is now governed by eco-responsibility standards when it comes to choosing subcontractors, etc. The design of the KM3NeT lines was also given as an example, which is more compact than the ANTARES line, making it possible to use the ships more efficiently, by allowing several compact lines to be stored on a ship. During the workshop, an extensive discussion was held on the changes required to make the sector more “eco-responsible”, stressing the importance of balancing economic, commercial and environmental considerations.

11. Optical fibers workshops

At the *Laboratori Nazionali del Sud* (LNS) in Catania, two different editions of workshops were organized with optical fibers as the main topic. In particular, these two workshops were organized within the *Istituto Nazionale di Fisica Nucleare* (INFN) training plan, inviting all INFN technicians and researchers interested. The organizer, Giuseppina Larosa, is the KM3NeT/LNS Base Module Integration Site responsible and local Quality Assurance/Quality Control (QA/QC) responsible. Additionally, Sara Pulvirenti served as the instructor for the optical fibers course. Both Giuseppina and Sara are researchers at LNS in Catania.

The title of the workshops was in Italian “Corso di fibre ottiche e applicazioni nella ricerca scientifica”, and in English “optical fibers course and applications in scientific research”. The practical sessions of the workshops took place at the Portopalo shore station.

Figure 18: *Course at LNS in Catania.*

Figure 19: *Practice session at Portopalo di Capo Passero.*

The first edition of the workshop lasted three days, from April 3rd to April 5th, 2024. The number of participants was 31 and the courses proceeded in the following way:

- First day: Four hours of courses covering basic theory of optical fibers, types of fibers, power budget, type of connectors, type of cables, and introduction to optical networks.
- Second day: Seven hours of courses were held at the Portopalo shore station (optical fibers instrumentation theory: optical power meter, use of Optical Time-Domain Reflectometer (OTDR) for characterisation of optical fiber cables and trouble shooting; Optical Spectrum Analyzer (OSA), a crucial instrument in fiber communication networks; methods for joining optical fibers). Participants were divided into five groups, each working with a different set of equipment corresponding to the instrumentation covered during the courses.
- Third day: Four hours of courses on theory of active and passive optical components and the operation of an optical network.

Figure 20: *Group picture of the first edition of the workshop held at Portopalo di Capo Passero shore station.*

The second edition of the workshop lasted four days; from December 9th to December 12th, 2024. Thirty three technicians and researchers participated. In the Portopalo shore station, two LNS technicians (Giuseppe Passaro and Bernadette Cavallaro) provided assistance during the practical training sessions. The workshop followed the structure outlined below:

- First day: Three hour courses were held. These covered basic theory of optical fibers, types of fibers, power budget, type of connectors, type of cables and different use and introduction to optical networks.
- Second day: Seven hours of courses covering optical fibers instrumentation theory: optical power meter, OTDR, OSA and methods for joining optical fibers.
- Third day: Practice sessions at the Portopalo shore station. Participants were divided into five groups, each working with a different set of equipment corresponding to the instrumentation covered during the courses.
- Fourth day: Courses covering the theory of active and passive optical components, and the operation of an optical network.

Figure 21: *Course at LNS in Catania.*

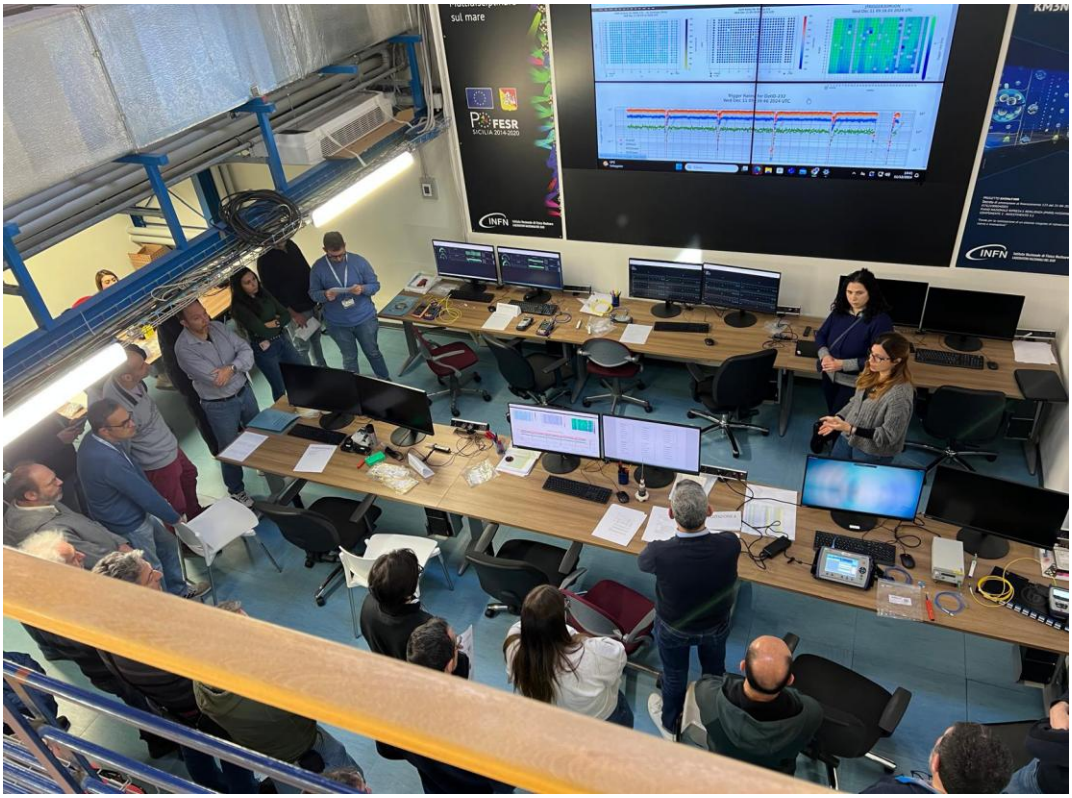

Figure 22: *Practice session at Portopalo di Capo Passero shore station.*

Figure 23: *Group picture, from the second edition of the workshop at Portopalo di Capo Passero shore station.*

Through both these workshops, company employees had the opportunity to learn from physicists and laboratory technicians on the theory of optical fibers and the basic principles of their operation. They also received advanced training on specific parts of optical fiber theory and instrumentation. Additionally, and through the practice sessions, they gained hands-on experience in working with optical fibers and optical networks. Both knowledge and expertise were transferred by INFN physicists and technicians to the private sector.

12. Participation in a technology exhibition

The KM3NeT technology was presented through our participation in the Thessaloniki International Fair (TIF) on technology and innovation in September 2024. TIF is an annual international exhibition event officially opened by the country's prime minister. TIF is the most important exhibition in Greece focusing on promoting new technologies, innovative ideas and ambitious entrepreneurial ventures. It is housed in a centre with indoor exhibition areas of a total of 62,000 m^2, distributed into a complex of 17 pavilions corresponding to different thematic entities.

The exhibition lasted for a week. University students, academics and technology experts were introduced by our team to the KM3NeT technology and physics objectives. As the digital optical module (DOM) is the core concept of the project, a specially built 'dummy' DOM for exhibition purposes was displayed, and videos were shown featuring impressive snapshots from the deployment of KM3NeT Detection Units.

Figure 24: *Introducing KM3NeT technology and physics objectives to the Deputy Minister of National Economy and Finance of Greece during the Thessaloniki International Fair.*

Figure 25: *Introducing KM3NeT technology and physics objectives to the Greek General Secretary for Research and Technology (GSRT) during the Thessaloniki International Fair.*

Figure 26: *Introducing KM3NeT technology and physics objectives to the Greek Deputy Minister of Development during the Thessaloniki International Fair.*

13. Conclusions

In this technical report, we presented a list of items needed for the instrumentation of the ARCA and ORCA detectors. These products were designed and constructed by KM3NeT institutes and laboratories, in close collaboration with private companies. In this respect, we showcased the exchange of knowledge and expertise that took place during the production of these components, and explained how the private sector has benefitted from this process. Most of these items are now available in the market (sold by the private companies), and several other experiments use them in their apparatuses. In addition, leading companies have benefited from the feedback resulting from the strategies implemented in KM3NeT for qualification and performance assessment and for improving reliability. Collaboration with KM3NeT has led to significant improvements in the latest generations of both photomultiplier tubes and electronics. We also reported on technology forums and on two editions of workshops that took place in 2024 between physicists, technicians and company employees. Finally, we summarised the presentation of the KM3NeT technology at the Thessaloniki International Fair (TIF) on technology and innovation.

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