The KM3NeT Acoustic Positioning System: the ARCA case

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Abstract: *KM3NeT is an underwater high-energy neutrino telescope, using the water-Cherenkov technique to reconstruct neutrino originated events in seawater. The telescope consists of two detectors located offshore Toulon, France, at 2500 m water depth (ORCA, Oscillation Research with Cosmics in the Abyss) and offshore Capo Passero, Italy, at about 3500 m water depth (ARCA, Astronomy Research with Cosmics in the Abyss). Both detectors require accurate time (1 ns) and position (20 cm) resolution to fully exploit the event reconstruction capabilities of their Digital Optical Modules (DOMs), in measuring neutrino energy and direction. A custom Acoustic Positioning System (APS) was designed and developed by the KM3NeT collaboration, to obtain the requested accuracy. This system, the largest and most accurate deep-sea positioning system worldwide, exploits the KM3NeT detector's precise time synchronization system based on the White Rabbit protocol. It consists of a phased array of several thousand acoustic receivers installed on each DOM to constantly monitor the position and movements of the detector elements, subject to underwater currents. A long baseline of active and passive acoustic elements is installed on the seafloor to provide geo-reference to the telescope. Acoustic data are continuously sampled at 195.3 kHz and streamed to shore for analysis. Time of arrival of acoustic signals is used to measure the distance between APS elements. This contribution presents the results and performance of this system, based on the reconstruction of the position of DOMs using a multilateration process.*

Keywords: *neutrino, KM3NeT, acoustic positioning system, multilatration, underwater acoustics*

1. HIGH-ENERGY NEUTRINO ASTRONOMY AND THE KM3NET NEUTRINO TELESCOPE

The field of high-energy astro-particle physics has entered a flourishing period. The discovery of gravitational waves and their joint observation with high energy photons from cosmic sources have paved the way to t multi-messenger astrophysics, widening the understanding of complex astrophysical phenomena through simultaneous observation of several astrophysical messengers: charged particles, photons, gravitational waves and neutrinos. Hundreds of galactic and extragalactic sources emitting photons with energies larger than 10^{12} eV have been identified over the last decade. This has significantly enhanced our understanding of the Universe, and the fundamental role of the non-thermal (or "explosive") cosmic phenomena and sources which are thought to accelerate charged particles -protons and nuclei, usually referred as "cosmic rays"- up to macroscopic energies (few 10^{20} eV). The establishment of a firm connection between explosive cosmic sources and production of High Energy (HE) cosmic rays, is an unsolved problem in astrophysics since about 100 years, known as the "cosmic ray puzzle". Many of the sources observed in $\geq$ TeV gamma-rays are supposed to be cosmic ray accelerators and, also, high energy neutrino emitters. Since HE neutrinos can be only produced through HE cosmic ray interactions, the identification of HE neutrino sources is expected to solve this long standing puzzle. Neutrinos are chargeless and nearly massless fundamental particles that make for excellent astrophysical probes. They can travel undisturbed across the entire universe and escape from the dense cores of their sources due to their low interaction probability with matter. However, this same characteristic makes them incredibly challenging to detect, requiring gigaton-scale masses of target matter to induce an interaction that can be observed.

The reference detection technique for cosmic HE neutrinos is the so-called water(ice)-Cherenkov method. These detectors use natural media like deep water or ice as a target. When a neutrino interacts, it produces charged particles that emit a cone of blue Cherenkov light. The amount of light is proportional to the neutrino energy; direction of light allows reconstruction of the neutrino source in the sky. In 2013 the IceCube neutrino telescope -which consists of thousands large-area photomultipliers buried between 1500 and 2500 m depth in the ice cap of Antarctica [1]- provided the first evidence of a cosmic neutrino flux originated outside the solar system [2]. Further analyses are suggesting the presence of point-like extragalactic sources of neutrinos associated to Active Galactic Nuclei (AGNs, see figure 1). Two years later, the first Detection Unit (DU) of the KM3NeT/ARCA (km3 neutrino telescope, astronomy with cosmic rays in the abysses) neutrino telescope was deployed at 3500 m water depth in the Western Ionan Sea, Lat N 36° 17′, Long E 16° 00′ [3].

ARCA is a 3-D matrix of few hundred thousand of 3-inches Photomultiplier Tubes (PMTs) grouped in clusters of 31 to form a Digital Optical Modules (DOM). The DOM contains readout, power and communication electronics as well as auxiliary sensors, including a compass and a piezo-electric device used for the Acoustic Positioning System (APS). Eighteen DOMs are assembled in vertical mooring lines, called Detection Units (DUs). KM3NeT/ARCA DUs are about 700m-high and their average distance is about 90 m, DOMs are equally spaced (36 m) along the DU length, interconnected by an electro-optical umbilical cable and are held taut between an anchor and a top buoy using a pair of Dyneema cables. The DU anchor hosts the electronics and the optical systems that allow communication between the DOMs and the shore. ARCA is located 90 km South-East off the coast of Porto di Capo Passero, Sicily, at a water depth of about 3500 meters. The full observatory will eventually be instrumented with about 200 DUs. As of now, 51 DUs are in operation.

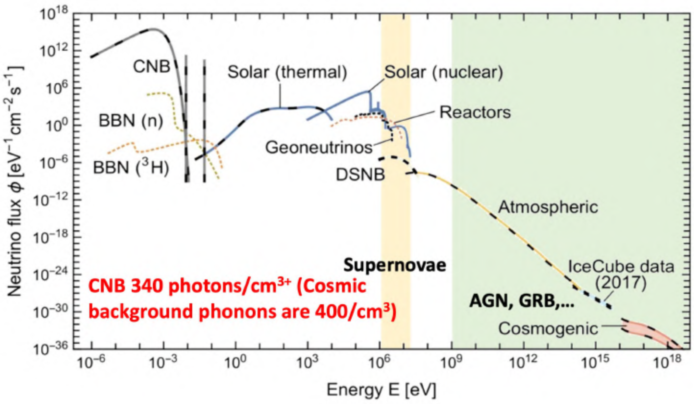

Figure 1: The spectrum of cosmic neutrinos. KM3NeT/ARCA is designed to detect neutrinos either directly or indirectly (i.e., through the interaction of ultra-high-energy protons with the cosmic microwave background), produced by cosmic sources such as Active Galactic Nuclei and Gamma-Ray Bursts. ARCA can also detect low-energy neutrinos from Galactic supernova explosions.

The KM3NeT collaboration is also building the KM3NeT/ORCA detector (Oscillation Research with Cosmics in the Abyss), located offshore the French Riviera in the Tyrrhenian Sea. ORCA is a more compact detector than ARCA, designed to host over 120 DUs, and is optimized for the study of neutrino oscillations at lower energies.

ARCA and ORCA while sharing the same technology, have different scientific goals: ARCA studies very high-energy (TeV and beyond) cosmic neutrinos; ORCA is designed to study the masses of neutrinos created by interaction of cosmic rays in the Earth's atmosphere.

The innovative design of the KM3NeT detector combined with the excellent optical properties of the deep Ionan seawater has already allowed ARCA to reach a sensitivity close to the one of ANTARES, the first-generation undersea neutrino telescope operated for more than 10 years [4]. On February 13^{th} 2023 ARCA detected the highest energy muon neutrino event ever recorded, named KM3-230213A, with an energy exceeding 10^{17} eV [5].

The KM3-230213A 2 neutrino has revived the quest for the measurement of the flux of the ultra high-energy neutrinos (neutrinos with energy above 10^{18} eV), produced in the interaction of $\geq 10^{20}$ eV protons with the cosmic microwave background radiation. The expected number of these events is so low that km3-scale Cherenkov detectors are too small to measure the flux with needed statistics. At these energies the interaction of neutrinos can produce an acoustic pulse whose spectrum is centered at about 30 kHz with a spread of few tens kHz and the expected pulse amplitude is about 100 mPa, for a $E = 10^{20}$ eV neutrino, at 1 km distance [6]. KM3NeT is equipped with acoustic sensors, mainly used for the APS as reported in the next section, but capable to detect these rare, high energy events [7].

2. THE KM3NET/ARCA ACOUSTIC POSITIONING SYSTEM

To accurately reconstruct the energy and direction of neutrinos, the position of the PMTs (in DOMs) of the neutrino telescope must be known with an uncertainty of about 20 cm. While IceCube optical sensors are stabily buried in the ice polar cap, the KM3NeT DOMs continuously move under the effect of sea currents. This is why a custom underwater APS is implemented to monitor DOM positions during detector live time.

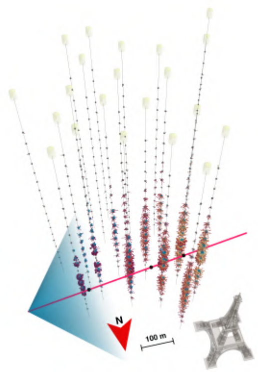

Figure 2: Visualization of the KM3-230213A event. Most PMTs in the detector recorded hits from photons originating from both primary and secondary particle showers [5].

The KM3NeT detector elements are situated at thousands of meters below the sea surface. The KM3NeT APS implements a Relative Acoustic Positioning System (RAPS) to localize the coordinates of acoustic receivers (piezo-electric sensors) installed on each DOM, relative to a geo-referenced Long Baseline (LBL) of acoustic elements. Unlike a traditional LBL system, which uses a network of transponders that both emit and receive signals, the KM3NeT RAPS-LBL consists of separate transmitters (beacons) and receivers (hydrophones) that are fixed in known positions on the seabed. This allows for the reconstruction of the positions of the piezo-electric sensors in the DOMs by measuring the Time of Arrival (ToA) of acoustic signals from the beacons and using a multilateration process to calculate the positions of the piezo-electric sensors. This enables continuous monitoring of the DUs' movements

When the KM3NeT RAPS-LBL elements are properly geo-referenced with absolute position in geographical coordinates is known with uncertainty better than 1 m, the DOMs themselves can also be accurately geo-referenced. The absolute geo-referencing is obtained using a Navigation and Absolute Acoustic Positioning System (NAAPS). So far, during the maritime KM3NeT/ARCA deployment campaigns commercial Ultra Short baseline System (USBL) available onboard the deployment ships have been used. In this paper a proposal for a custom-design, more accurate NAAPS is described.

2.1. ACOUSTIC BEACONS

KM3NeT's acoustic emitters are called Acoustic Beacons (ABs). An AB is a broadband acoustic emitter in the frequency range of 20 to 50 kHz. They are installed in fixed positions of the seabed including on tripods, within the DU bases and Junction Boxes (JBs). Each AB is pre-loaded with a unique and distinguishable sweep frequency signal for identification: a linear sweep with a 2 to 5 kHz bandwidth, a duration of 5 ms, and a unique repetition rate. During the early stages of construction, the ABs were mostly installed on tripods operated autonomously with a battery pack. Today they are still used for the purpose of optimizing the RAPS-LBL geometry (installing around the DUs footprint), as they offer the possibility of being replaced and moved whenever the battery life expires (approximately every four years [8]). Currently, at the ARCA site, there are three active ABs on tripods /see figure 3), three on JBs, and two on DU bases. ABs in DUs and JBs can be fully controlled from the shore, including the ability to switch them on or off and to change their emission patterns remotely.

Figure 3: A tripod hosting the autonomous Acoustic Beacons for the Relative and Absolute acoustic positioning system.

2.2. DIGITAL ACOUSTIC RECEIVERS

The main purpose of the Digital Acoustic Receivers (DARs) is to receive the emitted signals from the ABs. KM3NeT has two types of installed DARs: the internal DARs, which are piezo-electric sensors installed inside each DOM, and the external DARs, which are hydrophones installed and fixed in each DU base and ARCA JBs. The signals are recorded with a sampling frequency of 195.3125 kHz (25MHz/($2^{8_{bits}-1}$), so they can be used to study signals of frequency lower than about 100 kHz. This opens up a wide range of applications for commercial and scientific use (bioacoustics, geophysics, environmental monitoring, et cetera). The piezo-electric in a DOM is a low-cost and low noise sensor. The Received Voltage Response (RVR) is -160±6 dB re 1 V/μPa in the 10–70 kHz range [9]. The external DARs are omnidirectional DG0330 hydrophones, specifically designed for KM3NeT and manufactured by the Co.1.Mar Company. They operate in the 5–90 kHz range and have two channels with different gain settings (+26 dB and +46 dB). These different gains allow for the study of both distant, faint signals and nearby, loud sources without signal saturation. The RVR for the low-gain channel is around -176 dB re 1 V/µPa. Both types of DARs continuously stream ”raw data” to shore.

The DAR array of KM3NeT can also allow in future the study of acoustic signatures of high-energy particles and it already provides valuable information such as the noise level in the area produced by ship traffic and marine mammals close to the site.

3. DOM POSITIONING PROCEDURE

3.1. LBL CALIBRATION

The first critical step in the DOM positioning workflow is the calibration of the Long Base-Line (LBL) acoustic network. The LBL system consists of fixed acoustic emitters (beacons) and Hydrophones installed on the detector’s infrastructure. Initial deployment uncertainties of up to ±10 m make the raw estimated positions of these elements insufficient for the sub-meter accuracy required for DOM positioning.

To address this, an auto-calibration process refines the relative positions of LBL elements using Difference Time-of-Arrival (DToA) measurements of acoustic signals. Specifically, the time difference between signals received by pairs of hydrophones from the same emitter is used to build a system of nonlinear equations linking emitter and hydrophone coordinates:

$$c_{\text{sound}} \cdot \text{DToA}_{ij} = \|\vec{H}_i - \vec{E}_j\| - \|\vec{H}_r - \vec{E}_j\| \quad (1)$$

where c_{sound} is the effective sound speed in water, $\vec{H}_i$ and $\vec{H}_r$ are positions of hydrophone i and reference hydrophone r, and $\vec{E}_j$ is the j emitter position.

To ensure the stability of the estimated positions and avoid local minima, a Monte Carlo-based minimization procedure is used [10]. Solving this over-constrained system through a global minimization reduces the positioning uncertainty of the LBL elements to approximately 1 m, thus providing a robust acoustic framework for subsequent DOM localization. To further enhance accuracy, depth-dependent sound speed variations are accounted for using an empirical model calibrated with in situ oceanographic data. Although not detailed here, this correction mitigates systematic biases due to pressure, temperature, and salinity gradients in the deep-sea environment.

3.2. RAPS OPERATION

With the calibrated LBL framework in place, the RAPS (Relative Acoustic Positioning System) operation determines the coordinates of each DOM's piezo-electric sensors via multilateration. A digital signal processing algorithm known as the Acoustic Data Filter (ADF) extracts precise ToA measurements and identifies their emitter through cross-correlation with expected signal templates [11]. Following the LBL calibration, the positions of the piezo-electric sensors (P) integrated into the DOMs are determined using hyperbolic multi-lateration. This method relies on DToA measurements between each sensor (P_α) and a reference hydrophone (H_r), based on AB signals.

The precision of the multilateration strongly depends on the accuracy of ToA time stamp, sound speed estimates, and the stability of ABs and hydrophones locations. Currently, the dominant source of uncertainty arises from residual positioning errors of the LBL elements, especially the autonomous ABs on tripods, where deviations up to 10 m have been observed during initial deployment phases. These uncertainties hinder the positioning algorithm's ability to achieve the required sub-meter accuracy.

Latency in sensor electronics and variability in environmental sound speed are secondary but non-negligible contributors to the overall error budget. The cross-correlation algorithm's time tagging has sub-millisecond resolution, allowing ToA uncertainties to be kept minimal.

Typically, the system calculates DOM positions in time windows of approximately 10 minutes, aggregating enough ToA measurements from multiple beacons to over-constrain the multilateration system and improve robustness (see figure 4). To address these limitations, the acoustic positioning system is currently being upgraded with commercial beacons from Exail. These new beacons are expected to provide absolute positions for the tripods and achieve the milliradian precision necessary for advanced neutrino astronomy.

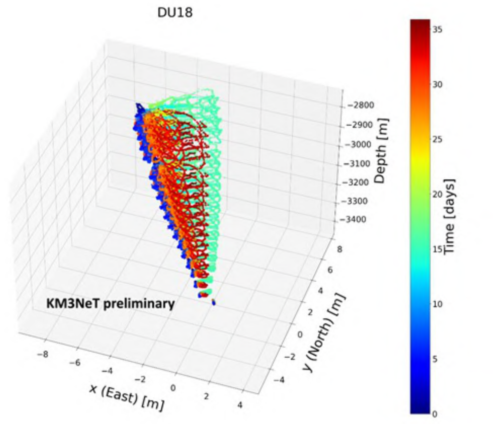

Figure 4: Movements of one Detection Unit of ARCA, monitored via the KM3NeT acoustic positioning system [10].

4. OUTLOOK: THE IONIAN DEEP SEA LABORATORY

The operation of KM3NeT/ARCA and its cabled infrastructure, initially coordinated under the IDMAR project, is enabling a wide range of multidisciplinary studies in underwater acoustics. Thanks to the precise time synchronization system provided by the White Rabbit protocol, hydrophones can be used to study and locate acoustic sources. In addition to the KM3NeT infrastructure, a Distributed Acoustic Sensing (DAS) has been installed in Capo Passero as part of the Lownoiser Horizon Project to study underwater noise radiated from ships, monitoring the 100 km cable down to a depth of about 3500 m depth. At the Port of Catania, INFN–LNS operates a deep-sea infrastructure in collaboration with the Istituto Nazionale di Geofisica e Vulcanologia (INGV). The site is connected to another 28km-long electro-optical fiber-cable reacheing a depth of 2100 meters (see figure 5). It supports several devices, including a Brillouin Optical Time Domain Reflectometer (BOTDR) unit installed through the FOCUS-ERC project, the IPANEMA/CATANIA acoustic observatory (IPANEMA project), and a DAS system operated by the Centro Siciliano di Fisica Nucleare e Struttura della Materia (CSFNSM) as part of the VONGOLA–PNRR project. The ability to jointly operate all these devices makes the Western Ionian Sea an ideal open laboratory for underwater acoustics. The planned installation of cabled sensors at the KM3NeT site off the coast of Pylos will expand these capabilities, offering unprecedented potential for deep-sea scientific studies.

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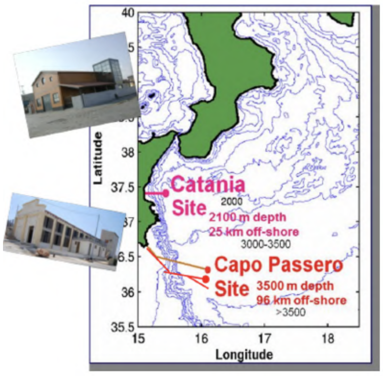

Figure 5: The cabled infrastructures of INFN-LNS in the Ionia Sea.

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