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A Tool for Improved Monitoring of Acoustic Beacons and Receivers of the KM3NeT Neutrino Telescope †

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Abstract: KM3NeT is an underwater neutrino detector currently under construction. Since the installation of its first detection unit in 2015, it has been continuously collecting data. Due to its complex design comprising a 3D array of sensors, an Acoustic Positioning System (APS) has been developed to monitor the position of each sensor. Given the increasing number of acoustic sensors used for the APS, both receivers and emitters, a solution has been implemented to check their status. In this contribution, a monitoring tool for this instrumentation is presented, capable of evaluating its status at both the data and operational levels. For effective monitoring, it is crucial to associate the signal recorded by a receiver with the corresponding transmitter. The Acoustic Data Filter (ADF) performs a cross-correlation between the signals retained in a buffer and those emitted by each installed emitter. It saves the maximum peak value and its associated time of arrival for each expected signal. However, the growing number of beacons complicates the differentiation of corresponding transmitters due to the huge amount of data recorded by the ADF needing post-processing. To address this challenge, a monitoring tool is developed that analyzes the internal clock of each emitter to distinguish and filter the data collected by the ADF. This tool has proven to be highly effective at verifying the correct operation of all acoustic devices deployed at sea. The acoustic monitoring graphical output produced for each data slot facilitates quick failure detection, enabling a swift response. Last but not least, the tool is modular and scalable, adapting to the addition or removal of sensors from the detector.

Keywords: monitoring tool; acoustic data filter; acoustic positioning system; KM3NeT

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1. Introduction

The underwater neutrino detector, KM3NeT (Kilometer Cube Neutrino Telescope), is currently under construction. Since the installation of its first Detection Unit (DU) in 2015, it has been actively collecting data. KM3NeT utilizes optical detection technology to observe the Cherenkov effect, which occurs when a neutrino interacts with water. This project employs this technology for its two detection nodes:

- ARCA (Astroparticle Research with Cosmics in the Abyss) is located 100 km from Portopalo di Capo Passero and has a maximum depth of 3500 m. It focuses on detecting and studying high-energy cosmic neutrinos.
- ORCA (Oscillation Research with Cosmics in the Abyss) is situated 40 km off the coast of Toulon, with a maximum depth of 2400 m. It is dedicated to studying atmospheric neutrino oscillations.

Both ARCA and ORCA use the same optical technology to achieve their goals [1]. The data stored by KM3NeT are organized into segments known as "runs", which have a typical duration of about 3 h). This structure helps manage and process large volumes of data efficiently by breaking them into manageable time intervals.

The detection sensors developed by KM3NeT are called Digital Optical Modules (DOMs), which are 17-inch-diameter glass spheres each equipped with 31 3″ Photomultiplier Tubes (PMTs). A DU in KM3NeT consists of 18 DOMs held by two parallel ropes. One end of the cables is anchored to the base of the DU, which secures the string to the seabed, while the other end is attached to a top buoy. The buoyancy of the line and each DOM keeps the entire string upright in the water [2]. By installing hundreds of these DUs on the seabed, a 3D network of DOMs is created, enabling the study of large volumes of water. At ARCA, two blocks of 115 DUs will be installed, covering a volume of about one cubic kilometer. In contrast, ORCA will have a single block of 115 DUs occupying a total of 8 Mt of water mass [1].

The main objective of the KM3NeT telescope is to detect and reconstruct the path of a neutrino and its energy. To accomplish this, precise temporal intersensor calibration and accurate knowledge of their positions at the time of the neutrino interaction is required. Since sea currents cause the DOMs to move, researchers have developed an Acoustic Positioning System (APS) to monitor their positions.

Given the importance of the APS for analysing the optical data, it is crucial to monitor the status of its acoustic sensors (both emitters and receivers). This work presents a tool designed for this purpose, considering that the number of sensors will continue to increase as the construction of the detectors progresses.

In Section 2, the APS of the detector is described, along with the instruments it uses and the operating principle. In Section 3, the monitoring tool for the acoustic instrumentation is detailed, with the first part focusing on recognizing the correct signal for each beacon, and the second part focusing on the construction of the graphical output and its interpretation. The article ends with the presentation of some results and the final conclusions.

2. The KM3NeT Acoustic Positioning System

The APS used in the KM3NeT telescope is based on a Long Baseline (LBL) system, where Acoustic Beacons (ABs) are installed on the seabed at fixed and known positions. This system is designed to monitor the position of the receivers within each DOM (piezoceramic sensors), the latter being specifically installed for this purpose.

The raw acoustic data recorded by each receiver are transmitted to computer farms onshore, where they are analyzed in near real-time to identify the Time of Arrival (ToA) of the recorded emitters and then saved in the KM3NeT database (KM3NeT-DB). This analysis is performed by the Acoustic Data Filter (ADF), which stores the ToAs in the KM3NeT-DB for offline post-processing. With this information, it is possible to position each receiver [3].

2.1. The APS Instrumentation

The APS has three different acoustic elements (see Figure 1). The Acoustic Beacons (ABs) serve as the emitters, currently using a unique waveform (WF) as a sweep signal for each beacon which is emitted cyclically based on a configured Repetition Rate (RR). The receivers include hydrophones, positioned at the DU bases, and piezoceramic sensors, which are glued to the glass of each DOM, facing downward. The primary purpose of the APS is to monitor the position of these DOMs by analyzing the signals received by the piezoceramic sensors.

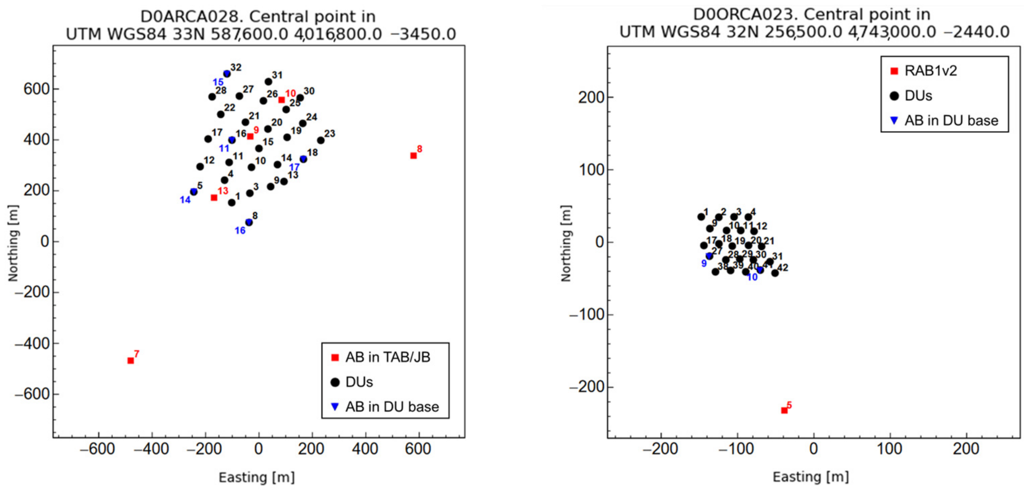
The primary function of the hydrophones in KM3NeT is to determine the positions of the DU bases and/or the ABs located on them. The ABs are spread across the seabed, attached to some DU bases or to ARCA's Junction Boxes (JBs), where they are encapsulated in titanium. Additionally, ABs are deployed more temporarily and autonomously, using aluminium encasements, either on Tripod ABs (TABs in ARCA) or on Removable AB bases (RABs in ORCA).

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

Figure 1. (**a**) Acoustic beacon MAB100 (aluminium version) produced by MSM, Valencia, Spain; (**b**) DG0330 hydrophone, produced by Colmar, La Spezia, Italy; (**c**) Pz27 encapsuled piezoceramic sensor, assembled by GCD-PCB-Design GmbH, Erlangen, Germany.

2.2. The ARCA and ORCA Current Status

Currently, ARCA has 28 DUs installed (D0ARCA028), along with three JBs and two TABs. Five of the DUs are equipped with an AB, and each of the JBs also has an AB. ORCA has 23 DUs (D0ORCA023), of which two have ABs and a single operational RAB (RAB1v2). The footprints of these detectors are illustrated in Figure 2.



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

Figure 2. (**a**) D0ARCA028 footprint; (**b**) D1ORCA019 footprint.

Tables 1 and 2 provide the characteristics of each installed AB, including their emitted WF and the configured RR.

Table 1. AB characteristics in ARCA.

AB ID	WF	Structure ID	RR [s]	AB ID	WF	Structure ID	RR [s]
7	14	TAB5	5	13	29	JB1	31
8	12	TAB4	4	14	34	DU5	42
9	28	JB2	32	15	26	DU32	44
10	25	JB3	33	16	33	DU8	41
11	27	DU16	51	17	22	DU18	50

Table 2. AB characteristics in ORCA.

AB ID	WF	Structure ID	RR [s]
5	23	RAB1v2	5
9	34	DU27	51
10	35	DU41	50

2.3. The ADF

The near real-time analysis of the signals recorded from each acoustic sensor is performed by the ADF. The ADF temporarily stores the signal from each channel in a buffer and then cross-correlates it with the expected signals emitted by the active ABs. The peak value of these correlations, known as the Quality Factor (QF), is stored in the KM3NeT-DB along with its associated ToA if it exceeds a certain threshold. Thus, for each time window, the ADF assigns a QF and ToA to each signal corresponding to the ABs.

The ADF serves as a preliminary step in the DOM positioning process, significantly reducing the memory required for storing APS data by avoiding the recording of the raw acoustic signal (although the APS does allow for raw data storage for other studies). The APS data can then be used in post-processing to distinguish the received signals, where high QF values indicate correctly assigned AB signals, facilitating accurate ToA determination for the DOM positioning process [4].

So far, the ADF does not apply a normalized correlation method. This approach has worked well during the preliminary phases of KM3NeT construction when there was only a reduced number of DUs and ABs. However, as the detector has expanded and the number of receivers and transmitters has increased, distinguishing the correct emitter for each received signal based only on the QF value has become more difficult. There are instances where the highest QF does not correspond to the correct emitter but instead to a closer one. This is due to the influence of the received signal's amplitude and the frequency overlap between different WFs which can affect the correlation values [5].

3. The Acoustic Monitoring Tool

Given the importance of the APS data, it is necessary to monitor the functioning of the acoustic sensors, beacons, and receivers that compose it. For an effective positioning and monitoring system, it is essential to correctly associate the signal recorded by each receiver to the appropriate beacon. The proposed monitoring system allows, in post-processing, to associate the correct signal to the beacon and, consequently, check the proper functioning of all acoustic sensors. The method used takes advantage of the common computational delay of AB electronic boards relative to the detector. The extent of the clock's delay is characteristic of each beacon, allowing for its identification. Additionally, this tool has the advantage of being scalable and modular, adapting to the addition or removal of sensors to and from the detector.

3.1. Correct ToAs Selection

As reported above, using only the highest QF value to assign the correct ToA may not always be reliable. To address this issue, the monitoring tool selects the number of APS values to consider in its analysis based on the n value. When $n = 1$, the analysis considers the expected number of ToAs as determined by the AB emissions' RR and duty cycle. For $n = 2$, it considers twice that number, and so on. Detailed examples of cases where the appropriate n value is crucial for accurate analysis are provided below. The optimum n value is specific to each AB and is determined as described below.

3.1.1. Preliminary Study for Acoustic Beacons

For a receiver–emitter pair, by default, the number n is set to 1, but some beacons have a lower emission intensity; therefore, there is the risk of selecting only the ToAs from other beacons that have a higher QF. In this study, a higher value of n was set to also select the ToAs from the correct beacon. By plotting the remainder of the division (modulus) between the selected ToAs and the RR as a function of time, the correct ToAs is expected to align along a straight line (see Figure 3). This alignment can be detected using a computer vision technique, implemented in Python V3, which employs the HoughLines() function from the OpenCV library to automatically detect straight lines in the image [6]. In this study, points that aligned with each detected line were selected, and a linear best fit was performed on them.

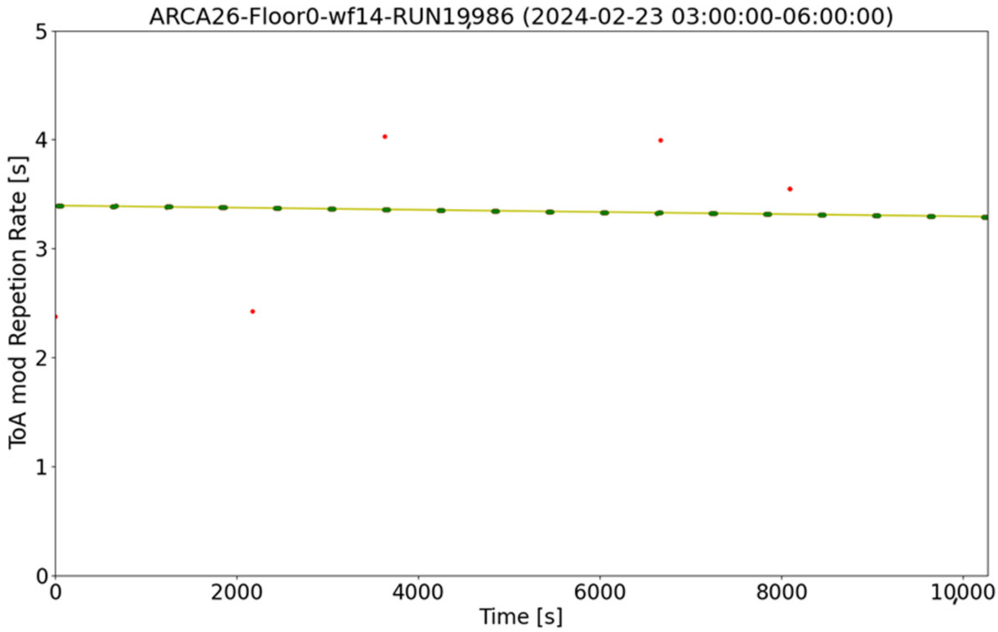


Figure 3. Modulus between the selected ToAs and the RR plotted as a function of time. The correct ToAs (highlighted in green) align along a straight line. This example illustrates the APS data from the ARCA hydrophone in DU26 related to WF14.

The slope of the line is indicative of the system's clock advance or delay and serves as a distinguishing feature for each beacon. Tables 3 and 4 show the slope value associated with each AB used in the KM3NeT telescope.

Table 3. Slope of the line for each beacon in D0ARCA028.

ARCA WF	Slope (10^{-5})	ARCA WF	Slope (10^{-5})
WF 12	−2.42	WF 22	2.11
WF 14	−1.02	WF 26	−5.59
WF 25	0.57	WF 27	−29.5
WF 28	1.44	WF 33	164
WF 29	2.09	WF 34	159

Table 4. Slope of the line for each beacon in D0ORCA023.

ORCA WF	Slope (10^{-5})
WF 23	−1.44
WF 34	0.24
WF 35	1.41

Once the characteristic slope for each AB is known, it is possible to select the correct ToAs using a simpler algorithm that selects the points distributed along a line with the slope of the studied beacon. This allows us to distinguish the correct ToAs from spurious signals or from signals of another beacon that the ADF possibly failed to filter out (Figure 4).

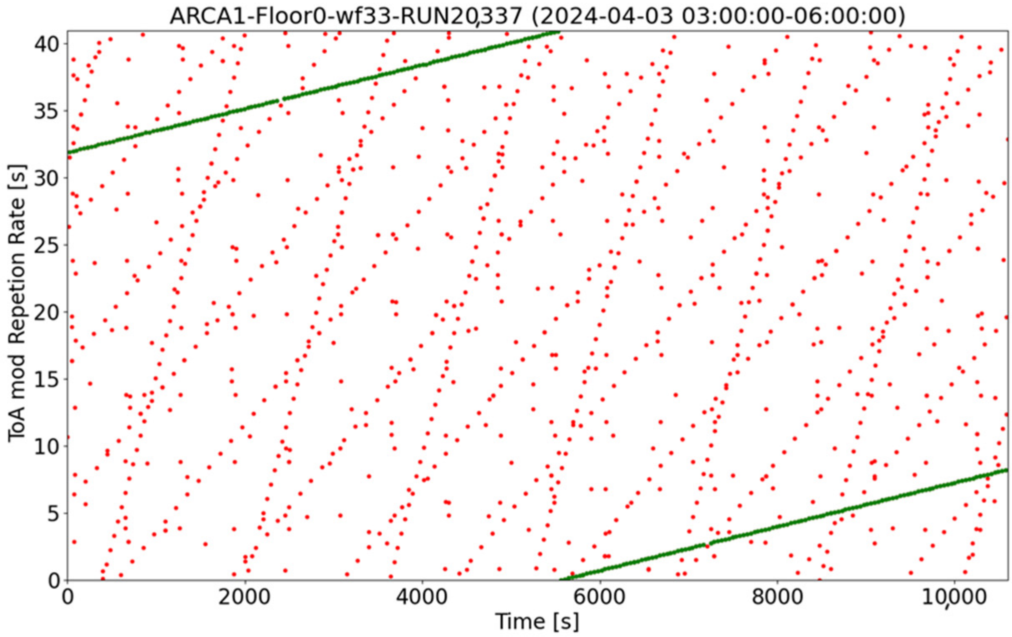


Figure 4. Modulus between the selected ToAs and the RR plotted as a function of time. This example illustrates the APS data from the ARCA hydrophone in DU1 related to WF33.

3.1.2. Set the Best Value for *n*

Setting the optimal value for *n* is crucial to ensure accurate ToA selection and effective monitoring. As mentioned previously, for some beacons with lower emission intensities, it is necessary to consider a greater number of ToAs than the expected one. Otherwise, only ToAs belonging to other beacons which emit at higher intensities and thus have a higher QF will be selected (see Figure 5).

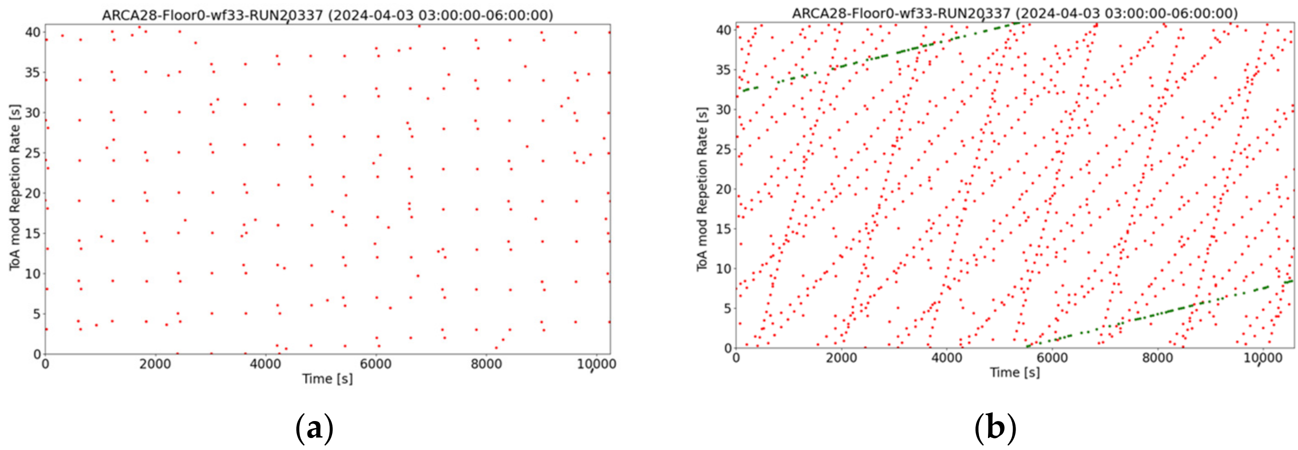


Figure 5. Modulus between the selected ToAs and the RR plotted as a function of time. This example illustrates the APS data from the ARCA hydrophone in DU28 related to WF33 using (**a**) $n = 1$, where all the data correspond to incorrect ToAs, and (**b**) $n = 5$, where there are some correct ToAs.

3.2. The Acoustic Monitoring Graphical Output

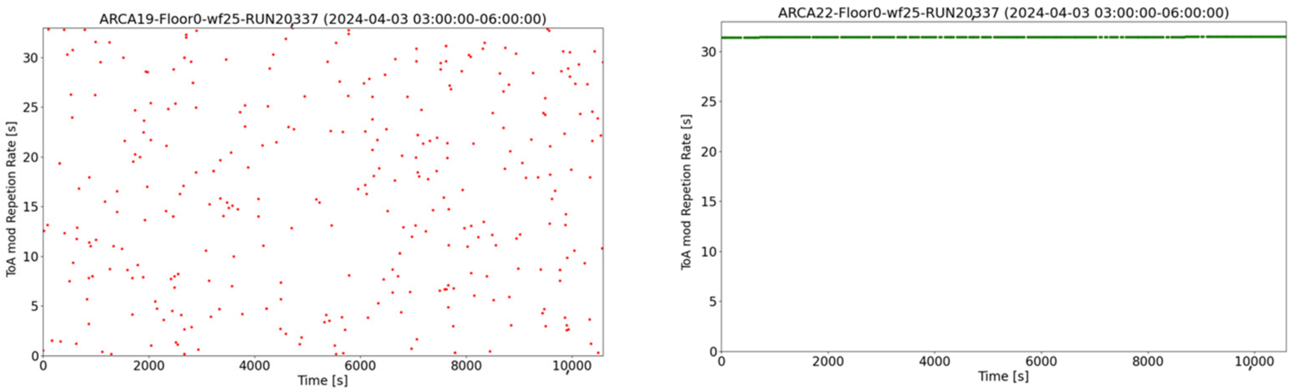
The acoustic monitoring tool features a single graph, providing a quick overview of the status of the transmitters and receivers installed in KM3NeT.

3.2.1. Construction of the Acoustic Monitoring Plot

Given a receiver–emitter pair, three scenarios can occur:

1. There are no ToAs in the database: this case is classified as MISSING, and the corresponding dot's edge in the plot will be black;
2. ToAs are present but incorrect because they do not distribute along the line with the desired slope in the module vs time plot: this case is classified as ANOMALOUS, and the corresponding dot's edge in the plot will be red;
3. ToAs are present and correct because they distribute along the line with the desired slope in the module vs time plot: this case is classified as NORMAL, and the corresponding dot's edge will be blue.

Figure 6 shows examples of the last two scenarios.



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

Figure 6. Modulus of the selected ToAs and the RR plotted as a function of time. (**a**) Incorrect ToAs. Data from the ARCA hydrophone in DU19, where ToAs deviate from the expected alignment, suggesting a potential issue with this hydrophone. (**b**) Correct ToAs. Data from the ARCA hydrophone in DU22, where ToAs align correctly along the expected straight line, indicating proper functioning of the AB.

In the case of a cumulative plot over multiple runs, the border of the dot will reflect the most common state during the studied runs and the fill of the circle will have a colour gradient depending on the percentage of runs in which the ToAs are present (to distinguish cases where, for example, an AB or hydrophone might only work for some runs):

- Black: ToAs missing in all of the analyzed runs;
- Dark gray: ToAs missing from 50% to 99% of the analyzed runs;
- Light gray: ToAs missing from less than 50% of the analyzed runs.

3.2.2. Monitoring Approach with Few ABs: ORCA Case

The ORCA detector currently hosts three ABs. The small number of beacons currently installed allows for the monitoring of all acoustic sensors. In this case, we can construct a plot for each beacon where the DUs are on the x-axis and the floors of the DU are on the y-axis (floor 0 corresponds to the hydrophone at the base of the DU). Figure 7 shows an example of a plot obtained for one of the active beacons in ORCA.

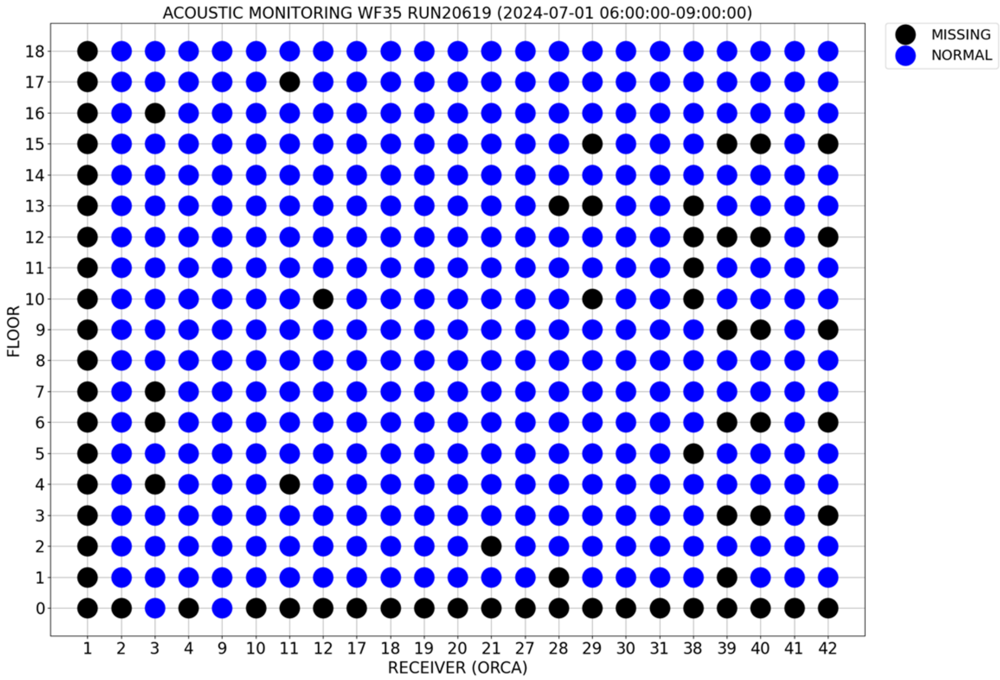


Figure 7. Example of a cumulative acoustic monitoring plot over multiple runs for ORCA.

3.2.3. Monitoring Approach for Huge Detectors: ARCA Case

The ARCA detector currently hosts ten ABs. Producing ten plots (one for each beacon) for the complete monitoring of all acoustic sensors would require significant execution time. For this reason, we decided to include only hydrophones and beacons in the monitoring plot. Therefore, we present a single plot with hydrophones on the x-axis and beacons on the y-axis. This choice was also driven by the fact that both detectors will grow significantly in the coming years, hosting more and more ABs and receivers. From this perspective, this second solution will soon be adopted for ORCA as well. Figure 8 shows an example of a cumulative acoustic monitoring plot over multiple runs produced for ARCA. Inactive hydrophones and ABs are easily recognizable, marked by the vertical and horizontal lines formed by black dots.

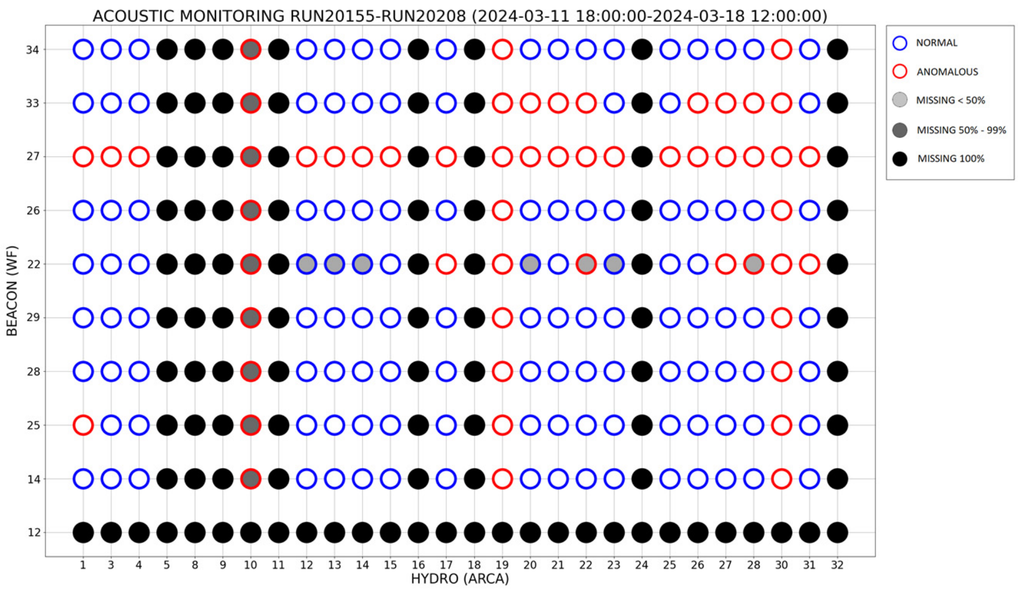


Figure 8. Example of a cumulative acoustic monitoring plot over multiple runs for ARCA.

3.2.4. Caveat and Interpretation of the Monitoring Plot

To properly understand the acoustic monitoring plot, it is essential to pay attention to the following critical points:

- Sometimes, the number associated with the parameter n can be excessive, even when the best value is used. Therefore, it may happen that the algorithm does not find the correct number of ToAs, and the corresponding dot in the plot is black or showing shades of gray. Thus, in some cases, it may happen that there are no ToAs even if the beacon is functioning.
- If a beacon is listed as active in the run setup, ToAs will still be selected, even if they belong to other beacons, and, in this case, we will have a dot with a red border instead of black.
- The ANOMALOUS state can occur in various cases: when the hydrophone is very far from the beacon and the beacon emits weak signals, when the hydrophone is in a "shadow zone" relative to a beacon, or when the hydrophone actually exhibits an anomalous and noisy behavior (in this case, the anomalous state appears with respect to all beacons).

For this reason, it is important to have an overall view: it can be reasonable to assume that the beacon is not functioning if it is not heard by all hydrophones. Similarly, we can assert with reasonable certainty that a hydrophone is off if it does not hear any of the beacons or that a hydrophone exhibits an anomalous behavior (noisy) if it does not receive the correct ToAs from all the beacons.

Taking these observations into consideration, for example, the plot in Figure 8 can be interpreted as follows:

- The beacon with WF 12 was not active.
- The beacon with WF 27 was not functioning but appeared to have been active in the run setup.
- The beacons with WF 22 and WF 33 were not recorded by some hydrophones (the farthest ones, see map in Figure 2).
- Hydrophones 5, 8, 9, 11, 16, 18, 24, and 32 were not active because they were not receiving ToAs.
- Hydrophone 10 was inactive for most runs, but, in some runs, it was active but not functioning correctly (the border is red).
- Hydrophones 19 and 30 exhibited an anomalous behavior and were noisy.

4. Conclusions

The described monitoring tool allows for the monitoring of the acoustic instrumentation located in the sea, something which is necessary for the APS of the KM3NeT neutrino telescope. Taking advantage of the characteristic clock delay of each beacon, the monitoring tool associates the correct signal to the beacon and enables run-by-run analysis. On more than one occasion, it has proven to be crucial for detecting malfunctions in beacons and receivers. It will soon be included in the official monitoring web page of the ARCA and ORCA detectors, featuring both daily cumulative plots and weekly cumulative plots. The system is also easily adaptable to any changes that occur during the evolution of the two detectors. Over the years, new acoustic sensors will be installed, and malfunctioning ones will be removed and replaced. Thanks to its modularity, the new sensors can be easily included in the monitoring plot.

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