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The data acquisition system for the complete KM3NeT/ARCA neutrino telescope

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The KM3NeT observatory hosts two undersea neutrino telescopes, ARCA and ORCA, located at two abyssal sites of the Mediterranean sea. The detectors consist of a 3D array of optical modules, each housing 31 3-inch photomultiplier tubes to detect the Cherenkov light emitted by charged particles produced in neutrino interactions in water. Although still under construction, both detectors are already in operation and use the same data acquisition model in compliance with a triggerless-streaming readout approach. In this architecture all the data collected by the optical modules are transmitted to shore, where online processes running on dedicated resources filter and record the relevant data for physics analyses and calibration procedures. To accomplish the target scientific goals, stringent constraints on the precision of the position and timing of the modules are set. In particular the clock distribution must provide a nanosecond synchronisation of the modules which are tens of kilometers away from the on-shore clock references and occupy a large volume that, in the case of ARCA, will reach the cubic kilometer scale. This requirement is met by exploiting the White Rabbit technology. During the initial phase of construction of KM3NeT, the data acquisition system was based on a custom White Rabbit implementation that deviates significantly from the standard design. This architecture concerns the first part (Phase 1) of ARCA and it will be used for the complete construction of ORCA. Recently the submarine architecture of the ARCA telescope was significantly revised to accomplish a mandatory optimisation necessary to scale it to the cubic kilometer size. In this new scenario, which is referred to as the Phase 2 of ARCA construction, it was possible to revise also the implementation of the White Rabbit technology for the experiment, aiming at a standard design.

In this contribution we review the evolution of the ARCA data acquisition system from Phase 1 to Phase 2, focussing on the new design, its implementation with the new detector components that were installed and are operational since the fall of 2024, and the integration of the Phase 1 and Phase 2 sectors.

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PoS(ICRC2025)987

1. Introduction

The KM3NeT Collaboration is deploying two large-scale neutrino detectors deep in the Mediterranean Sea: KM3NeT/ARCA and KM3NeT/ORCA [4]. ARCA is focused on the detection of high-energy cosmic neutrinos, targeting the TeV to PeV range to study astrophysical sources. In contrast, ORCA is optimized for lower-energy atmospheric neutrinos in the GeV range, enabling precise studies of neutrino oscillations. When a neutrino interacts with the medium, inside or nearby the detector volume, it produces relativistic charged particles whose passage in the water induce the emission of the Cherenkov light. Arrays of photomultiplier tubes (PMTs) housed within pressure-resistant optical modules, known as Digital Optical Modules (DOMs) [5], are used for detecting this light, providing data which will be used for estimating the energy and direction of the charged particles. From these, the ones of the parent neutrino are inferred. The DOMs are arranged vertically along flexible lines called Detection Units (DUs) which are anchored to the seafloor and kept taut with submersed buoys.

To achieve the precise timing and positioning required for accurate event reconstruction, the DOMs must be synchronized with precision of O(1) ns and located with an accuracy of O(10) cm. Timing synchronization is managed via the White Rabbit protocol, a high-precision timing system originally developed at CERN: onshore White Rabbit switches distribute the clock signal from a GPS source to the electronic boards inside the DOMs offshore, which run a White Rabbit core on their Field Programmable Gate Arrays. In parallel, an acoustic positioning system ensures accurate module localization: emitters placed in the seafloor infrastructure send acoustic waves that are picked up by receivers located inside the DOMs and on the DU anchors. By triangulating these signals, the positions of all modules can be determined with the necessary precision.

The KM3NeT Data Acquisition System (DAQ) is responsible for orchestrating the control of the DOMs, including the configuration of the PMTs, managing the collection of optical, acoustic, and monitoring data, and handling the processing of this information at the shore stations.

Although sharing the same detection principle, ARCA and ORCA differ in their network configuration, leading thus to different architectures of the onshore and offshore elements. ORCA and the first 30 DUs (Phase 1) of ARCA exploit a customized implementation of the White Rabbit protocol for time and data distribution, known as "Broadcast". The other DUs of ARCA (Phase 2) are designed to support the standard White Rabbit protocol.

The ARCA data acquisition network and the shore station resources have been configured to handle both "Broadcast" and "Standard White Rabbit" architectures so as to take and process data from the whole detector.

2. The KM3NeT detectors

The vertical Detection Units (DUs) of the KM3NeT detectors have 18 DOMs each and they are anchored to the seabed at a depth of ~3500 m in ARCA and of ~2450 m in ORCA. Each DOM contains 31 3-inch photomultiplier tubes which provide almost the full solid angle coverage. DUs are grouped in building blocks of 115 DUs. Currently (September 2025), ARCA and ORCA have 51 DUs and 28 DUs respectively. The footprint of ARCA showing the status in July 2025 is shown

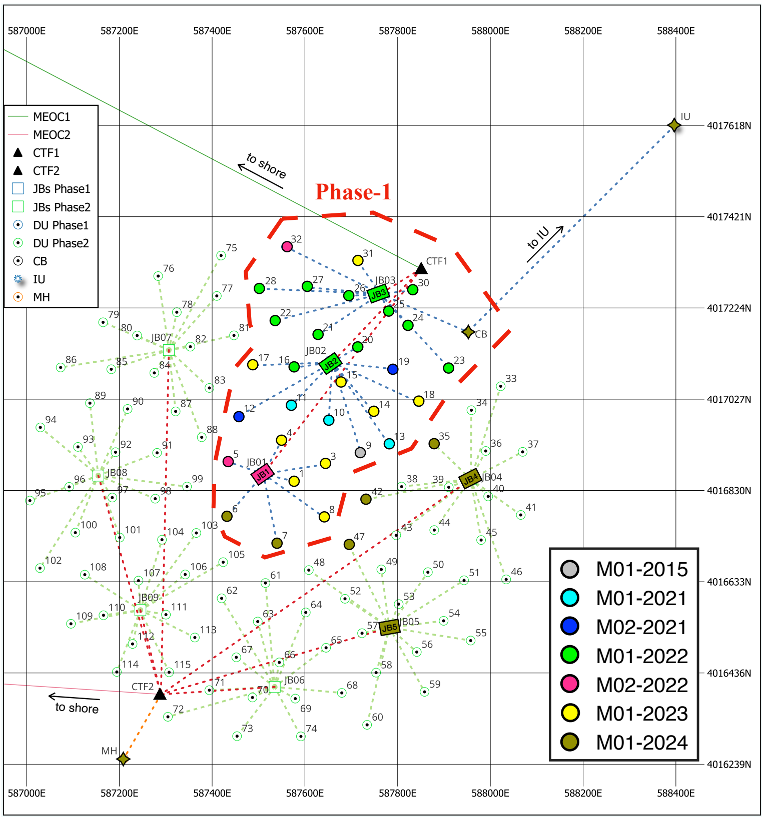

Figure 1: Seafloor map (as of July 2025) of the first building block (115 Detection Units) of ARCA. Detection Units (circles) of Phase 1, with the Broadcast architecture, are highlighted by the red contour. All others follow the Standard White Rabbit architecture. The colors of the circles represent the year of deployment. MEOC (Main Electro Optical Cable), CTF (Cable Termination Frame), JB (Junction Box), CB (Calibration Base), IU (Instrumentation Unit), MH (Marine Hazard) are other elements of the detector seafloor network, not discussed here.

in Fig. 1. At completion, ARCA will be composed of 2 building blocks, while ORCA of 1 building block.

The core of the DOM's readout system is the Central Logic Board (CLB) [6], which manages data acquisition from the 31 PMTs, a piezoelectric sensor which is part of an acoustic triangulation positioning system, and other integrated environmental and system monitoring sensors. The CLB handles data transmission via optical fibers to the shore station for further processing.

At the base of each DU, on the anchoring frame, a titanium pressure-resistant vessel called *Base Module* contains the power distribution electronics, a dedicated CLB for controlling the power system, and, in the case of the Standard White Rabbit architecture, two White Rabbit switches, featuring custom-designed backplanes developed by the KM3NeT collaboration. They act as aggregation points for DOMs data and as nodes of the White Rabbit network, synchronizing the CLBs of the DU. The Base Module of the Broadcast and Standard White Rabbit Detection Units are shown in Fig. 2.

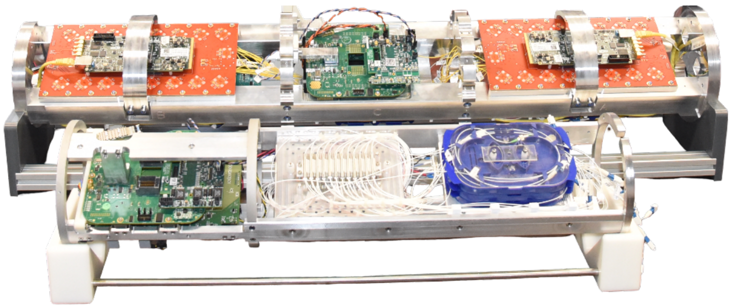

Figure 2: KM3NeT/ARCA Base Modules: Broadcast (in the foreground) and Standard White Rabbit (in the background). The red backplanes of the *Wet* White Rabbit switches are clearly visible in the Standard White Rabbit Base Module.

3. The *Broadcast* architecture

The *Broadcast* architecture is implemented in the optical [12] and networking systems of the initial 30 DUs of ARCA as well as in all DUs of ORCA. This architecture is characterized by an asymmetric, proprietary communication scheme between the shore station and the detector CLBs. Specifically, timing signals and control commands are distributed from the shore to all CLBs via a single downstream optical broadcast channel, while each CLB uses a dedicated uplink to transmit data and command acknowledgments to standard frontend switches (DFES, *DOM Front End Switches*) located onshore. In this configuration, the DOM CLBs do not engage in the standard White Rabbit protocol and do not emit White Rabbit packets. Instead, a modified White Rabbit protocol is employed using a custom White Rabbit switch referred to as the Broadcast switch. This switch transmits the Precision Time Protocol timestamps t_1 and t_2 along with all relevant control messages, to the CLBs of the DOMs. However, the CLBs do not return their local timestamps t_3 and t_4, thus preventing a complete Precision Time Protocol exchange and precluding accurate master-to-slave delay measurement and compensation. Consequently, the PMT timestamps are affected by the uncalibrated one-way propagation delay from shore to the DOMs, which is later corrected at the trigger level through a dedicated calibration. By contrast, the CLBs located within the DU Base Modules are integrated into a separate, bidirectional White Rabbit synchronization path. These CLBs are connected to a different custom White Rabbit switch onshore, referred to as the *Level 1* (L1) switch. Unlike DOMs, the Base Module CLBs do respond with their Precision Time Protocol timestamps, enabling a complete White Rabbit protocol exchange and precise timing synchronization. The L1 switch is itself connected upstream to the Broadcast switch, forming a hierarchical White Rabbit topology. Monitoring data and responses to control commands from the Base Module CLBs are likewise redirected to the standard switch fabric. This situation is depicted in Fig. 3.

To mitigate the risk of broadcast-induced packet loops in the switching network, the switches used to interface the frontend and White Rabbit switches with the Trigger and Data Acquisition systems are managed through Software Defined Networking (SDN) techniques [13]. These switches are shown in Fig. 3 labelled as SCSF (*Star Center Switch Fabric*) and SCBD (*Slow Control and Base Data*). The SDN rules explicitly define all permitted communication flows, enforcing deterministic routing by mapping packets to specific ports and preventing unintended circulation within the switching fabric.

4. KM3NeT/ARCA: the *Standard White Rabbit* architecture

Due to constraints on the number of optical fibers available in the deployed submarine electro-optical cables connecting the ARCA shore station to the deep-sea infrastructure, the Broadcast architecture is not scalable to the full deployment of the ARCA detector. As a result, its use is limited to the initial set of 31 Detection Units. For the remaining DUs, a different optical and synchronization architecture has been implemented, known as the *Standard White Rabbit* architecture.

In this configuration, the Base Module (shown in Fig. 2) has been re-engineered to accommodate two White Rabbit switches, each composed of standard switching core boards integrated with custom-designed backplanes tailored to the mechanical constraints of the pressure-resistant housing. These underwater switches, referred to as Wet White Rabbit switches (WWRS-A and WWRS-B), are connected via bidirectional optical fibers to their onshore counterparts, known as *Dry* WR switches. The Dry switches are standard White Rabbit switches that provide synchronization and control messages to the Wet switches using the standard White Rabbit protocol; the Wet switches, in turn, synchronize and handle data communication with the CLBs inside the DOMs of the DU through standard master-slave White Rabbit exchanges over bidirectional optical links.

This design allows the entire DU to be serviced using only two optical fibers in the submarine cable, each serving as an uplink from the Wet switches to the Dry switches, carrying both timing and data signals. Typically, each Wet switch manages communication with 9 DOMs, while 12 CLBs are connected to both switches to implement redundancy. These dual connections can be activated in the event of a primary link failure, ensuring operational continuity. Furthermore, the two Wet switches are interconnected, enabling synchronization between them and rerouting of data to shore via the functional uplink in case one uplink fails.

The 1 Gbps bandwidth of each Wet switch uplink exceeds the average total DU data throughput (~250 Mbps) by a factor of four, providing ample bandwidth for data transmission. Onshore, a network of White Rabbit switches disciplined by a GPS-referenced clock synchronizes all Dry switches. In particular, a single Grand-Master White Rabbit switch distributes the clock to a layer of standard White Rabbit switches named *Bridge*, which in turn synchronize the Dry switches for the Standard White Rabbit sector and the *Broadcast* switches for the Broadcast sector. The data transmitted from the Dry switches are then aggregated through standard Ethernet switch fabrics (named DryFES, *Dry Front End Switches*) for further processing and storage. This situation is schematized in Fig. 3.

5. The Data Acquisition System

Communication between the KM3NeT shore stations and the detector's CLBs is established via an Ethernet-based optical fiber network, which also supports the White Rabbit protocol. The KM3NeT data acquisition follows a triggerless readout architecture: no trigger logic is implemented offshore. Instead, all raw data collected from the PMTs and acoustic sensors are continuously streamed to the shore station.

PoS(ICRC2025)987

Each DU generates an average data throughput of approximately 250 Mbps. Only a small fraction of this bandwidth is consumed by traffic related to monitoring sensors, control command acknowledgments from CLBs, and White Rabbit protocol packets.

At the shore station, incoming optical and acoustic data streams are routed through a standard Ethernet switch fabric to the *Trigger and Data Acquisition System*. This system is composed of multiple processing stages, implemented as C++ software components running on dedicated servers.

The initial processing layer consists of *DataQueue* processes, modular programs that ingest incoming data from the CLBs and aggregate PMT and acoustic packets into unified time frames. These time-sliced data sets are then passed to the second processing stage: the DataFilter layer [7]. Here, filtering algorithms, implemented using the KM3NeT software framework Jpp [8], are applied to identify and extract physics-relevant events from the continuous data stream.

The filtered events are subsequently handled by output processes that serialize the data into ROOT format files [9], which are stored on local servers at the shore stations. Copies of these files are also automatically transferred to off-site storage facilities, specifically CNAF-INFN (Italy) and CC-IN2P3 in Lyon (France), for redundancy and long-term preservation.

The configuration, coordination, and execution of data acquisition are managed by the Control Unit [10], a suite of software services with a web-based interface used to configure, start, and stop acquisition sessions specifying the active DOMs, data-taking parameters, and trigger configurations. The Control Unit also collects monitoring data from auxiliary DOM sensors, which it logs into the central database of the experiment.

Both the Trigger and Data Acquisition and Control Unit components are deployed and managed using an automated orchestration framework based on Ansible [11]. The modular and scalable architecture of the DAQ system allows it to grow in parallel with detector expansion: as more DUs are installed and overall data volume increases, the system can be seamlessly scaled by adding network switches and deploying additional instances of the processing services on new computing nodes.

6. KM3NeT/ARCA: the hybrid scenario

The ARCA detector is designed to operate simultaneously with DUs of both the Broadcast and Standard White Rabbit architectures, treating them as a unified system. The scheme of the hybrid network is shown in Fig. 3. To manage this, specific DataQueue processes are assigned to handle the data from the Broadcast DUs, while others handle the data from Standard White Rabbit DUs. All DataQueues forward the assembled data to the DataFilter processes, which apply trigger algorithms across the entire detector dataset. At the shore station, a dedicated standard switch, named *STRIDAS*, aggregates and routes raw data traffic from both DU architectures, as well as communication with the Control Unit and the filtered data exchanged between the DataQueues, DataFilters, and the data writing processes. Because of the architectural differences between the Broadcast and Standard White Rabbit networks, their respective data streams are isolated using separate VLANs configured on the STRIDAS switch. Additionally, the Central Logic Boards in each sector are assigned distinct IP address ranges to prevent cross-traffic. The Control Unit, which interfaces with both network sectors, connects to the STRIDAS switch via two separate network interfaces, each assigned to a different IP subnet.

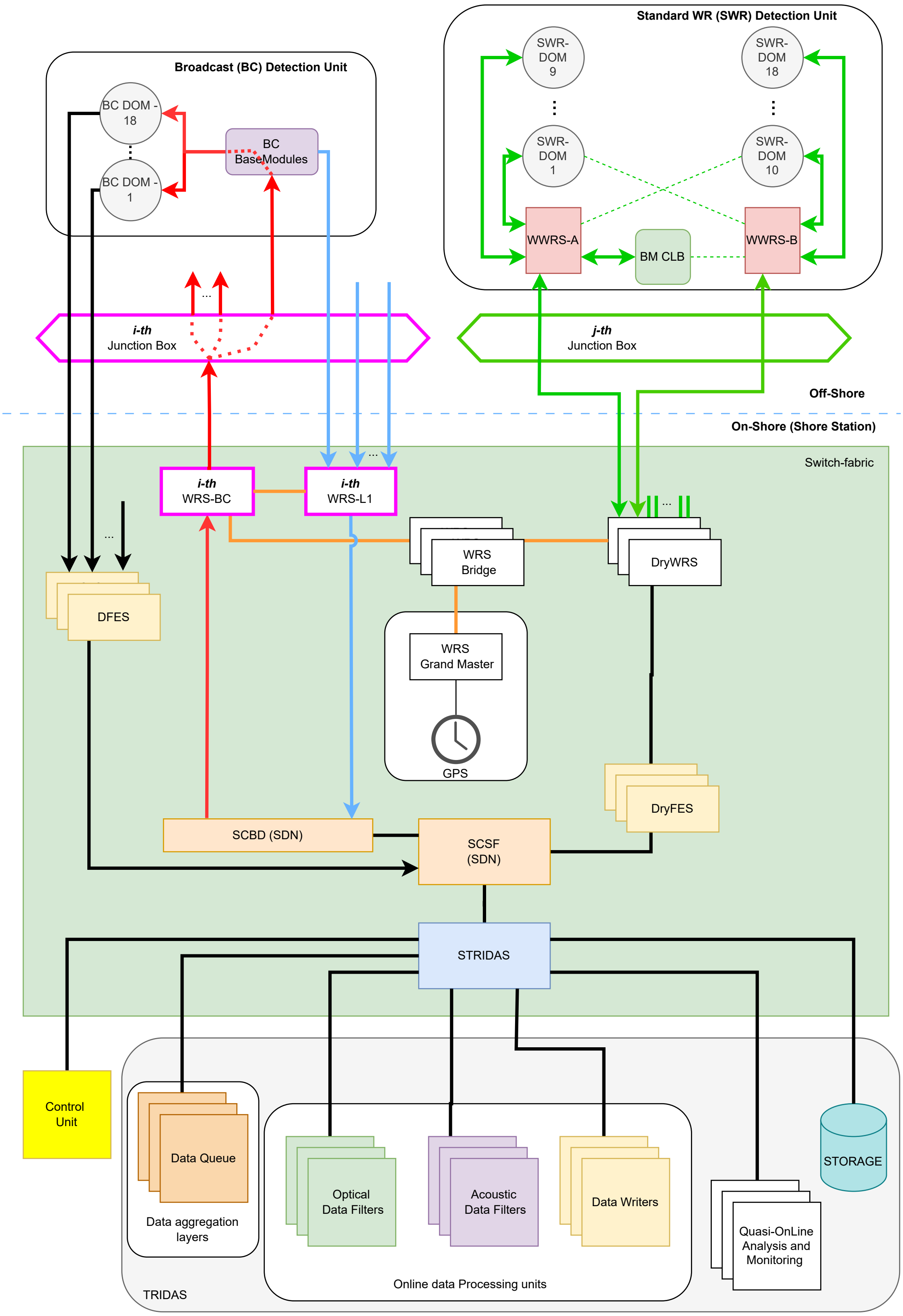

Figure 3: Scheme of the hybrid KM3NeT/ARCA network. See the text for details.

7. Conclusions

In this contribution, we have outlined the evolution of the data acquisition network for Phase 2 of KM3NeT/ARCA. The shore station's switching and computing infrastructure has been redesigned to support both the Phase 1 Broadcast and Phase 2 Standard White Rabbit architectures simultaneously. This hybrid approach ensures reliable data acquisition from all deployed Detection Units regardless of the architecture, and provides the scalability required for the full deployment of the detector.

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