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KM3NeT Data Acquisition and and Trigger System

The KM3NeT Collaboration‡∗

‡ *https://www.km3net.org/km3net-author-list-for-icrc-2019*

The KM3NeT collaboration is currently constructing a new generation neutrino telescope in the depths of the Mediterranean Sea. By recording the Cherenkov light originating from charged products of neutrino interactions in the water, the collaboration ultimately aims to investigate the sources of a high-energy neutrino flux with astrophysical origin and to determine the unknown neutrino mass hierarchy. To this aim, two independent detectors are built with an homologous design and data acquisition system. Digital Optical Modules contain the photo-multiplier tubes and data acquistion and control electronics and are organized along vertical assemblies called Detection Units. The photon arrival times are time-stamped to nanosecond accuracy, required to achieve background reduction and the required resolution on neutrino direction and energy. All recorded photon signals are sent to shore via an optical network able to cope with rates up to O(100) Gbps. An on-line software trigger system filters the photons from neutrino interactions from an overwhelming background (O(10^6)) of photons originating from ^{40}K decay and bioluminescence. The flexible software based trigger system allows for multiple algorithms to operate in parallel. This system is also the intended gateway for generating and receiving external triggers in the multi-messenger context. This contribution discusses the design of the data acquisition system with an emphasis on the trigger and reports on the experience of the first detection units.

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1. Introduction

The KM3NeT Collaboration [1] is constructing deep-sea neutrino detection infrastructure, consisting of two detectors. KM3NeT/ORCA (Oscillations Research with Cosmics in the Abyss) is located 40 km off-shore Toulon, France at 2.5 km depth and has the main aim to determine the neutrino mass ordering by measuring the atmospheric neutrino flux in the 2-30 GeV range. KM3NeT/ARCA (Astroparticle Research with Cosmics in the Abyss) is located 100 km off-shore Capo Passero, Sicily, Ital y at a depth of 3.5 km and has the main aim to study the flux of neutrinos in the TeV to PeV range with an astrophysical origin. The relative sizes of the instrumented volumes reflect the flux of the different sources; ORCA will be about 5 megatons, while ARCA will be about a gigaton. By recording the arrival times of Cherenkov photons from the charged products of neutrino interactions, the direction, energy and flavour of the incoming neutrinos can be reconstructed. The photons are detected by 3 inch photomultiplier tubes (PMTs) housed in 17 inch diameter pressure resistant glass spheres. These spheres, called Digital Optical Modules (DOMs) [2] each contain, besides 31 PMTs, the electronics for control, readout and data-communication and additional equipment such as hydrophones, tiltmeter-compasses, and LED based light emitters. Figure 1 shows a KM3NeT DOM. Two-way communication is done via optical Ethernet, enabled

Figure 1: A partial side-view of a KM3NeT Digital Optical Module. The bottom hemisphere, where 19 of the 31 PMTs are located, is oriented to the bottom left of the photo.

by a sea-floor network and each DOM is equipped with a laser-transceiver with a frequency from the ITU grid with 50 GHz spacing. While the scale of the detectors is different, the technology used is the same. Both detectors are organized in blocks of 115 detection units. A detection unit is a vertical assembly in which 18 DOMs, which are buoyant, are held by dyneema ropes and connected by a vertical-electro-optical-cable (VEOC) which carries fibres for communication and copper wires for power. At the bottom anchor, the VEOC connects to a container housing control and power electronics and where the DOM signals are multiplexed onto a single fibre that is connected via an interlink cable to the rest of the sea-floor network. ORCA will consist of one block of about 200

meter tall DUs, while ARCA will consist of 2 blocks of about 700 meters tall DUs.
Besides the signal expected from astrophysical neutrinos (3/day in ARCA) and atmospheric neutrinos (50.000/year reconstructed in ORCA), the bulk of the photons come from potassium-40 decays in the water at a rate of 7kHz per PMT, bioluminescence with bursts in excess of 100 kHz per PMT and atmospheric muons with a trigger rate of 100 Hz. These numbers represent a signal-to-background ratio of about 1 in a million. To deal with this challenge, and to achieve the detector performance required to achieve KM3NeT physics goals, both a timing accuracy on the photon arrival time of nanoseconds must be obtained and all recorded photons must be transported to shore. When these two conditions are met, on-shore trigger algorithms can exploit the good optical properties of sea-water which preserve the correlations between photon hits to reject the overwhelming background and find the sparse signal.

2. DAQ model overview

The DOMs, i.e. the components of the off-shore detector, and the computing resources of the shore-station are part of a computing network, which is called `RAW-LAN`, as sketched in Figure 2. The digitised PMT signals represent the physics raw data while the samplings of the submarine acoustic environment are exploited for measuring the detector positioning. Together with a continuous stream of summary information sent by each DOM, they form the *fast acquisition data* (FAD). It contributes to the largest part of the data-stream sent by the detector to shore, which can reach an aggregated continuous throughput up to O(100) Gbps. The load due to the slow-control traffic and from other instruments is practically negligible. While each DOM is linked to on-shore with a dedicated 1 Gbps connection, in the shore-station a 10 GbE bandwidth network infrastructure routes the incoming traffic to the computing farm. The `RAW-LAN` implements the main networking peculiarity of the experiment, which is the asymmetric layout of connections. Few downstream optical links "broadcast" the slow-control commands to each DOM by means of dedicated split-points. Many (one per DOM) upstream links transport the collected data and detector responses to the shore-station. In addition to that, a White Rabbit Switch fabric [3, 4] is used to achieve the sub-nanosecond time synchronisation among the DOMs. For this reason, such asymmetric and hybrid networking layout is handled via Software Defined Networks, as reported in [5].

The computing farm available in the shore-station runs processes with different tasks which can be subdivided into three groups: the Trigger and Data Acquisition System (TriDAS), the Control Unit (CU) and the Monitoring system.

The TriDAS is the software collection deputed to the read-out, aggregation and filtering of the FAD stream which arrives to the shore-station. All TriDAS components are inter-connected within the `RAW-LAN`, and managed throught the `CTL-LAN`, which is also exploited to route the selected data to the storage (local and/or remote) and to publish monitoring data outside of the shore-station. The first TriDAS stage is an aggregation step, performed by the *DataQueue* pool of processes. Each DataQueue client receives data from a group of DOMs, i.e. a sector of the detector. Such data is coherently gathered according to its timestamp and passed to the next TriDAS stage, the on-line filtering processes. These are divided in two sub-groups: the Optical and Acoustic *DataFilters*, described ahead in Sections 3 and 4. The selected PMT data is then routed to one DataWriter (DW) process which takes care to write them in a ROOT-based [6] file on a local storage. Acoustic

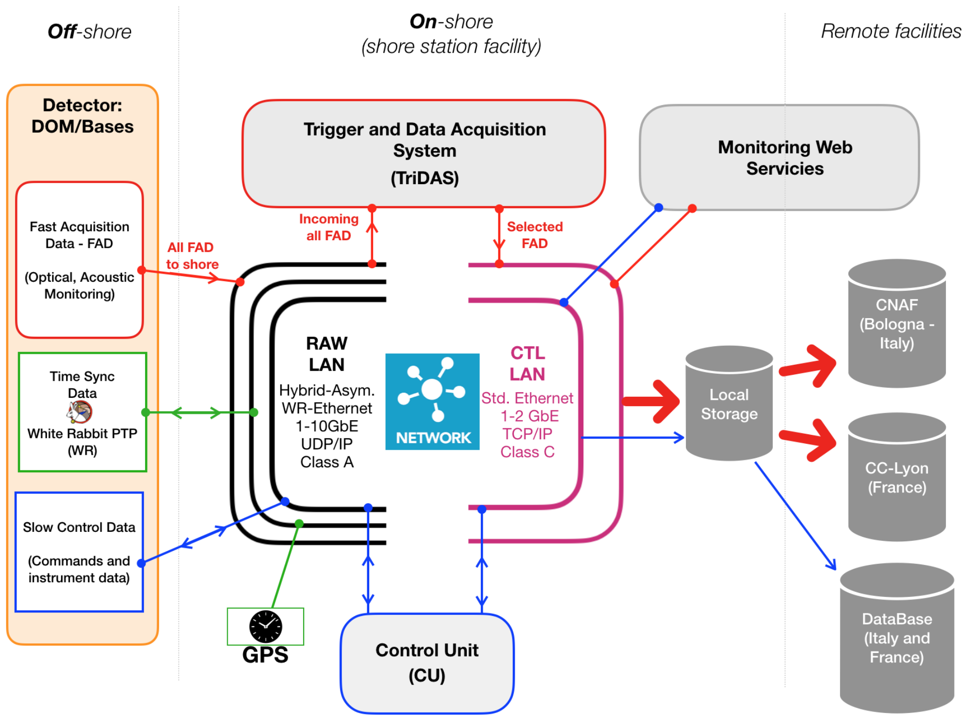

Figure 2: Outline of KM3NeT DAQ components.

data are processed to compute the position of each DOM with a precision of O(10) cm. Automatic processes periodically transfer the collected raw-data files to the permanent storage devices in the Computing Centers of INFN-CNAF [7] and IN2P3 [8].

The Control Unit is a collection of processes and web-server and represents the user interface to the detector. It aims at coordinating the TriDAS and the offshore detector through a dedicated state machine. The Control Unit is described in detail in the contribution [9] of these proceedings. It allows to start and stop the data acquisition, segmenting the operation of the detector in different *Runs*, for which a particular set of configurations for both the DOMs and the TriDAS are retrieved from the central authoritative Data Base (DB). The Control Unit is also responsible for collecting and logging to the DB all the instruments data.

The Monitoring system [10] comprises a suite of programs performing fast analysis, visualisation and monitoring out of a subset of the selected data. A Web server accessible from outside the shore-station is used to publish a set of plots, continuously updated, which show the status of the data taking (PMT and trigger rate counting, fast reconstruction and calibration checks). A number of programs run in the background for performing integrity checks on the continuous data streams. The outcome of such checks is then properly summarised into the DB and allows to determine the quality of the collected data.

The software tools described above are exploited not only in the "production sites", i.e. the ARCA and ORCA shore-stations, but also in different other sites where the detector components are integrated and tested, as well as in test-benches expressedly dedicated to DAQ and readout developments. The Automatic Installation And Configuration procedurE (AIACE), described in these proceedings at [11], is conceived to take care of the installation and configuration of all the computing resources required according to a certain experimental setup, deploying and characterising the due DAQ context.

3. Data handling and timeslicing

The main DAQ elements in the DOMs are implemented in an Xilinx Kintex FPGA which is part of the DOM electronics. At the base of the PMTs, the pulse is digitized in a low-voltage-differential-signal that is 'high' as long as the pulse is above a certain threshold, settable from on-shore. The digital acoustic piezo hydrophone samples at 193.5 kHz at 12 bit. The FPGA has 32 time-to-digital converters implemented via provided deserialisers to timestamp the 31 PMT signals, their pulse-durations and the acoustic data to nanosecond accuracy. The first-in-first-out buffers containing the hits are monitored to avoid overflow in case of excessive rates. For standard data-taking conditions a high-rate veto of 20 kHz was chosen.
Data are collected in *frames* of 100 ms and sent in several UDP/IP packets via the optical Ethernet network to shore. Each frame has a header, which contains an absolute timestamp. In case of photon data, the subsequent packets contain the photon hits, which are encoded in 6 bytes: 1 byte for the PMT channel, 1 byte for the pulse-duration and 4 bytes for photon hit-time with respect to the start of the frame. The status of the buffers are also sent to shore. The acoustic data consists of the digitized wave-forms. The timestamps marked in the DOM result from a White-Rabbit PTP core [12], which implements the White-Rabbit capable Ethernet in the FPGA. The optical data-stream is less than 20 Megabits per second per DOM (40 Gigabits per second per block) and the acoustic data-stream about half that.
All DOM sectors send their data to the related *DataQueue* processes which assemble the frames from the separate jumbo UDP packets (maximum of 9 kB) and send over TCP/IP all frames belonging to the same time-period to the same *Optical DataFilter* process. The Optical DataFilter processes collect all frames from the same time-period to obtain *timeslices* which thus contain all photons recorded in the whole detector in a 100 ms timespan. The Optical DataFilter applies the trigger algorithms to the data. If a timeslice causes a trigger, meanining that it potentially contains a neutrino event, the hits causing the trigger are collected in a *DAQ Event* together with all photon hits in the detector in a period of 10 microseconds before and after these hits. These data are sent to the *DataWriter* which writes all triggered events to file.
In case of acoustic data, the DataQueue sends all data from a specific DOM to the same *Acoustic DataFilter* process. This is required as the acoustic positioning needs to integrate over periods longer than a timeslice and at this level needs only to be done per DOM. The Acoustic Data Filters correlates the acoustic stream to a set of prefixed waveforms, for identifying the emissions of the pingers which are active on the seabed around the detector. The reconstructed Time Of Arrival of the emissions is used, off-line, to perform triangulations and obtain the position of each DOM with a precision of O(10) cm.

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4. Triggering, performances and first results

As all triggering is done in software (DataFilter processes), multiple trigger algorithms can be applied concurrently to the same set of data. The underlying principle shared by all trigger algorithms is that photon arrival times (hits) from a neutrino interaction are causally related in a known way. The aim is to find a set of pair-wise causally related hits with a minimum cluster size M, a so-called *clique* problem. The most general form of such a causality criterion restricts the time between hits on PMTs at different locations to be consistent with the travel time of light in water. This criterion can be made more restrictive by assuming a direction of travel of a potential muon resulting from a neutrino interaction. The latter requires an additional scan over directions in which a trigger is activated when at least one direction results in a cluster of minimum size. Also the geometrical dilution and absorption of the light are taken into account.

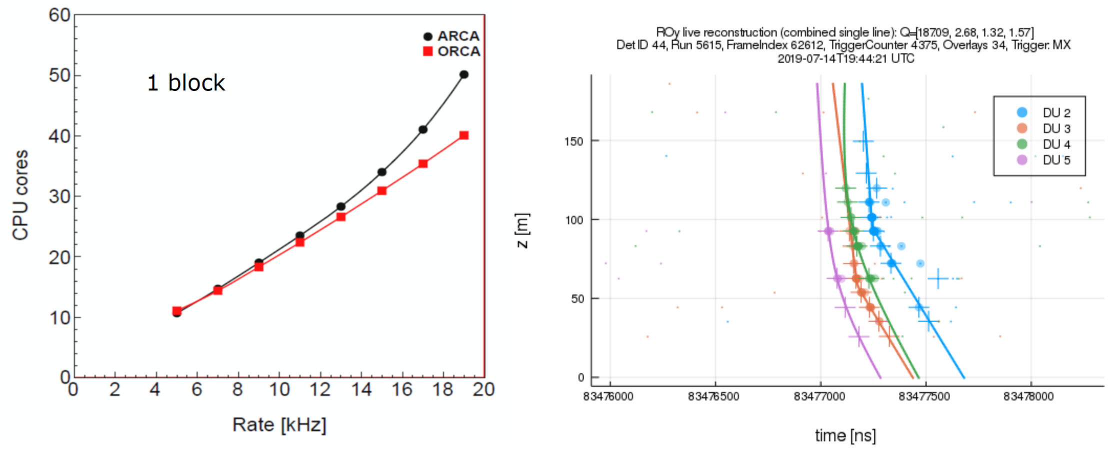

Figure 3: Left: CPU core requirements per building-block vs. PMT single rate; the estimate is obtained by using an Intel® Core^{TM} i5 4570 CPU at 3.20GHz. Right: Example of online monitoring: hit height versus time of the detection and fitted trajectories for the 4-DUs of ORCA .

It is obvious that the large amount of background photon-hits poses a computational problem. The problem of cluster finding is particularly hard and it is due to the nature of the causality criterion; no transitive properties can be taken into account. When hits a and b are related and so do b and c, it is not necessarily the case that a and c are related as well. Besides using the restrictive causality criteria, a way to deal with the amounts of data is by pre-selecting hits that are in coincidence with one or more hits on the same DOM in a window of about 10 nanoseconds. Additionally, the geometry of PMTs on a DOM can be exploited to reduce the amount of hits even further. The amount of hits to be considered is typically reduced by a factor of 400. In order to increase trigger efficiency, especially at lower energies of the candidate tracks and for electron-neutrino interactions in ORCA, one can add, to the sample of locally coincident hits, single hits from other DOMs under the criterion of vicinity.
The current default trigger algorithms are dedicated to muon tracks, applying the directional criterion as mentioned above, and algorithms tuned for 'shower-like' (e.g. electromagnetic cascade from an electron-neutrino event) events. Finally, the rate of local coincidences on the DOMs is supplied by the Optical DataFilter and used to monitor of Supernova occurences.

The required processing power depends on the background rate. As can be seen in Figure 3, left, the required amount of CPU power per building block (115 DU) is O(50) cores for optical triggering and a background rate of 7 kHz per PMT. In ARCA this leads to a trigger rate of about 100 Hz, dominated by atmospheric muons, while the efficiency exceeds 80% for all channels at neutrino energies above 10 TeV. In ORCA, the trigger rate for atmospheric muons is about 40 Hz, while 20 Hz is caused by random noise, with an efficiency for atmospheric neutrinos of an energy above 4 GeV which exceeds 80%.
Figure 3, right, shows an on-line triggered and reconstructed event in the ORCA detector which is currently operational with 4 DUs.

5. Conclusions and outlook

The KM3NeT experiment will perform continuous data taking for at least the next 15 years in two sites, reaching a total throughput up to O(100) Gbps per site. The construction and operation of the detector involves several challenging techniques, such as multi-PMT optical modules, asymmetric network and WhiteRabbit standard. The data acquisition system is implemented according to a custom framework, designed to be modular and to scale with a growing up detector. Two ARCA DUs were deployed in 2015 and 2016 [13]. Recently (June 2019) four ORCA DUs were set operational. In both ARCA and ORCA experimental sites data are continuously collected fulfilling the expectations. These two first scenarios have validated the design of the data-acquisition system. Future expansions of the DAQ system include exploiting the DataFilters for real-time source tracking and both the generation and reception of alerts in the multi-messenger context.

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