KM3NeT INFRADEV – H2020 – 739560

Report on the online event reconstruction development in the KM3NeT neutrino observatory.

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I. COPYRIGHT NOTICE

II. DELIVERY SLIP

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III. DOCUMENT LOG

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IV. APPLICATON AREA

This document is a formal deliverable for the GA of the project, applicable to all members of the KM3NeT INFRADEV project, beneficiaries and third parties, as well as its collaborating projects.

V. TERMINOLOGY

A complete project glossary is provided:

EM: electromagnetic
MM: multi-messenger
ARCA: Astroparticle Research with Cosmics in the Abyss
ORCA: Oscillation Research with Cosmics in the Abyss
CC: Charged Current
NC: Neutral Current
DAQ: Data ACquisition system
DOM: Digital Optical Module
CPU: Central Processing Unit
JPP: Java-inspired collection of C++ classes (framework for data taking, calibration et reconstruction)
MC: Monte Carlo
PMT: PhotoMultiplier Tube

VI. LIST OF FIGURES

VII. PROJECT SUMMARY

KM3NeT is a large Research Infrastructure that will consist of a network of deep-sea neutrino telescopes in the Mediterranean Sea with user ports for Earth and Sea sciences. Following the appearance of KM3NeT 2.0 on the ESFRI roadmap 2016 and in line with the recommendations of the Assessment Expert Group in 2013, the KM3NeT-INFRADEV project addresses the Coordination and Support Actions (CSA) to prepare a legal entity and appropriate services for KM3NeT, thereby providing a sustainable solution for the operation of the research infrastructure during ten (or more) years. The KM3NeT-INFRADEV is funded by the European Commission's Horizon 2020 framework and its objectives comprise, amongst others, the preparation of the multi-messenger activities in the KM3NeT Collaboration (work package 7).

VIII. EXECUTIVE SUMMARY

With the detection of gravitational waves (LIGO/VIRGO, [1-3]), cosmic high-energy neutrinos (IceCube, [4-5]) and the first Galactic PeVatron (H.E.S.S. [6]), we have entered the new era of multi-messenger astronomy. By observing astrophysical neutrinos with an unprecedented angular resolution, an extended energy range and a full sky coverage, KM3NeT will play a key role in this rapidly evolving field.

The KM3NeT Collaboration is instrumenting two deep-sea sites in France and in Italy to detect high-energy neutrinos from a detection threshold of few GeV up to few PeV, where the event rate dies out due to diminishing flux. This WP aims at maximizing the multi-messenger program of KM3NeT. The need to analyze neutrino events in real-time is identified, in order to either look quickly for time/space coincidences with transient alerts provided by external facilities or to select the most interesting cosmic neutrinos that will enable both ground and space based observatories to quickly point in the direction of the alert and identify the counterpart.

This document describes the status of the development of the online reconstruction system in the KM3NeT neutrino observatory. Section 1 shows the context for this project. Sections 2 and 3 describe how the event reconstructions are implemented and the performances achieved for ORCA and ARCA detectors, respectively. The framework to reconstruct all the events in real-time is presented in Section 4. Section 5 summarized the lessons learned during the first phase. Section 6 gives some conclusion and the next steps to fulfill this project.

Table of Contents

1. Introduction

The main goal of the WP7 is to pave the way to fully integrate the KM3NeT detector into the global multi-messenger worldwide network. The multi-messenger approach to astronomy makes use of the messenger particles carrying information from all four fundamental forces (photon, gravitational wave, neutrino and cosmic ray) to explore and understand the most violent phenomena in the universe such as gamma-ray bursts, outbursts of active galactic nuclei, fast radio bursts, supernova explosions, etc. One of the main characteristic of these extreme sources is that there are transient events with temporal variation of the flux of the order of milliseconds to few days/months. The study of these transient sources is called the "time-domain astronomy". The rapid analysis of the multi-wavelength and multi-messenger observations is the key to maximize the scientific potential of each event. This is perfectly illustrated in the discovery of the gravitational wave GW170817 from the merger of two neutron stars associated with the gamma-ray burst GRB170817 discovered by Fermi/GBM and INTEGRAL [3].

The KM3NeT Collaboration is instrumenting two deep-sea neutrino detectors in the Mediterranean Sea, a low energy site, ORCA, in France (typical energy range 3 GeV - 10 TeV) and a high energy site, ARCA, in Italy (1 TeV - 10 PeV) [7]. In the final configuration, ARCA will be composed of two building blocks of 115 lines, each line comprises 18 Digital Optical Modules (DOMs). ORCA, the denser detector, will comprise one building block with reduced spacing between lines and DOMs. The DOM is composed of 31 3-inch photomultiplier tubes in a 17 inches glass sphere. The construction is in progress on both sites, and by beginning of 2020, a larger sensitivity is already expected in the whole energy range compared to the operational ANTARES detector, the current most sensitive neutrino telescope in the Mediterranean Sea.

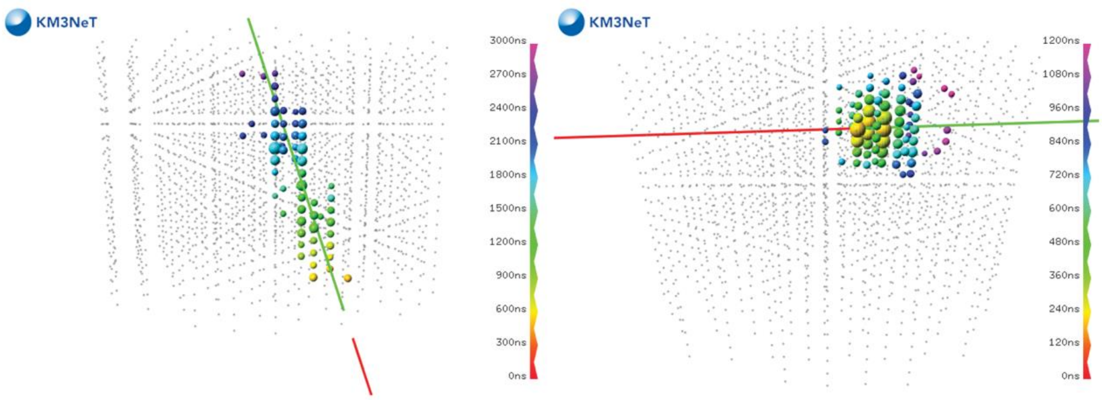


Figure 1: Event displays of a simulated νμ CC event (left) and a contained νμ NC event (right). The incoming neutrino is indicated by the red line, and the outgoing lepton (muon or neutrino) by the green line. The color scale gives the hit times with respect to the time of the neutrino interaction, while the size of the circles is proportional to the total charge on each DOM [7].

One neutrino may interact directly in the vicinity or inside the detector volume. In the interaction, relativistic charged leptons are generated that emit Cherenkov light. Cherenkov photons impinging on the photomultipliers produce signals ("hits"), which are collected in the DOMs and sent to the shore stations. Trigger algorithms based on combinations of local coincidences are applied to filter interesting events from the optical background produced by environmental light emitters like inorganic ^{40}K decays and organic bioluminescence. Finally, the position, time and collected charge of the hits are used to reconstruct the direction and the energy of the incident neutrino. Depending on the flavor of the neutrino, different topologies of the events can be identified (Figure 1). Events induced by charged-current interactions of muon neutrinos produce a track signature in the detector corresponding to a long extension of the signal in the direction of the neutrino track. All-flavor neutral-current and charged-current ν_e and ν_τ interactions produce electromagnetic and hadronic showers (so called cascades) in the instrumented volume. Dedicated algorithms have been developed for the offline analysis of track and cascade events for both ORCA and ARCA.

This real-time event reconstruction will feed a real-time analysis framework that will trigger an alert sending system (see Deliverable D7.3 KM3NeT-INFRADEV-WP7_D7.3-v1.1.docx) and a real-time physics analysis module (will be described in Deliverable D7.4).

2. Description of the event reconstructions

The neutrino-induced events are observed in two topologies, track-like and cascade-like events, each class is reconstructed by specific algorithms.

The reconstruction algorithm used for track-like events is described in Ref. [8]. The muon direction is reconstructed from the sequence of Cherenkov photon hits on the PMTs, profiting of the fact that photons are emitted along the particle track at the Cherenkov angle of about 42°. A suitable set of start values for the trajectory fit is obtained with a prefit scanning the full solid angle. For each prefit, the track is then reconstructed by maximizing a likelihood derived from a probability density function depending on the position and orientation of the photomultipliers with respect to the muon trajectory and on the hit times. Among these intermediate tracks, the one with the best likelihood is chosen. The energy is reconstructed from the spatial distribution of hit and non-hit photomultipliers.

The cascades are typically few meters long and therefore small compared to inter optical module distances. The direction reconstruction for such cascade-like events uses the fact that the Cherenkov light emission is peaked at the Cherenkov angle with respect to the cascade axis, albeit with a broader distribution than in the muon case [8].

The main framework hosting the different reconstruction strategies is JPP [9]. In KM3NeT, the open source JPP software package (a java-inspired collection of C++ classes) is primarily used in the data acquisition, offline triggering and calibration of the data sent to shore. The available extensive set of JPP methods has been successfully used for the development of fast, robust and detailed reconstruction algorithms for KM3NeT. The code design for these algorithms have been modified in order to be compliant with the event by event analyses needed for an online system (see Section 4).

3. Performances of the event reconstructions

The performances of the event reconstructions have been computed using extensive simulations of the detectors. Neutrinos are generated over the full solid angle to be able to estimate the global performances of the reconstructions. Simulations take into account the DOM properties (effective area, quantum efficiency and collection efficiency of the photomultipliers; the DOM electronics, transmission probability through glass and gel), the DOM orientations and positions with respect to the incident direction of the photon and the optical water properties.

With the very large volume of ARCA and the performances of the optical modules, a good angular resolution better than 0.3º is achieved for very high energy tracks (>10 TeV). This is the main channel for the neutrino astronomy since it is possible to point to the neutrino sources with competitive accuracy to other messengers. At lower energy in ORCA (>100 GeV), the angular resolution is around 1 - 2º. Even this is a rather coarse resolution, it can still be used to look for cosmic neutrinos as we will mainly use multiplet events to suppress the atmospheric background events, e.g. 2 - 3 neutrinos in a given time/angular interval (the angular resolution is improved by 1/√N, N is the number of neutrinos). Figure 2 shows the angular resolutions for track events plotted as a function of the simulated neutrino in ARCA and ORCA.

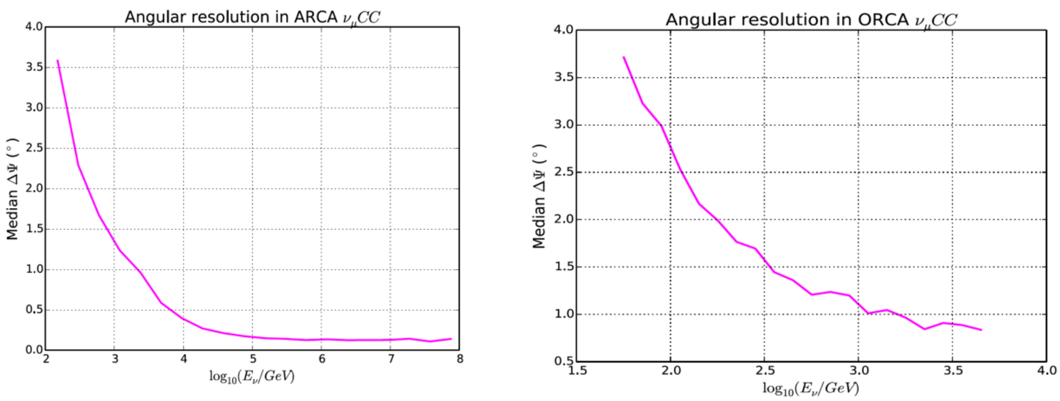


Figure 2: Angular resolution as a function of the neutrino energy for charged current muon neutrinos in ARCA (left) and in ORCA (right) detectors.

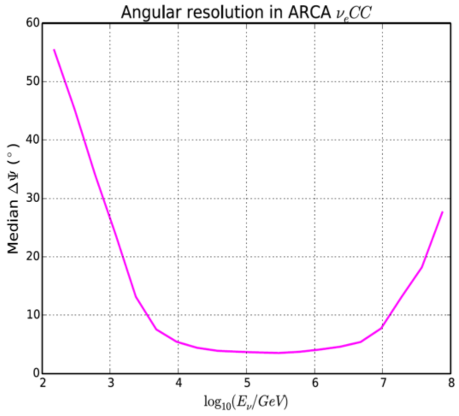


Figure 3: Angular resolution as a function of the neutrino energy for electron neutrinos in ARCA detector.

Even if the resolution for cascade events is worse (2 - 3° at high and >5° at low energies), they can be used in astronomy thanks to the smaller atmospheric background contamination. It is one of the most promising windows to detect astrophysical sources (very small atmospheric neutrino background). The angular resolution for cascade events in ARCA is plotted in Figure 3.

In a real-time implementation, it is necessary to be able to reconstruct all the events. With MC simulations of atmospheric muons, we have computed the time needed to reconstruct an event and the number of CPUs required for the reconstruction process. The processing of atmospheric muons dominates the reconstruction effort as the event rates are several orders of magnitudes higher than neutrino events. Figure 4 presents the atmospheric muon event rate and the CPU time per event for the ARCA 1-building block detector (half of the full ARCA), respectively. Figure 5 displays the same information for the ORCA detector.

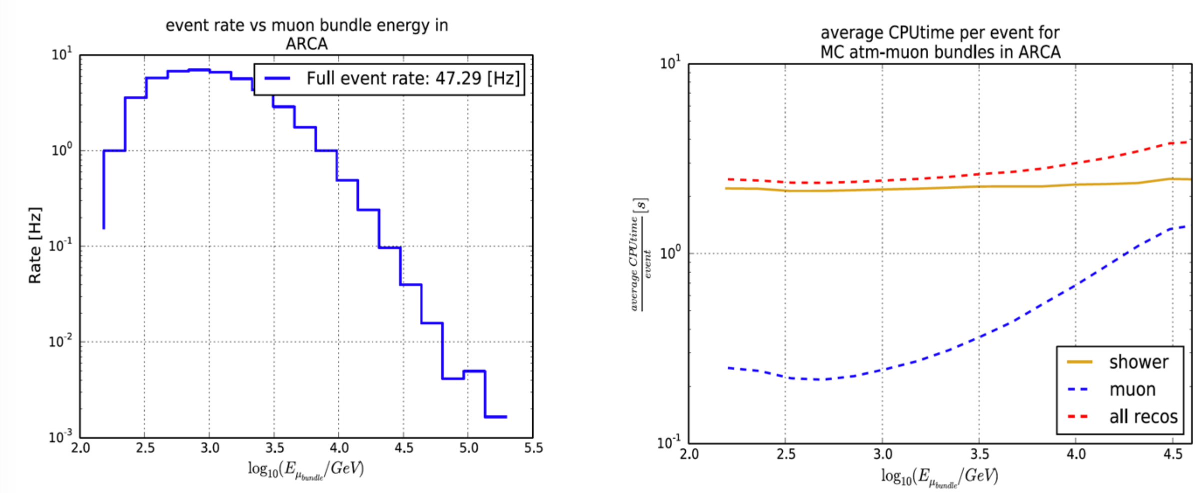
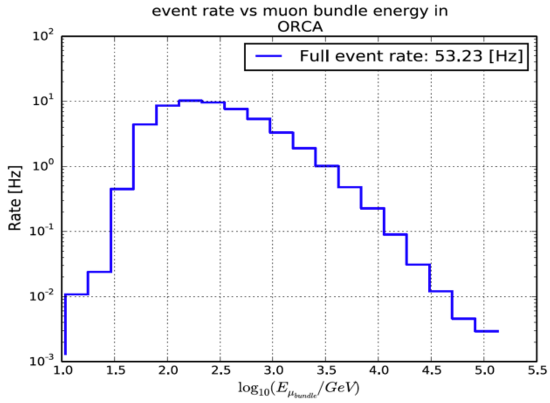


Figure 4: Atmospheric muon rate distribution at trigger level (left) and time performances of the track and cascade reconstruction algorithms (right) in one building block of ARCA detector.



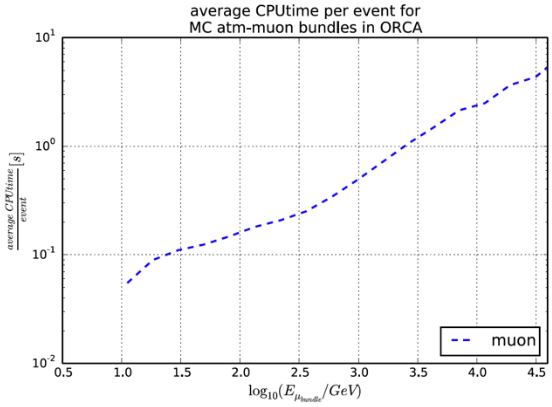


Figure 5: Atmospheric muon rate distribution at trigger level (left) and time performances of the trackreconstruction algorithm (right) in ORCA.

4. Implementation of the event reconstructions in the DAQ system

The real-time reconstruction algorithms will be implemented directly in the DAQ system. To not perturb the standard acquisition system, the event reconstructions are running on separated computers.

The DAQ follows an all-data-to-shore concept: all hits are sent to shore, where the trigger algorithms are running to filter events from the optical backgrounds (^{40}K decays and bioluminescence). At trigger level, the event rate of each of the two KM3NeT detectors, at ~100 Hz, is completely dominated by atmospheric muons (the rate of neutrinos is ~1 mHz). To account for this rate of events, the event reconstruction processes have to be distributed in a farm of several CPUs (distribution system). Based on MC simulations (see Section 3), the number of CPUs to process online events is estimated to ~200 cores per building block.

In order to have an operative real-time reconstruction system with the first data taking expected in March 2019, which corresponds to 6 and 2 lines for ORCA and ARCA respectively, a first distribution system has been developed. Figure 6 presents the data-flow of the online reconstruction processes. This system consists in receiving the DAQ events via socket connections. The reconstruction applications (processes) act as servers which wait for data. These processes will be distributed to several CPUs. The current computing infrastructure (1 computer of 16 CPUs) is sufficient to reconstruct online events for several lines. The results are transmitted via socket to a single application that works as a "listener". This listener will store the reconstruction results for interesting events in memory for further neutrino analysis and, in parallel writes these events to disk. This scheme has been successfully tested using Monte Carlo data. This reconstruction framework has been installed in the shore station of KM3NeT-ORCA and as soon as the first data are acquired, the final tests on real data will be performed.

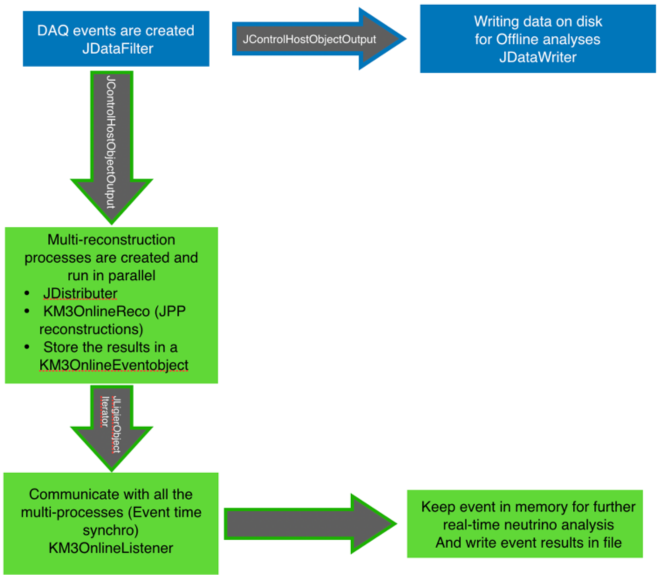


Figure 6: Data flow of the reconstruction processes. In blue, the standard DAQ while in green is the real-time reconstruction framework.

We plan to have first online analysis with the start of the run O3 of LIGO/VIRGO in April 2019. A more complete version is expected beginning of 2020 when KM3NeT-ARCA will have deployed a sufficient number of lines to have a larger sensitivity than ANTARES at high energies.

One other important task in the future is to have the calibration set in real-time with compatible precision to the one computed in offline, especially the time and positioning calibrations. Up to now, we are using idealized detectors for all the real-time tools, but we know that in periods of high sea current, the angular and efficiency performances are degraded. Having, a real-time positioning could solve this problem.

5. Lessons learned

In order to save time of development and human resources, it is crucial to use the same framework and analysis tools developed for the offline analysis in the online system. It facilitates the development of new functions, maintenance of the software and further cross-check between online and offline results.

Software development and maintenance are highly dynamic tasks, frequently updated for improvements in the data treatment, user facilities, efficiency, portability and so on. Therefore, it is important that all machines involved in the data treatment should ideally have similar working environment, e.g., operating system, compiler version, packages.

6. Conclusion and perspectives

Thanks to the unprecedented angular resolution, the extended energy range (~3 GeV; >10 PeV) and the full sky coverage, KM3NeT will play an important role in the rapidly evolving multi-messenger field.

With the WP7, we are contributing to this main objective by putting in place a real-time analysis scheme to look for the sources of high-energy neutrinos. The first step is to be able to quickly reconstruct all the events to select neutrinos and look for correlation with electromagnetic transients, counterparts of gravitational waves or high energy neutrinos detected by others neutrino experiments. A first online reconstruction system has been developed in KM3NeT and is ready for operation when the first data will be available. First results are expected in spring 2019. In order to achieve the event-by-event reconstruction for the full detector, a distribution system over 200 CPUs per building block will be implemented in the future.

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