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The KM3NeT online processing for multi-messenger alerts

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Abstract. KM3NeT is a deep-sea research infrastructure under construction in the Mediterranean Sea. It consists of two water-Cherenkov neutrino telescopes: ARCA (Italy), designed to identify and study TeV-PeV astrophysical neutrino sources, and ORCA (France), aiming at studying the intrinsic properties of neutrinos in the few-GeV range. Both detectors are also sensitive to neutrinos emitted in the MeV range by core-collapse supernovae. KM3NeT is actively involved in real-time multi-messenger searches, which aim at combining information from the simultaneous observation of complementary cosmic messengers with different observatories. These searches allow to increase the discovery potential of transient sources by sending alerts in real-time when potencial interesting events are detected. The KM3NeT online analysis framework is continuously reconstructing all ARCA and ORCA events, performing core-collapse supernova analyses and searching for spatial and temporal coincidences with alerts received from other multi-messenger instruments. This contribution deals with the description of the KM3NeT online processing system for multi-messenger alerts.

1 Introduction

Multi-messenger astrophysics allows to study cosmic phenomena by the simultaneous observation of different cosmic messengers. These messengers, consisting of cosmic rays, photons, gravitational waves and neutrinos, can originate from different astrophysical processes, so their coincident detection provides a more comprehensive understanding of the emitting sources than their individual measurements. Among them, neutrinos are ideal messengers because they are neutral particles that can travel vast distances without undergoing any significant absorption. However, they are difficult to detect because of their weakly interacting nature, requiring large volume detectors. A key aspect in the localisation and identification of transient sources is the delivery to multi-messenger detectors of real-time alerts whenever interesting events are detected. The large field of view and the almost 100% duty cycle of neutrino telescopes make them ideally suited to early notify other multi-messenger instruments and perform follow-up searches of external triggers. This is the reason why the KM3NeT Collaboration has implemented a Real-Time Analysis (RTA) framework, which is continuously processing events and launching automatic follow-up searches. The following

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sections provide a description of the KM3NeT telescope (Sect. 2), the KM3NeT RTA framework (Sect. 3) and the KM3NeT online processing (Sect. 4). The KM3NeT online analysis techniques and the latest results of the KM3NeT online system are reported in [1].

2 The KM3NeT telescope

KM3NeT [2] is a deep-sea neutrino telescope under construction in the Mediterranean Sea. It comprises two detectors at two different sites that use the same technology but have different physics goals. These detectors consist of a three-dimensional grid of Digital Optical Modules (DOMs) [2], arranged along vertically aligned Detection Units (DUs), each hosting 18 DOMs. The DUs are anchored to the seabed and kept vertical by buoyancy. Each DOM contains 31 photomultipliers (PMTs) aiming at detecting the Cherenkov light induced by relativistic charged particles produced in neutrino interactions. The detector called Astroparticle Research with Cosmics in the Abyss (ARCA) is located 100 km off-shore Portopalo di Capo Passero, Sicily, Italy at a depth of 3500 m and is optimised for the detection of cosmic neutrinos in the energy range 1 TeV−10 PeV. It has a DU horizontal spacing of 90 m and a DOM vertical spacing of 36 m. The detector named Oscillation Research with Cosmics in the Abyss (ORCA), on the other hand, is placed 40 km off-shore Toulon, France at a depth of 2450 m and is optimised to detect low-energy atmospheric neutrinos. It has a DU horizontal spacing of 20 m and a DOM vertical spacing of 9 m.

The complete layout of KM3NeT will consist of 3 Building Blocks (BBs), 2 for ARCA and 1 for ORCA, each containing 115 DUs. With more than 6200 DOMs, and a total of $\sim$ 200000 PMTs, KM3NeT will also be sensitive to $\sim$ 10 MeV neutrinos emitted by Core-Collapse Supernovae (CCSNe) through the observation of coincident PMT signals above the background. At the time of the Conference, ARCA was taking data with 28 DUs (ARCA28), while ORCA with 23 DUs (ORCA23).

3 The KM3NeT RTA framework

After being collected, data are sent from each detector to the corresponding shore station according to an *all-data-to-shore* approach, where they are filtered by the Data Acquisition (DAQ) system and then mirrored to the KM3NeT RTA framework, schematised in Fig. 1. At each shore station, data are continuously sent into two modules by a RTA dispatcher: a GeV-PeV module taking care of the multi-core reconstruction and classification of triggered events, and a MeV module [3] aiming at identifying MeV neutrinos from CCSNe. Once processed, data from each detector are sent to a common multi-messenger dispatcher and used for online analyses [1].

4 The KM3NeT online processing

GeV-PeV neutrino-induced events can be obsverved in two topologies: track-like and shower-like events. Track-like events are associated to muons produced in ν_μ charged current (CC) interactions and ν_τ CC interactions with the τ decaying into a muon. Since muons can travel long distances in the detector, producing a narrow and straight signal, a good angular resolution can be achieved for these events. Shower-like events, on the contrary, result from all-flavour neutral current (NC) interactions, ν_e CC interactions and ν_τ CC interactions with the τ decaying into an electron or hadrons. In this case, the energy deposition occurs within few meters from the interaction vertex, resulting in a better energy resolution but a worse angular resolution in comparison to track-like events [4]. Given these two event topologies,

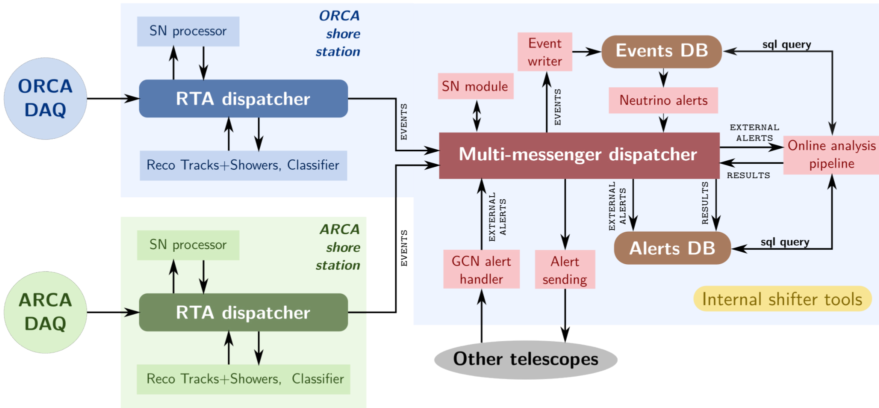

Figure 1. Schematic view of the KM3NeT RTA framework.

events are reconstructed both as track and shower by the GeV-PeV module of the KM3NeT RTA framework by using two different algorithms [5]. The algorithms used in the online reconstruction are the same as those used in the offline reconstruction. However, preliminary information on detector positioning, orientation and timing are applied because dynamic calibrations are not yet available at the online processing. In addition to the reconstruction algorithms, machine learning techniques are adopted to separate neutrinos from the atmospheric muon background.

The GeV-PeV online processing architecture is different between ORCA and ARCA. In ORCA, track reconstruction, shower reconstruction and classification are run in series, while in ARCA they are parallelised. Event classification is performed with a Boosted Decision Tree (BDT) in ORCA using the reconstruction outputs as input. In ARCA, a Graph Neural Network (GNN) operating independently of reconstruction outputs enables classification to be run in parallel to reconstruction [6]. As a result of the ARCA28 implementation, events are processed in a median time of ~ 6.8 s for track reconstruction, shower reconstruction and classification, as shown in Figures 2(a), 2(b) and 2(c), respectively. The ORCA23 sequential processing, on the other hand, allows to reconstruct and classify events in a median time of $\sim$ 10 s, as shown in Fig. 2(d).

Together with the GeV-PeV module, the MeV module processes data in order to search for MeV neutrinos from CCSNe, whose main detection channel for KM3NeT is the inverse beta decay of $\overline{\nu}_e$ on free protons in seawater. Since KM3NeT is optimised for energies above the GeV scale, the MeV module takes the raw PMT data as input and searches for an excess of coincidences between PMTs in single DOMs above the expected background [7, 8], such that each single DOM acts as a standalone detector.

5 Conclusions

A real-time analysis framework has been implemented in KM3NeT in order to fast process collected data, perform follow-up searches of external triggers and send alerts to the multi-messenger community. The KM3NeT online processing allows to reconstruct and classify events in a median time of ~ 6.8 s for ARCA28 and ~ 10 s for ORCA23, and to search for MeV core-collapse supernova neutrinos. Once processed, data are ready to be used in online follow-up analyses already implemented in the framework [1]. Moreover, interesting events

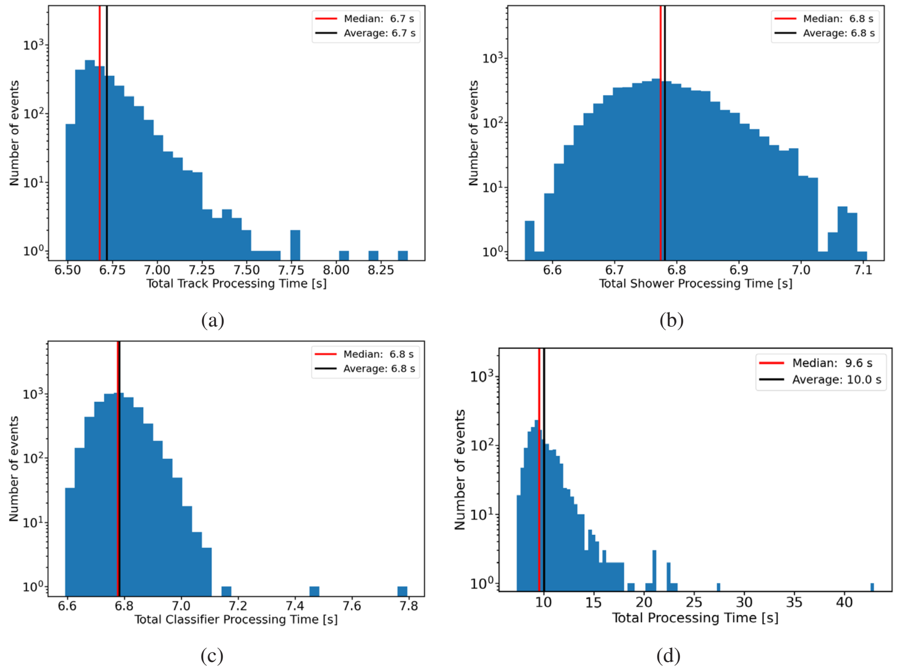

Figure 2. ARCA28 total processing time distributions for event acquisition, transmission and reconstruction for tracks (a) and showers (b), event acquisition, transmission and classification (c), and ORCA23 total processing time distribution for event acquisition, transmission, track/shower reconstruction and classification (d).

can be identified according to a certain event selection currently under study, and which is expected to be defined by the end of this year.

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