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Status of the Real-time Multi-messenger Program of KM3NeT

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Abstract. The KM3NeT research infrastructure in the Mediterranean Sea is a multi-purpose cubic-kilometre neutrino observatory hosting two detectors. ORCA is optimized to study atmospheric neutrinos between 1 and 100 GeV, while ARCA is primarily aimed at detecting cosmic neutrinos between several tens of GeV and PeV range. The real-time multi-messenger program of KM3NeT is oriented towards the study of astrophysical transients. It enables the bidirectional exchange of alerts for follow-up analyses as well as joint sub-threshold searches with a network of partner observatories. The prompt and open dissemination of the results to the astrophysical community is a key objective of the program. This contribution outlines the first developments of the KM3NeT multi-messenger infrastructure, covering two real-time analysis scenarios: the search for core-collapse supernova neutrino bursts and the search for astrophysical high-energy neutrinos. The data processing pipelines, the alert distribution systems and the perspectives for the KM3NeT integration in the global multi-messenger networks are described.

1. Introduction

KM3NeT is a research infrastructure installed in two abyssal sites of the Mediterranean Sea (Adrian-Martinez et al. 2016). It consists of two Cherenkov neutrino telescopes: ORCA, installed at 2500 m under s.l., offshore Toulon, and ARCA, at 3500 m under s.l. at about 100 km offshore the Sicily coast, respectively aimed to the determination of the neutrino mass ordering and the search for high-energy astrophysical neutrino sources. KM3NeT detectors are arrays of digital optical modules (DOMs). Each DOM hosts 31 80 mm photomultipliers (PMTs) and their readout electronics enclosed in a pressure-resistant glass sphere. DOMs are connected in groups of 18 to form vertical detection units (DUs) anchored to the seabed. A group of 115 detection units form a *building block*.

The PMT signals are digitised by a dedicated electronic board in the DOM. For each pulse above a threshold of 0.3 photoelectrons, the time of the leading edge and the time over threshold are recorded, packed as a *hit* and sent to shore (*all-data-to shore* approach) to be processed by an array of software data filters, see Fig. 1 (left). The data filters produce two types of data: *physics events*, identified by triggering algorithms looking for causally-connected hits from the Cherenkov signature of charged particles in the detector, and *raw hit* data streams with different coincidence selections,

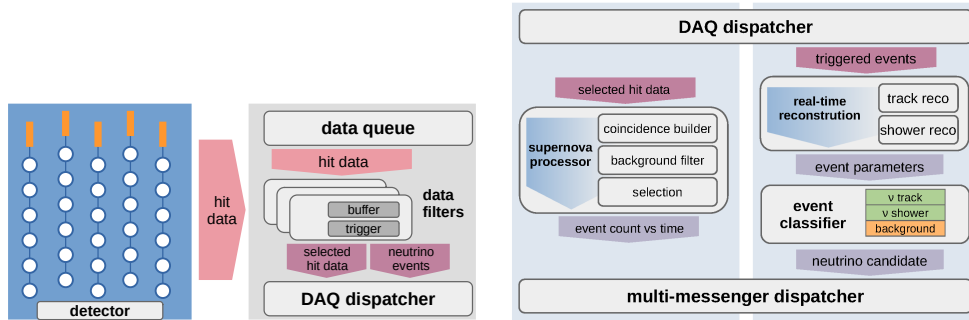


Figure 1. Overview of the two real-time analysis pipelines of the KM3NeT multi-messenger program

for monitoring and calibration purposes. The output of the data filter is distributed to the dispatcher of the data acquisition (DAQ) system. Data received from the dispatcher are written to permanent storage. In parallel, the data are fed to two real-time analysis pipelines: the supernova search and the high-energy neutrino search, see Fig. 1 (right).

2. Real-time supernova processing

The detection of a core-collapse supernova neutrino burst in KM3NeT is based on the search for an excess of coincidences above the background hits throughout all DOMs (Colomer Molla et al. 2020). For real-time processing, the *supernova* raw hit data stream implements a coincidence pre-selection to reduce the data throughput without affecting the signal detection capabilities. At each detector's shore station, a *supernova processor* application applies a real-time search for coincidences using a 10 ns time window, a filtering for the reduction of hits from the atmospheric muon background, and a selection based on the number of PMTs with coincident hits. The number of coincidences in the final selection is estimated every 100 ms over the previous 500 ms of data.

This information is sent to the central multi-messenger computing farm, where it is collected by a dedicated data dispatcher, see Fig. 2 (left). Here, the data streams from both ARCA and ORCA detectors are synchronised to perform a combined significance estimation. Information about significance as a function of time is distributed to the dispatcher and compared to a list of reference threshold values by an alert generator that produces alerts of different types. A threshold corresponding to a false-alarm-rate (FAR) below one per week is used to trigger the sending of an alert to the SNEWS global network (Antonioli et al. 2004).

At the same time, the data filters buffer all the coincidences recorded each detector over a time frame of ten minutes. This data can be exploited, in response to a trigger for a detailed analysis of the signal, as shown in Figure 2 (right). A dedicated module selects the internal alerts targeted for this purpose and propagates a control message to the DAQ of the ARCA and ORCA detectors. A *quasi-online* analysis pipeline for the buffered data is currently under development. The analysis of all coincidences enables the resolution of the signal time profile, with the possibility to infer the burst arrival time. The timing measurement and the signal time series can be shared with

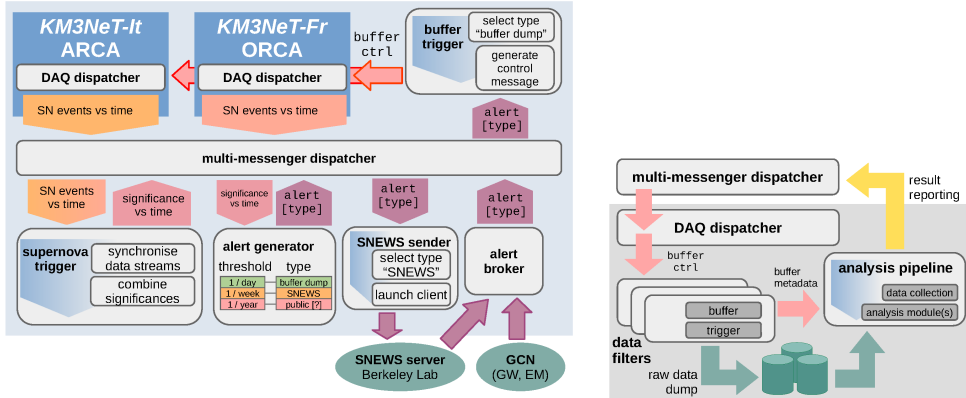


Figure 2. Overview of the section of the KM3NeT multi-messenger infrastructure dedicated to real-time supernova search.

external partners through a multi-messenger infrastructure as foreseen for the upcoming SNEWS 2.0 program (Al Kharusi et al. 2020).

The real-time supernova search of KM3NeT is operating since early 2019 with the first ARCA and ORCA detection units deployed in the sea. In 2020, the system has been integrated with the SNEWS infrastructure enabling the sending of alerts. The preparations to support the SNEWS 2.0 science program are ongoing.

3. Real-time astrophysical neutrino searches

A real-time event reconstruction and classification pipeline has been developed for the operation with the first KM3NeT detection units. The system is currently operating with the ORCA 6-DU detector. The standard KM3NeT reconstruction algorithms (Melis et al. 2018) are implemented in a real-time framework. For each physics event, a track reconstruction is performed. Tracks emerging from charged-current muon neutrino interactions are reconstructed with a median resolution of ~ 8 deg at 10 GeV of energy, which improves to 1 deg at 1 TeV. The shower reconstruction is being implemented.

The result of the reconstruction is fed to a classifier based on a gradient boosting decision tree, implemented using the LightGBM framework (Ke et al. 2017). The classifier is based on directional discrimination between background atmospheric muon tracks and muon tracks from neutrino interactions. The classifier is trained on a simulation of physics events produced in an ORCA 7-DU detector. A preliminary selection allows reaching a 30% neutrino efficiency with a 5% contamination from the atmospheric muon background. An optimisation of the selection is currently ongoing.

An event rate of ~ 100 Hz is expected for a KM3NeT building block. The computing time of the track and shower reconstruction is 0.1 s and 1 s per event respectively. The mean total processing latency of the reconstruction and classification chain is 4 s from the generation of the data off-shore.

The real-time selection is aimed to realise an all-sky, all-flavour neutrino search, capable to promptly search for space and time correlations with electromagnetic and multi-messenger alerts, as well as source catalogues. For this purpose, a suite of online

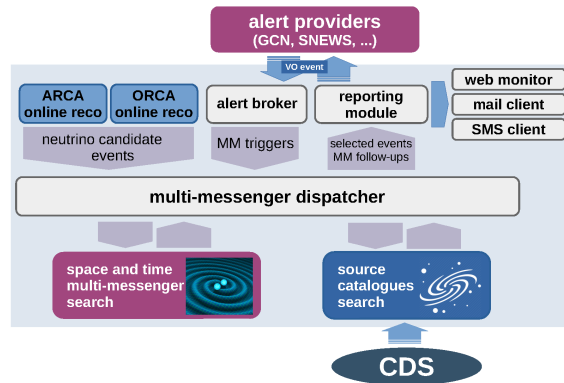


Figure 3. Overview of the section of the KM3NeT multi-messenger infrastructure dedicated to the all-sky all-flavour astrophysical neutrino search.

analysis modules, see Fig. 3, is foreseen. An alert broker, distributing the alerts received from global alert networks (such as the GCN) to the internal KM3NeT infrastructure, is operational. The real-time analysis modules for the correlation of the selected events with external alerts and source catalogues are under development. A reporting module will take care of sending selected events, as well as the results of the multi-messenger searches, to the alert networks and the KM3NeT science partners. Reporting of selected events through a web interface, plus e-mail and SMS communications, will be supported.

4. Conclusion

The first realisation of the real-time multi-messenger system of KM3NeT is currently operational. The supernova search pipeline has been online since early 2019 for the first ARCA and ORCA detection units and has been integrated with the SNEWS global alert network. In parallel, a real-time reconstruction and classification event pipeline is running for the ORCA 6-DU detector. A preliminary real-time neutrino event selection is in place. With the further developments, the system will implement advanced analysis modules and will be integrated into new global multi-messenger networks.

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