KM3NeT INFRADEV

KM3NeT INFRADEV – H2020 – 739560

Report on the implementation of the online analysis framework of KM3NeT

KM3NeT INFRADEV GA DELIVERABLE: D7.5

Document identifier:	**KM3NeT-INFRADEV-WP7-D7.5**
Date:	**02/12/2019**
Work package:	**7**
Lead partner:	**CNRS**
Document status:	**Final**
Dissemination level:	**Public**
Document link:	

I. COPYRIGHT NOTICE

II. DELIVERY SLIP

	Name	Partner/WP	Date
From	Damien Dornic	CNRS / WP7	03/12/2019
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Approved by	PMB		18/12/2019

III. DOCUMENT LOG

Issue	Date	Comment	Author/Partner
1	20/11/2019	First draft version	D. Dornic
2	3/12/2019	2nd draft including comments from S. Navas and Paschal Coyle	D. Dornic
3			
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IV. APPLICATON ARE

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
UTC: Coordinated Universal Time
VO: Virtual Observatory
IVOA: International Virtual Observatory Alliance
GCN: Gamma-ray Coordination Network
DAQ: Data Acquisition system

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 described in this Work Package (WP7).

VIII. EXECUTIVE SUMMARY

The main goal of the WP7 is to trace the path to fully integrate KM3NeT into the global multi-messenger worldwide network. The multi-messenger approach to astronomy makes use of the messenger particles of 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 burst, outburst of active galactic nuclei, fast radio burst, supernova explosion, etc.

Thanks to the unprecedented angular resolution, the extended energy range (~10 MeV; >10 PeV) and the full sky coverage, KM3NeT will play an important role in the rapidly evolving multi-messenger field. The task 7.5 of the WP7 consists on implementing an analysis framework that is able to reconstruct and to classify all the KM3NeT data in real time, to trigger and send neutrino alerts to the astronomy community and to look for time/space coincidence with external triggers. This analysis framework will assure the real-time follow-up of any multi-messenger and multi-wavelength triggers from cataclysmic astrophysical phenomena such as gamma-ray bursts, fast radio burst, supernova, merger of compact objects (black hole, neutron star), blazars…

A first version of the analysis framework has been deployed in the ORCA shore station. Since mid 2019, it is analyzing ORCA 4 DU detector data.

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1. Introduction to KM3NeT neutrino detection

Neutrinos are unique messengers to study the high-energy Universe as they are neutral and interact weakly and therefore travel directly from their point of creation to the Earth without absorption. Neutrinos could play an important role in understanding the mechanisms of cosmic ray acceleration and their detection from a cosmic source would be a direct evidence of the presence of hadronic acceleration.

The KM3NeT neutrino detectors ORCA and ARCA (Oscillation & Astroparticle Research with Cosmic in the Abyss) are under construction in two deep-sea sites in the Mediterranean Sea. ORCA is located off the French coast (Toulon), and ARCA off the Italian coast (Capo Passero). The main goal of ORCA is the determination of the neutrino mass ordering, exploiting a densely instrumented detector with sensitivity at the GeV scale. ARCA is dedicated to the search for high-energy (TeV-PeV) astrophysical neutrino sources, using a large km^3-scale instrumented volume [1]. However, it is possible to use ARCA for particle physics research (dark matter, sterile neutrino) and ORCA for astronomy (solar flares, merger of neutron stars, X-ray/gamma-ray binaries…). Both detectors are based on the same technology: the Cherenkov light induced by charged secondary particles emerging from neutrino interactions is detected using a three-dimensional deep-sea grid of photo-sensors with single-photon sensitivity and nanosecond time resolution. The core element of the KM3NeT detectors is the digital optical module (DOM) featuring 31 directional photomultiplier tubes (PMTs) in a spherical glass sphere [2]. DOMs are connected in groups of 18 to form a vertical line called detection unit (DU), while a group of 115 DUs forms a building block. ORCA contains 1 building block while ARCA has 2. Both detectors are already collecting data with first detection units since few years. By end of 2020, a larger sensitivity is already expected in the whole energy range compared to the ANTARES detector.

All data above noise threshold are sent to shore via optical fibers and are filtered for event signatures in an online computer cluster (see [1] for more details). The standard analysis chain consists on applying triggers to filter events from the noise (~99% reduction of the rate) and then estimate the event parameters (time, direction, energy, topology, quality) using very performant event reconstruction algorithms.

One neutrino may interact directly in the vicinity or inside the detector volume, producing a relativistic charged lepton emitting Cherenkov light. Cherenkov photons impinging on the photomultipliers produce signals ("hits"), which are collected in the shore station. 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 (CC) interactions of muon neutrinos produce a track signature in the detector corresponding to a long extension of the signal in the track direction. All-flavor neutral-current (NC) and CC ν_e and ν_τ interactions produce electromagnetic and hadronic showers (named as cascades) in the instrumented volume. The implementation and the detailed performances of the real-time reconstructions both for tracks and cascades are summarized in the deliverable KM3NeT-INFRADEV-WP7_D7.2.pdf.

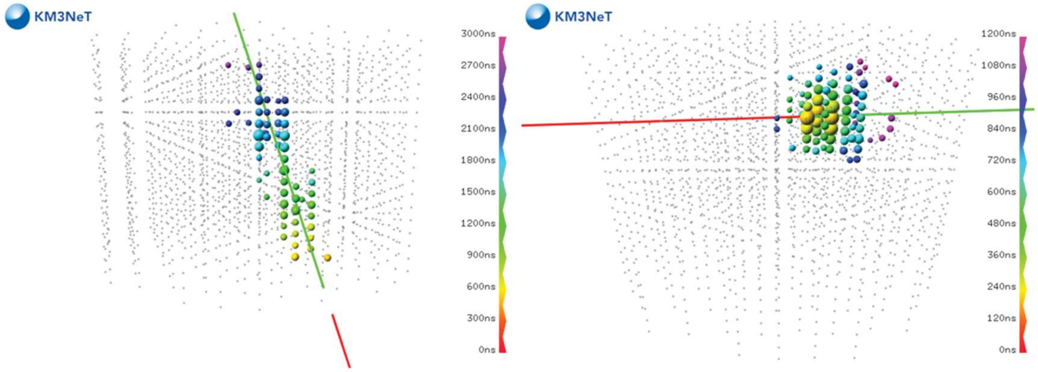

Figure 1: Event displays for a simulated ν_μ CC event (left) and a contained ν_μ NC event (right). The incoming neutrino is indicated by the red line, and the outgoing lepton (muon or neutrino) by the green line. The color scale gives the hit times with respect to the time of the neutrino interaction, while the size of the circles is proportional to the total charge on each DOM. DOMs without hits are shown by grey dots [1].

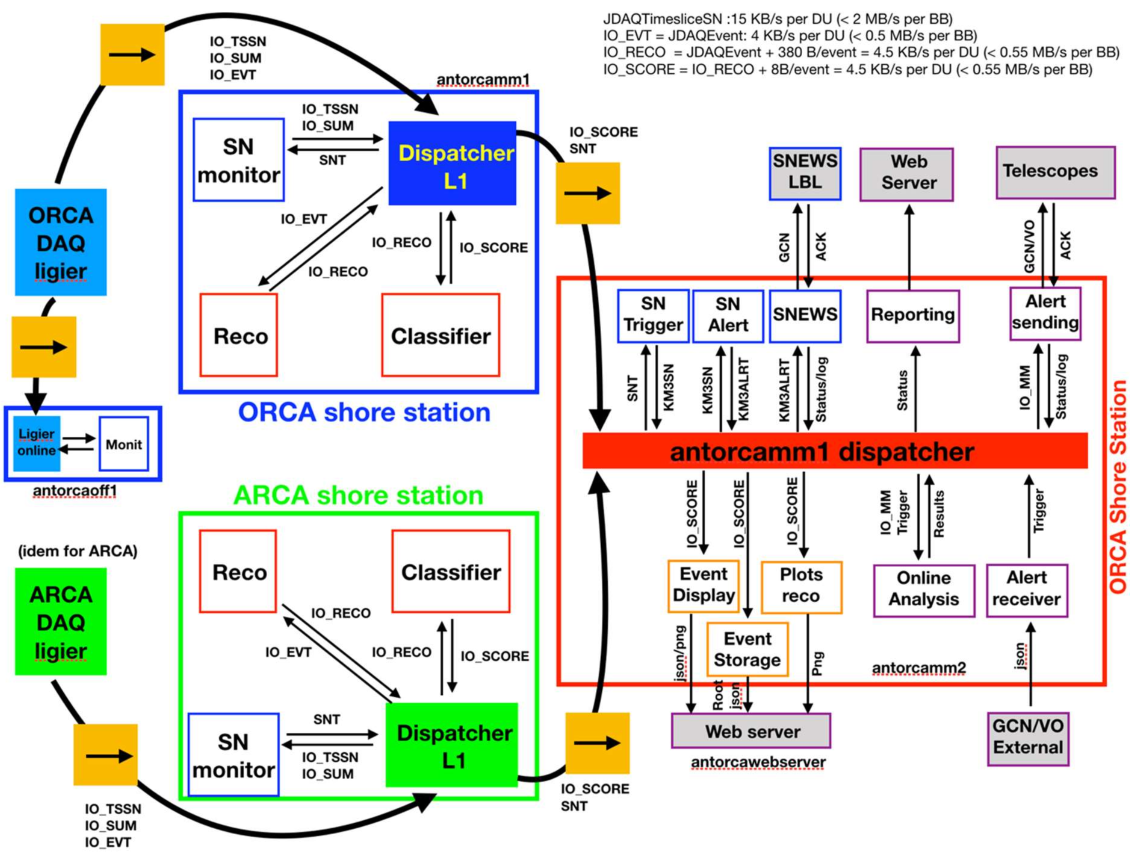

Figure 2: Architecture scheme and dataflow model of the KM3NeT real-time analysis framework.

The real-time multi-messenger analysis framework is currently being implemented to reconstruct rapidly track and cascade neutrino events, to provide rapid public/private alerts to the external telescopes for the most interesting neutrino candidates, and also to perform real-time follow-ups of external transient signals, such as gravitational waves, neutrinos and electromagnetic events. Figure 2 shows a detailed scheme of the architecture and the data flow of the online analysis framework. This architecture is composed of three main parts: one specific to ORCA (blue rectangle), one to ARCA (green rectangle) and one common to both detectors (red rectangle). In order to limit the huge data flow of each detector, the heavy processing is performed directly in the shore station, and it contains the event reconstruction processes, the classifier and the supernova monitor (see KM3NeT-INFRADEV-WP7_D7.4.pdf). The common part contains some services (tools to make event display, event storage, monitoring and the internal/external reporting), the SN final processing processes (SN trigger, SN alert and SNEWS sender), the neutrino alert sending module and the online analysis module.

2. Description of the online neutrino selection

The first and most important task of the online analysis is to select neutrino streams over a large background of atmospheric muons (and bundles of muons) and badly reconstructed events. The identification of the nature of the event is performed by four classifier modules: one for ORCA and one for ARCA, one for tracks and one for cascades.

At the time of the writing of this document, only the muon neutrino classifier for ORCA has been developed. It uses as inputs the results of the track online reconstructions (IO_RECO) and produces in output a score (IO_SCORE). The score is 0 for an atmospheric muon and 1 for a muon neutrino. This algorithm is based on a Machine Learning method that uses several variables (number and total charge of the triggered hits, reconstructed zenith, quality of each step of the reconstruction, etc.) to build a discriminant variable (score). Before using the classifier with real data, the algorithm is first trained and tuned using two independent samples of very detailed Monte Carlo simulations of the atmospheric muons and atmospheric neutrinos. A third independent sample is used for the evaluation of the trained algorithm. These simulations take into account the best knowledge of the PMT response, the water properties and the acquisition electronic parameters. Figure 3 shows the results of the trained algorithm of the classifier to this third independent 'test' set.

Based on the value of the score, it is possible to select a muon neutrino sample with a given purity. For example, with 7 lines, we select ~10 muon neutrinos per day with 90% purity. The criteria are optimized using Monte Carlo simulations separately for each detector.

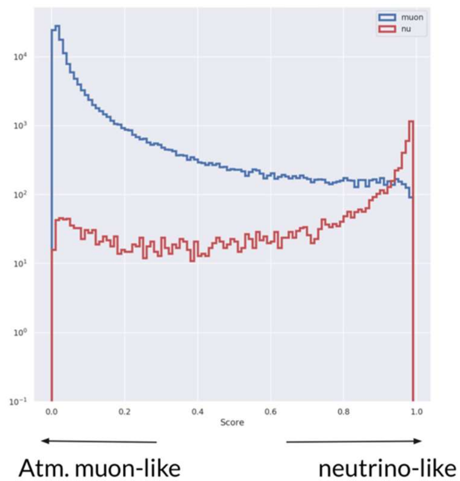

Figure 3: Preliminary results of the neutrino classification performed on two Monte Carlo simulations of atmospheric neutrinos (red) and muons (blue) after the training phase of the algorithm. This analysis is performed for ORCA 7 lines configuration.

A v0 version of the muon neutrino classifier is already in operation with the ORCA 4 lines detector since Summer 2019. Figure 4 displays examples of some distributions of the muon track reconstruction and the results of the classifier for the 15-min data taken on November 22, 2019 with the 4 lines of ORCA.

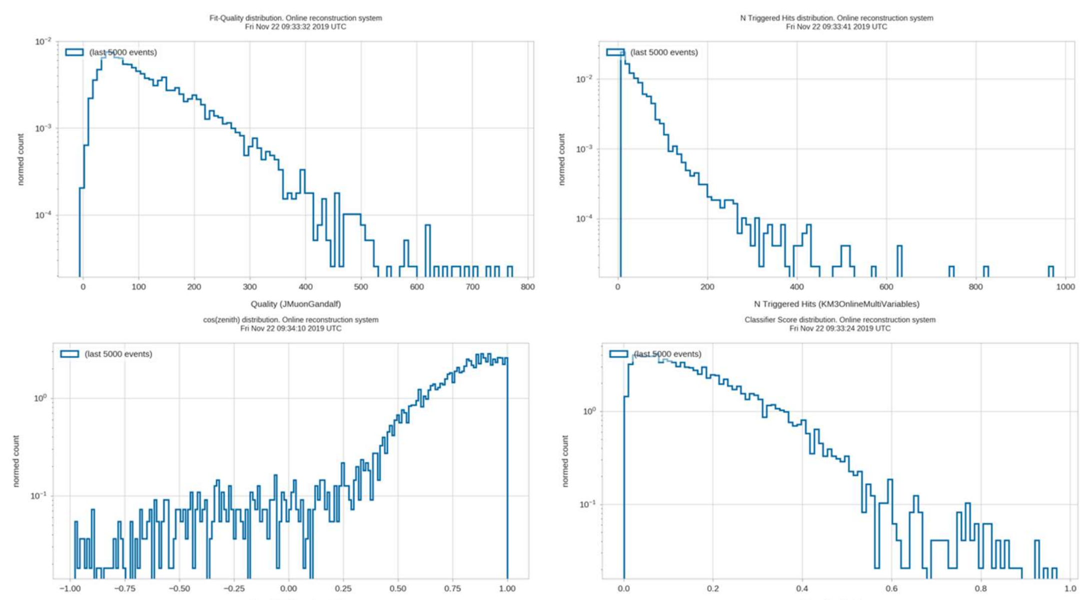

Figure 4: Examples of 3 distributions of the reconstructed parameters: quality of the track fit (top-left), number of triggered hits (top-right) and zenith (bottom-left). The results of the classification are shown in the bottom-right plot. These distributions are made with the 5000 events from data taken in roughly 15 min with 4 lines of ORCA.

Figure 5 shows the event displays of two nicely reconstructed and selected neutrino events (score=1).

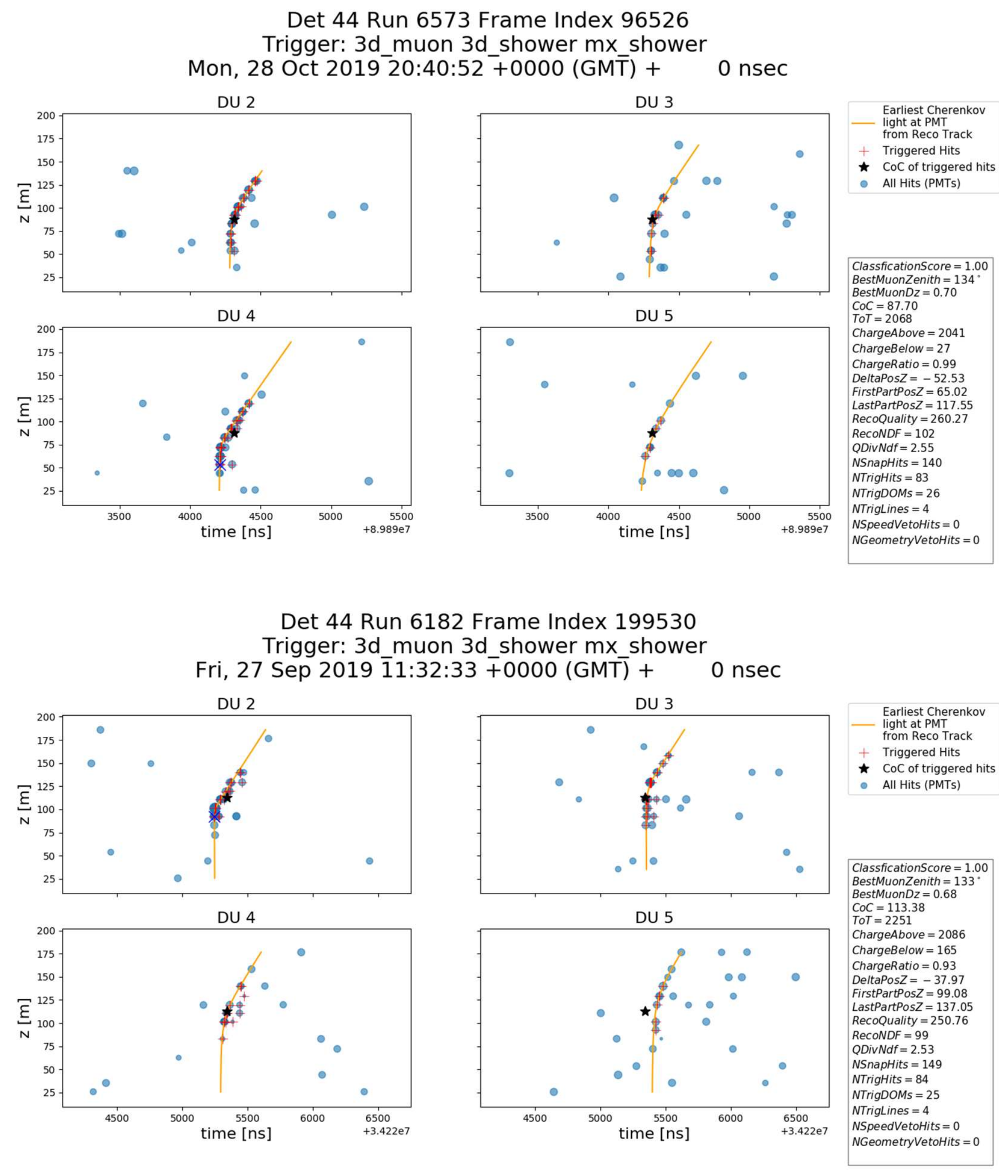

Figure 5: Two real event displays (z-t plot) selected by the classifier as neutrino candidates. The blues dots correspond to the hits, the red crosses are the triggered hits and the orange lines displays the results of the track fit.

3. Description of the external alert receiver

The second important step of the online analysis is to be able to receive and select external alerts. Figure 6 illustrates a scheme of this alert receiver. Some of the high-energy electromagnetic alerts are transmitted via the GCN network (GRB Coordinates Network [3]). This network was first developed to distribute gamma-ray burst triggers from various satellites.

It has been then extended to others types of sources such as LIGO/VIRGO gravitational alerts, ANTARES and IceCube neutrino triggers, others X-ray/gamma-ray transients (soft gamma-ray repeaters, tidal disruption events, etc.). The trigger distribution is performed completely automatically without humans-in-the-loop to allow the fastest dissemination. The trigger notices are transmitted either by sockets or by VO Events [4]. A notice contains a unique ID, the alert and the notice UTC times, the astronomical coordinates and the associated error boxes and some key parameters about the events (fluence, duration, type, etc.). The typical alert rate is about few per day. The alert receiver module assures the connection to the GCN server, the reception and the parsing of the notices and a log of the notice information.

Some Collaborations are not using the GCN to transmit their transient triggers. For example, the flare's activities of active galactic nuclei are distributed by others ways (Astronomer's Telegram, Fermi AGN advocates, private communication).

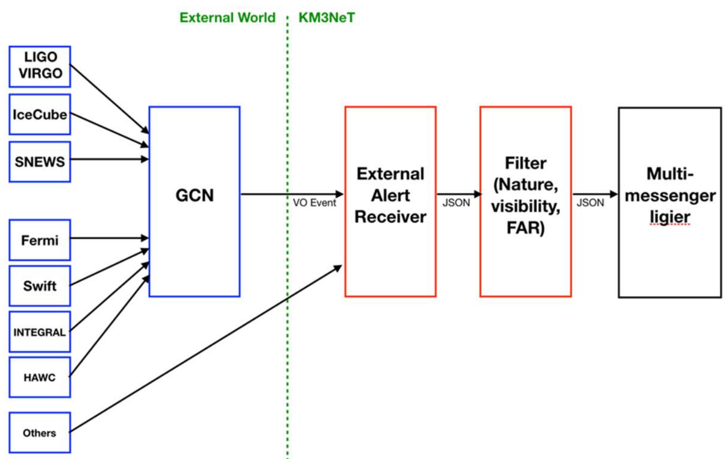

Figure 6: Scheme of the external alert reception.

An alert filter selecting only interesting triggers for KM3NeT has been implemented. This filter is using the type of sources that are promising neutrino emitters, the visibility of the sources, the size of the error boxes, the delay between the times of the trigger and the notice reception and the false alarm rate. In the first version, we are only selecting gamma-ray burst and LIGO/VIRGO, SNEWS and IceCube neutrino triggers for which the direction is below the KM3NeT horizon (mainly the Southern Sky). At the end of the filter module, the selected triggers are distributed to the multi-messenger dispatcher, an application running on the antorcamm1 computer that allows transmitting information (event file, JSON) between different applications.

4. Description of the correlation analysis method

The final important step of the online analysis is to look for time and space correlations between the online neutrino streams (Section 2) and the selected external triggers (Section 3). We are implementing an analysis framework that is quite opened and versatile. Any analysis methods that take as inputs the JSON trigger files and the JSON neutrino stream files can be implemented.

A very simple analysis is currently implemented to test the analysis chain and to get quick results. It is based on a counting analysis: looking for a signal excess in predefined search angular and time windows. The background is directly extracted in the data using an off-time window prior to the signal time window. The length of the search time window is adapted to each type of external alerts. It is a compromise between the amount of background and the duration of the astrophysical phenomena. For example, for a gamma-ray burst, we are using [T0 - 250s, T0 + 750s] as time window (T0 is the time of the GRB) largely dominated by the GRB duration. The size of the search window and the final event selection are optimized together based on Monte-Carlo simulations. To not bias the analysis, this event selection criteria and the radius of the search cone are fixed in advance (like in a "prescription"). The main advantage of this type of analysis does not rely on the Monte-Carlo simulations to obtain the results.

More sophisticated analysis methods based on maximum likelihood ratio will be implemented in the future when the knowledge of the online data will improve.

To advertise the KM3NeT online group, we have implemented an automatic mail and SMS reporting. Two mails are sent for each selected trigger: one at the reception of the notice with the main characteristics of the trigger and one after the end of the search time window with the results of the analysis. When the trigger is particularly interesting or when we have a positive correlation, SMSs are sent to the online group to accelerate the verification of the analysis.

For the reporting task, we plan to publish some circulars to the GCN to advertise the astronomy community. At the end of the full process, the results will be available on public webpages in the main KM3NeT website.

5. Challenges

There are two main challenges to achieve the implementation of the real-time analysis framework:

- When talking about analysis of neutrino data, the first difficulty is the delay in the KM3NeT construction and the relative uncertainties of the deployment calendar.
- To have enough statistics for the cascade events, we need to have at least 6 working DUs (due to the containment cut). With MC simulations, we have already tested the cascade reconstruction and selection but it has never been performed on real data. This is the main reason why the implementation of the cascade classifier in ORCA has not been started yet. For the same reason, the muon neutrino classifier in ARCA has not been implemented yet (only 1 DU working).

6. Conclusion and perspectives

The era of the multi-messenger astronomy has started with the detection of gravitational waves by LIGO/VIRGO, the first high-energy neutrino sources by IceCube and the evidence for the first galactic cosmic accelerator at PeV by H.E.S.S, we are pushing hard for KM3NeT to be a key player in the near future.

Thanks to the WP7 resources, we have been able to define and implement a first complete version of the online analysis framework that contains efficient event reconstructions and one neutrino classifier able to process all events in real-time. With the selected neutrino streams, we are also implementing online analyses that trigger KM3NeT neutrino alerts that will be sent to the world and that look for time/space correlation for external triggers (electromagnetic transients, gravitational waves and high-energy neutrino candidates). By the end of 2020, KM3NeT will have deployed a sufficient number of DUs in ORCA and ARCA to have better performances (effective areas and angular resolutions) than ANTARES in the whole energy range.

IX. REFERENCES

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