KM3NeT INFRADEV – H2020 – 739560

Report on the development of the real-time system to distribute neutrino alerts to the worldwide astrophysical community

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I. COPYRIGHT NOTICE

II. DELIVERY SLIP

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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:

MoU: Memorandum of Understanding
EM: electromagnetic
MM: multi-messenger
ARCA: Astroparticle Research with Cosmics in the Abyss
ORCA: Oscillation Research with Cosmics in the Abyss
AMON: Astrophysical Multi-messenger Observatory Network
IB: Institute Board (KM3NeT Collaboration)
PMB: Project Management Board (KM3NeT-INFRADEV)
CC: Charged Current
NC: Neutral Current
UTC: Coordinated Universal Time
VO: Virtual Object
IVOA: International Virtual Observatory Alliance
GCN: Gamma-ray Coordination Network
OPA: Open Public Alert
DAQ: Data Acquisition system
CDS: Centre de données Astronomiques de Strasbourg
HESE : High Energy Starting Event (IceCube)
VHE: Very High Energy
ROAst: Root extensions for ASTronomy library

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

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 (~3 GeV; >10 PeV) and the full sky coverage, KM3NeT will play an important role in the rapidly evolving multi-messenger field. The task 7.3 of the WP7 consists on implementing an alert framework that is able to select in real-time the most interesting neutrinos, send alerts to the worldwide astrophysical communities and look for electro-magnetic, gravitational waves or high energy neutrino counterparts.

The rapid provision of alerts for interesting neutrino events will enable both ground and space based observatories to quickly point in the direction of the alert. This fast follow-up will be vital to catch any multi-messenger and multi-wavelength counterparts of these cataclysmic but short-lived phenomena such as gamma-ray bursts, fast radio burst, supernova shock breakout…

Such alert sending system has been implemented in ANTARES (the first neutrino generation) in 2009 [2], sending regular alerts to our partners: the robotic telescopes of TAROT, ROTSE, ZADKO, MASTER, the X-ray telescopes of Neil Gehrels Swift Observatory and INTEGRAL, the radio telescope Murchison Wide-field Array and the very high energy facilities such as H.E.S.S. and HAWC. During more than ten years of operations, we have gained a lot of experiences that are at the bases of the development for the alert sending system of KM3NeT.

In this document, we report on the design study phases and on the start of the implementation of the alert sending system. Section 1 shows the multi-messenger context for this project. Sections 2 and 3 describe the alert sending framework and the "Open Public Alert" program we want to put in place in the future, respectively. Section 4 summarized the main challenges to fulfill this project.

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1. Multi-messenger context in the KM3NeT Collaboration

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 Collaboration is instrumenting two deep-sea neutrino detectors in the Mediterranean Sea, a low energy site ORCA in France (3 GeV-10 TeV) and a high energy site ARCA in Italy (1 TeV-10 PeV) [1]. 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 ANTARES detector.

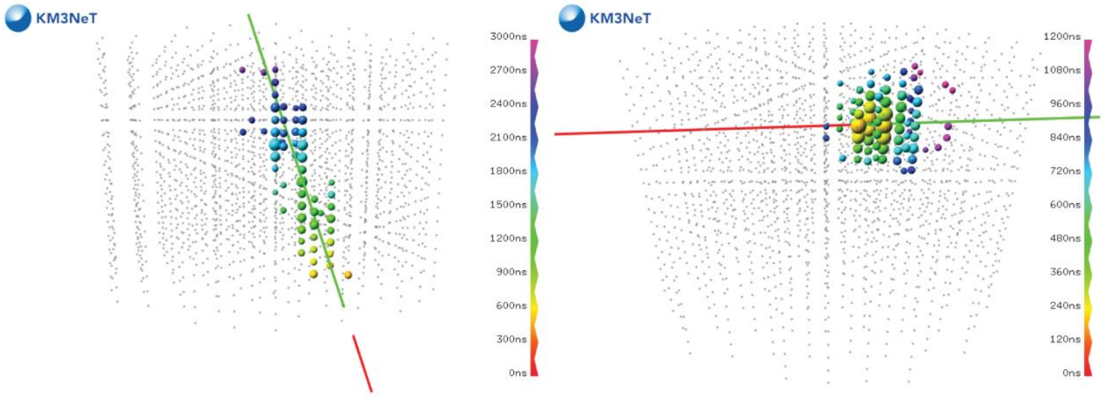

Figure 1: Event displays for a simulated ν_μ CC event (left) and a contained ν_μ NC event (right). The incoming neutrino is indicated by the red line, and the outgoing lepton (muon or neutrino) by the green line. The color scale gives the hit times with respect to the time of the neutrino interaction,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

One neutrino may interact directly in the vicinity or inside the detector volume, producing a relativistic charge lepton emitting Cherenkov light. Cherenkov photons impinging on the photomultipliers produce signals ("hits"), which are collected by the experiment. 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. With the very large volume and the performances of the optical modules, a very good angular resolution better than 0.2° is achieved for very high energy tracks (>10 TeV). Even at lower energy (>50 GeV), the angular resolution is lower than 1 degree. This is the main channel for the neutrino astronomy since it is possible to point to the neutrino sources. Even if the resolution for cascade events is lower (2-4° at high and low energies, respectively), 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. The implementation and the detailed performances of the real-time reconstructions both for tracks and cascades are summarized in the deliverable KM3NeT-INFREDEX-WP7_D7.2.pdf.

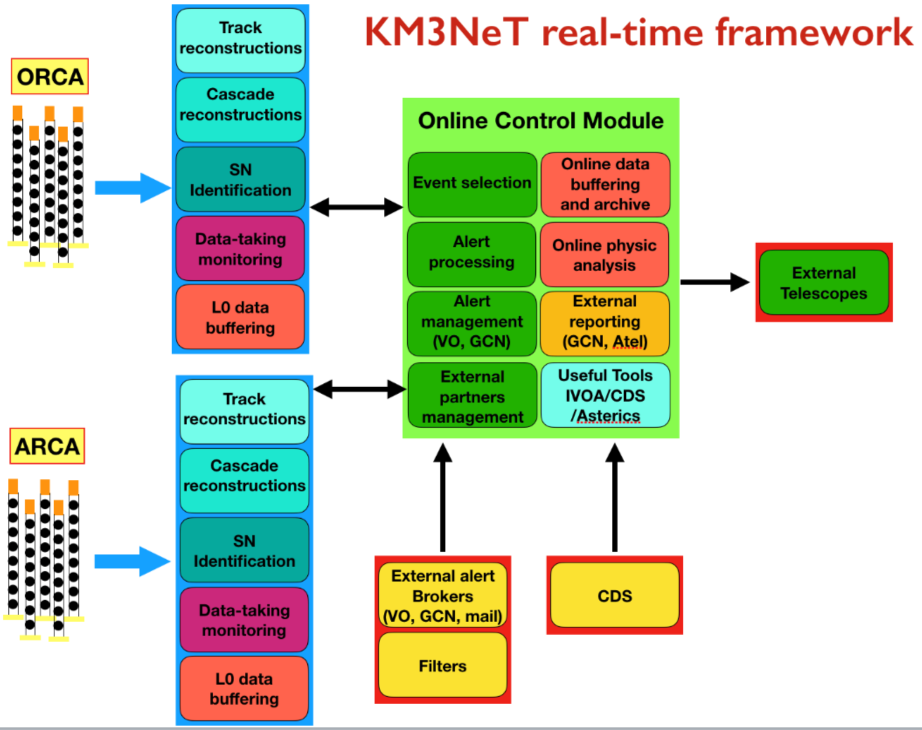

Figure 2: Functional scheme of the KM3NeT real-time analysis framework.

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 functional scheme of this online analysis framework. With this analysis approach, one single neutrino in coincidence with a transient astrophysical phenomenon may lead to a neutrino source discovery. Moreover, the main advantage is that no hypothesis is required on the nature of the source, only that it produces neutrino and photons. This implies a significant discovery potential already during the construction phase and is essential for future improvements of our understanding of highest-energy astrophysical sources such as gamma-ray bursts, fast radio bursts or blazar flares.

2. Description of the alert sending framework

The alert sending framework is distributed in two main parts: one located in the shore station to handle the large rate of data and one common part which is installed in only one shore station. Although this system is designed to handle alerts for both ORCA and ARCA, only one module will assure the management of the alerts to have a single contact point between KM3NeT and the external world. Figure 3 shows the data flow model of the real-time framework part which concerns the alert sending modules. The typical event rates for ORCA and ARCA are about 100 Hz, after the neutrino selection, the rate is lower to ~100 events per day. Additional cuts reduced the rate of neutrino alerts to 2-4 per month. The alert rate is adjusted to the following capabilities of the external electromagnetic followers. It can be set observatory by observatory taking into account the location, the availability and the physics cases.

The alert sending framework consists of five main tasks:

- **Collect the results of the event reconstructions (tracks + cascades) from the ORCA and ARCA sites (Task "event selection")**. A time synchronisation module is necessary to wait the results for all reconstructions for each event.
- **Select the most interesting neutrino signal (Task "alert processing")**. The selection criteria are based on the nature of the neutrinos, the multiplicity (i.e. the number of neutrinos in the same time and space windows), the energy proxy, the direction (if it is consistent with the directions of preferred sources in the sky) and the probability to be a cosmic neutrino. The criteria are optimized using Monte Carlo simulations separately for each detector.
- **Create and distribute the alert message (Task "alert management").** The alert message should at least contain: a unique trigger ID, the time of the event (UTC), the latency, the equatorial coordinates (right ascension, declination) in J2000 and the 50 (90) % error box, the energy proxy, the reconstruction qualities, the neutrino purity, the astrophysical neutrino probability, the type of neutrino, the multiplicity, the type of trigger, etc. The distribution of the alert will be done using either the VO Event (XML file) [3] or the GCN socket formats [4]. One alert broker per neutrino stream will be implemented.
- **Report the alert information in the main KM3NeT database and the status in the public/private webpages (Task "external reporting").** If there is an interesting coincidence, generate new circulars in order to alert the public to request a more complete follow-up. For each alert, e-mails and SMSs will be sent to the alert group to alert and report the results. In this module, we plan also to perform some archive data analysis with previous KM3NeT data or with main astrophysical catalogues.
- **Manage the connections with our main external partners (Task "external partner management").** It consists of monitoring the connection between KM3NeT and the external facilities, alert in case of network losses.

For the implementation of the alert sending system, we are currently upgrading the tools used by ANTARES to send their alerts using the most recent standard defined by IVOA [3] (VO Event, Comet as broker, STARALT, OVAP, OLAP, etc.), use of CDS [5] (*Centre de Données* *astronomiques de Strasbourg*) softwares (Simbad, Aladin, Aladin-Little, VizieR, Xmatch…) and ASTERICS softwares (ROAst) [6].

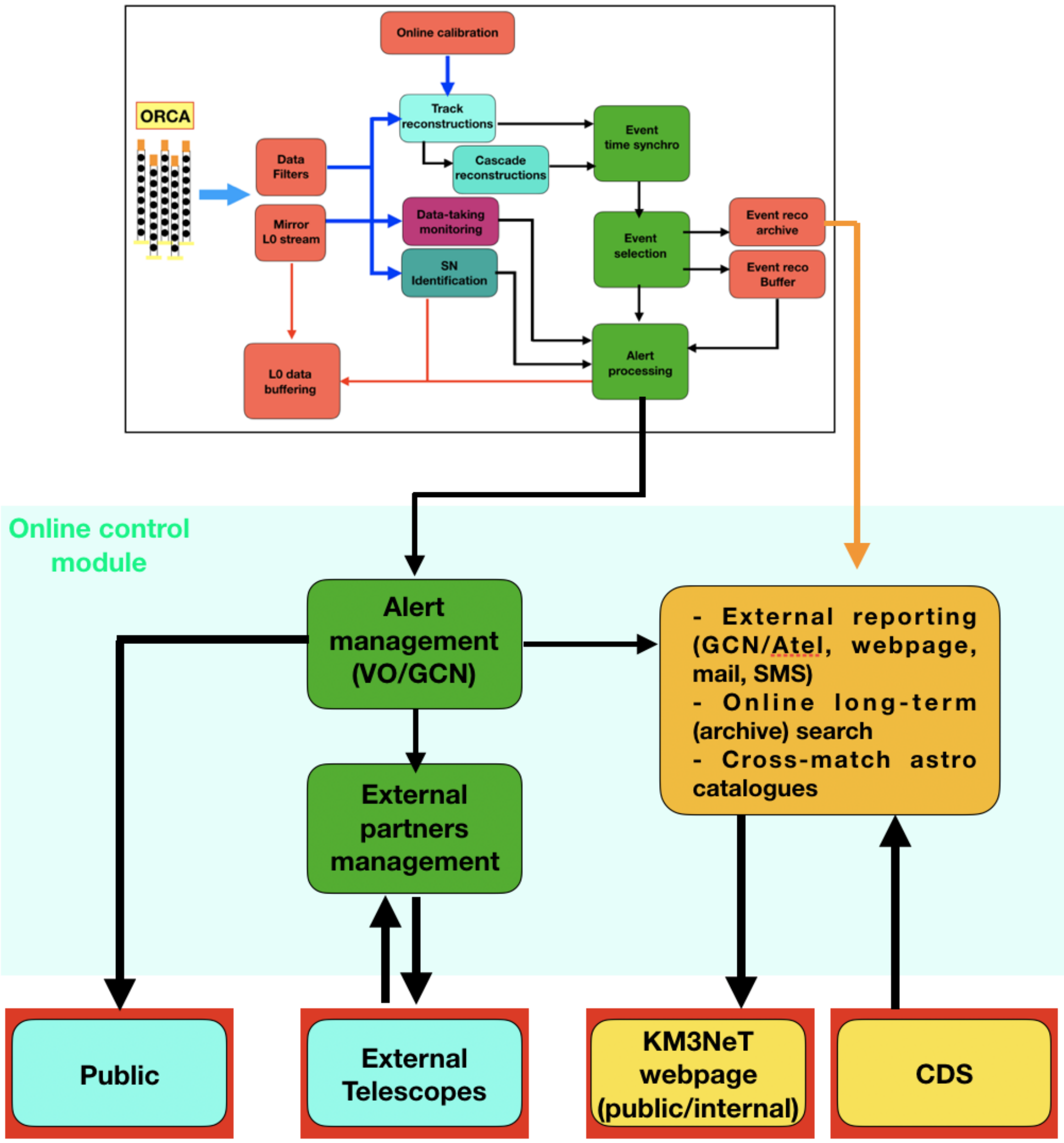

Figure 3: Data flow model of the KM3NeT real-time alert sending framework. The top part will be implemented in the shore station of both ORCA and ARCA (in this scheme, only ORCA is shown, the flow will be similar for ARCA). There will be only one Online control module which will proceed the alerts of both sites.

The implementation has just started. The specifications are written and we are currently working with the Software and DAQ groups on the choice of the technology (language, interaction with the main DAQ system). As the DAQ system is complex, this task has taken longer time than originally plan. A v0 version is expected to work March/April 2019 when we will have the 6 lines of ORCA in operation (after the commissioning phase) and the start of the run O3 of LIGO/VIRGO in April 2019. A more complete version is expected beginning of 2020 when the ARCA will have deployed a sufficient number of lines to have a larger sensitivity than ANTARES at high energies.

3. Toward an Open Public Alert program

The main data policy of KM3NeT is that the neutrino data are proprietary but become public after a latency of 2 years after the data taking. Even the neutrino alerts are private data that will be shared only to external partners who have signed a Memorandum of Understanding (MoU) with KM3NeT. The report on the status of the first MoU negotiations can be found in the deliverable KM3NeT-INFREDEX-WP7_D7.1.pdf.

However, significant events might trigger alerts that could be distributed publicly to the astronomy community. This is called an “Open Public Alert” (OPA) program. The set-up of the OPA will need the approval of the KM3NeT Institute Board. A document is in preparation to launch this discussion. Sub-threshold alerts and multiplets will be distributed through private channel to observing teams upon MoU agreements. The OPA will be activated after the approval of the KM3NeT Management and Institute Board after a commissioning phase that has demonstrated the stability of the alert sending system.

The two main actors in the multi-messenger communities IceCube and LIGO/VIRGO are already working on such OPA programs: started in 2016 and 2019 respectively. For example, IceCube provided a subset of high-energy neutrino candidates (HESE tracks and VHE tracks samples), the alerts are managed by AMON (Astrophysical Multi-messenger Observatory Network [7]) via the public GCN (Gamma-ray Coordination Network) network [4]. All the information is stored in the alert message. After the first notice, they may provide a second circular containing the alert retraction and the improved reconstruction results. The gravitational wave alerts are transmitted directly via VO Event or GCN socket, the alert information is provided through the GCN notices and circulars. An access to the LIGO/VIRGO data base (GraceDB) summarized all the information for the public.

For KM3NeT, the implementation of the OPA consists in defining a policy for the distribution of the public alerts (type of alerts, number of alerts, selection criteria, latency to send alert, etc.), deciding of the tools for the alert information dissemination and providing a tool to report external observations and promoting the KM3NeT OPA. We are currently working with precise Monte Carlo simulations of both ORCA and ARCA detectors and typical atmospheric and astrophysical neutrino fluxes on the definition of the selection of the type of alerts, the number of alerts and the selection criteria. As the data taking continues during the construction phase, this work of definition has to be done for each detector configuration.

For the reporting task, we plan to use the GCN framework with notice and circulars [4] and a public webpage available in the main KM3NeT website summarizing all the neutrino information of the alerts. A workshop will be organized end of 2019 beginning of 2020 in coordination with the KM3NeT-INFRADEV Work Package 4 to promote the multi-messenger programs of KM3NeT to the external astronomy and astrophysics communities, especially on the alert capabilities of ORCA and ARCA.

4. Challenges

There are four 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.
- Implementing a real-time analysis program means that you have to work in a very complex framework which needs a transverse coordination with the Software, DAQ, Multi-messenger working groups of KM3NeT.
- We have the ambition to be able to have a first working version of this online framework ready for March/April 2019 for the first KM3NeT data (ORCA 6 lines and ARCA 2 lines) and the start of the VIRGO/LIGO next scientific run (March/April 2019). This introduces a very tight scheduled. We had to prioritize the implementation work to have ready the critical modules.
- The question of the public/proprietary status of the neutrino alerts is important for the electro-magnetic partners since it affects their internal/external communication and therefore the visibility of their work for funding agencies. This point has been raised in the KM3NeT Collaboration and we are preparing the discussions with the Institute Board.

5. 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.

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. During the first two years, we have worked mainly in writing the scientific specifications for each module of the online analysis framework, prepare the implementation with the functional requirements and the data flow and start to prepare the neutrino analysis with Monte Carlo simulations. Dedicated discussions are regularly organized with the software and DAQ KM3NeT working groups to inform the collaboration and to choose the most optimal technic solutions. The full year 2019 and the beginning of 2020 will be devoted to the implementation of this very ambitious program. Already with partially constructed detectors, we can expect the first scientific results.

IX. REFERENCES

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