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Status of KM3NeT

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Abstract. The recent observation of cosmic neutrinos by IceCube has pushed the quest towards the identification of cosmic sources of high-energy particles. The KM3NeT Collaboration is now ready to launch the massive construction of detection units to be installed in deep sea to build a km-cubic size neutrino telescope. The main elements of the detector, the status of the project and the expected perfomances are briefly reported.

1. Introduction

The detection of high energy cosmic neutrinos is considered as the ultimate smoking gun to identify the sources of cosmic rays in our Galaxy and beyond. High energy γ-rays, succesfully detected by air Cherenkov telescopes can be, indeed, produced in sources where either hadronic or purely leptonic acceleration mechanisms occur. Moreover, the observed extragalactic γ-rays ($E_\gamma > 1\,\mathrm{TeV}$) arrive to the Earth with a reduced flux and a distorted energy spectrum, due to their interaction with the intergalactic environment. The high energy (HE) cosmic rays at enegies $\leq 10^{19}$ eV are deflected by the intergalactic magnetic fields and cannot be used to point back to the sources, at larger energies the GZK effect suppresses the CR flux from extragalactic sources [1]. Neutrinos, neutral, light, weakly interacting particles, are neither deflected nor absorbed in their journey to the Earth, thus they are considered as optimal astrophysical probes for high energy astronomy. The discovery of a neutrino flux originated outside the Solar System by the IceCube Collaboration [2] , has paved the way to high-energy neutrino astronomy. Whether these events have a Galactic or extragalactic origin is still an open question, since the sample collected so far (37 events) does not allow firm statistical analysis. IceCube will continue data taking for the next years, while the KM3NeT project plans to deploy, in the Northern Hemisphere of the Earth another km^3-scale neutrino telescope (the ARCA project: Astroparticle Research using Cosmics in the Abyss) aiming to larger detection area and better angular resolution, exploiting the optical characteristics of deep seawaters. The detection of cosmic high energy neutrinos produced in galactic and extragalactic sources is expected to provide missing information on the production mechanisms of high energy particles in astrophysical sources, being a clear signature of hadronic acceleartion of high energy particles. Neutrino sources could be also identified, using statistical analysis of the direction of arrival of the events. In this case a multi-messenger approach will be a powerful tool to study the correlation between high energy neutrinos, high energy cosmic rays and photons.

The most mature detection technique to identify neutrinos in the energy range between 100 GeV and 100 PeV is the underwater (or underice) Cherenkov technique, that is the use of a large array of optical sensors deployed in a transparent natural medium in known,

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or measurable, positions in order to reconstruct the Cherenkov wavefront radiated by high energy particles outgoing a neutrino interaction in water, or ice, inside or close to the detector volume. As foreseen by several models and now clearly shown by IceCube, the detector size must be close, or better exceed, the cubic-kilometer scale to identify a statistically significant number of events in the foreseen life of the detector (not less than 10 years). The golden channel for neutrino astronomy is the detection of HE muons produced in charged current interactions of ν_μ in water. Thanks to the muon long range (from few hundreds meters to several km, at such energies) the muon track direction can be reconstructed with sub-degree accuracy, allowing for source pointing, being the muon and the neutrino almost co-linear at such energies. Other neutrino flavours (both ν_e and oscillated ν_τ) and neutral currents are identified as short, but intense, glows of light, produced by showers outgoing the neutrino interaction. To suppress the background due to downgoing atmospheric muons, falsely reconstructed as up-going (good) tracks, neutrino telescopes have to be shielded using a thick layer of natural medium. In the case of KM3NeT, three sites in the Mediterranean Sea have been candidate for detector installation: Capo Passero (3500 m depth), Toulon (2500 m depth) and Pylos (3000÷4500 m depth). Located in the Northern Hemisphere of the Earth, KM3NeT will optimally look for neutrinos from point-like Galactic sources. In fact at the latitude of the Mediterranean Sea it is possible to detect neutrinos with a low energy threshold (about 100 GeV) in a large field of view (about 3.6π sr at Mediterranean Sea latitude) with an almost complete view of the Galactic plane. The collaboration has a defined the technical project and has started the construction of a research infrastructure hosting the high energy neutrino telescope and auxiliary nodes for Earth and Sea sciences. More recently the collaboration has proposed to extend the physics case to the measurement of the neutrino mass hierarchy using atmospheric neutrinos. A feasibility study, called ORCA, has started. From this study the best sensitivity to measure the neutrino mass hierarchy is obtained with a dense Mega-ton scale detector that can measure atmospheric neutrinos in the GeV region. For ORCA the same KM3NeT technology will be used with a much denser granularity of optical modules. An experimental proposal for a multisite experiment is underway: a Gigaton detector for high energy astronomy is foreseen in the Capo Passero italian site (KM3NeT-It) while a Mton-scale, denser, detector for neutrino mass hierarchy research is foreseen in the Toulon French site (KM3NeT-Fr). In this paper the detector technology, the status of the project and the performance of the Gigaton detectors for the neutrino astronomy will be briefly described. A description of the ORCA feasibility study can be found in [3].

2. The KM3NeT technology

The KM3NeT detector is a three dimensional array of Digital Optical Modules (DOMs) designed to detect Cherenkov photons radiated by charged particles in water. Each DOM, the basic unit of the detector, is made of 31 PMTs (3″ diameter) coupled with their active bases, providing High Voltage and equipped with the PMT read-out system. The “time over threshold” information of PMT signal, sampled at 1 GHz, is provided to shore for analysis. The threshold, adjustable, is typically set to the equivalent of 0.3 photo-electrons to reject most of the PMT dark noise. PMTs are hosted in a 3D-printed support structure and surrounded by a reflector ring that increases the collection efficiency per PMT by about 27% [4]. The DOM is contained in a pressure resistant 17″ glass sphere divided in two halves. The optical contact between PMTs and the glass is assured by optical gel. The lower hemisphere of each DOM has 19 of the PMTs, which are thus downward-looking, whereas the other 12 PMTs look upwards. The DOM contains a Central Logic Board (CLB), an FPGA based electronics board that provides control from shore and data transmission to shore over

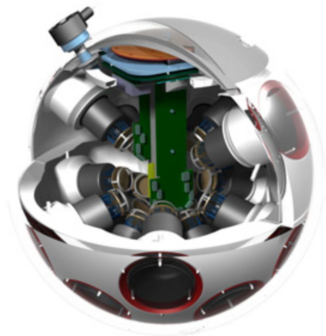

Figure 1. Drawing of the DOM.

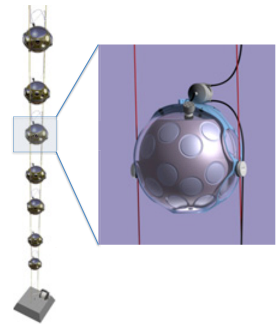

Figure 2. Drawing of DU and details of the DOM mounted into the string.

a fiber optic network via an SFP transceiver, coupled with 2 octopus boards, extenders that allow connection with the PMT bases. The DOM also contains auxiliary calibration sensors: a LED nano-beacon for time calibration and water properties study, that illuminates the neighbour DOMs; a compass and tiltmeter to monitor the absolute orientation of the DOM in water; a temperature and a humidity sensor; an acoustic piezo sensor glued to the inner surface aimed at the detection of acoustic signals for detector positioing. A drawing of the DOM is shown in Fig. 1. The DOM design has several advantages with respect to the large area PMT (10″ diameter) used in NEMO [6] and ANTARES [7]. The photo-cathode area in a single DOM is about three times that one of an ANTARES optical module and it has an almost uniform angular coverage in the solid angle. Because the photocathode is segmented, the identification of more than one photon arriving at the DOM can be done with extremely high efficiency and purity allowing a good optical background rejection and providing a directional information on the arrival photons. These feautures have been proven analysing the data collected in the first DOM prototype that has been integrated in the instrumented line of the ANTARES detector [8]. Moreover each DOM is a fully independent module, that does not need additional vessels for hosting communication and power electronics. From the optical communication point of view each DOM is characterised by the specific color, provided by its SFP transceiver (laser and receiver), defined in the Dense Wavelenghth Division Multiplexing standard grid. Using the DWDM techinque, data from about 80 DOMs can be transmistted over the same fiber. The DOMs are displaced on a vertical structure called Detection Units (DUs, see Fig. 2).The DUs are flexible slender strings anchored to the sea floor, kept vertical by buoys. Each DU hosts 18 DOMs starting 100 m above the sea floor and with 36 m of vertical distance between adjacent DOMs. The definition of the distances between DUs and between DOMs is the result of a detailed optimization performed by means of Monte Carlo simulations, focused on the observation of neutrinos from Galactic point-like sources. The DUs are mechanically sustained by two parallel Dyneema ropes. A vertical electro-optical backbone is used to connect the DOMs to the base of the DU. The backbone is a flexible, oil-filled plastic hose, in equi-pressure with the sea water, and it contains 18 optical fibers for data transport and two copper wires for the provision of electrical power to the DOMs. For each DOM, a break-out box provides connection to one fibre and two wires. Mechanical penetrators are used to route fibers and conductors from the backbone to the inner part of the DOM. For the deployment, the detection unit is wrapped on a spherical metallic frame with diameter of about 2 m (the Launcher of Optical Modules, LOM) which is deployed on the seabed, using a winch, and then unfurls in a rotating upwards movement.

After the unfurling, the DU is vertically displaced, and the LOM rises to the sea surface, where it is collected for reuse. The anchor hosts an additional vessel, the DU base, equipped with a CLB, an hydrophone for positioning, the power distribution and fiber distribution systems. The anchor has an electro-optical ROV mateable interface to the subsea network receiving 375 VDC from shore and connecting 2 fibers. One fiber is used bi-directionally to transmit the master clock (from shore to the sea) and slow controls to the DU base and to the DOMs, and to receive the detector control feedbacks from the DU base. The second fiber is used to transmit the DOMs' data to shore. The communication between shore and sea is based on the White Rabbit [5] precision time protocol, a new synchronous ethernet-based system that permits sub-nano second synchronisation of devices interconnected by an optical fiber link. All DUs are connected to shore by a network of electro-optical cables, that is adapted to the installation site as a function of the distance to shore (about 35 km for Toulon and 90 km for Capo Passero) and of the number of DUs to be served. In order to ensure scalability and future expansions, DUs are arranged in clusters: an array 115 DUs will constitute a detector building block. In the aim of neutrino astronomy research the average distance between neighboring DU is set in the range 90÷120 m and the single building block is made of 115 DUs. The building block concept allows also for a distributed detector deployment and management. The choice for a distributed research infrastructure made of several building blocks with common detector technology, management, data handling and operation control was based on both technical and funding arguments. Simulation results show that the building block concept does not affect the expected sensitivity with respect to a single larger detector. Moreover, the distributed infrastructure is the preferred choice of the Sea and Earth Science community that profits from KM3NeT infrastructures to install a distributed network of sensors in the Mediterranean Sea.

Neutrino events are reconstructed detecting Cherenkov light at each optical sensor and combining the arrival time and amplitude information with the detector position information recovered by the detector positioning system. Each photon hit time is time-stamped by the CLB, that recovers the absolute time information using the GPS signal distributed from shore. The CLB time is synchronised and synthonised (that is has a constant and measured phase) to the GPS time, thanks to the White Rabbit gear running in the CLB and in the shore station DAQ fabric. The number of photons detected by each PMT is recovered through the time-over-threshold information that is proportional to the PMT signal amplitude. Time-over-threshold data from all PMTs are sent to shore, where neutrino event candidates are selected by online filters running on a computer farm. The detector control system permits also setting of HV and threshold of the PMTs from shore. The position of each PMTs is measured acoustically and via a compass and tilt board: the AHRS (Altitude, Heading, Reference System) board. The acoustic positioning system is formed by three sub-systems: an array of receivers placed on the DOMs (piezos) and on the DU base (hydrophones); a long baseline of acoustic emitters (beacons) and receivers (hydrophones), placed in the installation field in geo-referenced positions; a farm of computers on shore running the position reconstruction algorithms [9]. The long baseline is formed by a synchronous and phased network of acoustic beacons which emit a known pulse at a known time in the detector clock reference and digital hydrophones placed close to digital hydrophones, whose read-out is time-stamped by the CLB. Hydrophones and beacons are placed on special bases, called calibration bases, whose position is geo-referenced during deployment operation from the ship. Once the long baseline is calibrated, that is the position of all emitters is reconsructed with the desired accuracy (< 10 cm), the positions of the DOM can be effectively reconstructed measuring the time of arrival of the beacon acoustic signals to each piezo in the DOM and via multi-lateration. The expected resolution of the position

Figure 3. The PPM-DOM installed in Toulon in 2013, and connected to the ANTARES instrumentation line.

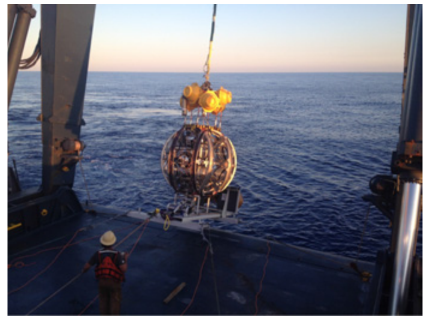

Figure 4. The PPM-DU was deployed in Capo Passero in 2014.

reconstruction is close to 10 cm. The DOM orientation, pitch and roll is also measured in real time, the expected accuracy is 3 degrees in orientation (yaw) and few tenth of degree in pitch and roll. Combining hit time information with measured DOM positions it is possible to reconstruct the trajectory of the muons producing Cherenkov light with a very good angular resolution (few tenths of a degree). The amount of detected light can provide information on the energy of the particle (see next sections).

3. Status of the KM3NeT project

The design of the KM3NeT detector has followed a severe validation procedure and prototyping activity. In parallel with the design and test of the full architecture, two prototypes (defined as Pre Production Models, PPM) have been deployed in Toulon and Capo Passero. The first one, the PPM-DOM (see Fig. 3), deployed in April 2013, consisted of a full DOM attached to an ANTARES line, the data transmission and power systems where harmonised to the ANTARES infrastrucure, nevertheless, the PPM-DOM included all the sub-systems of a final DOM: 31 PMT (3 inches diameter), electronics and auxiliary calibration systems, including an external hydrophone. The PPM-DOM, provided a technological proof of concept and a large dataset for analysis. The optical noise of the Toulon site (induced both by bioluminescence and ^{40}K) was monitored and atmospheric muon tracks were clearly identified over the optical noise, using time-coincidence among PMTs. Thanks to the DOM segmentation, and different PMT orientation, a clear "top-down" space-time sequence of hits is observed for high multiplicity events, associated -after comparison with simulations- to atmospheric muon tracks [8, 10].

A PPM-DU was deployed in May 2014 in Capo Passero. The PPM-DU (see Fig. 4) consisted of 3 DOMs assembled on a 160 m long string (using standard spacing) and with a DU base. The DOMs were built using both ETEL D783FLA PMTs (DOM 1 and 2) and Hamamatsu R12199-02 (DOM3, the uppermost). The PPM-DU was connected to the Capo Passero deep sea network and it is still active and taking data. On each DOM, atmospheric muon tracks are clearly separated from the, very low, optical noise, while the analysis of coincidence among DOM PMTs is in progress [10]. Following the success of the demostrators the collaboration has defined the detector a construction plan. The KM3NeT infrastructure will be constructed in three phases. The phase 1, fully funded, will consist of 24 DUs deployed in Capo Passero and 7 strings in Toulon and it will have a volume of about

0.1 km^3. The next phase 2.0 foresees the construction of ARCA: 2 building blocks of 115 DUs, with a volume of about 1÷1.6 km^3 (depending on the final DU spacing), at this stage KM3NeT will have a size comparable to IceCube and it will provide a benchmark for the IceCube cosmic neutrino signal. Meanwhile the ORCA project will be implemented. The neutrino astronomy era will be opened when the full KM3NeT detector will be completed – phase 3- with a size of about 3÷4.8 km^3.

In the Italian site, together with the standard 24 DUs, additional 8 DUs à la NEMO (flexible tower concept) will be deployed. A prototype tower has been already deployed in 2013 in Capo Passero and took data for about one year. From the data collected in this period the first measurement of vertical atmospheric muon flux at a depth of 3500m was made [12] and published in [11]. The long term measurements of the environmental parameters confirms that the bioluminescence optical noise is very low at the KM3NeT-It site [13]. The Capo Passero infrastructure is now ready to host the KM3NeT phase 1: the shore laboratory is refurbished with a large data acquisition room equipped with computing and power systems, the electro-optical cables of the submarine network have been purchased, the first (over a total of three) junction boxe has been deployed together with the first tower. The shore laboratory is connected with a dedicated optical fiber and backup copper links to the Laboratori Nazionali del Sud and, from there, to all the computing and storage resources of the collaboration. KM3NeT phase 1 in Capo Passero will be the most sensitive neutrino telescope in the Northern Hemisphere and it will be equivalent to about 10% of the IceCube detector. In the French site (KM3NeT-Fr) the first DU will be soon deployed, and six more strings will be constructed, according to the outcome of the ORCA feasibility study, with an interspacing between DUs of the order of 20 m and between DOMs of about 6 m, thus providing a demonstrator for the neutrino mass hierarchy experiment. The first full DU (equipped with 18 DOMs) is already assembled (see Fig. 5) and will be installed in Toulon in Spring 2015. The Toulon site has been refurbished with a new electro optical cable – already deployed- and with a new primary junction box (node), equipped with control systems, power and fiber distribution systems and electro-optical ROV mateable connectors for the connection of the DUs. After the deployment of the node, the first DU will be installed and connected. The construction of the 18 DOMs of the first DU allowed the set up of assembly, test and calibration procedures, that are now documented and distributed to the full collaboration to allow massive construction of the DUs. All the PMTs will be tested and characterised in a dedicated set-up, which permits testing of about 60 PMTs in parallel in a few hours, all the electronics boards, mechanical and optical parts and auxiliary sensors will be tested (and calibrated), prior the DOM assembly. After assembly, the full DOM is tested and released for integration. The phase 1 production plan foresees assembly and test of five DOMs per week in four different integration sites. To build a DU, DOMs are connected to the electro-optical backbone and to the DU-base, the DU is thus tested and calibrated. Eventually the DU is assembled on the anchor and folded in the LOM ready for the deployment (see Fig. 6). All the procedure is supervised via QA/QC system.

4. Physics performance

The IceCube discovery of a cosmic neutrino flux corresponds to a flux of about $3.6 \times 10^{-8}\,\mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$ with a cutoff at about 3 PeV, was measured in the energy range between 10 TeV to about 1 PeV and, a more recent analysis [14] extended the analysis at lower energies, but with a cut on the detector fiducial volume. Despite the muon channel has been condidered as the "golden" channel for nutrino detection, the IceCube analysis showed that most of these events are cascade events (showers induced by ν neutral current interacion

Figure 5. The first KM3NeT Detection Unit assembled, under test at CPPM.

Figure 6. The first DU: Anchor and LOM under assembly.

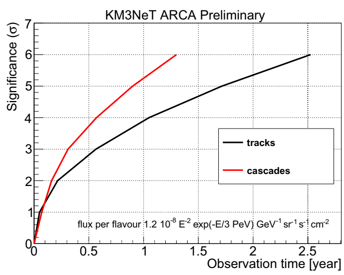

Figure 7. Significance as a function of the observation time for the detection of a neutrino diffuse flux corresponding to the signal reported by IceCube, in the up-going muon (black) and cascade (red) channels.

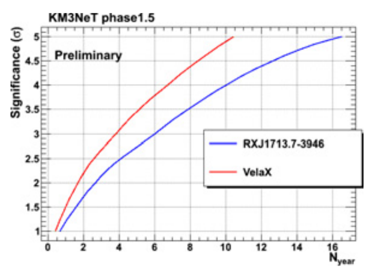

Figure 8. Significance as a function of the observation time for the detection of a neutrino diffuse from the RXJ1713 (blue) and the VelaX (red) sources.

and charged current interaction producing either e or τ). These events are detected with a poor angular resolution ($10^\circ \div 15^\circ$) strongly reducing the capabilities of source pointing. This discovery has led the KM3NeT collaboration to plan the construction of ARCA. Thanks to a better angular resolution with respect to IceCube, provided by design and seawater optical properties, larger field of view and, effective area, ARCA is expected to provide more information on the origin of the IceCube signal. In Fig. 7 the expected performance of ARCA are shown in terms of significance as a function of the observation time for the flux observed by IceCube. The significance, both for the cascade and track channels, includes all the neutrino flavors and it has been performed selecting tracks reconstructed in the full angular range (4π). The significance for the muon channel has been estimated for tracks reconstructed as up-going plus a small region of 10 degrees above the horizon. A significance of 5σ is obtained in about one year in the cascade channel and after about 2 years in the muon channel, for the flux reported by IceCube. A refined cascade reconstruction algorithm [15] shows also that a resolution of 3 degrees can be achieved is at 20 TeV, reaching a value of about 1 degree at higher energies.

For what concerns point source reconstruction, the collaboration focused its studies on the detection of Super Nova Remnants RXJ1713, Vela Junior and, the Pulsar Wind Nebula VelaX: the most intense high energy gamma-ray sources -thus possible neutrino sources- in the Galactic plane [16]. The expected KM3NeT-phase1.5 detection capability is reported for the RXJ1713 and VelaX in Fig. 8. These results were estimated in the hypotheses that the sources have a neutrino spectrum derived from the high energy γ-ray spectrum following the hypotheses in [17] and in [18, 19] and that the spatial extension of the neutrino emission region is the same of the measured γ-rays. ARCA is expected to detect the point-source signal with a significance level of 3σ in about 5 years of observation. The neutrino astronomy era will be ultimately open with the full KM3NeT detector that is expected to allow signal detection with a significance at 5σ in a couple of years of observation. KM3NeT phase 3 will complement and overlap the field of view of IceCube exceeding, by more than one order of magnitude, the IceCube sensitivity in the Southern Hemisphere.

5. Summary

The construction of the KM3NeT detector has started and it will be arranged in three phases. The refurbiushment of the shore and deep sea infrastructures of Capo Passero and Toulon in view of phase 1 is almost completed. In both infrastructures two prototypes of KM3NeT detectors have been sucessfully installed and operated. The collaboration has also completed the design and set up all the tools and actions for the mass production of DUs in view of the completion of KM3NeT phase 1. Twenty-four DU strings and 8 towers will be deployed in Capo Passero (Sicily) and 7 strings in Toulon. The first DU is now assembled and under test, to be ready for deployment in Spring in Toulon. The other six strings in Toulon will be arranged in a denser configuration to proof the KM3NeT ORCA concept aiming at neutrino mass hierarchy studies. The way to KM3NeT ARCA is paved and the detector is expected to confirm the IceCube signal with improved source pointing performance. Eventually, with KM3NeT phase 3 the Collabroation will operate a distributed infrastructure for high energy neutrino astromomy and neutrino physics reasearch.

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