First results of the ANTARES neutrino telescope

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Abstract. The ANTARES Collaboration successfully completed in May 2008 the deployment of an underwater neutrino detector in the Mediterranean Sea, offshore the France coast, at 2475 m b.s.l. The main purpose of this experiment is the detection of high energy neutrinos produced in astrophysical sources. Neutrinos being neutral, stable and weakly interacting particles can travel undeflected through the Universe reaching the Earth even from the inner core of very distant objects. They are therefore very powerful messengers which can provide us invaluable information about processes which are hardly accessible with other messengers like photons. The detection of astrophysical neutrinos is very challenging due to the very small neutrino interaction cross-section and the huge background produced by other cosmic rays. Very large instrumented volumes and a very efficient shielding are therefore needed to detect astrophysical neutrinos. Moreover a very good angular resolution is mandatory to trace detected neutrinos back to their origin. ANTARES with 0.04 km$^2$ muon effective area at $E_\nu > 10$ TeV shielded by more than 2000 m of water and an angular resolution of 0.3° at $E_\nu > 10$ TeV, perfectly fits these requirements. The ANTARES deployment started in 2006 and many data have been already collected with a partial detector. The detector in its final configuration is described and preliminary results of data analysis, especially about calibration issues, are shown. The completion of the ANTARES detector paved the way towards an even larger submarine neutrino telescope in the Mediterranean Sea like the one planned by the KM3NeT project.

1. Introduction
All astrophysical objects have been observed for centuries by naked-eye or by astronomical telescopes exploiting the visible light which reach the Earth. In the 20$^{th}$ century new detectors exploiting different ranges of the electromagnetic spectrum, from radio to gamma-rays, have been developed to study the Universe. Whenever a new detector came into play many new phenomena and completely new classes of astrophysical objects popped up. We can reasonably believe that detectors exploiting completely different astronomical messengers, like neutrinos, would provide us with at least the same number of discoveries.

Neutrinos are stable particles, like photons, so they don’t decay while traveling to the Earth. They are also neutral particles, again like photons, so they are not deflected by the magnetic fields they go through along their path towards the Earth. Contrary to photons, neutrinos don’t interact electromagnetically with the photons surrounding neutrino sources nor with the extragalactic background light. They can easily reach the Earth unabsorbed. Neutrinos are therefore ideal astronomical messengers which can provide us unaltered information from the very heart of their sources over cosmological distances.

We do know that astrophysical objects produce neutrinos because we can detect low energy neutrinos coming from the Sun [1, 2]. Moreover a burst of MeV neutrinos from SuperNova
SN 1987A was detected in 1987 by the KAMIOKANDE [3] and IMB [4] experiments. So far no astrophysical source of neutrinos above few GeV has ever been identified but physicists are confident that high energy neutrino sources exist because gamma-rays with such energies have already been detected from many astrophysical objects. A deep connection between high energy gamma-ray emission and neutrino production exists according to the “beam dump” model: protons or nuclei accelerated to relativistic energies interact with matter or photons which surround the source producing charged and neutral pions which in turn decay into neutrinos and gammas respectively [5].

\[
p + X \longrightarrow \pi^0 + \pi^\pm + \cdots
\]

\[
\downarrow \quad \downarrow
\gamma\gamma \quad \mu^\pm + \nu_\mu(\bar{\nu}_\mu)
\]

\[
\downarrow
\]

\[
e^\pm + \nu_e(\bar{\nu}_e) + \bar{\nu}_\mu(\nu_\mu)
\]

According to this scenario the flux of neutrinos from gamma-ray sources should be of the same order of the gamma-ray one. The neutrino flux could be even larger than the gamma-ray one in the case of very obscured sources, that is sources surrounded by a lot of matter or photons which absorb a large fraction of emitted gamma-rays while being nearly transparent for neutrinos [5]. There are also pure electromagnetic models for gamma-ray emission which do not foresee sizable neutrino flux but these models are disfavored for some sources. The combined radio, X-rays, and gamma-rays observation of the shell-type SuperNova Remnant RX J1713.7-3946 for example favors hadronic models [6] (but also pure leptonic process are possible [7]). The “orphan flares”, that is a gamma-ray flares not associated with any X-ray flare, observed for the Blazar 1ES 1959+650 [8] are difficult to account for in purely leptonic models. Moreover it is well known that very high energy protons reach the Earth too, and recent results by AUGER [9] start to shed light over the sites of their production. It seems very unlikely that the high energy proton sources do not produce neutrinos as well.

The list of possible neutrino sources comprises both galactic and extragalactic objects. Concerning the galactic ones, the most promising are SuperNova Remnants, Pulsars and Microquasars, while the most probable extragalactic neutrino sources are Active Galactic Nuclei and Gamma-ray Bursts. The last ones are thought to emit neutrinos in short bursts. It would be helpful to spot their neutrino signal because a very short integration time \(\sim 1 - 100 \text{ s}\) would eliminate nearly all background events.

Cosmic neutrinos can be produced also by self-annihilation of Dark Matter candidates like neutralinos. These particles lose their energy by elastic scattering and accumulate in massive objects, like the Sun or the Galactic Center, pulled by gravitational force. A neutrino telescope, therefore, can be used also for the indirect search of Dark Matter.

In spite of many efforts neutrino astronomy still lags behind gamma-ray astronomy due to the enormous difficulties encountered. Cosmic neutrinos are hard to detect and to distinguish from the background produced by the interaction of other cosmic rays with atmospheric nuclei. To detect a statistically significant amount of cosmic neutrinos in a reasonable time (\(\sim 1 \text{ year}\)), a very large instrumented volume is needed, due to the very low neutrino interaction cross section \(\sigma_\nu \approx 5 \times 10^{-36} \text{ cm}^2\) at \(E_\nu = 1 \text{ TeV}\). Moreover, cosmic neutrinos have to be separated from the particles, especially muons and neutrinos, produced by the interaction of other cosmic-rays with atmospheric nuclei. The only known way to reduce this background is to bury the detector deep underground, under ice or underwater.

2. Detection principle

Cosmic neutrinos can interact via charged-current interaction in the medium which surrounds the detector producing a lepton which carries away a large fraction of neutrino energy. At high
energy $E_\nu \gtrsim 10 \text{ GeV}$ the emitted lepton moves along a direction very close to the neutrino one. Muon neutrinos with energy $E_\nu > 30 \text{ GeV}$ produce muons whose range is $R_\mu > 100 \text{ m}$ and reach 10 km for PeV neutrinos. These muons can go through the detector even if produced far away. Since they travel at speed greater than the speed of light in sea-water they induce the emission of a Cherenkov light conical wave-front whose axis is the muon trajectory, see figure 1.

![Figure 1](image1.png)

**Figure 1.** Detection principle of an underwater neutrino telescope. A muon neutrino (red line) interacting close to the detector produces an ultra relativistic (blue line) muon which induces the emission of Cherenkov light. This light can be detected by a 3D array of photon-detectors. Other kinds of events are detectable but harder to reconstruct.

A 3-dimensional array of photon detectors can record the arrival times of Cherenkov photons at different points of the array. The muon track can be reconstructed knowing the position of the photon detectors and exploiting the geometry of Cherenkov light emission. Very good time and position resolution are needed to achieve a good angular resolution for muon tracks.

Electron neutrinos produce instead electrons that immediately interact again producing an electromagnetic shower. These showers induce Cherenkov emission too but in this case the determination of the primary electron track is much harder due to the smearing of the Cherenkov light front induced by the showering process. Moreover, these showers vanish very quickly and can be detected only if the primary interaction happens inside the detector itself or nearby.

Tau neutrinos produce $\tau$ particles which decay again very quickly due to the very short lifetime. The track length is too short for the track reconstruction unless the $\tau$ energy is $E_\tau \gtrsim 10^6 \text{ GeV}$. In this case the event is indistinguishable from a muon one with lower energy. At lower energies possible signatures of $\tau$ events are the so-called “double-bang” and “lollipop” events. In the first case both particle showers, produced at $\nu_\tau$ interaction point and at $\tau$ decay point, are inside the detector as well as the $\tau$ track. In the second case only one of the two showers and part of the $\tau$ track are inside the detector. These events will be very rare in ANTARES due to the limited extension of the detector.

3. The ANTARES detector

The ANTARES detector has been successfully deployed between March 2006 and May 2008 at 2475 m depth 40 km off La-Seine-Sur-Mer (French Mediterranean cost, close to Toulon) at $42^\circ50’\text{N}, 6^\circ10’\text{E}$ location. From this position ANTARES can observe the Northern Sky, see figure 2, and in particular a large fraction of the galactic plane and the galactic center itself.
This is a particularly interesting zone because many very high energy gamma-ray sources have been recently discovered in this region of the sky [10]. All these sources are promising neutrino source candidates. Moreover the Galactic Center can be an accumulation point for Dark Matter candidate particles, like the neutralinos, which could produce neutrinos by self-annihilation. A field of view covering the Galactic Center makes ANTARES suitable for the indirect Dark Matter search too.

The site had been long investigated before the beginning of the deployment. In particular, sea water properties have been extensively studied revealing a low light scattering [11] and an average noise trigger rate of 70 kHz per detection channel mainly due to bioluminescence and $^{40}$K decay. The detector consists of 12 flexible mooring lines made of mechanically resistant electro-optical cables weighted to the sea bed and kept under tension by syntactic-foam buoys. A schematic view of the detector is shown in figure 3.

![Figure 3. A schematic view of the ANTARES detector. The inset shows the basic element of the detector, the so-called storey.](image)

The average distance between lines at sea-bed is about 70 m while their length is 450 m. Each line is equipped with 25 titanium frames, called storeys, which hold a triplet of optical modules (OM), pressure-resistant glass spheres housing a 10 inch hemispherical photomultiplier (Hamamtsu R7081-20) shielded by a $\mu$-metal cage, the high voltage power supply, a LED system used to monitor the transit time of the photomultiplier and the associated electronics [12]. The storey holds the Local Control Module (LCM) too, a titanium cylinder housing the digitization electronics, the trigger discriminators and a compass/tilt-meter to measure the inclination and rotation of the storey. OMs are 120° spaced and oriented at 45° downward with respect to the vertical axis to ensure the maximum sensitivity to upward moving Cherenkov fronts. The inset of figure 3 shows a schematic view of a storey. The distance between adjacent storeys is 14.5 m and the lowest storey is placed at 100 m above the sea level to avoid the most turbid layer. One out of every five storeys is equipped with an optical beacon, a well controlled pulsed light, used for timing calibration purposes and five storeys of each line are equipped with a hydrophone which allows the measurement of these storey positions by acoustic triangulation.
An instrumented line is also present on site to monitor environmental parameters, like sea water temperature and salinity, sound velocity and the speed of sea current. A precise measurement of all these parameters is needed for an optimum track reconstruction. All lines are connected through electro-optical cables to the junction-box which, in turn, is connected to the on-shore station by the 40 km long main electro-optical cable. The lines have been connected to the junction-box after their deployment by a remote operated submarine vehicle.

4. Trigger system
The ANTARES collaboration decided to maximize the flexibility of the data acquisition system choosing a large bandwidth connection with the on-shore station and applying to the events the less stringent trigger condition compatible with this bandwidth. In this way, only a very preliminary selection of the events, aimed at eliminating only a large fraction of events due to $^{40}$K decay and the bioluminescence, is applied off-shore (L0 trigger) while a more stringent filtering is performed on-shore by a computer farm. The digitization of the OM signal is triggered when the pulse amplitude crosses a threshold set to a fraction (typically 0.3) of the single photoelectron average amplitude. Whenever this happens all data are sent to the on-shore station where data are firstly processed by the so-called DataFilter program which looks for correlated hits consistent with a specific physics signal. The DataFilter program incorporates different algorithms for different physics signals, like standard muon filter, magnetic monopole filter, optical beacon filter and also directional filters to look for events coming from specific positions in the sky (GRB filter, Center of Galaxy filter, etc.). The standard muon filter requires at least 2 L0 triggers in the same storey within 20 ns or one single L0 trigger with a pulse charge greater than 3 photoelectrons to consider one storey and at least 5 storeys whose hits are causally connected. The average L0 trigger rate is about 70 kHz for each OM while the overall event rate after the DataFilter selection is about 2 Hz.

5. Data Acquisition system
Each OM signal is processed by two Analogue Ring Samplers (ARS) in a token-ring configuration to minimize the dead time. Six ARSs measure arrival time and charge of the pulses for the three OMs present in a storey. Whenever the L0 trigger condition is fulfilled these data are sent through a 100 Mb/s link to a modified LCM (MLCM) which collects data from five storeys, merges them by an Ethernet switch and sends them through 1 Gb/s link to the string control module (SCM) at the bottom of the string, see figure 4. The SCM collects the data from all MLCMs in one line and multiplexes them onto one single optical fiber by Dense Wavelength Division Multiplexing technique (DWDM). The DWDM network enables the transmission of different streams of data along a single fiber using different wavelengths. In this way, data reach the junction-box and then the on-shore station where they are filtered and processed by a computer farm. A more detailed description of the ANTARES data acquisition system can be found in [13].

6. Detector Calibration
Good angular resolution is crucial to point back detected neutrinos to their sources. The pointing accuracy is closely related to the precision in the determination of the arrival time of Cherenkov photons at the OMs. Detector strings are not rigid but move slowly due to underwater currents, hence the second essential element to achieve a good angular resolution is precise monitoring of the OM positions. The ANTARES detector is equipped with redundant timing and positioning calibration systems which ensure a 0.5 ns relative time resolution and 0.2 m precision on OM position measurements. Actually, due to chromatic dispersion and scattering of Cherenkov light in sea water the attainable precision on the arrival time of photons at OMs depends on
the distance between the OM itself and the particle track. However, due to light absorption longer distances are highly disfavored and for distances usually involved in track reconstruction the time accuracy is about 1 ns. This value is well matched with the accuracy on the position measurement because the photon velocity is about 0.2 m/ns in sea-water: these two uncertainties contribute more or less equally to the uncertainty on the track direction.

6.1. Timing calibration
Relative time offsets between OMs of each line are measured before the deployment by illuminating them with a laser plus fibers system and measuring the arrival time of OM signals at read-out electronics (LCM). Once deployed, these offsets can be verified and monitored using the optical beacon system [14]. Optical beacons are controlled pulsed light sources which emit short intense light pulses at well-known times. Measuring the arrival time of OM signals at LCM and knowing the optical beacon emission time, the offsets between different OMs can be precisely determined whenever needed. In this way the RMS of the time offset distribution can be reduced to 0.7 ns and maintained stable over time, see figure 5. The time resolution of the ANTARES electronic chain can be measured by flashing OMs very close to an optical beacon. In this case, due to the large number of photons per flash which reach the OMs, all the contributions to the time resolution except the electronic one become negligible. Figure 6 shows the distribution of residuals \( \Delta T = T_{\text{Arrival}} - T_{\text{Emission}} - T_{\text{Direct}} \) for this setup, clearly demonstrating that a 0.4 ns time resolution has been achieved.

The \(^{40}\text{K}\) present in the sea-water provides another cheap way for relative time calibration of close-by OMs. Electrons emitted in \(^{40}\text{K}\) decay induce the emission of Cherenkov light which can reach two OMs of the same storey. The time distribution of coincidences between two OM signals shows a peak whose position is equal to the difference between the two OM time offsets. Same storey OMs can be inter calibrated in this way. The results obtained with \(^{40}\text{K}\) method and the OB system show a remarkable agreement. A 20 MHz echo-based clock signal synchronized with a GPS is generated on-shore and sent to all LCMs. In this way the round-trip delay between the on-shore station and all LCMs can be measured and regularly monitored to avoid drifts. This clock provides the interline relative calibration and the absolute time calibration of the detector.

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\( T_{\text{Arrival}} \) is the arrival time of photons at the OMs, \( T_{\text{Emission}} \) is the emission time by the OB, and \( T_{\text{Direct}} \) is the time-of-flight of photons which travel strightly from the OB to the OM.
6.2. Positioning calibration

The storeys equipped with hydrophones receive sound pulses from three emitters fixed on the sea-bed. In this way, the positions of these storeys with respect to the emitters can be measured by triangulation. A precision on acoustic distance measurements of about 2 cm and an accuracy on the 3D hydrophones spatial positions better than 5 cm can be achieved [15]. Moreover, every storey is equipped with a tilt-meter/compass board which measures the local tilt angles with respect to the horizontal plane (pitch and roll), as well as the orientation with respect to the Earth Magnetic North (heading). Using all this information, a 3D mechanical model of the string which takes into account the weight and drag of all string elements can be fitted. In this way, the relative 3D position of all OMs can be measured with an accuracy better than 20 cm.

7. Comparison with MC

The data collected with a partial detector during the completion of the deployment allow a preliminary comparison between real data and Monte Carlo simulations. In particular the large amount of data taken in homogeneous conditions with 5 strings are being used for this cross-checks. Although ANTARES is shielded by more than 2000 m of sea-water many so-called atmospheric muons reach its active volume. These are muons produced in the decay of charged mesons produced by the interactions of primary cosmic rays with atmospheric nuclei. Atmospheric muons constitute the major background for ANTARES mainly because they can be wrongly reconstructed as up-going particles. On the other hand these numerous particles are very useful to check the Monte Carlo simulation of the detector response to the passage of charged particles. Figure 7 and figure 8 show respectively the azimuth and zenith angle distributions of reconstructed tracks (without any quality cut) for data (black points) and Monte Carlo simulation (red solid line). The red shaded area shows the systematic uncertainty on Monte Carlo prediction due to uncertainties on primary cosmic-ray flux and on the hadronic interaction model. Taking into account systematic uncertainties, data and MC agree pretty well.

8. Expected performances

Once validated through its comparison with real data, Monte Carlo simulation chain has been used to estimate the full detector performances. The angular resolution for neutrinos with
Figure 7. Azimuth angle distribution of reconstructed tracks (black points) compared to MC prediction (red solid line). The red shaded area shows a 40% systematic uncertainty on the MC prediction.

Figure 8. Zenith angle distribution of reconstructed tracks (black points) compared to MC prediction (red solid line). The red shaded area shows a 40% systematic uncertainty on the MC prediction.

\( E_\nu > 10 \text{ TeV} \) results in 0.3°, see figure 9. Such a good angular resolution is extremely helpful for the search of point-like sources. Figure 10 shows the expected sensitivity for one year of data taking as a function of declination compared with flux upper limits already set by other experiments and the sensitivities of other neutrino telescopes.

Figure 9. Angular resolution as a function of neutrino energy. Below 10 TeV the resolution is dominated by the angle between muon and neutrino trajectories. At higher energies the detector resolution dominates and the angular resolution improves as neutrino energy increases staying below 0.3°.

Figure 10. The ANTARES sensitivity for point-like sources for one year of data taking as a function of declination (blue dotted line). Magenta squares are 90% c.l. upper limits by MACRO [16]. Red circles are similar limits by AMANDA-II, while the red dotted line is the average limit [17]. The black dotted line shows the expected sensitivity for IceCube in one year [18].
9. Conclusions
The ANTARES collaboration successfully completed the deployment of a neutrino detector at 2475 m depth in the Mediterranean Sea. All the technological challenges involved in this project were met. An increasing fraction of the detector took data without major problems over the last two years. The analysis of the data acquired so far confirmed that the ANTARES detector can perform well within design specifications. In particular, the timing calibration system can achieve a 0.5 ns timing resolution while the acoustic positioning system can measure photon-detector positions with 20 cm accuracy. These values imply an angular resolution on neutrino tracks below 0.3° for $E_\nu > 10$ TeV and consequently very good sensitivity for the point-like source search. Thanks to its location ANTARES can observe the Northern Sky, complementing neutrino telescopes at South Pole. Notably a large fraction of the galactic plane, where many promising neutrino source candidates are present, can be observed for 75% of the observational time. The ANTARES detector is presently the neutrino telescope with the biggest instrumented volume and the largest effective area in the Northern Hemisphere representing a clear proof of concept for an even larger submarine neutrino telescope like the one pursued by the KM3NeT network [19].

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