Search for cosmic high energy down-going neutrino fluxes from point-like sources with ANTARES

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Abstract. Installed in the Mediterranean Sea, at a depth of \( \sim 2.5 \) km, ANTARES is the largest undersea neutrino telescope currently operating. The search for point-like sources with neutrino telescopes is normally limited to a fraction of the sky, due to the selection of events for which the direction of the neutrino candidate has been reconstructed as coming from below the detector horizon, usually referred to as “up-going” events, in order to significantly reduce the atmospheric muons background. In this contribution we demonstrate that through an energy and direction dependent event selection the background can be effectively suppressed so that a part of the region above the horizon can be included in the search. The strategy for the study of a “down-going” neutrino flux is described and the ANTARES sensitivity is presented. No indication of a neutrino signal has been found in the analysed data and upper limits on the flux normalization of a \( \propto E_{\nu}^{-2} \) energy spectrum of neutrinos from several candidate point-like sources in that region have been set.

1. Introduction
Neutrinos represent a valid probe for the exploration of the high energy sky, they provide complementarity with photons and cosmic rays observations since they can emerge from dense media and travel across cosmological distances without being deflected by magnetic fields nor absorbed by ambient matter and radiation. High energy neutrinos (TeV and beyond) are expected to be produced by a wide variety of astrophysical objects. Along with gamma-rays, they originate from the decay of pions and kaons produced in the interactions of accelerated protons and nuclei with matter and radiation inside or in the vicinity of their sources. Candidate neutrino emitters include most known or putative cosmic ray accelerators, ranging from galactic sources such as supernovae remnants or microquasars to the most powerful extragalactic emitters such as active galactic nuclei and gamma-ray bursts \([1]\). The observation of cosmic neutrinos could allow the identification of known or unknown celestial objects and test the existence of hadronic processes inside astrophysical sources. Cosmic neutrino detectors, usually called “telescopes”, need to have a large collection area in order to intercept the faint flux of neutrino events at high energies. This requirement drives to the instrumentation of large volumes of transparent medium (as oceanic water or Antarctic ice) with arrays of photo-sensors, with the aim of detecting the Cherenkov light induced by relativistic charged particles produced when a neutrino interacts with material in or around the detector. Although the identification of muons by \( \nu_{\mu} \) charged current interactions represents the most straightforward detection channel, showers induced by electron and tau neutrinos can also be detected. Neutrino telescopes are installed at great depths...
and optimized to detect up-going muons produced by neutrinos that have traversed the Earth, in order to limit the background from down-going atmospheric muons. Atmospheric neutrinos, with an energy spectrum $\propto E^{-3.5}_\nu$, traverse the Earth and interact close to the detector representing an irreducible background. Neutrinos of cosmic origin which are expected to have an energy spectrum $\propto E^{-\alpha}_\nu$ with $\alpha = 2$ or 2.2 can be identified only on a statistical basis.

2. The ANTARES detector

ANTARES (Astronomy with a Neutrino Telescope and Abyss environmental RESearch) is the first undersea neutrino telescope and the only one currently operating [2]. Its main scientific target is the detection of high energy neutrinos of cosmic origin. It is located on the bottom of the Mediterranean Sea at a depth of $\sim 2475$ m, in French waters, at $\sim 40$ km south-east off the coast from Toulon. The apparatus consists in a matrix of 885 PhotoMultiplier Tubes (PMTs) arranged into 12 strings anchored to the sea bed and maintained vertical by buoys, connected to a junction box which distributes the electrical power and transmits the data to shore through an electro-optical cable. The PMTs are orientated at 45° downwards in order to maximize the sensitivity to Cherenkov light from up-going muons. Acoustic devices and inclinometers regularly spread along the strings allow to accurately monitor the position and orientation of the PMTs [3], the time calibration is performed by means of an array of laser and LED beacons [4]. Fig. 1 shows a pictorial illustration of the detector.

3. Data analysis

The analysis presented here has been developed using the data collected by ANTARES between June 2009 and June 2011. The analysed sample has been selected out of data recorded with the detector in perfect operational conditions and corresponds to a total live-time of 366.6 days. As well as for the analysis presented in the last ANTARES letter about the search for point-like sources [5], only events reconstructed as muon tracks have been considered. The special feature lies in the fact that here only down-going tracks have been considered. Fig. 2 and Fig. 3 show the sky visibility for ANTARES in up-going events only and down-going events only, respectively. For both figures, the map on the left panel is drawn in equatorial coordinates, the map on the right panel in galactic coordinates. As it is possible to notice, the region of the sky where declinations are larger than $\sim 45^\circ$ is not covered by the observation of up-going events, but it becomes accessible by studying down-going ones. Therefore, thanks to the analysis described...
here it has been possible to extend the field of view of ANTARES.

The performed search has been a “candidate-list” one, consisting in looking for an excess of events coming from predefined locations in the sky. Six candidate sources, listed in Table 1, have been selected taking into account their flux in gamma-rays and their visibility for the detector. The big challenge of the analysis of down-going events is due to atmospheric muons which can penetrate through several kilometres of water to the detector, providing the major component of the background. Two characteristics can be used to separate the cosmic signal from the atmospheric background: the difference among the slopes in the energy spectra ($E^{-3.5}$ for the background and $E^{-2}$ or $E^{-2.2}$ for the signal) and the angular distribution, which is isotropic for background but directional for signal from a point-like source. In order to enhance the telescope sensitivity to a cosmic neutrino flux it is necessary to boost the rejection power. An high rejection power has been achieved by means of

- a multivariate analysis, in which both the information about the energy of the event and its incoming direction have been used;
- a statistical technique, called Model Rejection Potential (MRP), which allows to optimize the aperture of the search angular interval around the source position selecting the condition for the best signal to background separation.

A Monte Carlo simulation has been performed in order to estimate neutrino fluxes coming from the sources considered; the background has been estimated from “blinded” experimental data. The “blinding” policy defined by the ANTARES Collaboration is intended to avoid that the selection process and the analysis strategy design are inadvertently tuned on the data sample. The applied procedure consists in the scrambling of the event right ascension: the true right ascension of an event is hidden and a false right ascension is attributed to the event. Muon neutrinos and muon anti-neutrinos charged-current interacted events, coming from the location of the considered candidate sources, with energy ranging from 5 GeV to 100 PeV, have been generated. Fig. 4 shows on the left the bi-dimensional distribution of the point-spread function...
Figure 4: Point-spread function in local coordinates ($\theta$, $\phi$) for down-going neutrino events generated from MGRO J2019+37 (left). Angular resolution of down-going neutrino events generated from Tycho, determined as the median of the cumulative distribution of the angle in the space, $\Psi$, between the generated neutrino direction and the reconstructed muon one. The black-dotted line indicates the median value (right). For both a source spectrum $\propto E_{\nu}^{-2}$ has been assumed.

for neutrino events generated from MGRO J2019+37. The angular resolution, defined as the median of the cumulative one-dimensional point-spread function distribution, shown in Fig. 4 on the right, is about 0.28°, assuming an energy spectrum $\propto E_{\nu}^{-2}$.

3.1. Signal to background separation: the multivariate analysis

The analysis of down-going events requests a great effort to obtain the best signal to background discrimination. This purpose has been achieved by performing a multivariate analysis instead of the classic cut-based one. A “Boosted Decision Tree” (BDT) method has been implemented, by using the Toolkit for Multivariate Analysis (TMVA) \[6\]. Three input variables have been considered: the parameter $\Lambda$, a maximum likelihood result of the track fitting procedure, which describes the quality of the track reconstruction \[7\], the zenith angle $\theta$ (ranging from 0° for vertical down-going tracks to 90° for horizontal ones) and the reconstructed energy of the event $E_{\text{reco}}$. Fig. 5 shows the distribution of signal events (by the Monte Carlo simulation) generated from MGRO J2019+37, and background events (by experimental blinded data) for the three input variables. As a result of the analysis of efficiencies and significances, the same cut on the so-called BDT response ($> 0.1$) has been set for all the sources.

3.2. Signal to background separation: the Model Rejection Potential approach

The aim of this step of the analysis consists in the search for the amplitude of the search cone that maximizes the discovery power. The search cone is defined as a cone with the axis in the direction of the considered source. If a significant excess (5$\sigma$) of experimental events over the expected background is observed inside the cone, a discovery can be claimed. The MRP technique \[8\] has been used. It optimises the amplitude of the cone in order to determine the detector sensitivity (the smallest signal flux that the detector is able to detect) by using signal and background estimates, without the use of experimental data. Around each source direction, cones of different amplitudes ($\alpha$, from 0.3° to 5° at steps of 0.1°) have been opened and the number of signal events ($n_s$) and background events ($n_b$) occurring in each cone, after the cut in the BDT response, have been determined. According to the MRP method, the strongest constraint on a possible signal flux is obtained when the cone amplitude ($\alpha_{\text{best}}$) minimises the
so-called Model Rejection Factor (MRF): 

$$MRF = \frac{\overline{\mu}_{90} (n_b)}{n_s}$$  \hspace{1cm} (1)$$

where $\overline{\mu}_{90}$ is the Feldman and Cousins 90% confidence interval \[9\], and its value is:

$$\overline{\Phi} (E)_{90\%} = \Phi_{\text{test}} \times MRF_{\text{min}}$$  \hspace{1cm} (2)$$

where $MRF_{\text{min}} = MRF (\alpha_{\text{best}})$. $\Phi_{\text{test}}$ represents the assumed neutrino flux from the source, in this analysis $\Phi_{\text{test}} = 10^{-8} E^{-2} \nu \text{ GeV cm}^{-2} \text{ s}^{-1}$. In Table 1 the best search cone amplitude for each source is indicated, together with the number of expected background and signal events inside the best cone, finally the ANTARES sensitivity to a neutrino flux, with an energy spectrum $\propto E^{-2}$, coming from the corresponding source is presented.

4. Results and Conclusions

The final step of the analysis consists in unblinding the experimental data. In such a way it has been possible to know the real incoming direction of detected events, and to count the events occurring within the cone towards each considered source with the aperture determined by means of the MRP technique. No significant excess over the expected background has been found in any of the six considered directions, therefore upper limits have been derived. The most significant cluster, with a significance of 2.1 $\sigma$, has been found for MGRO J2019+37 located at $(\alpha, \delta) = (304.65^\circ, 36.83^\circ)$. Results are summarized in Table 1 for each source, the number of events that have been observed in the best search cone ($n_{\text{obs}}$) is indicated as well as the 90% CL flux upper limit on a muon neutrino flux with an energy spectrum $\propto E^{-2}$, calculated by using the Feldman and Cousins method \[9\], is shown. Results are also presented in Fig. 6. Thanks to the analysis of the down-going events, the field of view of ANTARES has been extended at a very interesting region of the sky. The sensitivity of the detector and upper limits for a list of candidate sources with declinations ranging from 37° to 73° have been presented. A worsening of the limits set by the down-going events analysis with respect to those derived by the up-going events analysis was expected. Actually, IceCube \[10\] too shows a worsening of the sensitivity and of upper limits for neutrino fluxes coming from the Southern Hemisphere ($\sin \delta < 0$) set by means of down-going data with respect to the limits for neutrino fluxes coming from the Northern Hemisphere. Moreover, it should be noticed that the statistics used here is about 30% of the statistics already analysed by ANTARES \[5\]. By increasing the analysed data sample, even if there will not be discoveries, the limits could go down and ANTARES will be able to put stronger constraint to cosmic neutrino fluxes.
Table 1: The list of candidate sources. For each considered neutrino source, from the second column to the eighth one: the declination of the source, the best search cone amplitude, the number of observed events and expected background and signal events inside the best cone, the sensitivity of the detector and the 90% CL flux upper limit on a muon neutrino flux with an energy spectrum $\propto E^{-2}_\nu$.

| Source       | $\delta$ (deg) | $\alpha_{\text{best}}$ (deg) | $n_{\text{obs}}$ | $n_b$ | $n_s$ | Sensitivity (GeV cm$^{-2}$ s$^{-1}$) | 90% CL Upper Limit (GeV cm$^{-2}$ s$^{-1}$) |
|--------------|----------------|-----------------------------|-------------------|------|------|-----------------------------------|---------------------------------|
| CTA 1        | 72.98          | 0.6                         | 17                | 21   | 0.111 | $2.40 \times 10^{-7}$              | $4.17 \times 10^{-7}$           |
| Tycho        | 64.18          | 0.6                         | 5                 | 4    | 0.123 | $2.36 \times 10^{-7}$              | $4.87 \times 10^{-7}$           |
| Cassiopeia A | 58.81          | 0.8                         | 7                 | 4    | 0.208 | $1.51 \times 10^{-7}$              | $4.11 \times 10^{-7}$           |
| 3C 66A       | 43.04          | 0.7                         | 3                 | 1    | 0.215 | $1.41 \times 10^{-7}$              | $2.99 \times 10^{-7}$           |
| 3C 254       | 40.62          | 0.9                         | 3                 | 4    | 0.211 | $1.56 \times 10^{-7}$              | $1.67 \times 10^{-7}$           |
| MGRO J2019+37| 36.83          | 0.7                         | 5                 | 2    | 0.152 | $1.95 \times 10^{-7}$              | $5.27 \times 10^{-7}$           |

Figure 6: 90% CL flux upper limits on a muon neutrino flux $\propto E^{-2}_\nu$ and ANTARES sensitivity as a function of the source declination. The results of the down-going analysis described here are presented in azure. They provide the telescope sensitivity and upper limits on a cosmic neutrino flux originated from a list of candidate sources with $\delta > 36^\circ$. IceCube and ANTARES results, obtained through the analysis of up-going tracks, are also shown for comparison [5].

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