Search for point sources of cosmic neutrinos with the ANTARES neutrino telescope

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Abstract. The ANTARES detector is currently the largest deep-sea neutrino telescope in the Northern Hemisphere. Located on the bottom of the Mediterranean Sea, 40 km off the French coast, it consists of a three-dimensional array of 885 photomultiplier tubes which detect the Cherenkov light induced by the muons produced in the interaction of high energy cosmic neutrinos with the matter surrounding the detector. The main goal of ANTARES is the search for cosmic neutrinos and their sources. In this contribution preliminary results of the search for point sources of high energy neutrinos with the data gathered in 2007 and 2008 are presented, including some of the most stringent upper limits on the neutrino flux in the world.

1. Introduction
Neutrino Astronomy represents a new method to explore the Universe complementary to the multi-wavelength and cosmic rays observations. Furthermore, the neutrino, as weakly interacting and almost massless particle, represent a unique probe to obtain information from the inner core of distant astrophysical objects. Candidates for cosmic neutrino sources are considered to be both galactic, as X-ray Binary systems, and extragalactic, like Active Galactic Nuclei (AGNs). In such astrophysical scenarios acceleration of hadrons up to very high energies is predicted; their interaction with the ambient matter and dense photon fields will eventually create pions, which produce neutrinos in their decay. Therefore, the detection of a source of neutrinos will distinguish unambiguously between hadronic and electronic acceleration mechanisms.

The detection principle of a neutrino telescope is based on the collection of the Cherenkov light induced by the relativistic muons produced in the interaction of high energy neutrinos with the water or rock near the detector. The main source of background comes from the atmospheric muons and neutrinos produced by the interaction of cosmic rays in the Earth atmosphere. Due to the low interaction cross section of the neutrino, large instrumented volumes are required. ANTARES is the first deep sea full operational neutrino telescope. Searches for cosmic neutrinos and their sources are one of the main goals of the experiment. This contribution presents a search for point source analysis using 295 days of data livetime.

2. The ANTARES detector
The ANTARES (Astronomy with Neutrinos and Abyss RESearch) neutrino telescope [1] is deployed at a depth of 2475 m in the Mediterranean Sea, about 40 km offshore the coast of Toulon, at 42°48’N, 6°10’E. The detector is an array of photomultiplier tubes arranged in
twelve detection mooring lines (a schematic view is shown in figure 1). Each line is divided on 25 storeys holding a triplet of optical modules (OM), which are pressure resistant glass spheres equipped with a 10'' photomultiplier and facing downward at 45° from the line axis for an increased detection efficiency for up-going neutrinos. The lines are 450 m long and sustained vertically by means of a buoy at the top. The lowest storey is located 100 m above the sea bed. The spacing between lines is 60-70 m and the distance between adjacent storeys is 14.5 m. The Junction Box links all the lines and the Main Electro-Optical Cable transmits the power/data from/to shore station, where a computer farm applies the data filter algorithm based on different trigger criteria. ANTARES is equipped with a positioning system [2] which measures the line displacements with a precision on the relative location better than 10 cm. Time calibration [3] is performed in situ with a system of optical beacons distributed along the detector.

3. Data selection and track reconstruction
The analysis presented here use data gathered in the first two years of detector operation. During this time the ANTARES construction was still in progress; for most of 2007 the detector consisted of 5 lines, and of 9, 10 and 12 in 2008. A run selection criteria based on the number of active OMs (or active channels) during the run was applied considering each detector configuration, so 75%-80% of the OMs are required to be active when averaging over the full run. Trigger event selection requires at least 5 triplets of OMs detecting multiple photons through the detector. The difference in the arrival time of the hits must be compatible with coming from a relativistic particle. Also events for which multiple photons are collected on two adjacent storeys are considered. Taking into account the time spent on sea operations (like the deployment and connection of new lines) and sporadic data taking problems of the detector, the total livetime of the analysis is 295 days, of which 144 days correspond to data taken with the smaller configuration of 5 lines.

The reconstruction of the muon track is achieved using the timing and position information of the hits arriving to the PMTs. A dedicated offline algorithm [4] that consists of multiple fitting steps of increasing sophistication is used. The final step consists on the maximization of the likelihood of the observed hit times as a function of the muon direction and position. The goodness of the track reconstruction is described by the $\Lambda$ parameter, which is basically the log-likelihood of the fitted track. This parameter can be used to eliminate badly reconstructed tracks by selecting an appropriate cut on the $\Lambda$ value. Figure 2 shows the cumulative distribution of $\Lambda$.
for data events reconstructed as upgoing, together with the contribution from the components of the expected background of atmospheric muons and neutrinos. For this analysis atmospheric muons were simulated with the CORSIKA package [5] using QGSJET [6] for the hadronic interactions and cosmic ray composition described in [7]. The atmospheric neutrinos were generated with the GENNEU [8] package according to the Bartol model [9].

Neutrino candidates events are selected requiring an upward going track and applying a cut on the quality of the reconstruction $\Lambda > -5.4$. The latter was found to be the optimal for the search sensitivity obtained by optimizing the background reduction and the signal efficiency, in terms of the neutrino flux. Additionally, the uncertainty on the muon direction estimated from the fit is required to be $1^\circ$. The final sample consists of 2190 events, out of which about 60% are expected to be neutrino events and 40% downgoing atmospheric muons mis-reconstructed as upgoing.

4. Detector performance
The performance of a neutrino telescope is described by its angular resolution and effective area. Both parameters are estimated from simulation. Figure 3 shows the cumulative distribution of the angle between the reconstructed muon direction and the true neutrino direction for upgoing neutrino events assuming an $E^{-2}$ spectrum and complying the event selection criteria described in the previous section. The plot shows that roughly 75% of the signal events are reconstructed with an angular error less than $1^\circ$, being the median value of the reconstruction error, i.e. the angular resolution, $0.5 \pm 0.1^\circ$. The uncertainty here includes all effects which can be related to a reduction of the per-OM timing resolution, and was estimated by artificially degrading the simulated timing accuracy of the detector by randomly smearing the hit times according to a Gaussian with a width of $\sigma_t$. Requiring a reasonable agreement between simulation and the observed data a lower bound for $\sigma_t = 2.0 \pm 0.5$ ns was obtained, and consequently used for simulation. Furthermore, this study revealed that an additional smearing of 3 ns was incompatible with data at the 2$\sigma$ level.

The effective area is defined as the 100% efficient surface which detects the same number of events as the real one. An averaged effective area was computed considering the different detector configurations and selection criteria used for this analysis. It is shown in figure 3 as a function of the neutrino energy for a cosmic neutrino spectra of $E^{-2}$.

![Cumulative distribution of the reconstruction quality](image)

**Figure 2.** Cumulative distribution of the $\Lambda$ parameter describing the quality of the reconstruction. The ratio between data and Monte Carlo simulation is shown in the bottom.
between data and simulations a 15% systematic uncertainty on the detection efficiency has been considered.

5. Search method

The search algorithm used is an unbinned method based on the likelihood of the observed events as is defined in equation 1:

$$\log \mathcal{L}_{s+b} = \sum_i \log [ \mu_{\text{sig}} \times \mathcal{F}(\beta_i(\delta_s, \alpha_s)) + \mathcal{B}_i] - \mu_{\text{tot}}$$

where the sum is over the events, $\mathcal{F}$ is the point spread function (the probability to find the reconstructed event $i$ at an angular distance $\beta_i$ away from the true source coordinates $\delta_s, \alpha_s$), $\mathcal{B}$ is a parametrization of the background rate obtained from the observed declination distribution of the events, $\mu_{\text{sig}}$ is the mean number of the signal events emitted by the source and $\mu_{\text{tot}}$ stands for the total number of events in the selected sample.

The likelihood is numerically maximized yielding an estimate of the free parameters; in the case of a full sky search (see next section) these are $\delta_s, \alpha_s$, and $\mu_{\text{sig}}$, while in the candidate search only $\mu_{\text{sig}}$ is fitted as the coordinates of the sources are known. Point source searches involve testing the compatibility of the data with two hypothesis; that only background events are present in our sample ($H_0$), and that, over the distribution made up by the atmospheric background events, there exists a cluster of signal events produced by a source of cosmic neutrinos ($H_1$). To this end, the so called test statistic, defined as the log likelihood ratio of the two hypotheses under consideration (equation 2), is computed.

$$Q = \log \mathcal{L}_{s+b}^{\text{max}} - \log \mathcal{L}_b$$

where $\mathcal{L}_b$ is the likelihood of the background events. Lower $Q$ values indicate that data is more likely to be compatible with background, while larger values are more probably to be produced by the presence of the searched signal. This search method has shown a better efficiency in separating signal from background than others methods (binned and unbinned) used in ANTARES.
Figure 4. Limits set on the flux of an $E^{-2}$ neutrino spectrum from the sources in the candidate list. Several previously published limits on sources in both the Southern and Northern sky are included together with the ANTARES sensitivity.

6. Results
Two different searches have been conducted in this analysis. The first one is a blind search where no assumptions about the source location are made. In the second approach we look for an excess of events in the direction of 24 candidate sources selected considering gamma-ray telescopes observations and the ANTARES visibility (fraction of time when the source is below the horizon).

No significant clusters of events were found in the full sky search. The equatorial coordinates of the most signal-like cluster are \( \delta = -0.50^\circ, ra = 43.21^\circ \). The fit estimates 3.4 events as signal events. The value of the test statistic for this cluster is \( Q = 6.8 \). Such value, or a larger one, is found in the 88% of the background only experiments.

Results from the search using a candidate source list are summarized in table 1. No statistically significant excess was found near the 24 selected sources. The lowest p-value, defined as the fraction of the background only experiments that produce at least a larger \( Q \) value than the observed one, corresponds to GX 339, with a (post-trial) probability of 6.8% to occur when looking at 24 sources. Not having observed any significant point sources, limits on the \( E_{\nu}^{-2} \) flux has been obtained at 90% CL following the Feldman-Cousins [10] prescription. Figure 4 show the ANTARES upper limits and sensitivity (the median value of the expected limit) as a function of the source declination; the systematic uncertainties described in section 3 are taken into account. Limits reported by other neutrino experiments are included for comparison. Note that in this analysis, and for the flux model considered, 80% of the selected events are in the range \( 3 < E_{\nu} < 700 \) TeV.

The likelihood implementation described in the previous section was cross checked with an independent search method based on the EM-algorithm [11], using the same sample of events this search yields similar results. In addition, an auto-correlation study of the events did not reveal any structure in the data.

7. Conclusions
The ANTARES detector is the largest underwater neutrino telescope and the first full operational. Using data collected during the first two years of operation a search for point sources of high energy cosmic neutrinos has been conducted. Neither in the all sky search nor in the candidate list search has been found any significant excess of events. Many of the upper limits
Table 1. Results of the candidate source search showing the source coordinates, p-values and the limits on the flux $\phi^{90\%CL}$ obtained in this analysis (the latter is expressed in units of $GeV^{-1}cm^{-2}s^{-1}$.)

| Source name       | $\delta$ (°) | ra (°)    | p-value  | $\phi^{90\%CL}$ |
|-------------------|--------------|-----------|----------|-----------------|
| GX 339            | -48.79       | 255.70    | 0.068    | 2.13            |
| RX J0852.0-4622   | -46.37       | 133.0     | 0.397    | 1.78            |
| RX J1713.7-3946   | -39.75       | 258.25    | 0.399    | 2.25            |
| 1ES 0347-121      | -11.99       | 57.35     | 0.574    | 2.57            |
| HESS J1837-069    | -6.95        | 279.41    | 0.705    | 2.45            |
| 3C 279            | -5.79        | 194.05    | 0.743    | 2.44            |
| PSR B1259-63      | -63.83       | 195.70    | 0.879    | 1.45            |
| HESS J1023-575    | -57.76       | 155.83    | 0.952    | 1.36            |
| PKS 2005-489      | -48.82       | 302.37    | ~1       | 1.14            |
| RGB J0152+017     | 1.78         | 28.17     | ~1       | 1.87            |
| Galactic Center   | -29.01       | 266.42    | ~1       | 1.30            |
| LS 5039           | -14.83       | 276.56    | ~1       | 1.34            |
| H 2356-309        | -30.63       | 359.78    | ~1       | 1.13            |
| PKS 0548-322      | -32.27       | 87.67     | ~1       | 1.01            |
| W28               | -23.34       | 270.43    | ~1       | 0.97            |
| HESS J1614-518    | -51.82       | 243.58    | ~1       | 0.55            |
| 1ES 1101-232      | -23.49       | 165.91    | ~1       | 0.70            |
| Cir X-1           | -57.17       | 230.17    | ~1       | 0.41            |
| RCW 86            | -62.48       | 220.68    | ~1       | 0.41            |
| ESO 139-G12       | -59.94       | 264.41    | ~1       | 0.41            |
| PKS 2155-304      | -30.22       | 329.72    | ~1       | 0.58            |
| HESS J0632+057    | 5.81         | 98.24     | ~1       | 0.82            |
| Centaurus A       | -43.02       | 201.36    | ~1       | 0.35            |
| SS 433            | 4.98         | 287.96    | ~1       | 0.83            |

on the neutrino flux obtained are the most stringent in the world. These are preliminary results (the corresponding paper is in preparation and will be published soon). Analysis of new data is underway.

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