

# POINT-LIKE SOURCE SEARCH WITH THE 5-LINE ANTARES DATA

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ANTARES, the world's largest operational underwater neutrino experiment, is taking data with its complete layout since the end of May 2008. During the year 2007 it has been operating with 5 active detector lines out of 12. Results of the point-like search analyses performed on the data collected in this period are presented, showing that even for this first small data sample, the limits are competitive with previous experiments looking at the Southern hemisphere.

## 1 Introduction

The search for high energy (10 *TeV* - 100 *PeV*) neutrino sources is one of the most interesting challenges faced in the astroparticle physics field. It is strongly linked to the problem of the origin of the cosmic rays: in fact, the discovery of the neutrino production from a source is the only clear evidence for the source to be a cosmic ray emitter<sup>1</sup>.

The ANTARES experiment and its main physics results have already been presented in this Conference<sup>2</sup>. Here, the point-like source search carried out by the ANTARES collaboration is described. The general approach is to perform a blind analysis of the 5-line data, which consists in scrambling the right ascension coordinate. Two kinds of search have been developed: the fixed source search (Sec. 5), where the direction of the source is assumed to be known, and the all sky search (Sec. 6), where the whole sky is probed. Two different methods, previously optimised by calculating the sensitivity as a function of the declination, have been used in these searches for point-like sources: the cone method (Sec. 3) and the Expectation Maximisation (EM) method (Sec. 4): the first one has been used as a cross-check of the second one, which is more powerful, as expected from being an unbinned method<sup>3</sup>. The results obtained after unblinding the data are discussed in Sec. 5 and Sec. 6.

## 2 Data selection

In 2007 the duty cycle was  $\sim 80\%$ . After excluding high bioluminescence periods, the number of effective data taking days is 140. The data are selected by applying two cuts: a cut on the elevation,  $\Theta < -10^\circ$ , to reduce further the contamination from the atmospheric muons, and a cut on a reconstruction quality parameter  $\Lambda^2$ ,  $\Lambda > -4.7$ . In Figure 1(a) the number of events selected as a function of the cut value on the  $\Lambda$  parameter shows that the applied cut selects 96 events. In figure 1(b), the distribution of the elevation, resulting after applying the cut on  $\Lambda$ , for real (black line), MC atmospheric muon (red line) and MC neutrino (green line) data, shows that the final selection results in a high purity sample ( $\sim 80\%$ ). In the region selected there is a good agreement between real and MC data. The distribution of the time residuals of the hits

used in the reconstructed tracks (Fig. 1(c)) also shows a good agreement between real (black line) and MC (blue histogram) data. The angular resolution obtained at high energy depends on the reconstruction algorithm used which is based on the time residuals: the good agreement shown, supports our estimation of the angular resolution.

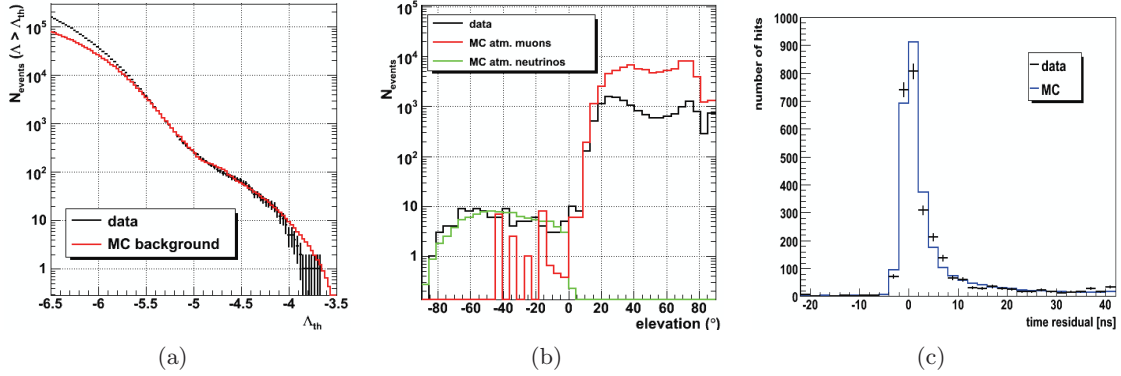


Figure 1: Integrated distribution of the  $\Lambda$  parameter, an indicator of the reconstruction quality, for real (black line) and MC (red line) data (a). Elevation distribution, for real (black line), MC atmospheric muon (red line) and MC atmospheric neutrino (green line) data when  $\Lambda > -4.7$  (b). Time residual distribution of the hits used in the reconstructed tracks for real (black line) and MC (blue line) data.

### 3 The cone method

The cone method provides the source to be observed inside a cone having the centre in the source position and the opening angle chosen in order to minimise the sensitivity to the source flux (optimum cone aperture). In the Feldman and Cousins framework<sup>4</sup>, the sensitivity is defined as the average upper limit at a given confidence level (90%) over all the possible experiments with number of expected background events  $n_b$  and no signal. Assuming the background follows a Poisson distribution, the average upper limit on the number of observed event is:

$$\bar{\mu}_{90}(n_b) = \sum_{n_{\text{obs}}=0}^{\infty} \mu_{90}(n_{\text{obs}}, n_b) \cdot \frac{(n_b)^{n_{\text{obs}}}}{(n_{\text{obs}})!} \exp(-n_b) \quad (1)$$

where  $n_{\text{obs}}$  is the total number of detected events and  $\mu_{90}(n_{\text{obs}}, n_b)$  the set upper limit, for each experiment. The average upper limit on the flux is:

$$\bar{\Phi}_{90}(E, \Theta) = \frac{\bar{\mu}_{90}(n_b)}{n_s} \cdot \Phi(E, \Theta) \quad (2)$$

where  $n_s$  is the number of signal events expected from a source emitting the flux  $\Phi(E, \Theta)$ , which is supposed to be a power law with spectral index  $\gamma = -2$ . The ratio  $\text{MRF} = \frac{\bar{\mu}_{90}(n_b)}{n_s}$  is called Model Rejection Factor. The method consists in the minimisation of this ratio as a function of the cone aperture, with the aim of finding the optimum cone which minimises the sensitivity. In order to calculate the MRF,  $n_b$  and  $n_s$  have been estimated from the angular error distribution, inferred by MC simulation of an energy spectrum like  $E^{-2}$  and real scrambled data respectively, for each declination band. The optimum cone aperture ranges from  $3^\circ$  to  $4.5^\circ$ . Figure 2(a) (red line) shows the sensitivity as a function of the declination.

### 4 The Expectation-Minimisation (EM) method

The identification of signal events coming from a source above the background level from the atmospheric neutrino events can be performed by a clustering analysis, which looks for structures

in the data. In the framework of the mixture model method<sup>5</sup>, the probability density function for the ANTARES data can be described by the sum of two components:

$$p(\mathbf{x}) = \Pi_{BG}P_{BG}(\delta) + \Pi_S P_S(\mathbf{x}; \mu, \Sigma) \quad (3)$$

where  $\mathbf{x} = (\delta, RA)$  is the event position and  $\Pi_{BG}$  and  $\Pi_S$  are the fractions of the background and signal component respectively. The pdf of the background component  $P_{BG}$  is inferred by the real scrambled data and the pdf of the signal one is supposed to be a two-dimension Gaussian function, with  $\mu$  and  $\Sigma$  being the mean and covariance vector respectively. In this description, the values ( $\Psi_1^{(m)}$ ) of the parameters left floating in the fit which maximise the likelihood function related to our data sample are calculated by means of the EM algorithm<sup>5</sup>. The two possible hypotheses, signal + background ( $M_1$ ) and the background-only ( $M_0$ ), are compared using the Bayesian Information Criterion (BIC), which basically uses the maximum likelihood ratio of the models with a penalty that takes into account the number of free parameters  $\nu_1$  weighed by the number of the events  $n$  in the data sample  $\{\mathbf{x}\}$ :

$$BIC = 2 \log(p\{x\}|\Psi_1^{(m)}, M_1) - 2 \log(p\{x\}|M_0) - \nu_1 \log(n) \quad (4)$$

Each experiment is characterised by a BIC value. In order to calculate the sensitivity, the average value of the background-only BIC distribution, calculated over a set of scrambled real data samples, has been chosen as the BIC observed value:  $BIC_{obs}$ . The signal hypothesis which produces a probability equal to 90% of obtaining a BIC value equal or higher than  $BIC_{obs}$  has been taken as the sensitivity (Fig. 2(a) blue line).

## 5 Fixed point-like source search

25 sources, listed in table 1, have been selected among the most promising neutrino source candidates in the ANTARES field of view for the 5-line point-like source analysis.

Table 1: List of the selected sources, their position and the calculated p-value.

Source	DECL	RA	$pvalue_{bin}$	$pvalue_{unbin}$
PSR B1259-63	-63.83	195.70	1	1
RCW 86	-62.48	220.68	1	1
ESO139-G12	-59.94	264.41	1	1
HESS J1023-575	-57.77	155.82	0.062	0.004
Cir X-1	-57.17	230.17	1	1
HESS J1614-518	-51.82	243.58	0.086	0.088
PKS 2005-489	-48.82	302.37	1	1
GX 339	-48.79	255.70	1	1
RX J0852.0-4622	-46.37	133.00	1	1
Centaurus A	-43.02	201.36	1	1
RX J1713.7-3946	-39.75	258.25	1	1
PKS 0548-322	-32.27	87.67	1	1
H 2356-309	-30.63	359.78	1	1
PKS 2155-304	-30.22	329.72	1	1
Galactic Center	-29.00	266.42	0.140	0.055
1ES 1101-232	-23.49	165.91	1	1
W28	-23.33	270.42	1	1
LS 5039	-14.82	276.56	1	1
1ES 0347-121	-11.99	57.34	1	1
HESS J1837-069	-6.95	279.41	1	1
3C 279	-5.79	194.05	0.11	0.03
RGB J0152+017	1.79	28.17	1	1
SS 433	4.98	287.96	1	1
HESS J0632+057	5.80	98.24	1	1
IceCube HotSpot	11.00	153.00	1	1

The p-value, which is the probability of the background to produce the measured (or higher) value for the observable (BIC for the EM method or  $n_{obs}$  for the cone one), has been calculated for each source. No statistically significant excess has been found. The lowest value corresponds to a pre-trial p-value of  $2.8\sigma$  found with the EM method. It is expected in 10% of the experiments when looking at 25 sources (post-trial probability). In the case of the EM method, the upper limits (Fig. 2(a) blue square) come out considering the signal hypothesis which produces a probability equal to 90% to obtain a BIC value equal or higher than  $BIC_{obs}$ , calculated on the real data sample after unblinding it. In the case of the cone method the upper limits (Fig. 2(a) red square) are given by  $\mu(n_{obs}, n_b)$  defined in Eq.1.

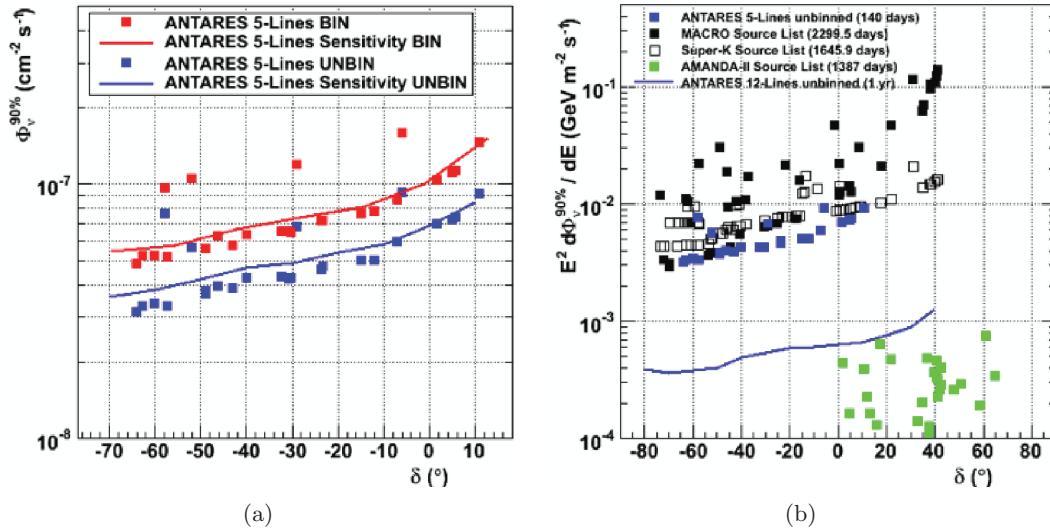


Figure 2: The sensitivity (line) and the upper limits (square) calculated with the 5-line ANTARES data by means of the cone (red) and EM (blue) method respectively (a). Comparison of the ANTARES 5-line data upper limits with those from other experiments: MACRO, AMANDA, Super-K. The ANTARES sensitivity for the 12-line detector in one year of data taking is also shown (b). The sensitivity and the upper limits are calculated in terms of the integrated flux in plot (a) and of the differential flux in plot (b).

## 6 All sky point-like source search

In this kind of search, sources are looked for in the whole sky, and no assumption on their position is made. In the case of the EM method, a pre-clustering algorithm searches for event accumulations within a cone with aperture  $5^\circ$ . The center of gravity of each identified cluster has been used as initial value of the position of the source candidate and finally the cluster with the highest significance (evaluated respect to the only background BIC distribution) has been selected. In the ANTARES data sample the highest BIC value found is  $BIC_{obs} = 1.4$ , corresponding to a p-value = 0.3 ( $1\sigma$  excess) in the position  $\delta = -63.7^\circ$   $RA = 243.9^\circ$ .

## 7 Conclusion

The point-like source search on the 5-line data has been performed by means of two different methods: EM method and the cone method. The first one is more powerful: the second one has been used as a cross check. The sensitivity as a function of the declination has been calculated for both methods: the EM one, in average, is 27% more sensitive than the cone one. Unblinding the 5-line data did not show any statistically significant excess in both the fixed source search and the all sky search. The upper limits set with less than a half of the detector and in only 140 days of data taking are competitive with those calculated by other experiments which have run for a much longer time in the Northern hemisphere.

## References

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