Autocorrelation analysis of ANTARES data

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Abstract: Clustering of neutrino arrival directions would provide hints for their astrophysical origin. The two-point autocorrelation method is sensitive to a large variety of cluster morphologies and, due to its independence from Monte Carlo simulations, provides complementary information to searches for the astrophysical sources of high energy muon neutrinos. We present the analysis of the autocorrelation function as a function of the angular scale of data collected during 2007-08 with the ANTARES neutrino telescope.

Keywords: neutrino astronomy, neutrino telescopes, point sources, autocorrelation

1 Introduction

The key question to resolve the long standing mystery of the origin of cosmic rays is to locate the sources and study the acceleration mechanisms able to produce fundamental particles with energies orders of magnitude above man-made accelerators. Over the last years it has become more and more obvious that multiple messengers will be needed to achieve this task. Fundamental particle physics processes like the production and subsequent decay of pions in interactions of high energy particles predict that the acceleration sites of high energy cosmic rays are also sources of high energy gamma rays and neutrinos. The detection of astrophysical neutrinos and the identification of their sources is one of the main aims of large neutrino telescopes operated at the South Pole (IceCube), in Lake Baikal and in the Mediterranean Sea (ANTARES).

1.1 The ANTARES neutrino telescope

Whereas physics data taking started already during the deployment phase, the ANTARES detector [1] became fully equipped and operational in 2008. The detector is composed of 12 detection lines placed at a depth of 2475m off the French coast near Toulon. The detector lines are about 450m long and hold a total of 885 optical modules (OMs), 17” glass spheres housing each a 10” photomultiplier tube. The OMs look downward at 45° in order to optimize the detection of upgoing, i.e. neutrino induced, tracks. The geometry and size of the detector makes it sensitive to neutrinos in the TeV-PeV energy range. A schematic layout is shown in Fig. 1.

1.2 Neutrino detection

The neutrino detection relies on the emission of Cherenkov light by high energy muons originating from charged current neutrino interactions inside or near the instrumented volume. All detected signals are transmitted via an optical cable to a shore station, where a farm of CPUs filters the data for coincident signals or hits in several adjacent OMs. The muon direction is then determined by maximising a likelihood which compares the times of the hits with

Figure 1: Schematic view of the ANTARES detector.
the expectation from the Cherenkov signal of a muon track.

1.3 Astrophysical neutrinos

Two main backgrounds for the search for astrophysical neutrinos can be identified: downgoing atmospheric muons which have been mis-reconstructed as upgoing and atmospheric neutrinos originating in cosmic ray induced air showers at the opposite side of the Earth. Depending on the requirements of the analysis both backgrounds can at least partially be discriminated using various parameters like the quality of the event reconstruction or an estimator for the deposited energy [2].

In addition, analysing the reconstructed arrival directions of the events allows to search for an excess over the uniform atmospheric backgrounds. Despite important efforts, no clear signature for point sources of astrophysical neutrinos has been found so far [3, 4, 5, 6]. Both the distribution and morphologies of sources potentially emitting neutrinos in the TeV energy range are yet unknown but are possibly very inhomogeneous with most of them being located in the Galactic disk and spatially extended (e.g. shell type supernova remnants like RXJ1713 [7]). It seems therefore interesting to study the intrinsic clustering of the arrival directions of neutrinos. Possible analysis biases are naturally avoided as no prior information about the potential sources is required. Covering a large angular range, i.e. neutrino emission regions of very different sizes, this study complements the searches for point like sources and, if successful, would provide hints for underlying, yet unresolved, source morphologies and source distributions.

2 Autocorrelation analysis

The most commonly used method to detect intrinsic clusters within a set of \( N \) events is the standard 2-point autocorrelation distribution. It is defined as the differential distribution of the number of observed event pairs \( N_p \) in the data set as a function their mutual angular distance \( \Delta \Omega \). To suppress statistical fluctuations that would reduce the sensitivity of the method, we analyse here the cumulative autocorrelation distribution defined as

\[
N_p(\Delta \Omega) = \sum_{i=1}^{N} \sum_{j=i+1}^{N} H(\Delta \Omega_{ij} - \Delta \Omega),
\]

where \( H \) is the Heaviside step function.

2.1 Data set

The analysed data set has been recorded by the ANTARES neutrino telescope in 2007 and 2008. During this period the detector was in its construction phase and has been operated in various setups ranging from 5 active lines at the beginning of 2007 to a fully operational detector of 12 lines since mid 2008. After applying a run selection removing for example periods without precise detector alignment information, the dataset corresponds to about 300 effective days. Comprising mainly atmospheric muons, about 100 million events were reconstructed with the standard ANTARES reconstruction algorithm. Basic selection criteria include a cut on the reconstructed zenith angle \( \theta \) to ensure that only upgoing muon tracks are selected (\( \cos(\theta) > 0 \)) and a cut on the angular uncertainty \( \beta \) given by the covariance matrix of the final likelihood fit (\( \beta < 1^\circ \)). The final selection criteria is a cut on the fit quality parameter \( \Lambda \), which is derived from the value of the maximal likelihood itself. Before unblinding the data, this cut has been optimized by means of MC simulations to yield the best average upper limit on the neutrino flux in the search for point like sources [5, 6].
events pass the final criterion $\Lambda > -5.4$. The $\Lambda$ and zenith angle distributions of events passing all quality criteria (except the ones shown in the plot) are shown in figure 2.

Following eq. 1, the cumulative autocorrelation distribution of the selected events has been determined. It is shown in the left plot of figure 3.

### 2.2 Reference autocorrelation distribution

To detect structures in the sky distribution of the analysed events we need a reference autocorrelation distribution to compare with. This reference has been determined by scrambling the data themselves, a method which allows to avoid systematic uncertainties introduced by the use of Monte Carlo simulations. The scrambling method uses the local coordinates (zenith and azimuth) and the detection time $T_i$ of all selected data events. While keeping the pairs of zenith/azimuth for all events in order to avoid losing information about possible correlations between them, the detection time is drawn randomly from another event within the same detector configuration in order to keep track of the changing asymmetry of the detector. Using all selected events, a randomized sky map with the same number of events as in the data and naturally the same sky coverage is constructed. This randomized sky is then analysed in exactly the same way as described above. As can be seen in the right plot of figure 3, the algorithm is sensitive enough to obtain a $3\sigma$ evidence in the exemplary case of 3 point-like sources emitting each about 6 events. This source luminosity is at the detection threshold of the dedicated search for a point like excess in the same dataset [5, 6], which underlines the complementarity of the two methods.

### 2.3 Comparison between data and reference

Structures in the sky distribution of our data will show up as differences between the autocorrelation distributions of the data and the reference distribution. The comparison between them is performed by using the formalism introduced by Li&Ma [8]. This formalism results in the raw significances of the differences as a function of the cumulative angular scale which is shown in figure 4. As the comparison is performed bin-by-bin and as we scan over different angular scales, this result has to be corrected for the corresponding trial factor. We apply the method proposed by Finley and Westerhoff [9] and perform about $10^5$ pseudo experiments in which the autocorrelation distributions of randomized sky maps are compared with the reference distribution. The probability to obtain the same or higher significance as the maximum deviation observed in the data is calculated and given as final $p$-value of the analysis.

### 2.4 Performance and sensitivity

The performance of the algorithm has been determined using mock data sets for which we scrambled the selected data events as described above. While keeping the total number of events in the toy model constant and taking into account the angular resolution, we added predefined source structures with various sizes and source luminosities. These mock data sets where then analysed in exactly the same way as described above. As can be seen in the right plot of figure 3, the algorithm is sensitive enough to obtain a $3\sigma$ evidence in the exemplary case of 3 point like sources emitting each about 6 events. This source luminosity is at the detection threshold of the dedicated search for a point like excess in the same dataset [5, 6], which underlines the complementarity of the two methods.

An important free parameter of the analysis is the binning of the autocorrelation distribution as it will determine the sensitivity to certain angular scales and which is connected to the angular resolution. For the used quality selection an average angular resolution of $0.5^\circ$ has been determined from Monte Carlo simulations. Using toy simulations with various source scenarios an optimal binning of $0.1^\circ$ has been determined.
2.5 Results and discussion

The described analysis has been applied to the 2090 s-selected data events recorded by the ANTARES neutrino telescope between 2007 and 2008. The uncorrected significance as a function of the cumulative angular scale is shown in figure 4. A maximum deviation between the data and the reference distribution of $1.1 \sigma$ is found for an angular scale $< 7^\circ$. Correcting for the scanning trial factor this corresponds to a p-value of 55% and is therefore not significant.

In the search for the sources of high energy cosmic rays, the detection of astrophysical sources of neutrinos may play a crucial role. Various experiments are currently taking data or are in a preparatory phase to achieve this goal and the recorded data is scrutinized in numerous ways in order to extract a maximum of information. We presented here the first search for intrinsic clustering of data recorded with the ANTARES neutrino telescope. The data, taken during the deployment phase of the detector, do not show evidence for deviations from the isotropic arrival direction distribution expected for the background of atmospheric neutrinos and contamination by mis-reconstructed atmospheric muons.

References

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