Reconstruction of Atmospheric Neutrinos in Antares

Aart Heijboer*, **for the Antares Collaboration**

**Nikhef, Amsterdam.*

***Abstract*. In May 2008, the Antares neutrino telescope was completed at 2.5 km depth in the Mediterranean Sea; data taking has been going on since. A prerequisite for neutrino astronomy is an accurate reconstruction of the neutrino events, as well as a detailed understanding of the atmospheric muon and neutrino backgrounds. Several methods have been developed to confront the challenges of muon reconstruction in the sea water environment, which are posed by e.g. backgrounds due to radioactivity and bioluminescence. I will discuss the techniques that allowed Antares to confidently identify its first neutrino events, as well as recent results on the measurement of atmospheric neutrinos.**

***Keywords*: neutrino astronomy reconstruction**

I. INTRODUCTION

The Antares collaboration is currently operating a 12-line neutrino telescope in the Mediterranean Sea, at a depth of about 2500 m, 40 km from the shore of southern France (see [1] for a full status report). The full detector comprises 12 lines, each fitting 75 Optical Modules (OMs), arranged in 25 triplets, also called 'floors', which are placed 14.5 metres apart along the line. The OMs house a 10 inch photomultiplier tube, which is oriented downward at a 45 degree angle to optimise the detection efficiency for neutrino-induced, upgoing muons. The positions of the OMs are measured using the systems described in [2].

The deployment of the first detector line took place at the beginning of 2006. This line was used to measure the flux of atmospheric muons using a specialised reconstruction algorithm [4]. By January 2007, five such detector lines were operational, allowing the application of the methods developed for the 3d reconstruction of muon trajectories. This led to the identification of the first neutrino events; see Fig. 3. The 12th line was deployed in May 2008, which completed the construction of the detector.

II. MUON RECONSTRUCTION

The challenge of measuring muon neutrinos consists of fitting the trajectory of the muon to the arrival times, and -to a lesser extent- to the amplitudes the Cherenkov light detected by the OMs.

For a given muon position (at an arbitrarily chosen time t^0) and direction, the expected arrival time $t^{\exp}$ of the Cherenkov photons follows from the geometric orientation of the OM with respect to the muon path:

$$t^{\exp} = t^0 + \frac{1}{c}\left(l - \frac{k}{\tan\theta_C}\right) + \frac{1}{v}\left(\frac{k}{\sin\theta_C}\right), \quad (1)$$

where the distances l and k are defined in Fig. 1, θ_C is the Cherenkov angle ($\sim 42^o$ in water) and v is the group velocity of light in the water. The difference between $t^{\exp}$ and the measured arrival time of the photon (i.e. the 'hit time) defines the time residual: $r \equiv t^{\mathrm{measured}} - t^{\exp}$.

Photons that scatter in the water and photons emitted by secondary particles (e.g. electromagnetic showers created along the muon trajectory) will arrive at the OM later than $t^{\exp}$, leading to positive residuals. The residual distribution obtained from in data is shown in Fig. 2. The tail on right due to late photons is clearly visible.

The reconstruction algorithms attempt to find muon track parameters (i.e. three numbers for the position and two for the direction) for which the residuals are small. This can be done by minimising a quantity like $\chi^2 = \sum_{i=1}^{N_{\mathrm{hits}}} r_i^2$ or by maximising the likelihood function $\log L = \sum_{i=1}^{N_{\mathrm{hits}}} \log P(r_i)$. Here, $P(r)$ is the probability density function (PDF) for the residuals. While relatively simple, the equation to compute the residuals is non-linear in the track parameters. As a consequence, iterative methods are required for minimising a χ^2-like variable or maximising the likelihood.

A complicating factor in the reconstruction process is the presence of background hits, caused by decaying K^{40} in the sea water and by aquatic life (bioluminescence). If not accounted for in the muon reconstruction, the background light degrades both the angular resolution and the reconstruction efficiency. Antares has developed several strategies to deal with this problem. Two of them will be discussed in the following sections. We refer to these two as the 'full likelihood' and 'online' algorithms. They are currently widely used for data analysis.

III. FULL LIKELIHOOD FIT

The first algorithm was developed several years before deployment of the detector and is described in detail in [3]. This method is based on a likelihood fit that uses a detailed parametrisation, derived from simulation, for the PDF of the arrival time of the hits $P(r)$, which takes into account the probability of hits arriving late due to Cherenkov emission by secondary particles or light scattering. Moreover, the probability of a hit being due to background is accounted for as a function of the hit amplitude and the orientation of the OM with respect to the muon track. It was found that the likelihood function
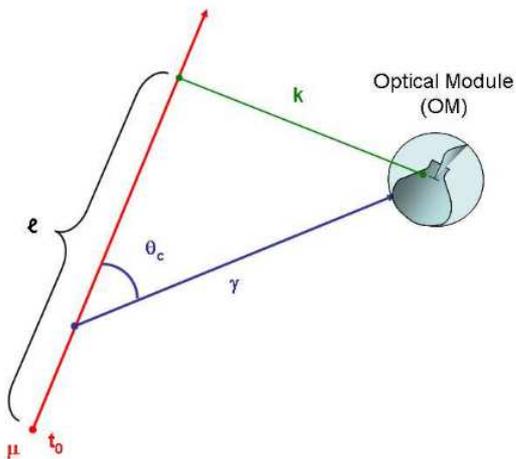
Fig. 1. Schematic representation of the relation between the muon trajectory and the OM. The line labelled γ indicates the path travelled by a Cherenkov photon from the muon to the OM.
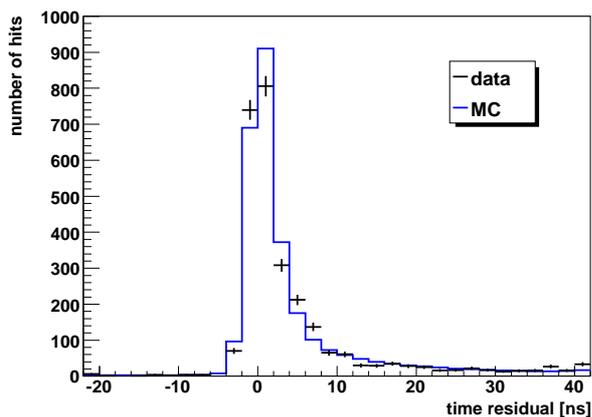

Fig. 2. Time residuals of the hits with respect to the result of the full likelihood fit for selected, upgoing events (neutrino candidates). The data were taken in 2007 with 5 detector lines. The peak shows the (order 1 ns) intrinsic timing resolution of the OMs. The tail is due to light from secondary particles and to scattered photons.

has many local maxima and that the likelihood fit is only successful if the maximisation procedure is started with track parameters that are already a good approximation to the optimal solution. To obtain this approximate solution, the full likelihood fit is preceded by a series of 'prefit' algorithms of increasing sophistication. An important ingredient in the prefit stage is the use of a so-called 'M-estimator', which is a variant of a χ^2-fit in which hits with large residuals are given less importance compared to a regular χ^2. This is crucial, as it allows the fit to converge to a solution relatively close (typically a few degrees) to the true muon parameters, while being robust against the presence of background hits at large residuals. The M-estimate is followed by two different versions of the likelihood fit, the last of which fully accounts for the presence of background

hits. The procedure is started at nine different starting points to increase the probability of finding the global minimum. To mitigate the associated loss in speed, analytical expressions for the gradient of the likelihood function are used in the min/maximisation processes.

The value of the final log-likelihood per degree of freedom that is obtained from the final fit is used as a measure of the goodness of fit. This is combined with information on the number of times the repeated procedure converged to the same result, N_{comp} to provide a value $\Lambda = \log(L)/N_{\mathrm{dof}} - 0.1(N_{\mathrm{comp}} - 1)$. The variable Λ can be used to reject badly reconstructed events; in particular atmospheric muons that are reconstructed as upward-going. An example of the use of this algorithm for reconstructing and selecting neutrinos for a point source search is given in [6].

A. Results

The full likelihood fit is optimised for the high energy neutrinos that are expected from astrophysical sources (E_ν^{-2} spectrum, yielding muons in the multi-TeV range). Simulations indicate that, with this algorithm, Antares reaches an angular resolution (defined as the median angle between the true and reconstructed muon) smaller than 0.3 degrees for neutrino energies above 10 TeV. Below this energy the scattering angle of the neutrino interaction dominates.

As the hit residuals are the main ingredient driving the angular resolution, the agreement observed between data and simulation in the residual distribution (see Fig. 2) is good evidence that the algorithm is performing as expected.
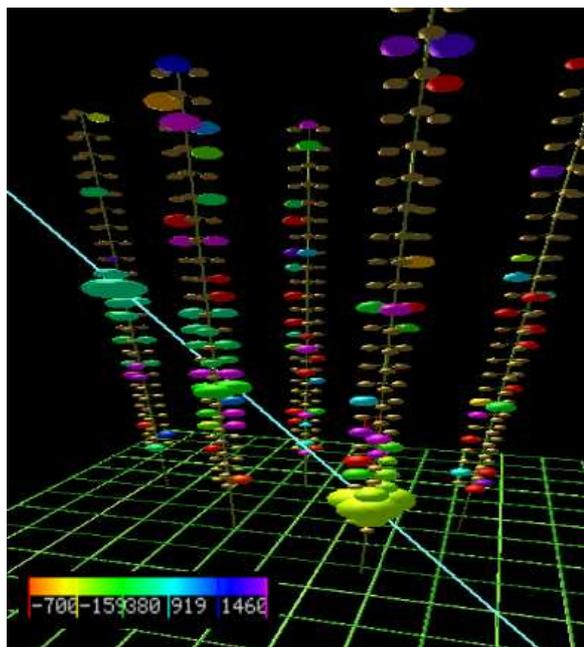

Fig. 3. Event display of one of the first neutrino candidates detected with Antares. This event was found and reconstructed using the full likelihood fit. The colour of the hits indicates the time (according to the legend in the lower left corner), while the size indicates the collected charge.

IV. ONLINE ALGORITHM

The second approach to reconstructing tracks in the presence of background hits was developed during the commissioning of the detector for the online event display that is used for monitoring the detector. We therefore refer to this fit as the 'online algorithm', although it is now also frequently used for offline data analysis.

Whereas the full likelihood fit described above attempts to incorporate all the background hits in the fit, the philosophy of the online algorithm is to select a very high purity sample of signal hits. This is followed by a fit of the muon trajectory using a model that can be relatively simple. In this case a χ^2-like fit is performed.

The algorithm merges hits on the three OMs in a floor and uses the centre of the triplets in the fit. While degrading the timing precision (and therefore, in theory the angular resolution) somewhat, this does make the algorithm independent of measurements of the azimuthal orientation of the triplets, which vary due to sea currents and which normally need to be measured using compasses located on the floors.

A. Hit Selection

The selection of hits starts by identifying floors that collected an amplitude (i.e. charge collected on the PMTs) corresponding to more than 2.5 photo-electrons (pe), or 1.5 pe in case multiple hits were detected within a time window of 20 ns. Such configurations are rarely produced by optical backgrounds, but occur in most of the signal events. Doublets of such floors are identified, allowing for no more than one empty floor in between and requiring that the time difference of the hits is smaller than 80ns per floor of separation. Only the detector lines which at least one such doublet are used in the fit. Clusters of hits are then formed by iteratively complementing the doublets with adjacent hits that are close in time (within 80ns per floor) and distance (no more than one empty floor) to the already identified cluster.

B. Fit

The fit is performed using a score function that is derived from the expression for the χ^2 of the hit residuals, with an added term that promotes solutions where hits with large amplitudes pass the OM at close range. The minimised function is:

$$Q = \sum_i \left[\frac{1}{\sigma^2} r_i^2 + \alpha q_i d_i \right], \qquad (2)$$

where the sum is over all selected hits and where r_i is the residual of hit i, q_i is the amplitude associated with that hit, and d_i is the distance from the hypothesised track to the OM. The constants σ and α were set to 10 ns and 50 m^{-1}pe^{-1}.

For events with multiple selected lines, the position of the track is determined using the Q fit to minimise the hit residuals. An additional fit is performed using a 'bright point' hypothesis corresponding to a single, localised flash of light. A comparison of the quality of the two fits is used to reject events in which downgoing muons create a bright electromagnetic shower that may mimic an upgoing track.

Events with only one selected detector line do not carry information on the azimuth direction of the muon. Hence, for these events, a four-parameter fit is performed, yielding the zenith angle of the muon track. Also in this case, a bright point fit is done for comparison.

As in the full likelihood fit, the value of Q found by the fit is used to reject badly reconstructed events; in particular atmospheric muons that are reconstructed as upward-going. The track fit quality is required to be better (i.e. smaller) than 1.35 (1.5) for reconstruction with two (more than two) lines; Events with a bright-point fit quality better than 1.8 are vetoed.

The fact that only a single minimisation is performed makes the online algorithm about an order of magnitude faster than the algorithm used for the full fit, which typically performs 20 full minimisations.

With the current trigger setup, both algorithms are fast enough to run on all triggered events in real time on a single CPU.

C. Results

Simulations show that, at high energies, the online algorithm achieves a typical angular resolution on the muon direction of 2 degrees (1 degree for more stringent cuts), independently of the energy. At high energies, this is a factor 6 to 3 significantly worse than the resolution o f the full likelihood fit, which is not unexpected as the assumption of Gaussianity of the time residuals that underlies the χ^2-fit is known to be an approximation. The online algorithm is therefore not well suited for those neutrino astronomy studies that require optimal angular resolution. On the other hand, the simplicity of the algorithm and the (expected) robustness against inaccuracies in the detector description, have made it a good alternative for the initial studies of the atmospheric muon (see [5]) and neutrino fluxes.

Figure 4 shows the elevation above the horizon for the data taken in 2008 for the multi-line events in comparison to simulation. The data were taken using a 9,10 and 12 line detector and represent a total live time of 173 days. The atmospheric muons were simulated using Corsika with Horandel fluxes and the QGSJET hadronic model. A combined theoretical and systematic uncertainty of 30 (50)% on the expected number of neutrinos (muons) accounts for uncertainties in the (primary) flux and interaction model, and in detector acceptance.

A total of 582 upward going multi-line events were reconstructed, whereas the simulation predicts 494(13) events due to atmospheric neutrinos (muons). The difference, a factor of 0.87, is within the systematic uncertainty on the simulation.
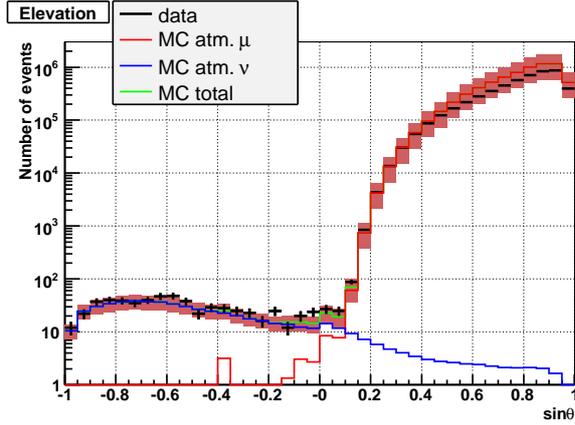
Fig. 4.   Distribution of the sine of the elevation angle for muons obtained from the multi-line online reconstruction algorithm for the 2008 data, i.e. 9-12 lines.
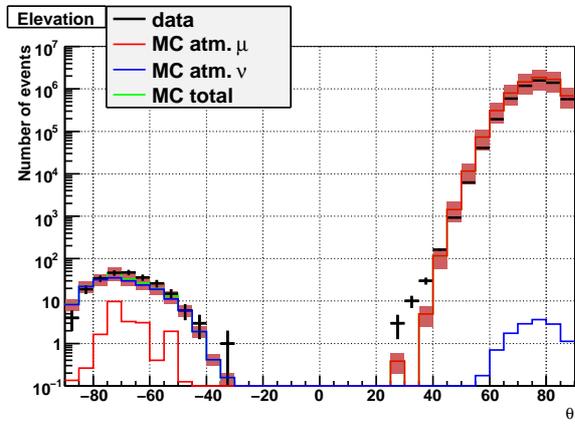

Fig. 5.   Distribution of the elevation angle f muons reconstructed on a single line using the online reconstruction algorithm for 2008 data, i.e. 9-12 lines.

Figure 5 shows the elevation angle for events fit on a single line using the online algorithm. The efficiency for such events is greatly enhanced for vertical (either upward, or downward-going) tracks. The data agree well with the simulation, which is dominated by the atmospheric neutrino contribution for upward-going tracks. A total of 237 upward going single-line events are found, while simulation predicts 190 (21) due to atmospheric neutrino (muon) events. The MC/data ratio is 0.89, which is similar to the ratio reported above for multi-line events.

V. Conclusion

Since the deployment of the first five lines of the detector, the Antares collaboration has been routinely detecting muons and atmospheric neutrinos. About five high-quality upgoing neutrino candidates are detected per day. The number of detected neutrinos and their zenith and azimuth angle distributions agree well with simulations. The observed time residuals of the hits with respect to reconstructed neutrino candidate tracks is in good agreement to the corresponding simulation. This further strengthens the confidence that Antares is performing as expected and that it is achieving sub-degree angular resolution.

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