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Reconstruction methods for the ANTARES neutrino telescope

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Abstract. The ANTARES collaboration aims to deploy a 0.1 km^2 neutrino telescope in the Mediterranean sea by 2004. Neutrinos will be detected through the muons produced in their interaction with the surrounding matter. The muon trajectory in turn can be reconstructed from the arrival time of the emitted Cherenkov photons at the detector's photomultipliers. The reconstruction software should be highly efficient and able to provide the best possible angular resolution for astronomy. In this work the various reconstruction methods developed within the ANTARES collaboration, some of them based on novel concepts, are reviewed. We mainly focus on muon reconstruction, but dedicated techniques for neutrino oscillations and electromagnetic shower reconstruction are briefly presented as well. The performances of the different reconstruction algorithms estimated using Monte Carlo simulated events are given. Finally, the method used to reconstruct real atmospheric muons recorded with a first prototype string is explained.

1 Introduction

The detection of high energy neutrinos is the main goal of the ANTARES neutrino telescope. Several theoretical models predict the production of energetic neutrinos from a variety of extraterrestrial sources. Together with indirect dark matter searches and the quest for new complementary evidence for atmospheric neutrino oscillations underpins the ANTARES scientific programme. Neutrinos are indeed very interesting probes capable of delivering useful information from their sources, provided that the experimentally challenging goal of building a detector to observe them and deduce their origin is met.

Neutrinos cannot be directly detected, but they produce a unique signature when an up-going muon coming from the Earth itself is detected. Since only neutrinos are able to cross large distances in matter, the up-going muons must come from up-going neutrinos that interact somewhere near the detector. The muon carries an important fraction of the initial neutrino energy and, for high energies, nearly the same direction.

In the ANTARES detector (ANTARES Collab. , 1999) the detection of up-going muons will be performed through the detection of the Cherenkov light that they produce when traversing the sea water. This light will be detected by means of an array of photomultiplier tubes (PMTs) pointing downwards (45° from the vertical). The information collected by the PMTs, which will cover an effective surface of $\sim 0.1\ km^2$, will be used to reconstruct the muon track. The final performances –efficiency and angular resolution– will depend on detector features, such as geometry, optical properties of the medium, photomultiplier characteristics, etc, but also on the reconstruction procedure.

The reconstruction procedure is required to be highly efficient and able to provide the maximum angular resolution that can be potentially obtained with a given detector design. It has to be able as well to reduce to a minimum the number of down-going tracks wrongly reconstructed as up-going.

In this work, the reconstruction algorithms used and developed inside the ANTARES collaboration, some of them based on novel concepts, are summarized. The main focus is on high energy muon reconstruction, but some other studies are also presented. The reconstruction programs have been tested using Monte Carlo data. However, in order to analyze the data collected from a first prototype string, a special reconstruction code was developed, whose performance with real data is also presented.

2 Muon Reconstruction

A muon track is described using 5 parameters: two angles (θ and ϕ), two coordinates (x, y) in the plane perpendicular to the track that contains the coordinate system's center and the corresponding time of passage (t). In general, energy is separated from reconstruction of the muon track. The muon's

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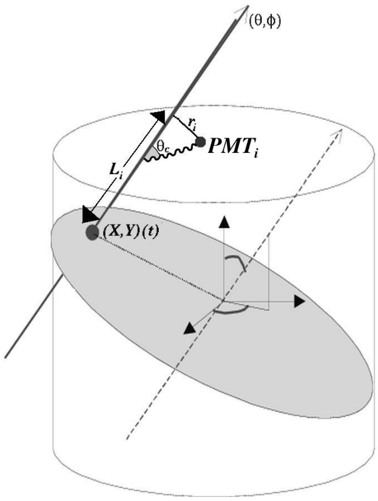

Fig. 1. Definition of the muon track parameters.

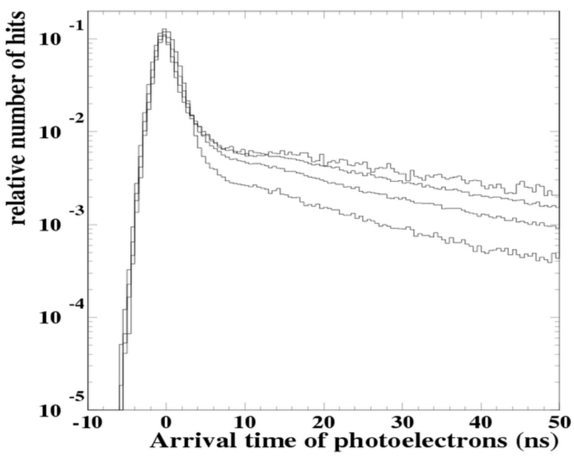

Fig. 2. Pdf of the arrival time of the photons to the photomultipliers with respect to direct Cherenkov photons, obtained by Monte Carlo. Different muon energies are plotted: 2 TeV, 10 TeV, 50 TeV and 250 TeV.

energy can be estimated after the track reconstruction, using the amplitude of the fired PMTs (F. Hubaut , 1999). Figure 1 is a schematic view of the track parameter definition. The arrival time of a Cherenkov photon to a given photomultiplier is related to the track parameters by Eq. 1:

$$t_i = t + \frac{1}{c}(L_i + r_i \cdot \tan(\theta_c)) \quad (1)$$

where t_i is the time recorded in the i-th PMT, c is the speed of light in vacuum and θ_c is the Cherenkov angle in water.

The time difference between the time recorded in a given PMT and the time given by Eq. 1 follows a probability density function (*pdf*) similar to those given in Fig. 2. The main peak in Fig. 2 is produced by direct photons, its width being mainly due to the PMT time resolution. The tails of the *pdf*s are due to scattered photons or photons not directly produced by the muon's Cherenkov emission. Since the tails have smaller influence than the peaks, a common parameterization independent of the muon energy can be used. This parameterization is used to associate to every hit a probability of coming from a given track, according to the time difference between the recorded and the expected arrival times (Eq. 1), taking into account the probability for a given PMT of detecting that photon. In most reconstruction methods, these probabilities are used to compute a likelihood function ($\mathcal{L}$), whose maximum is used to obtain estimates of the muon track parameters from the recorded hit information. In addition, all the reconstruction processes need a filtering of the hits using causality filters to reject the hits produced by ^{40}K or bioluminescence.

The first reconstruction code (F. Hubaut , 1999) developed within the ANTARES collaboration used the likelihood method combined with a pre-fit based on a method from V. J. Stenger (1990). The pre-fit, used as a first rough estimate of the track parameters, amounts to a straight line fitted to the fired PMTs in the event, leaving the speed of the muon as a free parameter. The minimization of $-\log\mathcal{L}$ starting from the pre-fitted parameters is then performed using standard methods (NAG numerical libraries). In addition to this basic strategy, two new approaches have been developed in the ANTARES collaboration that increase the reconstruction efficiency as well as the angular resolution.

In the first alternative approach, the positions of the hit PMTs and their orientations are used to obtain points that the track is likely to have crossed. Instead of the original position of the fired PMT, these points are then used to obtain a better pre-fit. This improved pre-fit is then combined with the minimization of the function:

$$M(x, y, \theta, \phi, t) = -\sum_i \sqrt{1 + \Delta t_i^2} - 1 \quad (2)$$

where $\Delta t_i = t_i - t_i^{fit}(x, y, \theta, \phi, t)$ are the residuals of the hits. This function behaves like a χ^2 when the residuals are small. Finding a global minimum of this function (M-estimator) turns out to be easier than finding a global maximum of the likelihood function, $\mathcal{L}$. As a result, the reconstruction efficiency improves a factor 2, while the angular resolution also improves. The effect of the background events for this reconstruction procedure is under study.

In the second approach an improvement in the pre-fit procedure is also performed, but taking advantage in this case of the geometrical relationships between the positions and times of the hits imposed by the Cherenkov effect. The technique, called the *iterative pre-fit*, is described in the following subsection. All the strategies are accessible from a single reconstruction program (*RECO*) to facilitate their use in different studies.

2.1 The iterative pre-fit

This technique is based on the derivation of the track's x, y and t parameters from its θ and ϕ parameters using the hit information and the known Cherenkov angle. From Eq. 1, the difference in transverse distance between two hits ($r_{ij} = r_i - r_j$) can be expressed as a function of the difference in time ($t_{ij} = t_i - t_j$) and their longitudinal distance ($L_{ij} = L_i - L_j$):

$$r_{ij} = \frac{c \cdot t_{ij} - L_{ij}}{\tan(\theta_c)} \qquad (3)$$

From Eq. 3, the r_{ij} can be obtained, provided that θ and ϕ are known. Since r_i is the distance in the transverse plane of the track projection (a point) to each hit, the differences r_{ij} define a hyperbola on which the track projection must lie and whose foci are the hit projections. After filtering the hits in an event in order to use only those most likely produced by Cherenkov photons, the hits can be combined in groups of three to compute analytically the intersection of two hyperbolas. The maximum of the histogram of all the possible intersection points between the different hit combinations corresponds to the projection of the muon track in the perpendicular plane. The x and y parameters can be used in Eq. 1 to obtain a t of the track from each hit in the event. The distribution of t is similar to the *pdf*s in Fig. 2 and the maximum of this distribution corresponds to the t parameter of the track (see Fig. 3).

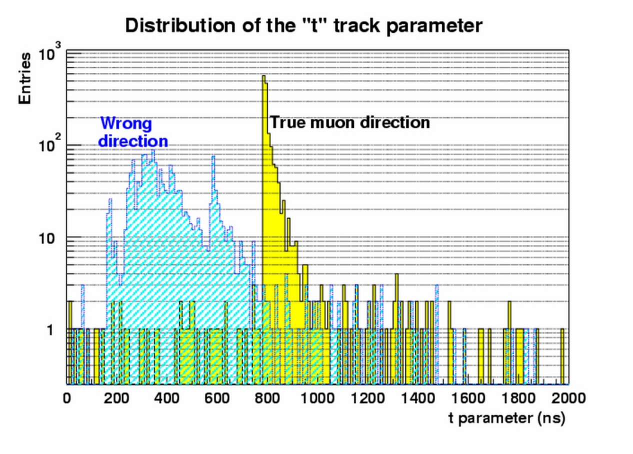

Fig. 3. Parameter t computed from Eq. 1, using an arbitrary direction (dashed line) and the true muon direction (solid line).

This technique can be used as a pre-fit for tracks expected to come from a given direction in the sky (known θ and ϕ) as in dark matter searches from the Sun or the galactic center. However, the technique has been extended to the general case where θ and ϕ are unknown. When the technique is applied for values of θ and ϕ which are not those of the real track, the track projection is no longer in the hyperbola defined by Eq. 3. A narrow peak in the time distribution is not seen anymore (see Fig. 3). Maximizing the number of hits in a narrow window around the highest peak in the time distribution, the θ and ϕ of the track can be obtained. To this end, an iterative process can be used. Starting with a given value of θ and ϕ, a small number of hits in the event –the most likely to be direct Cherenkov photons– can be used in order to obtain x, y and t. A fit is then made using the maximum likelihood method to obtain a new set of parameters. Then the new θ and ϕ are used again to obtain x, y and t, repeating the process until it converges. Finally, a maximization of $\mathcal{L}$ with all the hits compatible with the pre-fitted parameters is used as in the standard procedure. However, this step only serves as a final fine tuning of the parameters, since in this case the pre-fit gives values very close to the final ones, providing also a good selection of the hits compatible with Cherenkov photons.

With different starting points and using the number of hits around the peak of the t histograms as a reference, it is obtained up to a factor $\sim$2 more reconstructed tracks than in the standard reconstruction and with much better angular resolution. A comparison of the performances is shown in Fig. 4.

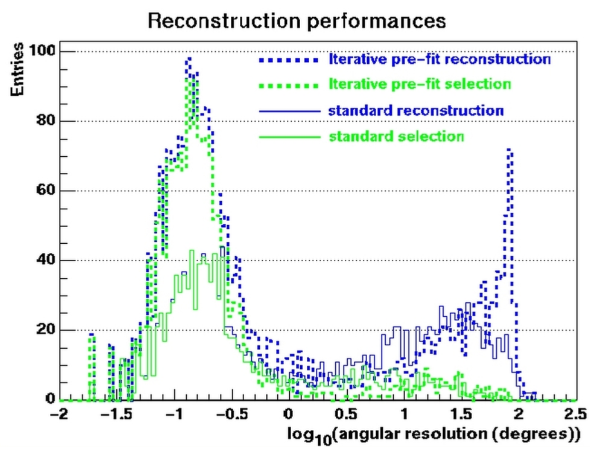

Fig. 4. Comparison of performances between the iterative pre-fit (dashed line) and the standard reconstruction (solid line).

This technique has been complemented with tight selection criteria that use the ability to obtain 3 track parameters from the other 2. Up to now, this method has shown the best rejection factor for down-going background events reconstructed as up-going tracks. For down-going single muons, no event is reconstructed as an up-going track in ~ 24 hours of simulated data (4.2×10^6 events). For down-going multi-muons (two or more parallel muons produced in the same atmospheric cascade), in $\sim$ 9 days of simulated primaries with energy above 2 TeV (40×10^6 events), only 2 events were reconstructed as up-going.

2.2 1-D Reconstruction

At energies below the range of interest to neutrino astronomy, it is possible to perform other studies like neutrino oscillations or dark matter searches. In this case, almost vertical events are important (larger oscillation lengths and neutralinos from the Earth's center). These events may only produce hits in one of the strings, then a reconstruction procedure slightly different from the general multi-string case must be applied (C. Cârloganu , 1999). The first step consists in a special single-string event trigger that, if passed, is followed by the selection of the string with the largest hit amplitudes. Then, a filter to reject hits from ^{40}K and bioluminescence is applied. The pre-fit is substituted in this case by a scanning of the track parameter space. The values that give the maximum likelihood are kept as the starting point for the fit. Finally, the same fitting procedure as in the multi-string case –a maximization of the Likelihood function with 5 track parameters– is followed.

3 Other reconstruction techniques

Other reconstruction techniques have also been developed for special purposes within the ANTARES collaboration. For the reconstruction of electromagnetic showers, a fit is performed with 7 parameters: the position (x, y, z), the time (t), the direction (θ, ϕ) and the energy (E) of the shower. In this case, a pre-fit is applied in which the shower's energy, position, time and direction are each studied separately. The energy is estimated using the sum of amplitudes of all the selected hits. Considering that the light from the interaction shower is point-like and propagates as a spherical wave, using χ^2 minimization the time and position can be obtained. The direction is obtained using a χ^2 function that takes into account the amplitude of the recorded hits and approximates the propagation according to a plane wave perpendicular to the event direction with speed c/n^2. The final fit fixes the x, y, z and t parameters to those obtained in the pre-fit while the energy and the direction of the shower are fitted using a χ^2 function that takes into account the amplitude expected in each PMT according to its orientation and the shower parameters.

4 Reconstruction with real data

A first prototype string was deployed in the Mediterranean sea at 1000 m depth at the end of 1999. This prototype was equipped with 7 photomultiplier tubes (PMTs), an acoustic positioning system, compasses, tiltmeters, controls, read-out and data transmission. The line was connected to the shore via a 37 km electro-optical cable. The main goal of the prototype string was to validate the full series of ANTARES procedures, from production, deployment, calibration and data-acquisition to sustained operation from a shore base.

For a muon event to be accepted, a coincidence in all 7 PMTs was required. More than 5×10^4 such coincidences were collected. In this prototype string, all 7 PMTs can be considered to be aligned in a vertical line. The time (t) and altitude (z) of the hits produced by down-going atmospheric muons is given by Eq. 4:

$$t = t_0 + \frac{(z - z_0)\cos\theta + \sqrt{n^2 - 1}\sqrt{d^2 + (z - z_0)^2 \sin^2\theta}}{c} \quad (4)$$

this equation is an hyperbola with four parameters (t_0, z_0, θ, d), d is the closest distance from the muon track to the string, θ is the zenith angle of the track. When the distance d is small compared to $z_i - z_0$, then the asymptote equation can be derived:

$$c(t_i - t_0) = (z_i - z_0)(\cos\theta + \sqrt{n^2 - 1} \cdot \sin\theta) \quad (5)$$

which is a straight line. This approximation can be used as starting point for the zenith angle in the hyperbolic fit. A special reconstruction code (*Antarec*) has been developed for this particular reconstruction case. In Fig. 5, the distribution of the reconstructed zenith angle of the collected down-going muons is compared with a full Monte Carlo simulation, accounting for muon multiplicity (A. Kouchner , 2001). The real and simulation data are in good agreement with each other what proved the validity of the reconstruction concepts presented here.

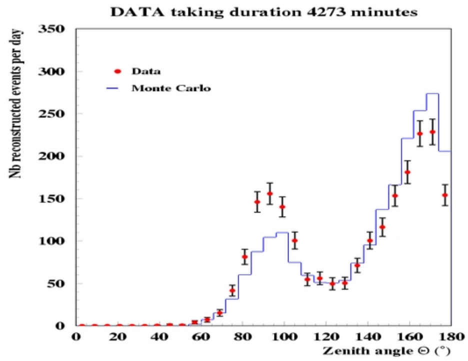

Fig. 5. Comparison of Monte Carlo data and real data collected with the prototype string. All data are reconstructed with the *Antarec* reconstruction program.

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(*) *These documents can be found on the ANTARES web pages, http://antares.in2p3.fr*