The Antares neutrino telescope : performance studies and analysis of first data

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Chapter 6

Summary and conclusion

Earth's atmosphere is continuously being bombarded by energetic particles. Much is unknown about these cosmic rays. There are many uncertainties about the exact elemental composition and the origin of these high-energy particles. A well established experimental fact is the large range of energies measured. The highest energy cosmic rays which are measured have energies exceeding 10^{19} eV. As the cosmic rays are charged, they are deviated from their paths and thus cannot be used to trace their sources, except at the highest energies. Photons, the traditional probes for astronomy, have limited range at high energies due to interactions with background photons. Interactions of high-energy protons can lead to the production of neutrinos. This could also happen at the sites where the cosmic rays attain their energies. The Antares collaboration is building a telescope that can detect neutrinos. These particles, leptons, are neutral and only interact through the weak force with an extremely small cross section. Because of these properties, a neutrino is not deflected by galactic and extra-galactic magnetic fields and not easily absorbed by matter that makes up the universe. In short, neutrinos are a good probe for astrophysical research because they point straight to their source and can travel larger distances than high energy photons, as they are not easily absorbed or scattered. Measurements of neutrinos with an extra-terrestrial origin could shed light on the production processes of cosmic rays. The Antares neutrino telescope detects neutrinos by measuring the luminous products of neutrino interactions in sea-water or the Earth below it. In this thesis, the main focus is on muon-neutrinos. The interaction of a muon-neutrino can result in a muon. At sufficiently high energies, muons can travel large distances in rock or water and retain the information on the neutrino direction. When the velocity of a muon exceeds the speed of light in water, it emits Cherenkov light along its path. The use of sea-water as the detection medium caters for the need of a large detection volume which is required due to the small interaction cross section of neutrinos. Due to the transparency of sea-water, Cherenkov light can travel significant distances before being absorbed. The Antares neutrino telescope implements an array of light-sensitive photo-multiplier tubes to detect this light. The photo-multiplier tubes are encased in pressure-resistant glass spheres, called optical modules. A triplet of optical modules makes up a storey, of which there are 25 along a vertical line. By attaching buoyant elements to the top of the line, they are kept upright. A total of 12 lines makes up the Antares detector, thus 900 optical modules. The lines are installed at about 2.5 km depth in the Mediterranean Sea. Each line has an active length of about 350 meters and the footprint of the detector on the seabed measures approximately 180×180 m^2. The signals from the photo-multiplier tubes are digitized and sent to shore through a 40 km long electro-optical cable. The data consists of the arrival times of photons on the photo-multiplier tubes together with the number of photo-electrons that were recorded, these are referred to as hits. On shore, a farm of commodity PC's filters the data by making use of causal relations between hits that originate from muons, this process is called triggering. From the filtered data, the parameters of the muon track that caused the photons can be estimated. This process is called muon track reconstruction, and is essential for neutrino astronomy, as it allows the association of a point in the sky to the potential muon. Unfortunately, astrophysical neutrinos are not the only source of light at the location of the detector. In the interactions of cosmic rays with the atmosphere, muons are produced. Despite the column of more than 2 km of water, some muons reach the detector and generate a detectable signal. A way of reducing this background is by only considering muons that travel upwards through the detector, as no muon makes it through the Earth. Signals from neutrinos generated in the interactions of cosmic rays cannot be distinguished from astrophysical neutrinos at the event level. Another form of background manifests itself as a continuous rate of detected photons by the photo-multiplier tubes. The two major causes of this are the decay of ^{40}K present in the sea-water and biological activity, called bioluminescence. The counting rate is characterized by a continuous component and a bursting component. The continuous component varies between 50 kHz and several hundred kHz, while the bursts can last from milliseconds to minutes. This continuous background can result in the false identification of a muon.

This thesis covers two subjects. The first is the development of a muon track reconstruction algorithm. The performance of the reconstruction algorithm is studied as is the resulting performance of the Antares detector under realistic conditions. This is done using simulations. This thesis further contains an analysis of the first data taken with the Antares neutrino telescope. For this analysis, the track reconstruction is essential.

Muon track reconstruction, besides being a non-linear problem, which makes it necessary to use iterative algorithms, is complicated by several factors. First are the stochastic processes via which a muon can lose its energy. Electro-magnetic showers occurring along the track cause detectable photons. Due to their stochastic nature, the number of showers, their positions along the track and energies are unknown, complicating the muon track reconstruction. Secondly, in order to achieve optimal angular resolution, the properties of the sea-water and the detector should be known in detail. These include for example the scattering and absorption lengths of the sea-water. The algorithm described in this thesis is designed to have a minimal dependence on the model describing all the processes leading to recorded photons. The main assumption is that of a charged particle traveling at relativistic speed which emits Cherenkov light along its path through sea-water. By aiming to maximize the purity of the measured photons with respect to the assumed hypothesis, extensive modeling is avoided. This makes the algorithm particularly suitable for use during the initial phase of detector operation. A common problem with parameter estimation algorithms is that of local solutions. By implementing a scan over the solid angle, a maximum number of possible solutions is charted, from which an optimal is chosen. The scan over solid angle additionally allows for a hit selection procedure which makes use of pair-wise causal relations between hits caused by a muon. In the final stage of the fit, the χ^2 based on the differences between the estimated and measured photon arrival times (hits) is minimized. Due to the scanning, several track candidates are found for a given event. Depending on the subsequent analysis, either one or several track candidates can be chosen. In this work, the track with the largest number of hits, and, if necessary, the smallest χ^2 is used.

In order to study the full potential of the Antares neutrino detector, a maximum likelihood is added to the algorithm. For this procedure, a probability density function (PDF), describing the probability of photon arrival times is used. This PDF is derived from simulations. An existing PDF is modified to reduce the influence of correlations between hits. The new PDF shows a better behavior as a function of energy. Even when the likelihood fit with the full PDF is started at the true values of the muon track parameters, it can converge to estimates of the track parameters which differ significantly from the true ones. Among the causes for this are statistical fluctuations and electro-magnetic showers occurring along a muon track.

Operation of the Antares neutrino telescope began on the 2^{nd} of March 2006. On that date the first detector line was connected. The muon track reconstruction algorithm described in this work was used to reconstruct the first muons. On the 21^{st} of September, a second line was connected. In this work, an analysis of the data that was collected with the single line is described. The use of a single line introduces some limitations in reconstruction and analysis with respect to using multiple lines. As a single vertical line has a rotational symmetry, the azimuthal angle of the muons can not be determined. Also, when only part of the Cherenkov wave-front is sampled, the track fit problem allows for two equally likely solutions. These solutions differ in zenith angle by two times the Cherenkov angle and are called 'ghost'-solutions.

In order to ensure a good quality sample, a selection is made from the total available data. The main selection criteria are a random background rate below 120 kHz, and no more than 15 % bursts from bioluminescence. The total sample corresponds to 9.3 days, in which 75621 events were triggered, corresponding to an average trigger rate of 0.094 Hz. The rate of events due to pure random background is estimated to be less than 0.01 Hz. No use is made of the dynamic alignment of the detector, as it was not consistently available yet. The analysis includes simulations of atmospheric muons, atmospheric neutrinos and random background.

The negative effect of electro-magnetic showers along muon tracks on the angular resolution is especially apparent when considering atmospheric muons. The downward orientation of the optical modules favors the detection of photons traveling in upward directions. In case of atmospheric muons, the direct Cherenkov light travels in downward directions, while the light from electro-magnetic showers can reach the optical modules in upward directions. So, there is a bias to detect photons from electro-magnetic showers on atmospheric muon tracks. Also, when considering a single line, the signal from an electro-magnetic shower can mimic the signal from a muon traveling in a (near) vertical direction. A way of dealing with electro-magnetic shower events is to require a minimum number of hits which are used to reconstruct a track. As the track reconstruction algorithm takes no more than one hit per floor, this requirement is translated in a length along the detector line. Due to the size of electro-magnetic showers, which is of the order of a few meters, compared to the muon track, these events are suppressed. While requiring a minimum χ^2 probability generally improves the angular resolution for neutrino events, it is less effective for atmospheric muon events. A robust method of improving the angular resolution, is requiring a minimum number of hits (thus floors) used in the track reconstruction.

The geometry of the detector allows it to be split up in almost identical sub-detectors. This is done in the analysis of the data from Line 1. By splitting the detector an estimate of the resolution on the zenith angle can be made using only data. The resolution found in this way can be better than 1°, which corresponds to about 0.5° for the complete line.

An important quantity in describing the detector response is the angular acceptance of the optical modules. The angular acceptance is the relative sensitivity of the optical module to photons arriving at different angles. In this work, three models of the angular acceptance are considered. Two of those are most relevant, as they are based on measurements on and simulations of the current optical module design. The third is based on measurements of an older optical module design. The main differences between the parameterisations of the angular acceptance lies in the backward region. This leads to different predictions in the rates of detected events for different parameterisations. The largest differences in rate are found for atmospheric muons. Due to the downward facing orientation of the optical modules and the downward going direction of the muons, most photons arrive at the optical modules from backward directions. When confronting the data from Line 1 with the simulation, the measured rates of reconstructed events lie within the uncertainties due to the angular acceptance.

A study of the residuals of the hit times shows a good agreement between simulation of atmospheric muons and data. Thus, the simulation of the processes influencing the measured arrival times of photons is understood. At low numbers of hits used in the fit, the error on the hit time residual is underestimated.

Thus, a selection based on the χ^2 probability of the fit is less effective at low hit numbers. From the simulation it is found that the deterioration of the fit quality is due to both electro-magnetic showers and multiple muons from a cosmic ray interaction arriving simultaneously.

The rate of atmospheric muons as a function of vertical depth in water is calculated from the data of Line 1. Different zenith angle bins are converted to different depths. An acceptance correction is applied which is calculated from simulation. The depth range is limited by the divergence of the correction factor. This divergence is a result of the bias towards horizontal directions due to electro-magnetic showers. The measured depth-intensity relation agrees with that of other experiments within the uncertainties on the angular acceptance.

A search for neutrino candidates is presented. Background from atmospheric muon events that are reconstructed as upward is suppressed by requiring an increasing number of hits in the reconstruction. This search resulted in one neutrino candidate measured with Line 1 having 10 hits. This is consistent with the predictions.

The final part of the this thesis investigates the new track reconstruction algorithm for a full detector using simulation. Three main quantities are used to suppress the background events that are falsely reconstructed as upward going. These quantities are available through the newly developed reconstruction algorithm. In this study, several levels of random background are considered. The background from atmospheric muons is reduced to the same level of about 1 event per day for all levels of background. The numbers of remaining atmospheric neutrinos are about 10, 6 and 5 at background rates of 60 kHz, 120 kHz and 240 kHz, respectively.

Before this work, estimates of the effect of the backgrounds on the performance of the Antares detector were done with the old angular acceptance. This led to an underestimate of the backgrounds due to atmospheric muons and neutrinos. The predicted trigger rates due to atmospheric muons are about a factor 2 higher using the current parameterisation.

The length of the track is shown to be a good measure of the quality of the track in terms of angular resolution. The length is defined by the maximum distance between two hits, measured along the track. Only hits that are selected by the causality relation are considered to suppress background hits. When considering neutrino events, the angular resolution increases with track length. The maximum track length is limited by the dimensions of the detector. At this maximum value, the median angular residual is less than 0.1 degrees. Atmospheric muons that are reconstructed as going upward, show a particular distribution of track lengths. In this distribution, inter-line distances can clearly be seen. This is caused by the large contribution of tracks that are reconstructed with a bias to horizontal directions. This bias is due to electro-magnetic showers along the tracks. There is an excess at low track lengths compared to neutrino events. By requiring at least 120 m of track length, at least 40 % of this background can be rejected.

The scanning of the solid angle leads in general to a number of possible solutions, from which one is selected. If the result of the reconstruction is an upward going track, and the collection of remaining solutions contains a downward going solution, they are compared. In case of an atmospheric muon event, the likelihood per degree of freedom for the upward and (best) downward going solutions are numerically close. By requiring a minimum difference in likelihood per degree of freedom, the number of falsely upward going reconstructed atmospheric muons can be reduced by 58 to 78 %, depending on random background rate. The efficiency for the detection of neutrinos drops by no more than 14 %. The final cut is based on the value of the likelihood per degree of freedom, combined with the number of starting directions that converged to the final solution.

With the cuts applied, the performance of the detector can be evaluated. The performance is compared to the performance using the standard reconstruction method and quality cuts. The standard cuts have been re-evaluated to take into account the trigger and new parameterisation of the angular acceptance. The angular resolution is described by the median of the distribution of the residuals on the angle. For a random background rate of 60 kHz, the resolution is about 0.26 degrees, assuming a flux proportional to E_ν^{-2} (E_ν is the neutrino energy). This is the same as found for the standard reconstruction. This is expected as the resolution is limited by the detector geometry and the width of the probability density of the hit time residuals. This width remained unchanged. The resolution as a function of energy, after applying the cuts, is found to be independent of background rate. The efficiency of the Antares detector can be expressed by the effective area for neutrinos, which is the ratio of the rate of detected events over the incident flux of neutrinos at Earth. The effective area at a background rate of 60 kHz is improved above 50 TeV and below 4 TeV. At 10 PeV, the improvement reaches about a factor 2 and at 100 GeV about 40 %. While an increase in efficiency is achieved, there is still room for improvement. The combined reconstruction of muon tracks and electro-magnetic showers occurring along the track should be pursued.