Determination of the Average Sensitivity of AMANDA Optical Modules

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The sensitivity of the Optical Modules used in the AMANDA neutrino telescope were investigated using the average energy loss of muons in the detector and the zenith distribution as parameters. These were simulated for various sensitivities and compared with real data taken from the years 2001 and 2003. Standard Monte Carlo simulations use a sensitivity of 100%, from this work the average sensitivity of the optical modules was determined to be 92 ± 10%.

1 Introduction

1.1 The AMANDA Neutrino Telescope

The Antarctic Muon And Neutrino Detector Array (AMANDA) (Fig.1) is a neutrino detector located at the geographic South Pole that aims to observe high energy extraterrestrial neutrinos. Neutrinos are weakly interacting particles and posses a very small cross section [1]. As a result large interaction volumes are needed to detect a significant flux. Neutrino telescopes detect Cherenkov radiation and therefore, require large transparent media in which to operate. AMANDA (and later IceCube) operate in ice, whilst ANTARES, NEMO and BAIKAL are water-based [2]. In the study of high-energy astrophysics neutrinos are ideal cosmic messengers. They are neutral, so are not deflected by galactic magnetic fields (hence they point back to their source) and they are also abundant, with large fluxes predicted from catastrophic cosmic events. Neutrinos interact weakly via charged and neutral current interactions, the mechanisms proceed as follows:

$$\nu_l + N \rightarrow l + X \tag{1}$$
$$\nu_l + N \rightarrow \nu_l + N \tag{2}$$

Where N and X are some atomic nuclei and l represents a lepton (of any flavour). Leptons produced in charged current events are highly relativistic (due to the high energy of the initial neutrino and the relatively large mass of the nuclei) and posses a velocity greater than the speed of light in the medium (c/n where n is the refractive index). A consequence of this is the production of Cherenkov light. AMANDA is designed to detect Cherenkov photons produced by muons and as such is only sensitive to charged current interactions. The photons are detected by an array of regularly spaced optical modules (OMs, Fig.2). The sensitivity of the OMs has been measured in laboratories prior to deployment, attempting to determine the average sensitivity of the OMs *in situ* is the focus of this work.

1.2 Neutrino Background events

The largest obstacle faced during data analysis is background reduction. High energy muons are produced from charged pion decays in the upper atmosphere and (due to relativistic effects) can traverse the atmosphere and km of ice into the detector. Around 10^9 atmospheric muons reach the detector each year, compared to 1000 atmospheric neutrinos. To overcome the orders of magnitude AMANDA uses the earth as a shield; neutrinos are the only known particle that can pass through the earth, so any up-going muon event must have been produced from a neutrino near the detection volume.

1.3 The Role of Muons

As there exists charged current reactions for every flavour of lepton, it is not immediately obvious why muons are chosen as signal. Electron and tau events result in short cascades, meaning that a large amount of energy is deposited

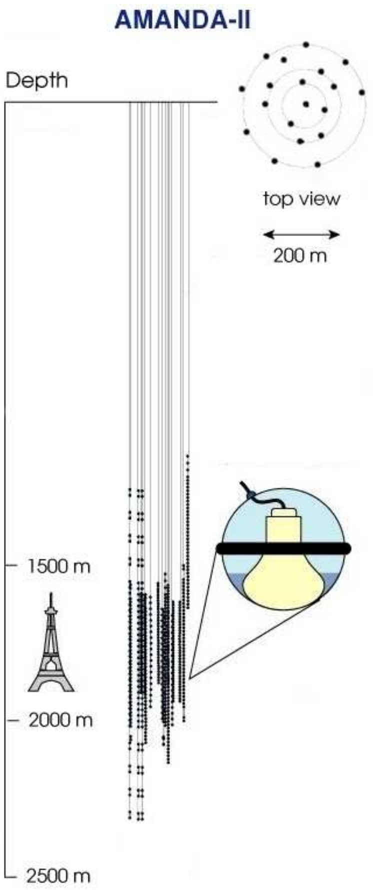

Fig. 1: *The AMANDA-II detector [3], consisting of 677 optical modules arranged on 19 strings, which are on average deployed between 1.5 and 2 km.*

in a small region. This leads to the ability to reconstruct the energy accurately, but not the direction of the incident neutrino. For electrons this occurs because they loose energy rapidly via processes such as ionisation, bremsstrahlung and pair production. Tau particles simply decay shortly after they are created, leaving short tracks. Since in astronomy it is desirable to know the direction of the messenger particle, muons are studied as they produce long tracks in the detector.

2 Data Cuts and Optimisation

2.1 Introduction

To begin looking for objects of interest, such as point or diffuse sources of neutrinos it is necessary to remove the background, which contains atmospheric neutrinos and down-going muons.

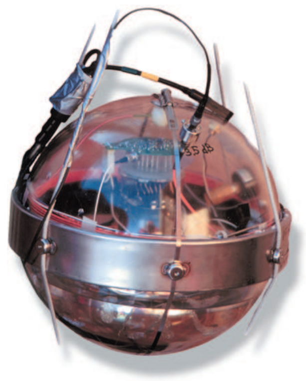

Fig. 2: *A standard optical module, shown at the bottom is the sensitive region, optical contact is maintained via an optical gel. The upper half of the OM consists of the electronics that send the signal to the surface.*

For certain purposes atmospheric neutrinos can be used as a valuable tool. By studying Monte Carlo simulation of atmospheric neutrinos generated for different detector sensitivities and comparing the results to real data the average sensitivity of AMANDA can be determined.

2.2 Cut Parameters

The cuts used are optimised to obtain the best fit between Monte Carlo and data. The variables used in the cut process were: zenith, resolution, smoothness and likelihood. The zenith angle is simply the latitudinal angle, such that 90° corresponds to the equator and 180° to the North Pole. Cuts act on the zenith variable to quench events near the horizon as these events contain down-going muons. Also the detector geometry (cylindrical) is such that lever arm near the horizon is much shorter leading to poor event reconstruction.

Resolution is a quantity that determines the error of the track reconstruction for a given event, it can loosely be thought of as the angular region spanned by an muon track. By forcing the resolution to be below 3.25° it is possible to remove electron cascades and also to reduce the likelihood of miss-reconstructed down-going events.

Smoothness is defined as a measure of how homogenous the hit distribution is along the track, the smallest possible smoothness is defined as 0, the cut used allows the absolute smoothness to be less than 0.36.

The likelihood is defined as the probability to observe a certain hit pattern, given an assumption of a certain track direction. Cuts use likelihood differences, which take the difference between the likelihood for a certain track with no directional assumption and the likelihood assuming *a priori* down-going muons only. The cut ensures that the likelihood difference is sufficiently high so that the number of down-going muons is drastically reduced.

3 Sensitivity Measurements

3.1 Introduction

Sensitivity is defined as the performance of the OMs relative to that assumed in simulations. The performance of the OMs has been measured in surface laboratories under conditions believed similar to those experienced at the South Pole. Standard Monte Carlo simulations used by the collaboration are set at 100%, therefore a measurement of 114% would correspond to the current assumed sensitivity being under-estimated by 14%.

The average sensitivity of the optical modules can be determined by producing simulated data for different sensitivities and evaluating variations of certain parameters. Then by comparing these values to actual data the sensitivity of AMANDA can be inferred. The parameters studied were the average energy loss dE/dx of muons in the detector and the (-)cosine of the Zenith angle. These two independent parameters were simulated with sensitivities of 70, 85, 94, 100, 115 and 130 %.

3.2 Zenith Sensitivity

The variation of the number of events recorded with different zenith angles is a good candidate for a sensitivity dependant variable, due to the asymmetry of AMANDA. Due to its cylindrical nature, events close to the horizon cannot lead to as many hits as those that traverse the longer z-axis. If the sensitivity is increased, however, the trigger condition (at least 24 hits in 2.5μs) is more likely to be satisfied. Therefore, it is expected that for low sensitivities the distribution will be strongly peaked around 180° and for much larger values the directional dependance should drop leaving a flatter distribution. The -cosine of the zenith angle (in radians) was used, as this removes the effect of the varying area of latitudinal bins. The results from the simulations indicated that around -cos(zenith) = 0.7 all of the distributions are roughly equal. This lead to investigation into the suitability of the integral between 0 and 0.7 of the distribution as a parameter for sensitive dependant behaviour.

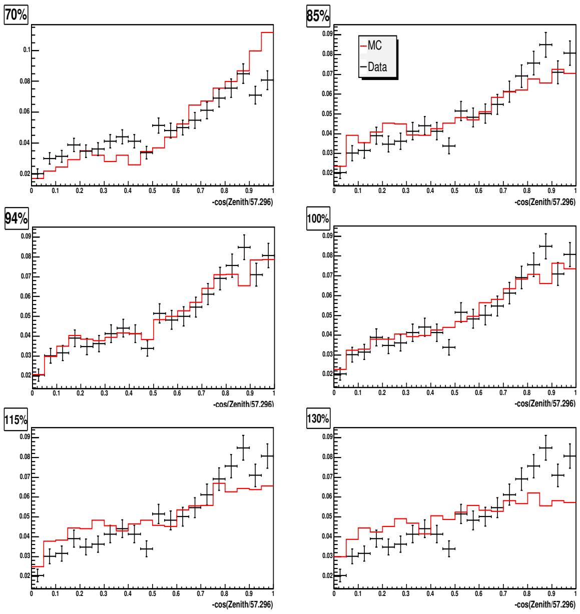

Fig. 3: *Plots of normalised zenith distribution with simulated and actual data taken from the years 2001 and 2003. As is clear from the graphs as the sensitivity is increased the MC distribution flattens. It is also immediately clear that the zenith distribution predicts a sensitivity near 94% due to the high accuracy to which data matches Monte Carlo.*

3.3 dE/dx Sensitivity

As muons propagate through ice they lose energy due to a combination of processes, both a constant term and a stochastic term which is proportional to the energy of the particle.[5] Muons lose energy constantly via ionisation of the medium. Stochastic processes include the production of δ-electrons and muon-nucleus interactions. The energy loss behaves approximately as:

$$-\frac{dE}{dx} = a + b \cdot E \tag{3}$$

With a $\approx$ 2 MeV cm^{-1} and b $\approx$ 3.4 10^{-6}cm^{-1}. For sensitivity studies the average muon energy loss is investigated. This involves a comparison between the observed and expected light (for a given track reconstruction), a more sensitive detector records more hits and hence sees a higher average energy loss. Also, as the number of hits increases the range of observed energy loss increases, thus as the sensitivity increases a broader peak at higher dE/dx is expected to emerge.

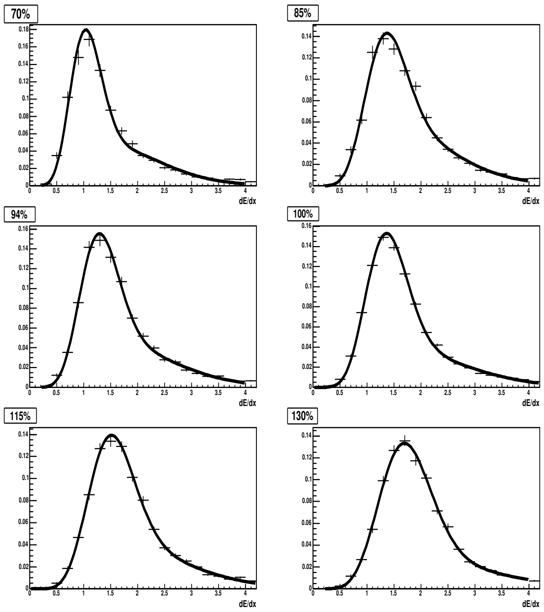

Fig. 4: *Normalised av(dE/dx) for different sensitivities, aparent is the broadening of the distribution and the shifting of the peak towards larger average energy loss for high sensitivities.*

4 Analysis

4.1 Introduction

The bin content between -cos(zenith)=0 and cos(zenith)=0.7 was investigated and a curve was fitted to the dE/dx distribution with the resulting parameters used to estimate the sensitivity of AMANDA. It was found routinely in the analysis that the Monte Carlo simulations for 85% showed distinctly different traits to that of the other simulations. This lead to suspicion that the simulation was processed with incorrect settings and hence the 85% Monte Carlo was removed from further analysis. Therefore, all quoted results refer to the sensitivities 70, 94, 100, 115 and 130.

4.2 Zenith Analysis

The bin content of the zenith distribution was found to vary linearly with sensitivity (Fig.5). Meaning that as the detector becomes more sensitive an increasing number events occur in the lower half of the sky, as expected. Comparison with the bin content from real data for the years 2001 and 2003 gave a value for the sensitivity of $92 \pm 10.2\%$. The dominant source of error arises from the uncertainty in the calculated gradient for the fit function (which also has an error of around 11%). The calculations were then preformed with the two years separately to investigate whether the sensitivity changed over the course of 3 years, no significant deviation was found.

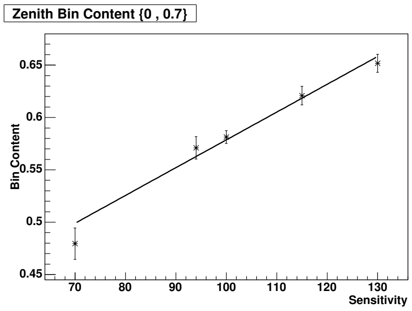

Fig. 5: *The normalised bin content between 0 and 0.7 for the zenith distribution as a function of sensitivity. The Monte Carlo data was parameterised with a straight line fit and the actual sensitivity was inferred from the fit and the bin content of actual data over the desired range.*

4.3 dE/dx Analysis

The function

$$f(x) = \frac{ax^6}{exp(bx)} + \frac{cx^6}{exp(dx^2)} \qquad (4)$$

was fitted to the dE/dx Monte Carlo simulations and from this the peak height, position and width were found to be linear functions of sensitivity. The height decreased with increased sensitivity (due to normalisation) whilst the position and width increased. From the fits the sensitivity was determined to be $77.3 \pm 3.5\%$ (position), $81 \pm 10\%$ (width) and $99 \pm 41\%$ (height). Once again the errors on the gradient dominate the calculation, which explains the large error on the height (this is almost a flat distribution within the errors see Fig.7). The dE/dx analysis used only data and Monte Carlo from the year 2001, as the 2003 data has not currently been processed for this quantity. By combining the results from the position and width calculations an overall measure of the sensitivity for dE/dx was found to be $77.7 \pm 3.3\%$.

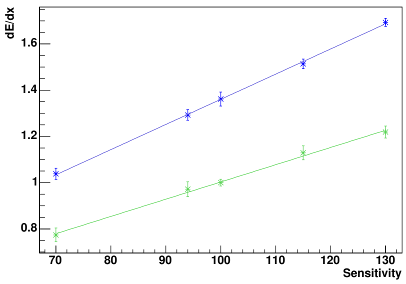

Fig. 6: *The peak position (blue) and width (green) are shown for different simulated sensitivities.*

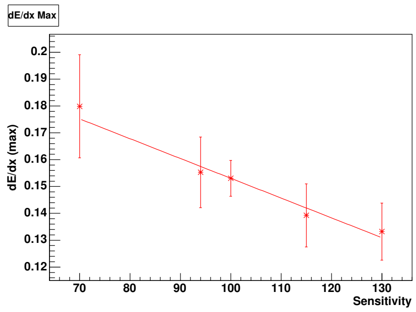

Fig. 7: *The peak height, shown for different simulated sensitivities.*

5 Conclusion

From the two independent quantities studied two separate values for the sensitivity were determined. The dE/dx analysis determined the average sensitivity to be 77.7 ± 3.3%. Whereas, the zenith analysis determined the value 92.0 ± 10.2% for the same quantity. These values appear to contradict each other, the upper bound of dE/dx (81%) only roughly agrees with the lower limit from the zenith calculations (81.8%). The value of the sensitivity obtained from dE/dx calculations was dis-regarded (even though it had a lower error) because the data does not fit the Monte Carlo to high precision, this is shown in Fig.8. For the zenith distribution there is a much better agreement between data and Monte Carlo. The final average sensitivity of AMANDA is thus 92 ± 10%, this value explains why current Monte Carlo simulations are not observed to be largely erroneous when compared with real data (as they would be if the sensitivity was grossly over-estimated).
There is no clear reason as to the disagreement between data and Monte Carlo for the dE/dx distribution, as Fig.8 shows there is considerable disagreement between the two distributions

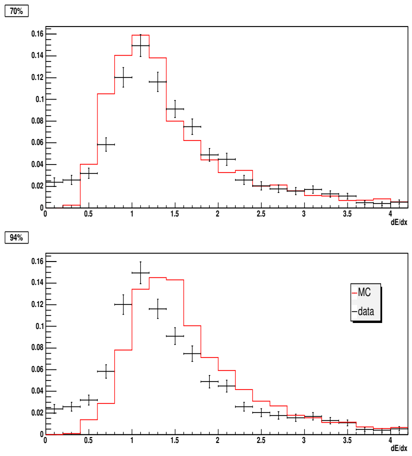

Fig. 8: *Examples of the poor correlation between data and Monte Carlo for the dE/dx distribution, shown here are simulated sensitivities for 94% and 70%. There is no single clear reason for this poor agreement.*

for the smallest values of dE/dx. This undermines the reliability of the Monte Carlo simulations and further sensitivity estimates, resulting in further errors that are not included in the 3.3% statistical error quoted. Suggested reasons for the discrepancy include:
Ice properties - the properties of the ice are simulated using simplifications, this means that local changes in the absorption or scattering length could be missed by the simulations.
It is also possible that errors on the amplitude simulation (signal from the OMs proportional to the number of photons received) are responsible for the poor correlation between data and Monte Carlo. The zenith distribution relies primarily on accurate time reconstruction rather than accurate amplitude information. This is not the case for dE/dx, which is heavily reliant on accurate amplitude knowledge. Therefore, inaccurate amplitude information could result in miss-calculated simulations.
Further work to determine the average sensitivity of the OMs might involve studies of other variables for sensitivity dependant behaviour, or refinement of the dE/dx Monte Carlo so as to obtain accurate fits between data and simulation. The study of sensitivies as a function of depth/position may also provide insights into the inner workings of the telescope.

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