The AMANDA Neutrino Telescope: Design, Construction, and Performance

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Abstract. The AMANDA collaboration has successfully deployed a 10-string array at the South Pole at a depth of 1.5 to 1.9 km. We have measured the optical properties of the ice, reconstructed tracks from high-energy cosmic ray muons, measured the energy of electromagnetic cascades, and established a burst detector for MeV neutrinos. I will outline the detector’s principles of operation, construction, and expected performance; our simulation studies indicate that this detector has an effective area of \( \sim 10,000 \text{ m}^2 \) for throughgoing neutrino-induced muons, with an angular resolution of 2.5\(^\circ\) and good rejection (\( > 10^5 \)) of down-going cosmic ray muons. I will also describe the methods used to simulate the detector and to reconstruct muon tracks, and compare our results with data taken with the first four strings of the array during 1996. Finally, I will discuss future work, including the construction of the AMANDA-II array (beginning this year) which will have an effective area of up to \( 10^5 \text{ m}^2 \) depending on muon energy, and angular resolution of \( \sim 1^\circ \).

1. Introduction

Techniques are now being developed to use high energy (\( > 10^{12} \text{ eV} \)) neutrinos to provide a new window on the universe, yielding information complementary to that obtained from observations of high energy photons and charged particles. Neutrinos can provide direct information about the highest energy phenomena including blazars (active galactic nuclei with a jet pointing toward the observer) and GRBs (gamma ray bursts); besides this primary goal, a full scale neutrino telescope will have numerous other applications, including an indirect search for dark matter, a search for neutrino oscillations, and a supernova monitor. A full discussion of the physics motivation for AMANDA is presented elsewhere (Gaisser 1995, Halzen 1997, Hill 1997).

Arguments presented in the above papers indicate that the required effective volume of a neutrino telescope is of order 1 km\(^3\) (see also Halzen 1995). However, some models suggest that the detection of these sources may be within reach of much smaller detectors with effective area of order \( 10^4 \text{ m}^2 \). The AMANDA collaboration has completed the first deep detector of this size.
Figure 1. *Left:* Principle of $\nu_\mu$ detection through upward going muons. The angle between the neutrino and the muon it produces is exaggerated for clarity; in fact it is typically $\sim 1^\circ$ for 1 TeV neutrinos. *Right:* Schematic view of the Earth with a neutrino detector, showing extraterrestrial neutrinos (1) and their backgrounds: atmospheric neutrinos (2) and punch-through muons from above (3).

2. Principles of Operation

The traditional approach to underwater/ice neutrino detection (see fig. 1) is the observation of a $\nu_\mu$ by its charged-current interaction in the rock, water, or ice below the detector, producing a muon which traverses the detector and emits Čerenkov light observable by photomultiplier tubes (PMTs) (see fig. 2). For detectors up to 1 km on a side, the effective volume $V_{\text{eff}}$ exceeds the actual detector volume, since $V_{\text{eff}} = A \times R_\mu$, where $A$ = effective area, and $R_\mu$ = muon range. Muon range rises linearly with energy up to a few kilometers at an energy of $\sim 5$ TeV and continues to rise as $\sim \log(E_\mu)$ at higher energies. Therefore, the muon range dominates over the scale of the detector in the calculation of effective volume, and we may use the effective area as a figure of merit instead.

Neutrino detectors must be placed at great depth in order to shield them from the large flux of downward going muons produced in the atmosphere above the detector (see fig. 1). After rejecting muons coming down through the detector, one is left with the extraterrestrial neutrinos we wish to observe, seen against an irreducible background of atmospheric neutrinos generated by cosmic ray interactions in the atmosphere on the other side of the earth.

2.1. Muon tracking

To detect these energetic muons, a telescope may be built consisting of a lattice of PMTs spread over a large volume deep in the ocean, in ice, or in lakes. The PMTs measure the arrival time and amplitude of Čerenkov light emitted by the
muon; this information can be used to reconstruct the muon’s trajectory (fig. 2).

A single relativistic particle emits $\sim 300$ Čerenkov photons per cm in the 300 - 600 nm wavelength range; they are all emitted in a cone of angle 40°. The electromagnetic showers accompanying a high energy muon increase the light output per unit track length in proportion to the muon’s energy; most of the Čerenkov light produced by these showers is emitted within a few degrees of the same cone as the light from the primary particle. So high energy muons are visible over larger distances than those at lower energies, and the effective area of the detector increases with muon energy. AMANDA and other planned detectors of this type are designed primarily for the TeV ($10^{12}$ electron volt) energy range, for several reasons: a) the kinematics of the reaction $\nu_\mu + A \rightarrow \mu + X$ aligns the outgoing muon with its parent neutrino with a mean angle $\theta_{\nu\mu} \sim 1.5^\circ \times [E_\nu(\text{TeV})]^{-0.5}$, enabling one to find a point source of neutrinos to $1^\circ$ accuracy; b) neutrino cross section and muon range both rise with energy; c) above a few TeV, the energy spectrum for atmospheric neutrinos is considerably steeper than that predicted for extraterrestrial neutrinos.

The rate of neutrino-induced muons is obtained by integrating the neutrino flux times the probability $P_{\nu\rightarrow\mu}$ that a neutrino of energy $E_\nu$ moving towards the detector will produce a muon with sufficient energy to reach and trigger the detector. $P_{\nu\rightarrow\mu}$ is basically the product of the cross section for muon production and the muon’s range, and is $\sim 10^{-6}$ for 1 TeV neutrinos and a low muon detection threshold (few tens of GeV).

2.2. Other modes of operation

An array of PMTs can also be used to reconstruct the energy and location of electromagnetic or hadronic showers (see fig. 2). The energy threshold for successful reconstruction depends on the PMT spacing and the absorption length.
of light in the medium; the presence of scattering can improve the reconstruction of such events by containing the light within a smaller volume and increasing the number of PMTs that are hit. It may be possible to use this method to observe the PeV (10^{15} electron volt) showers produced by electron antineutrinos in the Glashow resonance reaction ν_e + e^- → W^- → shower. We have analyzed the data from the AMANDA-A detector to search for shower events and obtained a preliminary limit on the diffuse flux of ν_e + ν_µ (Porrata 1997). Finally, AMANDA can be used to detect the onset of a supernova by simply measuring the counting rate of each PMT (Wischnewski 1995). The few second burst of low energy neutrinos from a nearby supernova lead to an increased rate in each PMT from light produced by neutrino interactions near the PMT. With many PMTs in an array, this increased rate should become statistically significant when adding the rates from all the PMTs together.

3. Detector construction

To build a PMT array in ice, AMANDA drills holes in the ice using a hot water drill. The drill creates a water-filled hole of diameter ~ 50 cm, down to a depth of 2 km. The hole takes typically 2 days to refreeze, allowing ample time to drop an AMANDA string into the hole. Each string consists of many optical modules (OMs). Each OM contains an 8-inch hemispherical PMT and its voltage divider, inside a transparent glass sphere to resist the high pressure at the large depth of AMANDA, with an electrical cable going to the surface. In this way, each OM is made independent of all others, receiving power and transmitting signals over its own cable. All signal processing, acquisition, and trigger electronics are placed on the surface. This system provides high reliability against single point failure and makes gradual evolution of the detector possible. Because of the low temperature (-40°C) and the absence of radioactive backgrounds in the ice, the PMTs have extremely low background counting rates, of order a few hundred Hz. This allows an extremely simple triggering scheme; we simply require a certain number (usually 16) of PMTs to produce a photoelectron within a 2 μsec time window.

In addition to the electrical cable that connects each OM to the surface, there is a fiber optic line for each OM. The upper end is connected to a YAG laser system at the surface that sends very short light pulses down the fiber. The light exits the lower end of the fiber in the center of a small nylon sphere placed ~ 30 cm from an OM. Small amplitude light pulses are sent down to calibrate the single photoelectron response and the timing characteristics of the OM. We can send down larger pulses that are bright enough to be detected by OMs in neighboring strings; this data is used to determine the overall geometry of the array and the optical quality of the ice. Many other calibration devices and diagnostic sensors are also placed on the strings and deployed (see discussion of AMANDA-B below and table 1).

3.1. Brief History

Preliminary site studies and drilling tests were performed at the South Pole in the 1991-92 austral summer. During the 1993-94 campaign, four strings each with 20 OMs were deployed, with OMs at depths of 800 to 1000 m (the
“AMANDA-A” array). Timing distributions were obtained from calibrations using the surface laser and optical fiber system; these showed that photons do not propagate along straight paths in the ice but are scattered and delayed due to residual bubbles, preventing a proper reconstruction of the Čerenkov cone. However, the ice has an enormous mean free path for absorption of light, exceeding 200 m for short wavelengths. While AMANDA-A cannot be used to reconstruct muons, the long absorption length makes it extremely useful for the observation of contained electron showers (Porrata 1997).

A deeper array, AMANDA-B, has been deployed in bubble-free ice below 1500 m. In 1995-96, the first four new strings, with 20 OMs each at depths from 1600 to 1950 m, were deployed. Each OM in these strings contains a 14 stage Hamamatsu R5912-2 PMT, operated at $10^9$ gain, with signals transmitted to the surface via a coaxial cable. The single photoelectron timing resolution of these PMTs is $\sim 4$ ns. Calibration measurements done with the new strings show that the optical quality of the ice at these depths is extremely good; the absorption length is still very long, $\sim 100$ m, while the bubbles have disappeared and the scattering length has increased by 2 orders of magnitude, to $\sim 25$ m (Halzen 1997). The ice at these depths is good enough to allow reconstruction of muon tracks with the 4-string array, as will be shown below. An additional 6 OMs were deployed on a test string which connects OMs to the surface via twisted pair cables; results indicated a factor of 3 improvement in both rise-time and amplitude over the coax cables. 79 of the 86 OMs survived refreeze, and none have failed since.

3.2. 1996-97 activities

Based on initial results from the first four AMANDA-B strings and our simulations, we deployed 6 new strings during the most recent Antarctic season. The new holes were drilled to a depth of 1900 m; the new holes combine with the previous four to form a ring of radius $\sim 60$ m with one string at the center, completing the new array. Fig. 3 shows the current configuration of AMANDA, including both AMANDA-A and -B. Use of the new twisted pair cables allows each of the six new strings to have 36 OMs, nearly twice as many as the previous strings, and with 10 m between adjacent OMs on a string instead of 20 m. Nearly all OMs in the first four strings, and all the OMs in the new strings, face straight down to improve sensitivity to upgoing muons and decrease the rate of downgoing events.

Including both the 1995-96 and 1996-97 strings, a total of 306 OMs are deployed in AMANDA-B; 289 survived refreezing. Of those OMs that have survived refreezing, none have failed since deployment, indicating that the deep ice environment is very stable and benign once freezing of a hole is complete. Many new calibration devices and prototypes of new technology were installed as well. Table 1 summarizes what has been achieved over the past two seasons and the current status. Besides the detector itself, highlights include 1) in situ nitrogen lasers that produce pulses of 337 nm ultraviolet light, visible by OMs 200 m away; 2) a lamp that when operating emits light continuously at an adjustable wavelength; and 3) prototypes of new OM technologies.

These new OM technologies are attempts to overcome the limitations of the current OMs, which are run at very high gain to produce signals large
Figure 3. Schematic view of AMANDA-A and AMANDA-B.
Table 1. Summary of AMANDA-B activities at Pole during 1996-1997 and the detector’s current status.

| Drilling and deployment | 6 holes drilled to a depth of 2 km  
6 day turnaround time  
8 - 10 hours to mount OMs and other devices  
4 hours to drop string and route cables |
|-------------------------|----------------------------------------------------------------------------------|
| Detector                | 6 new strings with 36 OMs per string  
Full array has 289 OMs operating  
Failure rate < 3%  
Trigger rate ~ 100 Hz  
- 16 fold maj. trigger, 2 µsec window |
| Calibration devices     | Laser diode pumped YAG at surface  
- 10 kHz rep rate, 532 nm, 100 µJ / pulse  
YAG laser + dye, at surface  
- 475-610 nm  
- redundant matrix of measurements  
Blue LED beacons, various depths  
- 390 nm and 450 nm  
- DC or pulsed operation  
- 500-5000 Hz rep rate in pulsed mode  
DC lamps, various depths  
- seen > 200 m from source  
- 313 nm, 350 nm, 380 nm, and broadband  
- one tunable source (350-650 nm)  
N2 lasers, 1800 m depth  
- 337 nm output, 100 µJ / pulse  
- seen > 200 m from source |
| Prototype devices       | Analog optical fiber optical modules  
- send analog signal up optical fiber  
Digital OMs  
- digital signal at OM, send data up twisted pair  
Radio receivers and transmitters (Bartol, U. Kansas) |
| Ice diagnostic devices  | Thermistors  
- temperature vs. depth, onset of freezing  
Pressure sensors  
- determine string depth, monitor freezing  
Inclinometers  
- ice shear vs. time  
Transmissometer  
- measure quality of ice/water in hole |
enough to send directly over an electrical cable to the surface. This technique allows the arrival times of pulses to be measured well, approaching the intrinsic timing resolution of the PMT itself (4 ns FWHM), and enhances reliability by minimizing the amount of hardware that goes into the OM itself. However, there are some important drawbacks to this technology: 1) the PMTs are run at such high gain that their signal saturates at only the 10 photoelectron level, and 2) the pulses received at the surface have a long rise time (30 ns) and even longer fall time, making it impossible to resolve PMT pulses separated by less than 100 nsec. Two approaches are now being tried to solve these problems.

The first is the analog fiber technique. In this approach, the PMT signal drives an optical transducer (a laser or photodiode) to produce an optical pulse that travels to the surface via optical fiber and is then converted back to an electrical pulse that can be used by the AMANDA trigger and data acquisition electronics. This technique reproduces the shape of the input PMT pulses very well, retaining the \( \sim 5 \) ns rise time of the original pulse, and provides a dynamic range of \( \sim 100 \) photoelectrons. Several analog fiber OMs have been deployed in AMANDA-B.

The second new OM technology is the digital optical module (DOM). In this approach, electronics inside the OM sample the PMT waveform and send it to the surface in digital form, allowing the twisted pair electrical cables to be used. This technique has some important advantages in scalability (several DOMs can be connected locally and use only one cable to send signals) and dynamic range (one can get waveforms simultaneously from the anode and one or more dynodes), which may become important as AMANDA expands to larger volume. Two such modules were deployed in AMANDA-B, and the results so far are promising, with good separation demonstrated between pulses separated by as little as 10 ns.

4. Simulations and first data

4.1. Simulation and reconstruction programs

Understanding the capabilities of AMANDA for the detection of neutrino-induced muons requires the simulation of both upgoing (signal) muons produced by neutrinos and downgoing (background) muons produced by cosmic ray showers in the atmosphere above the detector. Upgoing and downgoing muons are generated by separate programs; they are then used as input for a simulation of AMANDA itself, producing events in exactly the same format as the experimental data, which can then be reconstructed with the same programs used to reconstruct real data. The steps in the simulation are described below.

Input particles: Downgoing muons are generated by a full atmospheric shower program that simulates the production of muons by isotropic primary protons with energies up to 1000 TeV, and propagates them down to a plane just above the detector; the shower program is designed to reproduce correctly the angular and energy distributions of atmospheric muons reaching AMANDA, and also the multiplicity distribution; since more than 10% of the downgoing muons reaching AMANDA come in bundles of 2 or more from a single shower, inclusion of bundles is critical for background calculations. Upgoing single muons are sim-
ulated with various angular distributions (isotropic, point source) and various energy distributions; they may start anywhere within the detector volume.

Generation of OM signals: It would be computationally impractical to generate and follow the path of each Čerenkov photon produced by the input muons and secondary showers for every simulated event. Therefore, this step is accomplished by doing the photon propagation only once and storing the results in large multidimensional tables. One table gives the distribution of the mean number of photoelectrons expected as a function of the position and orientation of an OM relative to a muon track, and the other gives the time delay distribution of photoelectrons as a function of the same variables. The tables include the effects of the wavelength dependent quantum efficiency and transmission efficiency of the AMANDA OMs, and the absorption and scattering properties of the ice. Once the tables are compiled, events can be simulated quickly by locating the OM relative to any input particle and looking up the expected number and time distribution of photoelectrons in the tables. The known characteristics of the AMANDA OMs and electronics are then used to generate amplitude and timing information and create an event in the same format as the events generated by the experiment itself.

Reconstruction: In an ideal medium without scattering, and with gaussian timing errors, one could in principle reconstruct the path of a muon by a $\chi^2$ minimization process. Because there is residual scattering in the ice, the distribution of arrival times of photoelectrons seen by an OM from a muon is not gaussian, but has a long tail on the high side. The correct method to use with nongaussian timing errors is likelihood analysis, which is more robust and much less sensitive to outliers. In this analysis, one develops a normalized probability function $p_i(t)$ that gives the probability of a certain delay time $t$ for a given OM $i$, and is a function of the position and orientation of the OM. Using this function, the reconstruction is done by maximizing the likelihood function

$$
\log(L) = \log\left( \prod_{\text{all hits}} p_i \right) = \sum_{\text{all hits}} \log(p_i) .
$$

In the case of AMANDA, the functions $p_i(t)$ are formed by starting with the analytic solution for diffusion of photons from a point source with scattering (Pandel 1996). This solution is “patched” to include the gaussian timing errors associated with the PMT and electronics (Weibusch 1997).

Reconstruction proceeds by a multistep process. First, a 0th order guess is made by a simple line fit. Using this guess as a starting point, likelihood reconstruction is performed one or more times; at each stage, “hit cleaning” is performed to throw out individual OM hits using topological criteria without rejecting the event itself. Finally, quality criteria are used to reject badly fit events. The most important quality criterion is $N_{\text{direct}}$, the number of OMs that are hit within 20 nsec of the time expected for unscattered Čerenkov photons from the fitted track. The requirement that $N_{\text{direct}} > 5$ provides our single strongest cut for elimination of misreconstructed downgoing muons.

4.2. Results for AMANDA-B

With the 10 string AMANDA-B detector, simulations indicate excellent angular resolution and background rejection, as shown in Figure 4. With the require-
Figure 4. Reconstruction results of the AMANDA-B 10-string array, after quality cuts. Left: angular error (mismatch angle) distribution of upgoing muons. Right: Input and reconstructed zenith angle distributions for upgoing muons. Adapted from (Wiebusch 1997).

ment that at least 5 hits in each event be unscattered, less than one in 10^6 downgoing events is misreconstructed, and the detector has an effective area of \( \sim 10,000 \text{ m}^2 \) for upgoing neutrino-induced muons with 2.5° mean angular resolution; reconstruction efficiency (the percentage of triggers that are successfully reconstructed) is \( \sim 25\% \).

4.3. Comparison with data

The 6 additional strings deployed in 1996-97 are being calibrated at present, so a full comparison between data and simulation must be done using the data from the first four strings deployed in 1995-96. These strings are not adequate to form a full-scale detector, since the background from misreconstructed muons exceeds the expected number of signal events from atmospheric neutrinos if only these strings are used (they contain only about 1/4 of the OMs in the full AMANDA-B array). Nevertheless, they can be used to test the accuracy of the simulations and the quality of the track reconstruction software.

Two tests have been performed that indicate excellent agreement between data and simulation. The first is the direct comparison of the 4-string data with simulation. Figure 5 shows that the simulations reproduce the overall timing distribution of hits and the hit multiplicity distribution. Figure 6 shows the zenith angle distribution at different points in the series of quality cuts used to reject background. The simulated and experimental distributions remain normalized to one another at every cut level. This is strong evidence that the simulations are reproducing the observed data well.

AMANDA is unique in that it can be calibrated using tagged muons with known zenith and azimuth angles, thanks to the presence of surface air shower arrays at the South Pole. AMANDA has been running in coincidence with SPASE (South Pole Air Shower Experiment) since 1994, and now runs in coincidence with both SPASE arrays (SPASE1 and SPASE2), providing AMANDA with the unique ability to use “tagged” muons with known arrival directions as a calibration tool. Air showers with sufficient energy to trigger SPASE2 and aimed in
Figure 5. Comparison between AMANDA-B4 data and simulated downgoing muons, from (Tilav 1997). Left: The times of all hits in events, plotted with respect to the first hit in each event.Muon events. Right: OM multiplicity distribution.

Figure 6. Reconstructed zenith angle distribution at different cut levels for data and the RAVEN Monte Carlo, adapted from (Tilav 1997). Both event sets have the same number of events before cuts and are not renormalized for the cut distributions. The \(N_{\text{direct}}\) cut is as described in the text; the \(\sum P_{\text{hit}}\) cut is designed to reject events where too many PMTs close to the track saw no light, or too many PMTs far away from the track were hit.
the direction of AMANDA-B will contain an average of one or two muons with sufficient energy to reach and trigger AMANDA-B (Miller 1997). We have used a sample of SPASE2-AMANDA-B coincidences to show that the reconstruction of 4-string data contains no detectable systematic errors (Figure 7).

5. Conclusions and Future Outlook

Based on the results that we have now, we have concluded that the ice between 1500 and 2000 m depth is adequate for neutrino astronomy with the full 10 string AMANDA-B array. The deployment technique is reliable, and costs per OM are well established from our past experience. Data and simulations agree very well, and there is excellent absolute pointing agreement between AMANDA and the surface arrays. We are pressing forward with the construction of the next stage of AMANDA, called AMANDA-II. This will consist of 10 new strings, with much larger instrumented length (~ 1000 m), arranged in a circle of radius 100 m centered on the existing array. We will be deploying the first three strings of the new array during the upcoming season (1997-98); these will be used to test the optical quality of the ice over a larger depth range, from 1300 to 2600 m, and test new OM technologies and surface electronics. Preliminary simulations of a 21-string AMANDA-II array (which would include the current AMANDA-B array) lead us to expect greatly improved performance, with an effective area of up to 10^5 m^2, 1° angular resolution, and much higher reconstruction efficiency (60%). As discussed in (Halzen 1997), we expect that as the size of the array increases, reconstruction efficiency improves and track reconstruction becomes easier. Finally, we will obtain the raw data from a full year of successful operation of the 10-string AMANDA-B detector at the opening of the 1997-98 Pole season, and will immediately begin the analysis of this data.
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