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Time calibration of the AMANDA neutrino telescope with cosmic ray muons

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Abstract. The AMANDA-II neutrino telescope is an array of optical sensors which detect Cherenkov light emitted by passing charged particles. Reconstruction of the trajectories of these particles depends crucially on the measurement of relative arrival times of the Cherenkov photons at each detector. This, in turn, requires precise knowledge of the travel delay times for signals from each sensor. Currently, AMANDA uses a laser system to calibrate these times. We have implemented a new method using down-going muons which supplements and may eventually replace the existing calibration procedure. Our studies of this method indicate that it is robust and able to achieve the precision required by our reconstruction algorithms.

1 Introduction

Large sub-glacial and submarine neutrino telescopes are built from great numbers of photomultiplier tubes (PMTs) arrayed deep beneath the surface of the water or ice. The AMANDA-II neutrino telescope comprises 677 8" PMTs housed in glass pressure spheres – the assembly being called an *optical module*, or OM. The OMs used in the various astrophysics analyses are deployed at depths between 1500 m and 2000 m below the surface of the ice sheet covering the South Pole. Other OMs used primarily for the study of ice properties extend several hundred meters both above and below this region. Further information on AMANDA-II, its construction and capabilities may be found elsewhere in these proceedings (Wischnewski, these proceedings).

In AMANDA, the PMT signals must propagate approximately 2 km over electrical or fiber optic transmission lines to the readout electronics on the surface, inducing a significant delay in the measured time of signals. Other much smaller, but still non-negligible delays enter in the OM itself as well as in the surface electronics. We call this total delay time T_0.

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Each of the OMs in AMANDA sees a different signal path and consequently, each T_0 must be individually calibrated in order to calculate the true hit times of the OM. This calibration has heretofore been carried out using a solid-state YAG laser, located on the surface in the AMANDA counting house (Andres, 2000). For most of the OMs, the laser is connected via an optical fiber to an emitter in close proximity to that OM. This procedure is very robust and provides ancillary pulse risetime corrections in addition to the T_0 information for that phototube. However, it is a time-intensive task that consumes precious manpower each year at the South Pole. Also, there are several OMs which have broken laser fibers and are not otherwise able to be calibrated with the laser.

AMANDA records approximately 10^9 cosmic ray muons annually. In this paper we shall demonstrate a method which utilizes this data to provide an independent T_0 calibration.

2 Description of Method

Given a known muon track passing nearby an optical module, and emitting a Cherenkov photon which strikes that OM, the *time residual*, t_R, is defined to be the difference between the real time of the photon's arrival at the OM, t_{OM} and the expected arrival time from analysis of the kinematics of the track, t_γ:

$$t_R \equiv f(t_{OM} - t_\gamma) \tag{1}$$

In an ideal world where Cherenkov photons never scattered, t_R would be a delta function:

$$t_R = \delta(t_{OM} - t_\gamma). \tag{2}$$

Multiple scattering of photons in the surrounding ice distorts this distribution so that it no longer has a known analytic form. The distribution can be experimentally measured and is shown in Figure 1.
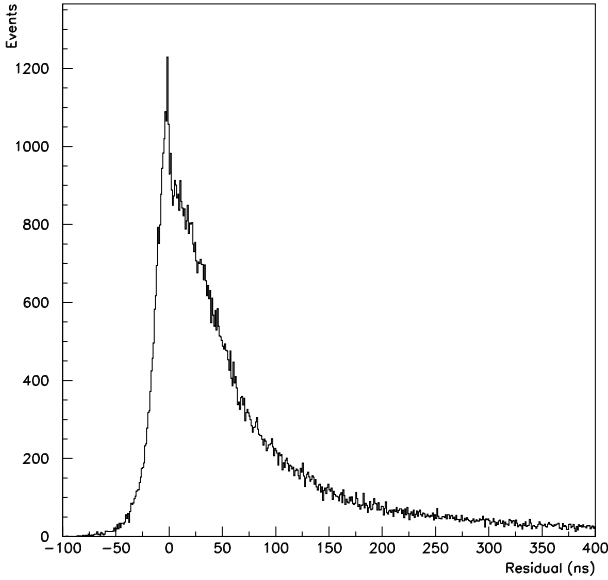
Fig. 1. Time residual distribution measured for an AMANDA optical module. The large peak close to the origin is populated by Cherenkov photons which arrive directly at the OM from point of emission with little or no scattering. The extended tail at large residual times is created by photons which scatter in the ice and arrive at the OM late. Negative times, which are acausal, are caused by electronic time jitter in the PMTs ($\sigma \approx 10$ ns) and track misreconstructions.

The quantity T_0 enters Eq. 1 since the OM hit time, t_{OM}, is reconstructed from the time measured by the surface electronics, t_{TDC}, by $t_{OM} = t_{TDC} - T_0$. The muon T_0 calibration varies each OM's T_0 in order to correct offsets in the measured timing residuals for that channel. It does this for all channels simultaneously, iteratively as follows:

1. Estimate the initial T_0s.

2. Fit tracks using standard reconstruction software.

3. Looping over all tracks, accumulate the time residuals for each OM and store in a histogram or other convenient structure.

4. For each OM, determine the effective offset from the residual distribution. A method to accomplish this is described below.

5. Subtract a fraction, α, of this offset from that OM's T_0. Using $0 < \alpha < 1$ ensures that each step does not overcorrect the offset and speeds convergence.

6. Return to step 2, terminating when the mean effective offsets have all become sufficiently small.

3 Practical implementation issues

3.1 Determining the initial calibrations

In order to produce time residual distributions, the telescope must have a source of muon tracks which pass sufficiently

close to the optical detecting elements. These could come from a surface array, as in the situation of the SPASE and AMANDA detectors (Andres, 2000). If the telescope itself is needed to reconstruct these tracks then a preexisting set of calibrations is required. These calibrations could be provided by previous calibrations, if the detector is calibrated in a periodic fashion, or rough first guesses if no prior information exists. Another likely scenario for neutrino telescopes under construction is that a portion of the detector has been deployed and is already calibrated. In that case, tracks from this portion which extend into the region containing newly-deployed modules can be used to bootstrap the calibrations of the new modules.

For the case of seeding the calibration with guesses, the question arises as to how stable this procedure is against poor first guesses. This is a general problem in nonlinear minimization problems where often it is impossible to tell whether the system has converged to a true minimum or rather just one of many local minima. Since we do have an alternate means of obtaining the global solution in AMANDA (the laser calibration system) it is possible to experimentally determine whether the muon T_0 calibration does indeed converge to the correct minimum from a crude first guess. We have performed several tests to demonstrate that the muon calibration can recover the global solution.

Shown in Figure 2 is a summary of the results of a test on the full AMANDA-II detector where we had intentionally shifted the T_0s for a large fraction of the OMs by significant amount and asked the muon T_0 calibration to return the detector to the correct timing calibration. The solid line shown in the figure shows the amount by which the modules were shifted: to explore the resilience against different types of systematic offsets we decided to change strings 2, 14, and 15 by ± 100 ns, strings 7 and 8 by a depth-dependent amount, and string 19 with a sinusoidal pattern. The muon calibration iterated over this configuration 50 times and arrived at the answer that the detector T_0s should be shifted by an amount indicated by the triangles.

3.2 Calculation of offsets from time residuals

The distribution of time residuals is a complex structure arising from optical photon scattering in the ice. Determining what offset to apply to a particular OM solely from this distribution is therefore not straightforward. There are several solutions to this problem. Fitting the distribution with heuristic functions and statistical comparisons of the histograms with Monte Carlo generated distributions with null offset were considered. In the end we decided to use a *matched filter* correlation since it was applicable to distributions with very sparse statistics. The matched filter correlation finds the maximum cross-correlations of a measured time residual distribution against Monte Carlo generated distributions at various predetermined offsets (Ifeachor and Jervis, 1993). The offset that produces the maximum cross-correlation is
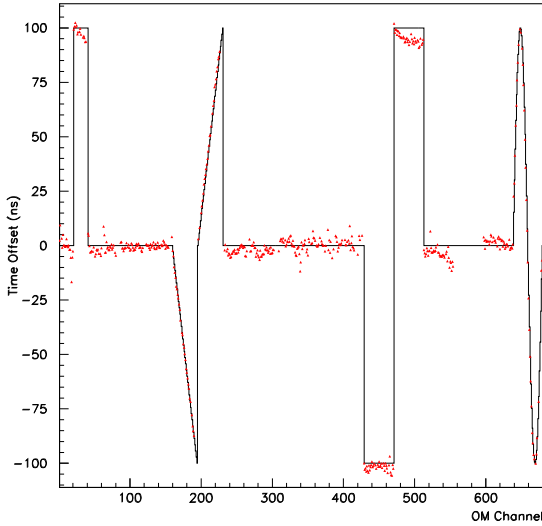
Fig. 2. Results of a muon calibration of AMANDA-II where the correct solution was known from laser calibration. Each OM along the x-axis was intentionally shifted away from its calibrated value by an amount shown as the solid line. The muon calibration had to recover from this shift by correcting in the opposite direction. After 50 iterations the calibration had achieved the shift shown by the triangles.

Fig. 3. The width of the distribution of timing corrections applied, $\sigma(\Delta T_i)$, as it diminishes versus iteration count (solid line). The mean track fit quality versus iteration, given in arbitrary units (dashed line); larger values imply better track fits. As is evidenced from the figure, most of the movement for both curves occurs during the first few iterations. This is caused by the presence of outliers which are very quickly moved into the bulk of the distribution. Once this happens, convergence slows.

taken as the offset of the measured distribution. Since it effectively integrates over all bins of the histograms it continues to give reliable results at low histogram occupancies. By exploiting the convolution theorem (Press, 1992), this procedure can also be executed very quickly with FFTs (Frigo and Johnson, 2001).

3.3 Convergence

At the end of each iteration, the timing corrections applied during that iteration step are histogrammed and the width of the distribution is recorded. As the system converges to a solution, the individual T_0 corrections should converge to a common limit [1] and the magnitude of the spread of the points about this limit provides an estimator of the RMS error of the T_0 quantities.

Additionally, an average quality of fit – proportional to the track likelihood used in the maximum likelihood fitting (see Andres (2000) for a description of track reconstruction techniques) – is monitored for each iteration. An increase in overall fit quality is observed at successive iterative steps. These points are illustrated in Figure 3, taken from a recent muon calibration of AMANDA-II T_0s.

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[1]This limit is not necessarily zero in AMANDA. AMANDA T_0s are unique up to a global offset. Thus in each iteration the average value of the timing corrections applied to all channels is a free parameter. This point is brought up since it does occur in practice.
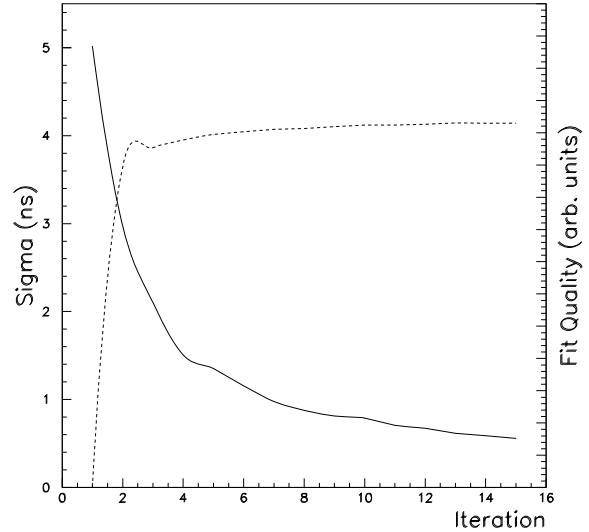
3.4 Data processing requirements

A high-statistics muon calibration for AMANDA requires approximately 5×10^5 raw events. While this data volume represents only a small fraction of the data recorded by the detector each day – about 2 hr of continuous live-time – the time required to process the many iterations necessitated by the muon T_0 calibration is large. Fortunately, recent developments in AMANDA reconstruction techniques have delivered fast track fitting code which should greatly reduce the computing cost of this calibration method.

4 Accuracy

The theoretical accuracy of the muon calibration is estimated to be less than 1 ns. This is taken from the plot of the width of the distribution of timing corrections at the final iteration step (Figure 3). However, systematic effects introduce an RMS error of 8 ns when the muon and laser calibrations are compared. These systematics, which are as yet not completely understood, give a relative difference between laser and muon T_0 which is depth-dependent. At any rate, the laser calibration is estimated accurate to 8 ns itself, and, moreover, detailed studies of the effects of T_0 calibration on reconstruction have shown that errors of order even 20 ns do not significantly affect the reconstruction (Biron, 2000).

5 Other calibration applications of downward muons

In the next-generation deep ice detector, IceCube, the optical modules are expected to digitize the PMT pulses *in situ* and will additionally calibrate their own timing offsets (Goldschmidt, these proceedings). In such a situation we have recently begun to explore the possibility of obtaining other calibration information from the downward muons. Results from recent simulations indicate the possibility of calibrating geometrical positions of the detectors by minimizing a reconstruction likelihood function over a discrete grid of points surrounding each OM.

We also believe that detector monitoring tools could incorporate an automatic calibration process such as has been described here. Since the calibration relies on higher level event information, and T_0 values should not be volatile quantities, monitoring the stability of T_0 values could be an elegant way to check the detector performance at the highest levels.

6 Conclusions

We have discussed a method by which calibration of relative timing offsets between the optical detectors in Cherenkov neutrino telescopes may be obtained using atmospheric muon data. The method outlined was specific to the AMANDA detector, however, the technique is applicable to other existing and nascent neutrino telescopes provided the flux of atmospheric muons is not too low. The muon calibration has been shown to furnish OM timing offset measurements accurate at least to the level of 8 ns, the timing precision required of the laser calibration. It has also provided the only means of calibrating the T_0s for OMs that had broken laser fibers: this includes most of string 17 which deployed several hundred meters above the other strings of AMANDA-II. An event showing track reconstruction from hits on this string as well as the lower AMANDA-II strings – and thus an observable track length of over 1 kilometer – is presented in Figure 4. The AMANDA collaboration has adopted the muon calibration in conjunction with the laser calibration for data collected from 2000 onward.
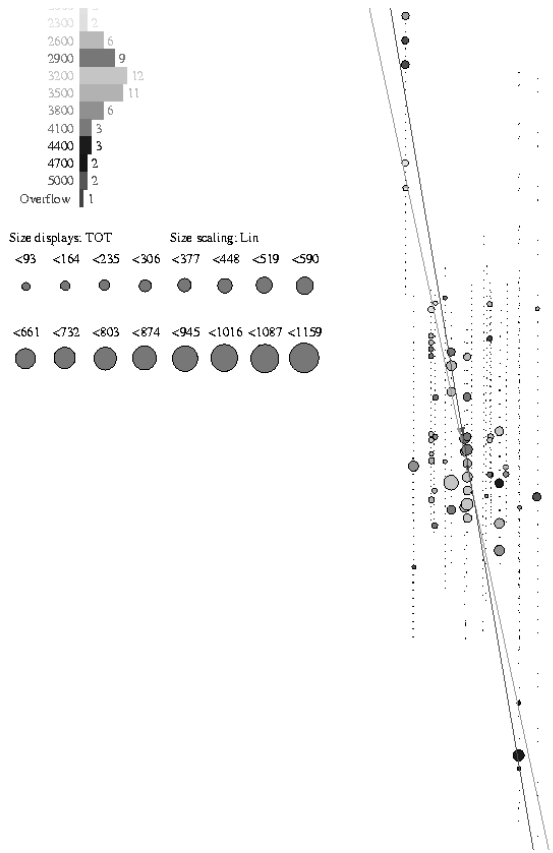
Fig. 4. A muon track reconstructed using optical hits from over 1 km of the muon's pathlength. This is the longest track so far reconstructed by the AMANDA-II detector.

References

Andres, E. et. al. (2000), The AMANDA neutrino telescope: principle of operation and first results, Astropart. Phys., 13, 1–20, 2000.

Biron, A. (2000), Reconstruction uncertainties due to time calibration errors, AMANDA Internal Report AMANDA-IR/20001101.

Frigo, M. and Johnson, S., FFTW Homepage, *http://www.fftw.org*

Goldschmidt, A. for the AMANDA Collaboration (2001), these proceedings.

Ifeachor, E. and Jervis, B. (1993), *Digital Signal Processing*, Chapters 4 and 12. Workingham: Addison-Wesley

Wischnewski, R. for the AMANDA Collaboration (2001), these proceedings.

Press, W., Teukolsky, S., Vetterling, W., and Flannery, B. (1992) *Numerical Recipes in FORTRAN*, Chapter 13. Cambridge: Cambridge University Press