Improved Reconstruction of Cascade-like Events in IceCube

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Abstract. **Cascade-like events are one of the main signatures in the IceCube neutrino detector. This signature includes electromagnetic and hadronic particle showers from charged or neutral current interactions and hence it provides sensitivity to all neutrino flavours. At energies below 10 PeV these cascades have characteristic lengths of only several meters. Compared to the dimensions of the detector they appear as point-like but anisotropic light sources. We present a new approach to the reconstruction of such events. A maximum likelihood algorithm that incorporates the results of detailed simulations of the light propagation in ice, allows for a significantly better analysis of the recorded photon intensities and arrival times. The performance of the algorithm is evaluated in a Monte Carlo study. It suggests that for cascades an angular resolution of 30° is possible.**

***Keywords*: IceCube, cascades, reconstruction**

I. INTRODUCTION

The IceCube detector [1] is being built at the geographical South Pole. It aims for the detection of neutrinos of cosmic origin, which could answer open questions in astroparticle physics such as the origin of cosmic rays and the nature of dark matter. In its originally planned setup the IceCube detector consists of 4800 digital optical modules (DOMs) on 80 strings. These are horizontally spaced by 125 m and located in depths ranging from 1.45 to 2.45 km, thereby spanning a volume of a cubic kilometer of glacial ice. In order to lower IceCube's energy threshold down to 10 GeV, the DeepCore extension will arrange 6 additional strings in the center of the array. On these strings the DOMs are closer to each other and are located in depths with optimal optical properties.

Each DOM contains a photomultiplier tube (PMT) and the necessary readout electronics. Two digitization devices allow for the measurement of time distributions and intensities of photon fluxes inside the detector: the Analog Transient Waveform Digitizer (ATWD) taking 128 samples over the first 420 ns and the Flash Analog-to-Digital Converter (FADC) taking 256 samples in an interval of 6.4 μs [2]. Presently three quarters of the detector are successfully deployed and are taking data.

Neutrinos can interact in the instrumented volume through neutrino-nucleon or neutrino-electron scattering. The former process dominates. One exception is the resonant scattering of anti-electron neutrinos on atomic electrons at energies of 6.3 PeV, known as the Glashow resonance. The neutrino interaction is not detected directly but it can produce charged particles which emit Cherenkov light in the transparent detector medium. The possible final states of a neutrino interaction depend on the flavour and interaction type. For neutrino astronomy the most prominent neutrino signature is formed by final states with an emerging muon. They allow to deduce the neutrino direction and provide large effective areas because of the large range of the muon.

The signatures of interest here are neutrino induced electromagnetic and hadronic particle showers. Such cascades can originate from all neutrino flavours and occur in many of the interaction scenarios. Assuming that the neutrinos were generated in pion decays one expects a flavour ratio at the source of $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$. Due to neutrino oscillations this ratio is transformed to $1 : 1 : 1$ before detection, which makes the sensitivity to all flavours important.

Furthermore, electromagnetic cascades allow for a good energy reconstruction, since the number of emitted photons scales linearly with the deposited energy. Hadronic cascades appear similar to electromagnetic ones, with the small correction that for the same deposited energy there are about 20% fewer photons produced [3].

Below 10 PeV cascades have characteristic lengths of several meters. Compared to the distances between the DOMs they appear as point-like light sources. Nevertheless, the angular emission profile of a cascade is anisotropic: the photons originate from one point but they are preferably emitted in the direction of the Cherenkov angle $\Theta_c = 41^\circ$ [4]. Therefore, close to the interaction vertex the neutrino direction can in principle be derived from the angular distribution of the Cherenkov photons. For the large spacing of the DOMs this ability is impaired due to the strong light scattering in the ice [5]. Because of this inherent difficulty of reconstructing the direction of particle showers in ice, studies of these events have been restricted to the search for a diffuse flux of neutrinos. In this situation even a rough estimate on the neutrino detection would enhance the possibilities of this detection channel.

II. NEW APPROACH TO CASCADE RECONSTRUCTION

The existing maximum likelihood reconstruction for cascades [3] does not account for the inhomogeneity of the ice and does not try to reconstruct the neutrino direction. It also does not exploit all the capabilities of the IceCube DAQ.

The aim of the current work is to use all relevant information in the waveforms captured by the DOMs to reconstruct the incident neutrino in a cascade-like event. The point-like but directed cascade can be fully described by 7 parameters: the time and vertex (t,x,y,z) of the neutrino interaction, the deposited energy E and the direction of the neutrino. The latter is described by the two angles zenith Θ and azimuth ϕ. The reconstruction searches for the set of these parameters $\underline{c} = (t,x,y,z,E,\Theta,\Phi)$ that fits the observation best.

A good understanding of the optical properties of the glacial ice is crucial to the IceCube experiment. The instrumented volume is pervaded with dust layers that track historic climatological changes. Since the propagation of light in such an inhomogeneous medium cannot be treated analytically, the Photonics Monte Carlo package [6], [7] has been used. Its simulation results are available in tabulated form. For a given setup of a light source and a DOM these tables allow to make predictions for the mean expected amplitude $\langle\mu(\underline{c})\rangle$ and the photon arrival time distribution $p(t_d,\underline{c})$, where t_d denotes the delay time. For a photon with speed c_{ice} that is emitted at $(t_e,\vec{x}_e)$ and recorded at $(t_r,\vec{x}_r)$ the time $t_d = t_r - t_e - |\vec{x}_r - \vec{x}_e|/c_{ice}$ denotes the additional time the photon takes to reach the receiver over a scattered path rather than a straight line. Scattering in ice can cause delay times up to a few microseconds. Depending on orientation and distance of the cascade with respect to the DOM the arrival time distributions differ in shape (compare Figure 1).

With the tabulated quantities the expected amplitude in a time interval $[t_1,t_2]$ calculates to:

$$\mu(\underline{c}) = f\,\langle\mu(\underline{c})\rangle \int_{t_1}^{t_2} p(t_d,\underline{c})\,dt_d + R_{\text{noise}}(t_2 - t_1) \qquad (1)$$

Two small corrections are applied to the prediction of Photonics. A constant rate R_{noise} accounts for noise hits and a factor f corrects for deviations from the mean amplitude due to the PMT response and charge reconstruction, which is not modelled by Photonics.

With this prediction a likelihood description of the measurement is possible. Assuming a Poisson process for every distinct[1]sample i taken by the ATWD and the FADC in DOM o, one can compare the measured amplitude n_{oi} to the mean expectation μ_{oi} and construct the likelihood:

$$L = \prod_{o,i} \frac{\mu_{oi}(\underline{c})^{n_{oi}}}{n_{oi}!} \exp\{-\mu_{oi}(\underline{c})\}. \qquad (2)$$

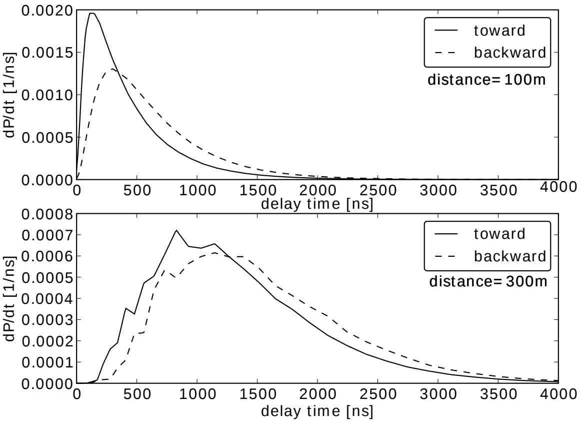

Fig. 1. Tabulated delay time distributions for a DOM at 100 m and 300 m distance to the cascade. The distributions are shown for two orientations of the cascade, pointing either toward or away from the DOM. Photons are increasingly delayed if they either travel larger distances or have to be backscattered to reach the DOM.

By taking the negative logarithm and rearranging the terms one obtains:

$$-\log(L) = \sum_o \langle\mu_o\rangle - n_o \log\langle\mu_o\rangle - \sum_i n_{oi} \log\left(\frac{\mu_{oi}}{\langle\mu_o\rangle}\right) \quad (3)$$

where $\langle\mu_o\rangle = \sum_i \mu_{oi}$ and $n_o = \sum_i n_{oi}$. The combinatorial term from the Poisson probability has been omitted since it does not depend on the reconstruction hypothesis.

A considerable speedup in the computation results from the fact that in the sum over the samples i only time intervals with $n_{oi} > 0$ contribute. Hence, periods in the DOM readout with no measured charge can be ignored. Practically this is implemented in two steps: first the waveform is scanned for pulses, then these pulses are used to calculate the likelihood.

The cascade reconstruction is performed by searching numerically for the minimum of $-\log(L)$, which is a function of the seven cascade parameters. This minimization is seeded with the time, vertex and direction estimates that one obtains from calculating the center of gravity and tensor of inertia of the hit pattern. These calculations are implemented in IceCube's first-guess reconstruction algorithms. The number of triggered DOMs provides a rough estimate of the deposited energy. The minimization is done by MINUIT with a simplex algorithm that is executed iteratively to improve the result stepwise.

The problem can be significantly simplified if the vertex and the time of the interaction are already known (e.g. when they are determined by another method) and the orientation of the cascade is neglected. Then the likelihood, which now only depends on the cascade energy, provides an energy reconstruction that benefits

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[1] In the first 420 ns the readout windows of the ATWD and FADC overlap. One has to choose between both measurements. Because of its precision, the samples from the ATWD are preferred.

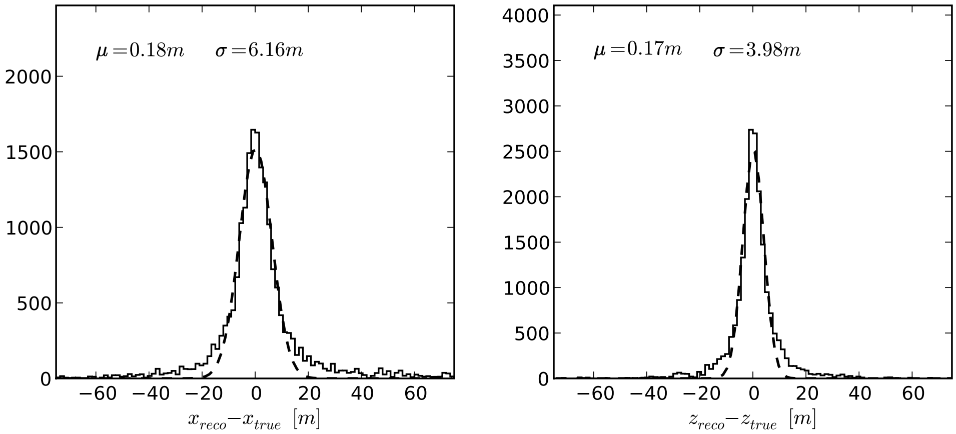

Fig. 2. Offsets between the reconstructed and the true x and z coordinates obtained from an iterative minimization of the 7 dimensional likelihood. Only cascades are selected, whose reconstructed vertex is contained in IC40. The width σ of a fitted Gaussian defines the resolution, which is better for z because of the denser DOM spacing along the string.

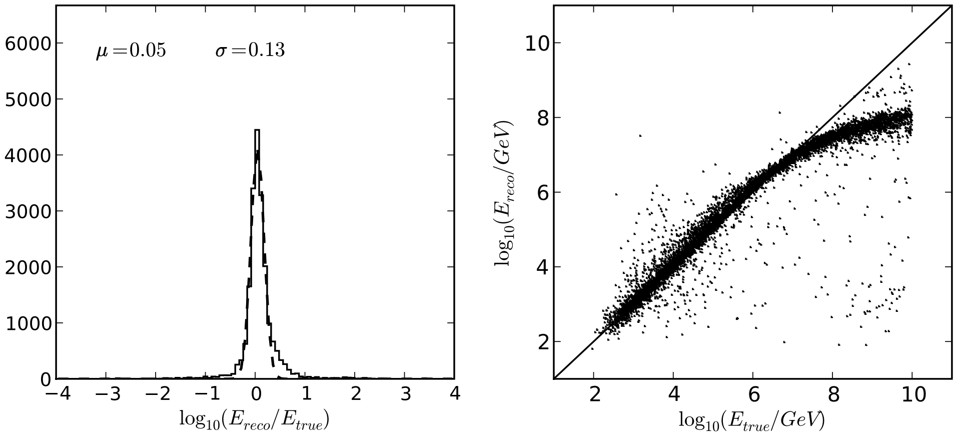

Fig. 3. Left: Offset between the reconstructed and the deposited logarithmic energy for the same event sample. Right: Comparison between the reconstructed and the deposited logarithmic energy. The deviation from the identity line above 10 PeV illustrates the increasing impact of saturation effects on the energy reconstruction.

from the improved light-propagation model. In this case, the search for the minimum is reduced to a numerical root finding problem:

$$\frac{\partial(-\log(L))}{\partial E} = \sum_o \left(\mu_o - \frac{n_o}{1 + \frac{R_{noise}\Delta t}{\mu_o}} \right) = 0 \qquad (4)$$

where Δt denotes the readout window length.

III. RESULTS

The reconstruction algorithm has been tested with a simulated electron neutrino dataset for IceCube in its year 2008 configuration with 40 strings. The primary neutrinos have energies in the range from $10^{1.7}$ GeV to 10^{10} GeV and are weighted to an E^{-2} spectrum. For the simulation of showers the parametrization derived in [4] and implemented in Photonics is used. Lower energetic showers ($<$ PeV) are represented as point-like light source with an anisotropic emission profile. At PeV energies the cascade is split up into several cascades to simulate the elongation due to the LPM effect.

To be part of the further on used event selection, an event has to trigger the detector, the reconstruction must converge (fulfilled by 79%) and the reconstructed vertex has to be located inside the geometric boundaries of the detector (fulfilled by 38%).

To evaluate the resolution of the reconstruction the distribution of offsets between the reconstructed and the true vertex coordinates and energies are shown in Figures 2 and 3. The obtained vertex resolutions are about 7 m in x and y and 4 m in z. This is an improvement with respect to the existing likelihood reconstruction [8]. For the same dataset and selection criteria it yields resolutions of 15 m in x and y and 8 m in z. The better resolution in z results from the smaller distances of only

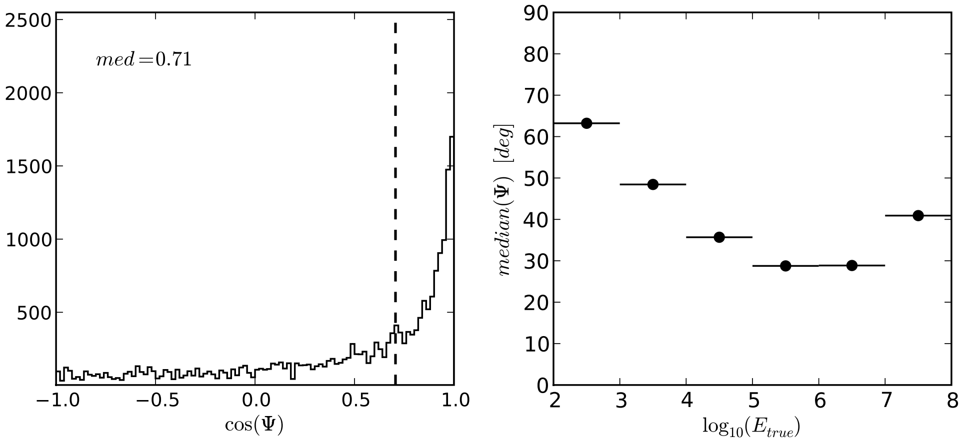

Fig. 4. Left: Distribution of the cosine of the angle between the reconstructed and the true direction. The angular resolution is given by the median. Right: Angular resolution as a function of the energy.

17 m between the DOMs on one string.

The result of the energy reconstruction is shown in Figure 3. A resolution of $\sigma(\log_{10}(E_{reco}/E_{true})) = 0.13$ has been obtained. For large photon fluxes, which can originate from highly energetic or nearby cascades, the saturation of the PMT limits the recorded charge. This affects the energy reconstruction as can be seen in the right plot of Figure 3. Above 10 PeV the reconstructed energy is systematically too low due to the saturation.

A useful measure for the angular resolution is the median of the $\cos(\Psi)$ distribution, where Ψ is the angle between the true and the reconstructed direction. For all events that fulfill the selection criterion this distribution is plotted in the left plot of Figure 4. A study of the energy dependence suggests that for the interesting energy range of 10 TeV to 10 PeV an angular resolution of $30^\circ - 35^\circ$ is possible (right plot in Figure 4). At energies above 10 PeV, the LPM effect leads to an elongation of the cascade and the reconstruction hypothesis of a point-like light source becomes no longer applicable.

IV. SUMMARY AND OUTLOOK

A maximum likelihood reconstruction for cascade-like events has been developed. It takes into account the full recorded waveform information as well as the ice properties. A simulation study for the 40 string detector geometry of the year 2008 demonstrates the feasibility of an angular resolution of down to 30°. Compared to muons this is still a very limited precision, but it can provide new opportunities for neutrino searches with cascade-like events. With the angular resolution achieved, the discrimination between upward and downward going neutrinos becomes possible as well as the identification of neutrinos originating from the galactic plane. With the DeepCore extension a further improvement is expected.

The achieved results have to withstand further verification. The next step is to test the performance of the algorithm on measurements with LED and laser light sources in the detector and muon events with bright bremsstrahlung cascades. Several possibilities to enhance the algorithm exist. A different description of saturated DOMs in the likelihood could improve the performance at higher energies. It will be investigated if the shape of the likelihood could be used to estimate the error of the reconstruction. Finally, the presented approach can be extended to reconstruct combined events with more than one light source in the detector.

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