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Robust Statistics in IceCube Initial Muon Reconstruction

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Abstract: In the IceCube Neutrino Detector, muon tracks are reconstructed from the muon's light emission. The initial track reconstruction serves as a starting point for more sophisticated track fitting using detailed knowledge of the ice and the detector. We describe here a substantial improvement on the initial track reconstruction for muons. The approach is to use simple physical models coupled with robust statistical techniques. Using the metric of median angular accuracy, a standard metric for path reconstruction, this solution improves the accuracy in the reconstructed direction by 13 percent.

Keywords: Icecube, Muons, Track Reconstruction.

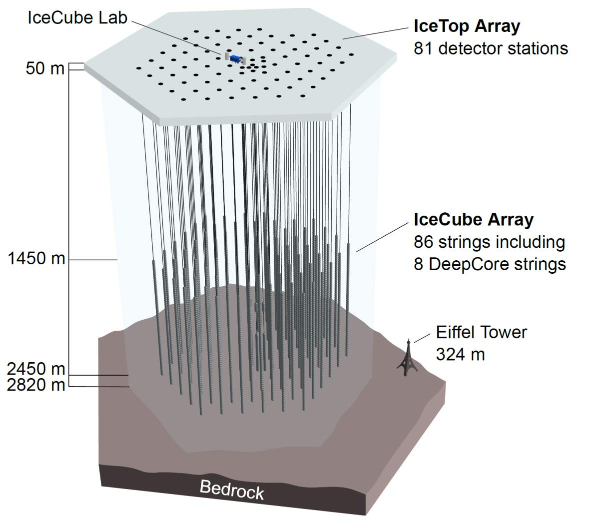

Fig. 1: The IceCube neutrino detector in the Antarctic ice. A picture of the Eiffel Tower is shown for scale.

1 Introduction

The IceCube neutrino detector searches for neutrinos that are generated by the universe's most violent astrophysical events: exploding stars, gamma ray bursts, and cataclysmic phenomena involving black holes and neutron stars [1]. The detector, roughly a cubic kilometer in size, is located near the geographic South Pole and is buried to a depth of about 2.5 km in the Antarctic ice [2]. The detector is illustrated in Figure 1 and a more complete description is given in Section 2.

This manuscript describes an improvement in the reconstruction algorithm used to generate the initial path reconstruction of detected muons.

2 Background

The IceCube detector is composed of 5160 optical detectors, each composed of a photomultiplier tube (PMT) and onboard digitizer[5]. The PMTs are spread over 86 vertical strings arranged in a hexagonal shape, with a total instrumented volume of approximately a cubic kilometer. The PMTs on a given string are separated vertically by 17 m, and the string-to-string separation is roughly 125 m.

When a neutrino enters the telescope, it sometimes interacts with the ice and generates a muon. As the muon travels though the detector, it radiates light[6], which is observed by the PMTs and broken down into discrete *hits*[7]. A collection of hits is called an *event*, and if the number of hits in an event is sufficiently large, the muon path reconstruction algorithm is triggered.

2.1 Cosmic Ray Background

In addition to neutrinos, muons can also be generated by cosmic rays. IceCube analyses on neutrinos are not interested in cosmic ray muons, and the detector attempts to separate out the cosmic ray muons from the neutrino muons.

The primary mechanism for this separation is reconstructing the muon path, and determining if the muon was traveling downwards into the Earth or upwards out of the Earth. Since neutrinos can penetrate the Earth but cosmic ray muons cannot, it follows that a muon traveling out of the Earth must have been caused by a neutrino. Thus, by selecting only the muons that are reconstructed as up-going, the cosmic ray muons can, in principle, be removed from the data.

2.2 Challenges in Neutrino Detection

Recovering the muon path from the light measurements is the *reconstruction* problem. The reconstruction algorithms used in the detector have several challenges which must be overcome. The underlying mechanics are stochastic and incompletely modeled, the data is noisy and contains outliers, and the computational abilities of the detector are limited.

Modeling Difficulties The underlying physics of the system are nontrivial to model. The muon's light is scattered by the dust and air crystals in the ice medium. This scattering is both complex and stochastic, and the scattering properties of the ice vary with depth [8].

Noise An unescapable challenge is the noise inherent in the data. The PMTs are so sensitive to light that they can record hits even in the absence of nearby muons. These hits can arise from photons generated either by radioactive decay inside the PMT or the triboluminescence [9] of the ice.

Computational Constraints The reconstruction algorithms are also limited in complexity by the computing resources available at the South Pole. The path reconstruction algorithm has to process about 3000 muons per second, so algorithms with excessive computational demands are discouraged.

Cosmic Ray to Neutrino Ratio While the cosmic ray muons can in principle be removed by selecting only muons reconstructed as up-going, the number of observed cosmic ray muons exceeds the number of observed neutrino muons by five orders of magnitude [3]. Thus, high accuracy reconstructions are critical for preventing erroneously reconstructed cosmic ray muons from dominating the neutrino analysis.

3 Reconstruction Problem

By augmenting the reconstruction algorithm with some more robust data analysis techniques, we show significant improvement in the reconstruction algorithm's accuracy.

3.1 Prior IceCube Software

The muon path reconstruction process (outlined in Figure 2) starts when the number of detected hits exceeds a preset threshold and the data collection step triggers. After the initial data is collected, it then passes though a series of simple filters to remove obvious outliers, described more in [10].

This is followed by a simple reconstruction algorithm *linefit*, which simply finds the track that minimizes the sum of the squares of the distances between the track and the hits. More formally, assume there are N hits, and denote the position and time of the ith hit as $\vec{x}_i$ and t_i respectively. Let the reconstructed muon path have a velocity of $\vec{v}$, and let the reconstructed path pass though point $\vec{x}_0$ at time t_0. Then linefit reconstruction solves the *least-squares* optimization problem

$$\min_{t_0,\vec{x}_0,\vec{v}} \sum_{i=1}^{N} \rho_i(t_0,\vec{x}_0,\vec{v})^2, \tag{1}$$

where

$$\rho_i(t_0,\vec{x}_0,\vec{v}) = \|\vec{v}(t_i - t_0) + \vec{x}_0 - \vec{x}_i\|_2 \,. \tag{2}$$

The linefit reconstruction is primarily used to generate an initial track or *seed* for a more sophisticated reconstruction.

The reconstruction algorithm used in the sophisticated reconstruction *SPE*, is described further in [3]. SPE takes as input the least-squares reconstruction and the event data, and uses a likelihood maximization algorithm to reconstruct the muon path.

3.2 Algorithm Improvement

SPE is dependent on the seed. Given a seed that is inaccurate by greater than or equal to 6°, SPE typically cannot recover, and also produces a reconstruction inaccurate by greater than or equal to 6°. In addition, the likelihood space for SPE can contain multiple local maxima, so improving the accuracy of a seed already near the true solution still improves the accuracy of SPE. Thus, we focused our work on improving the quality of the seed.

As indicated in Equation 1, a least-squares fit models the muon as a single point moving in a straight line, and hits are penalized quadratically in their distance from this line. Thus there is an implicit assumption in this model, which is that all the hits will be near the muon. There are several pitfalls in this assumption:

1. It ignores the scattering effects of the ice medium. Some of the photons can scatter for over a microsecond, which means that when they are recorded by a PMT, the muon will be over 300 m away.

2. While the noise reduction steps remove most of the outlier noise, the noise hits that survive can be far from the muon. Since these outliers are given quadratic weight, they exert a huge influence over the model.

The first pitfall is a case of the model being incomplete and not modeling the data, and the second amounts to the model not being robust to noise. Our solution was twofold: improve the model and increase the noise robustness by replacing least squares with robust statistical techniques.

3.2.1 Improving the Model

The least-squares model does not model the scattering, and thus hits generated by photons that scattered for a significant length of time are not useful predictors of the muon's position. We found that a simple filter could identify these scattered hits, and generate an accuracy improvement of almost a factor of two by removing them from the dataset.

More formally, for each hit h_i, the algorithm looks at all neighboring hits within a neighborhood of r, and if there exists a neighboring hit h_j with a time stamp that is t earlier than h_i, then h_i is considered a scattered hit, and is not used in the simple reconstruction algorithm. Optimal values of r and t were found to be 156 m and 778 ns by parameter search.

3.2.2 Adding Robustness to Noise

One of the fundamental problems with least squares is that outliers are given a quadratic influence, whereas an ideal model would give outliers zero influence. Such an ideal model does not exist, but classical statistics has developed models where outliers can be marginalized. We experimented replacing the least-squares model with a variety of more robust models: a deadzone-linear fit, a one-norm fit, and a Huber fit [11].

Of the models that we tested, the Huber penalty function gave the greatest increase in reconstruction accuracy. More formally, we replace Equation 1 with the optimization problem

$$\min_{t_0,\vec{x}_0,\vec{v}} \sum_{i=1}^{N} \phi(\rho_i(t_0,\vec{x}_0,\vec{v})), \tag{3}$$

where the Huber penalty function $\phi(\rho)$ is defined as

$$\phi(\rho) \equiv \begin{cases} \rho^2 & \text{if } \rho < \mu \\ \mu(2\rho - \mu) & \text{if } \rho \geq \mu \end{cases} . \tag{4}$$

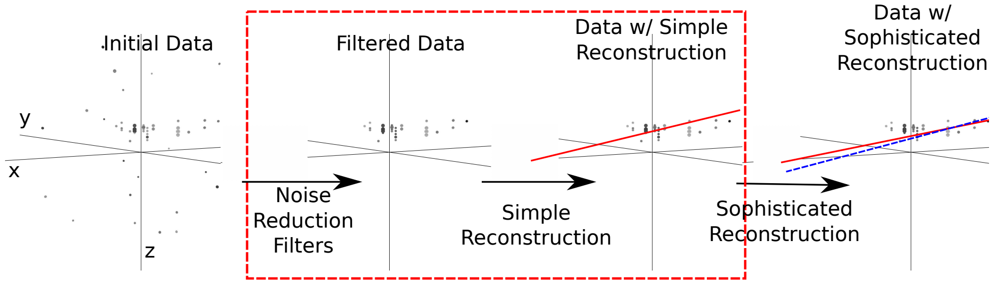

Fig. 2: The reconstruction pipeline used to process data in the IceCube detector. After initial data is collected, it is then processed by some simple noise filters, which remove clear outliers. This cleaned data is processed by a simple reconstruction algorithm (red line), which is used as the seed for the more sophisticated reconstruction algorithm (dashed blue line). The sophisticated reconstruction is then evaluated as a potential neutrino. Our work in the reconstruction problem makes changes to the filtering and simple reconstruction step (indicated by the dashed red box).

Table 1: Median angular resolution (degrees) for reconstruction improvements. The first line is the accuracy of the prior least-squares model, and the subsequent lines are the accuracy measurements from cumulatively adding improvements into the simple reconstruction algorithm.

Algorithm	θ_{med}
Linefit Reconstruction (Least-Squares)	9.917
With Addition of Logical Filter	5.205
With Addition of Huber Regression	4.672
With Addition of Outlier Removal	4.211

Here, $\rho_i(t_0, \vec{x}, \vec{v})$ is defined in Equation 2 and μ is a constant calibrated to the data (for this application, the optimal value of μ is 153 m).

The Huber penalty function has two regimes. In the near-hit regime ($\rho < \mu$) hits are assumed to be strongly correlated with the muon's path, and the Huber penalty function behaves like least squares, giving these hits quadratic weight. In the far-hit regime ($\rho \geq \mu$), hits are given linear weights as they are more likely to be noise.

In addition to its attractive robustness properties, the Huber fit's weight assignment also has the added benefit that it inherently labels points as outliers (those with $\rho \geq \mu$). Thus, once the Huber fit is computed, we can go one step farther and simply remove the labeled outliers from the dataset. A better fit is then obtained by computing the least-squares fit on the data with the outliers removed. The mean total runtime of the new algorithm is approximately six times that of Linefits mean runtime.

3.3 Results

To measure the improvement generated by our changes, we use the metric of *median angular resolution* θ_{med}, which is a standard metric used in the collaboration. The angular resolution of a reconstruction is the arc-distance between the reconstruction and the true path. Removing the scattered hits and adding robustness to the model generates measurable a improvement to the model's accuracy, as shown in Table 1.

We can improve the median angular resolution of the simple reconstruction by 57.6%. Seeding SPE with the improved simple reconstruction generates an improvement in the angular resolution of 12.9%. These improvements in the reconstruction algorithm result in 10% fewer atmospheric muons erroneously reconstructed as up-going, and 1% more muons correctly reconstructed as up-going.

4 Conclusions

The challenges in the IceCube detector are complex. Despite this complexity, we found that we can achieve significant improvement via classical data analysis algorithms and simple models.

We looked at the problem of general reconstruction improvement, and found that by applying a simple filter to the data and adding some robustness to the fitting algorithm, we got superior reconstructions in the noisy environments of the IceCube data. Our reconstruction software runs on-site, and is included in all IceCube analysis.

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