ROBUST STATISTICS IN ICECUBE INITIAL MUON RECONSTRUCTION

THE ICECUBE COLLABORATION,
M. WELLONS[1] (MWELLONS@CS.WISC.EDU), B. RECHT[1], C. RÉ[1]
[1]Dept. of Computer Sciences, University of Wisconsin, Madison, WI 53706, USA

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. The improvement in the initial track reconstruction described here uses simple physical models with robust statistical techniques to improve the accuracy in the initial track reconstruction for muons. Using the metric of median angular accuracy, this solution improves the accuracy in the reconstructed direction by 13%.

BACKGROUND

The IceCube neutrino detector is

- near the geographic South Pole, buried at depths 1.5-2.5 km in the Antarctic ice
- composed of 5,160 optical detectors, spread over 86 vertical strings arranged in a hexagonal shape
- has a total instrumented volume of approximately one cubic kilometer

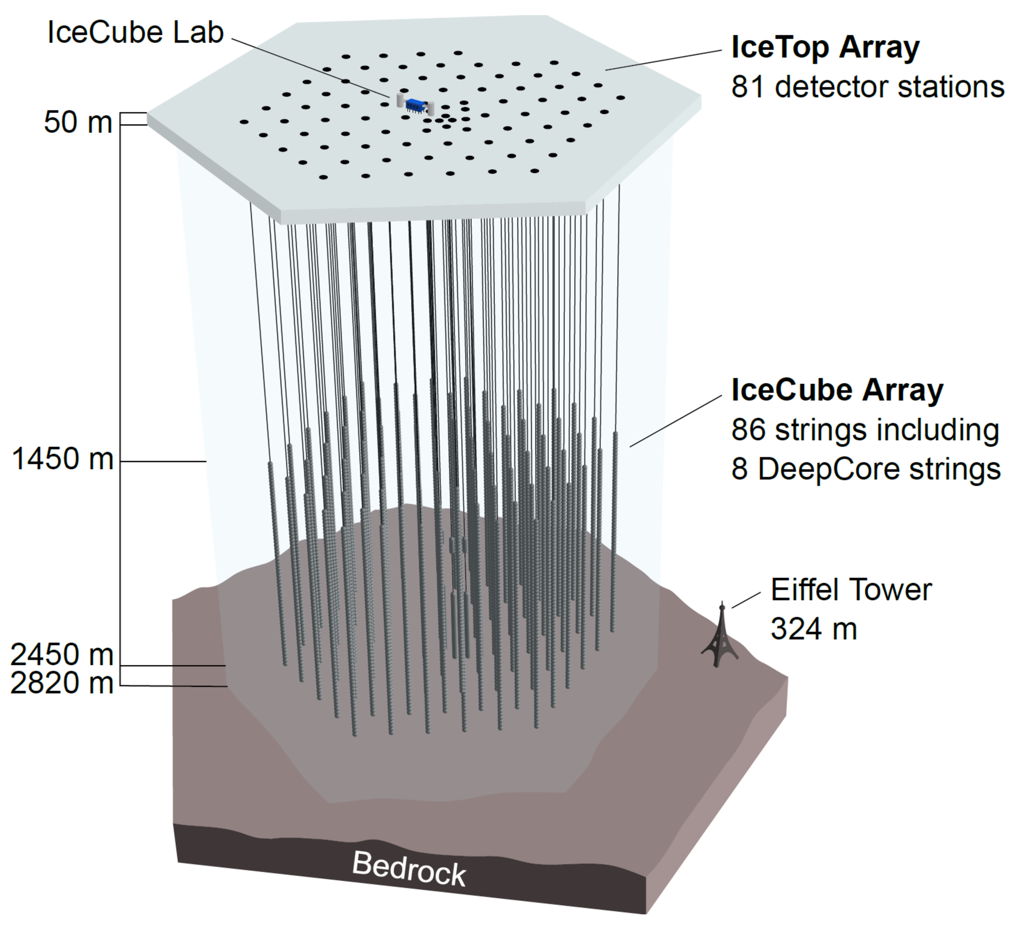
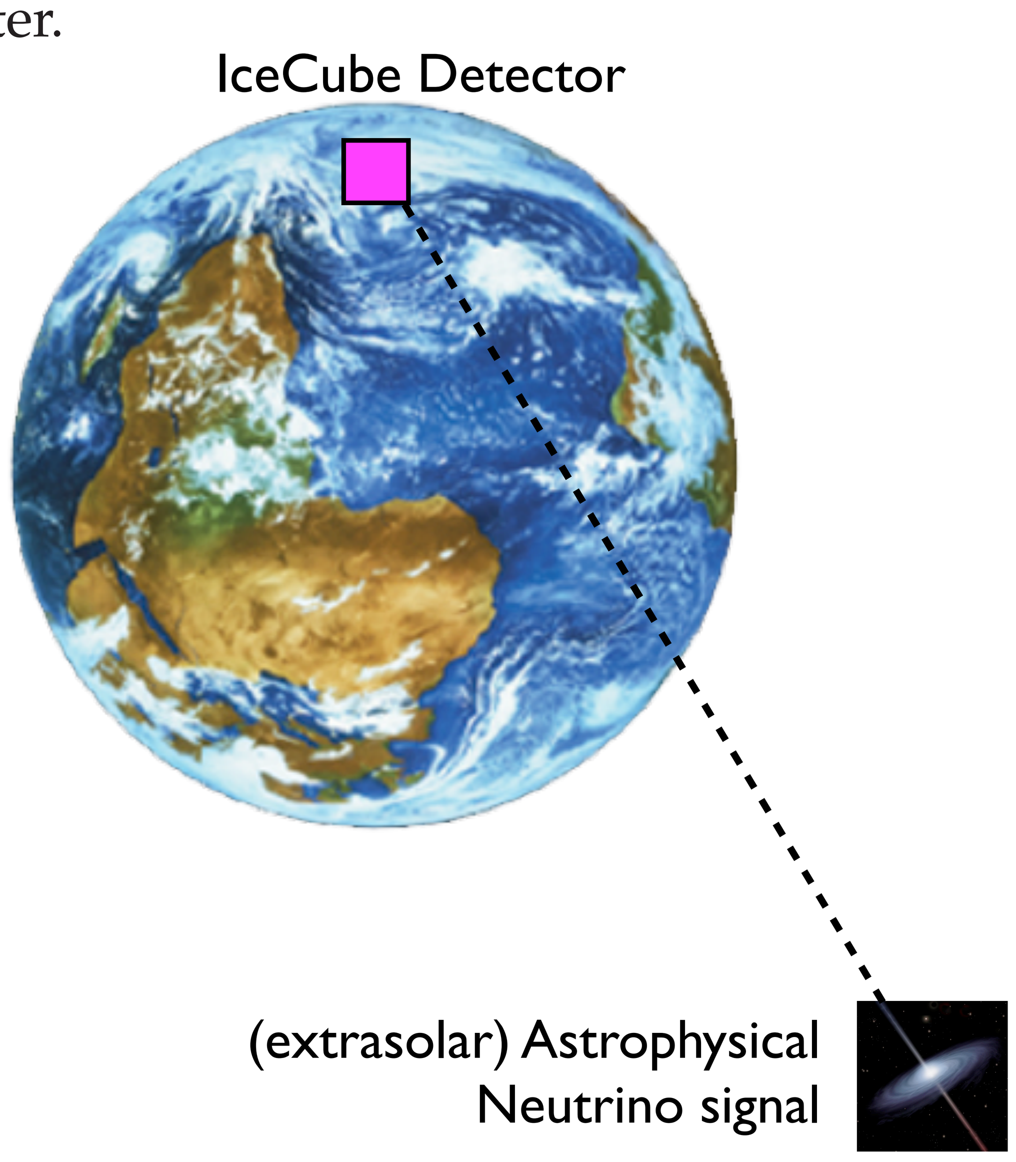


Diagram of the IceCube Detector

As neutrinos can travel through the Earth but other particles cannot, the Earth is used as a filter.

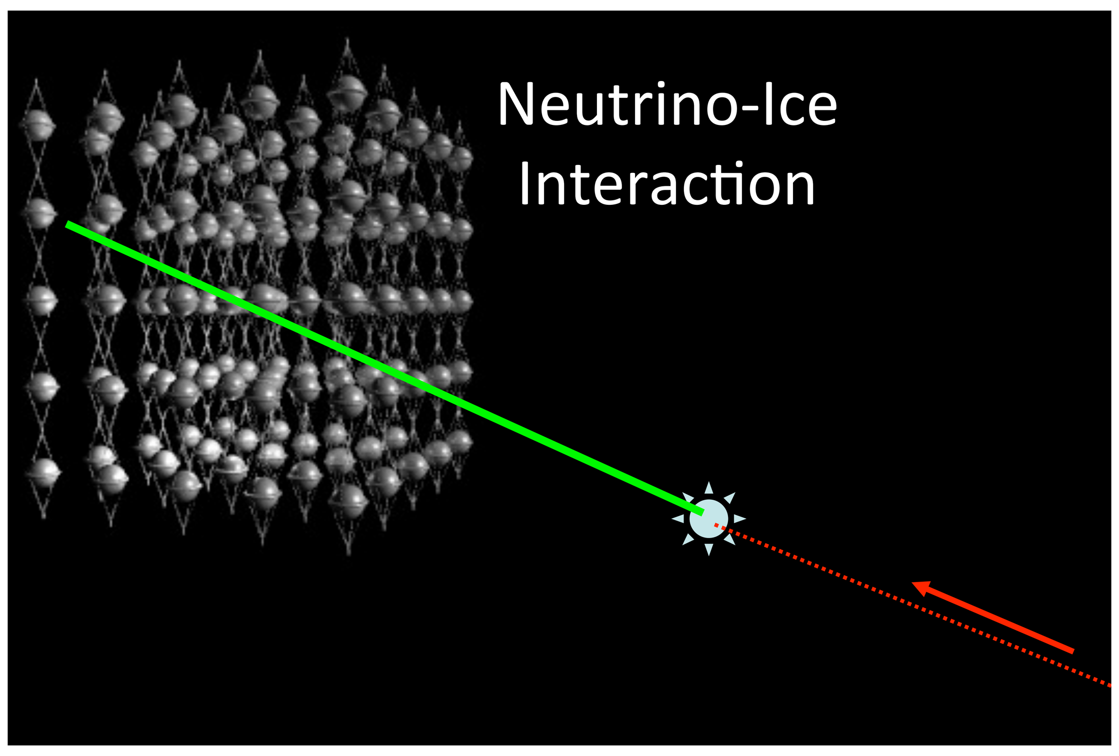


A neutrino source being detected.

Neutrinos are detected by the charged particles, often a muon, produced in neutrino interactions with the rock or ice near the detector.

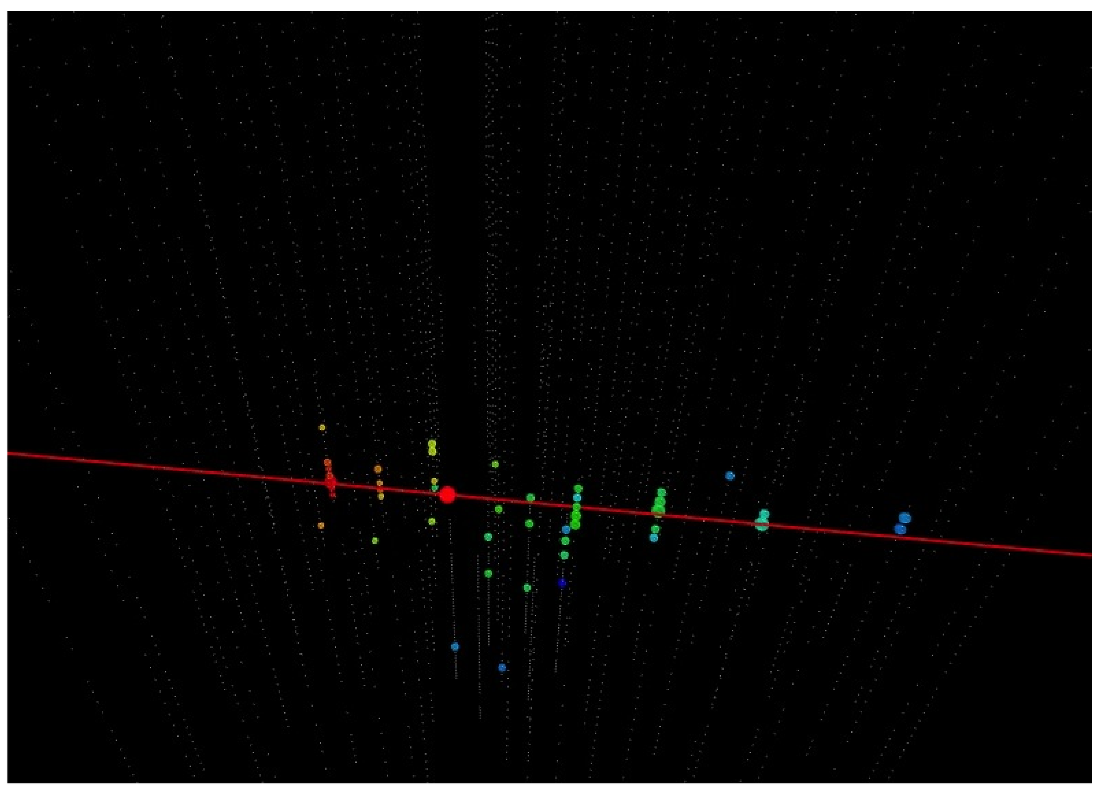
PROBLEM

Muon from neutrinos release light, which is observed by the detector.



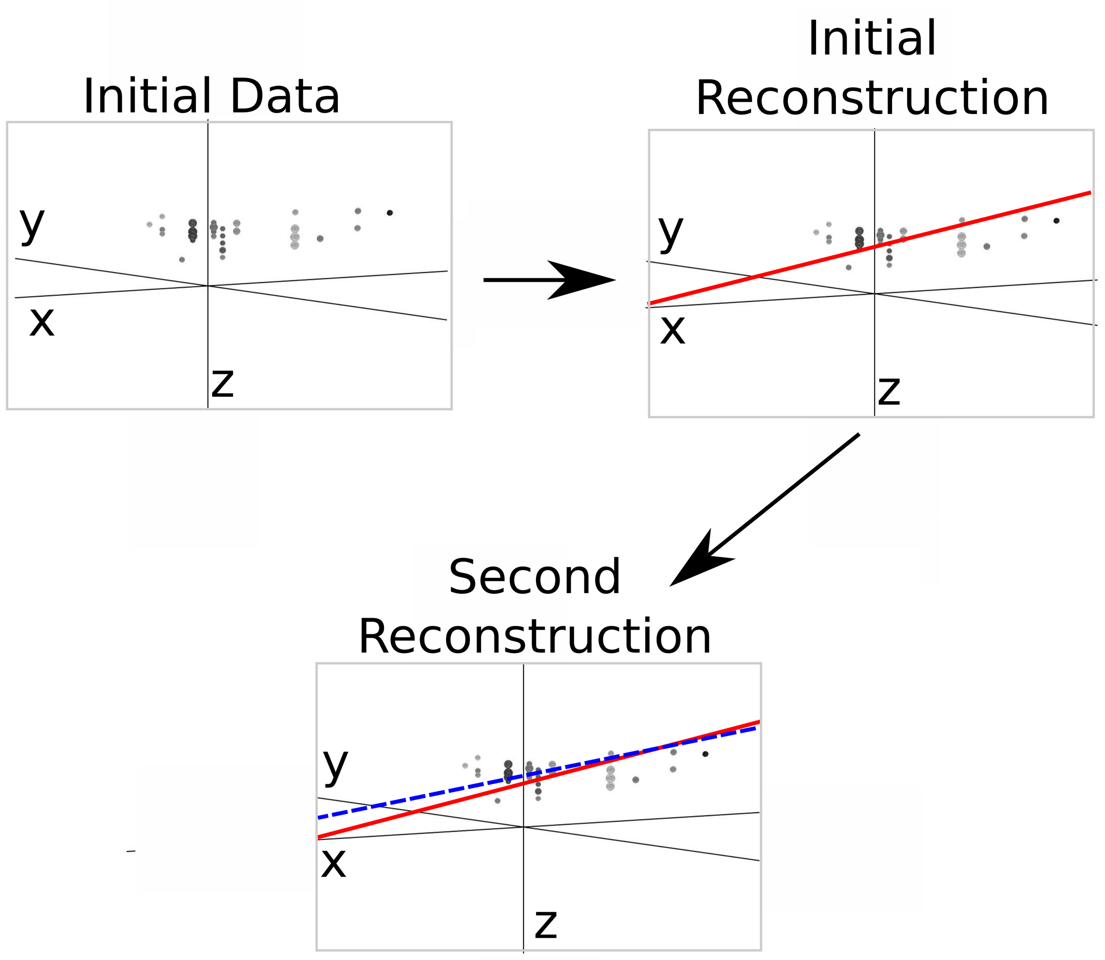
A neutrino ice interaction generating a muon.

The IceCube Neutrino Detector uses these light emissions to reconstruction muon tracks, as shown below.



A reconstruction of the muon path.

The reconstruction algorithm uses a simple first-pass algorithm to generate an initial guess, which is then refined by a more sophisticated algorithm, illustrated below



The reconstruction pipeline

The initial reconstruction solves the for the muon track $(t_0, \vec{x}_0, \vec{v})$ with the equation

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

where

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

We improve the reconstruction's accuracy by improving the initial reconstruction, thus giving the second reconstruction a better starting point.

CONTRIBUTION

Reconstructing the muon track is a difficult problem due to outliers and noise. The muon's light is scattered by dust impurities and air bubbles in the ice medium, and the PMTs can record hits from the radioactive decay in the surrounding glass.

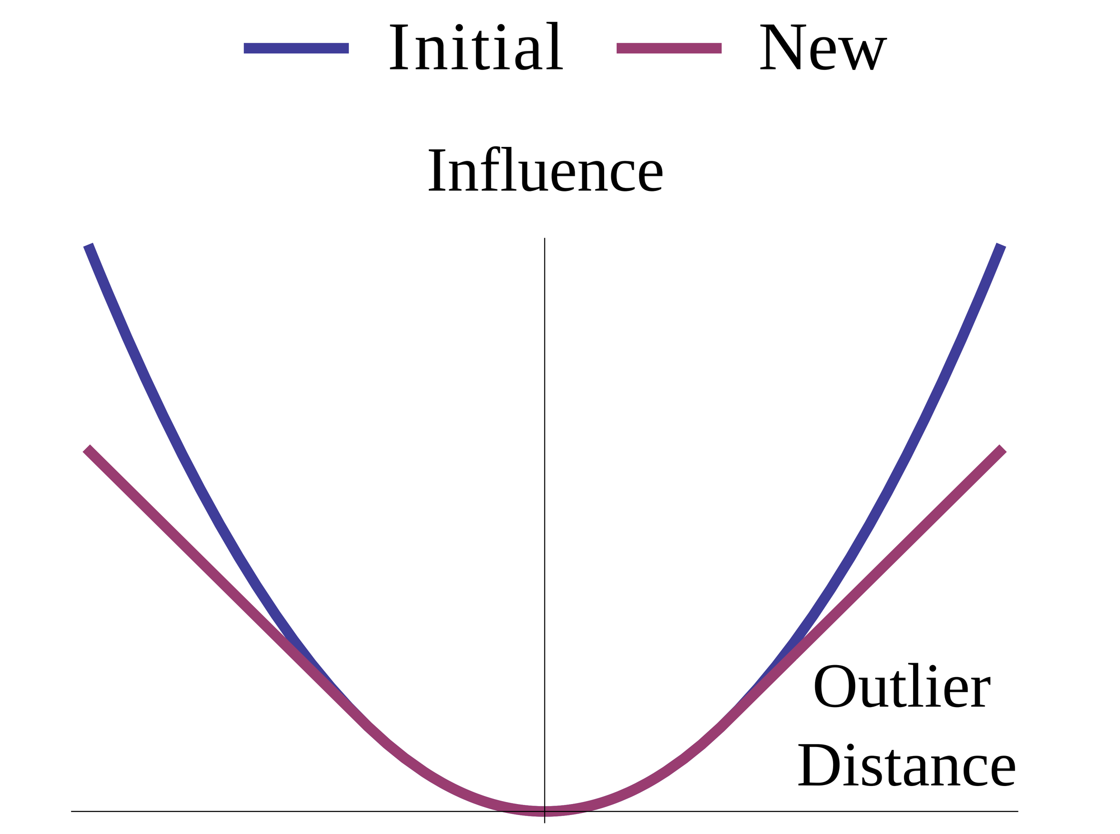
We improve the initial reconstruction algorithm with robust statistical techniques. We replace the initial reconstruction with an reconstruction that solves the equation

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

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

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

The Huber function reduces outlier influence.



Outlier influence of the initial reconstruction verses the new reconstruction.

RESULTS

Implementing our changes to the algorithm generates several improvements:

- 57.6% improvement in the median angular resolution of initial reconstruction.

Reconstruction	θ_{med} (°)
Initial	9.917
Improved	4.211

13% improvement in the median angular resolution of the second reconstruction.
10% fewer atmospheric muons erroneously classified as neutrinos.
1% more muons correctly classified as neutrinos.

Our algorithm improvements only add about 125 μs to the reconstruction time.

Reconstruction	Mean Runtime (μs)
Initial	24.2
Improved	155.9

Our algorithm runs inside the detector, and is included in all IceCube analyses.