Simulation of Ice Cherenkov Detectors for IceTop

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Abstract

IceTop is the km^2 surface array component [1] of the IceCube neutrino telescope at the South Pole. The array will consist of 80 ice-Cherenkov-stations on a hexagonal grid with spacing of 125 m. In order to design the stations and the array we developed a detailed detector simulation based on GEANT4. The simulation was used to understand and interpret the data taken by two test tanks located at the commercial freezer room at the Port of Wilmington (DE).

1. Introduction

Each IceTop station will consist of two frozen water tanks, each with a radius and height of 1 m viewed by two digital optical modules (DOM) looking downwards. The DOMs provide digitized waveforms, with a time resolution of 5 ns. One of the DOMs will operate in high gain mode to detect small signals. The other DOM will be in low gain mode to increase the dynamic range up to $\approx 10^5$. High gain is needed to use the surface stations to recognize small air showers, while large dynamic range is necessary for studies of high-energy air showers. The aim of the simulation is to define the degree of homogeneity and ice clarity that is needed for the operation of the air shower array.

2. Testing Environment

We check the quality of the simulations by comparing the results to measurements made with two test tanks that have geometry similar to the IceTop tanks, but only one optical module (OM) located at the center. Each OM consists of a 13" glass pressure housing and a 10" PMT which is coupled to the housing by optical gel. The OMs were operated in high gain mode to see single PE waveforms.

The tanks were filled with filtered tap water. Their walls were lined with Tyvek and the inside top lid surface was painted black. There are some differences in the air gaps between the water surface and the covers of the tanks (see below). The waveforms were recorded with an HP oscilloscope with a sampling time of 0.5 ns. One of the two tanks was insulated so that the ice grew from the top to the bottom (T1) and the other tank from the bottom to the top (T2).

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3. Input to the Simulation

The simulation is based on GEANT4 [2] and includes all physical processes for e^+/e^-, μ^+/μ^-, γ's and low energy (optical) photons. The spectral and directional reflectivity of Tyvek as measured by Filevich et al [3] were implemented into GEANT4 by modifying the standard GEANT4 optical boundary process. The spectral absorption length and refractive indices of all OM materials and the spectral PMT quantum efficiency were implemented as measured in Ref. [4]. The refractive index of ice for wavelengths of interest was calculated using a parametrization provided by Price & Woschnagg [5] and the absorption length of ice was assumed to be 30 m with a realistic spectral shape. The scattering in ice at micro air bubbles and other small impurities was assumed to be forward with a mean $cos(\theta) = 0.87$ [6]. The scattering length λ_s is expected to depend strongly on the ice quality and is a major free parameter. Sets of 10000 measured single PE waveforms from each OM were used to simulate the combined PMT and electronics response.

4. Comparison between Simulation and Data

All muon data were triggered using two scintillator modules (hexagonal with an area of 0.2 m^2) as a muon telescope above and below the tank. For each muon-telescope position 10000 events were measured and simulated. Table 1 shows the result for tanks filled with water before freezing in comparison to simulations. T1 seems to have a higher PE yield by 20-25%. This may be due to frost building on the inside black top surface ($\rightarrow$ *gray*-top). The top surface of T2 was protected from freezing and agrees very well with the black top simulations. The standard deviations are also in good agreement, although the simulation tends to generate more symmetric distributions. The agreement is also seen in the waveform-comparison (figure 1) and by looking at the distributions of rise time, decay time and full-width-half-maximum of the waveforms (not shown). Note that the differences between the shapes of the waveforms are caused by the different PMTs and electronics of the test tanks. The mean number of generated PEs per muon event for the T1 tank is between the white and black top simulations.

Next we compare the simulation to muon data in ice. Ice in both tanks contains imperfections that are hard to simulate. In addition, T2 froze up to $\approx 2/3$ with only a small layer of lower quality ice. The last third of the water was intentionally frozen quickly to test a worst-case scenario. Thus the top layer of ice is somewhat opaque and its internal structure is invisible and unknown.

In both cases the simulation made significant simplifications. The complicated ice structure of T2 was assumed to be a simple two layer-system with good ice on the bottom and bad ice on top of it. T1 was treated as solid block of homogeneous ice without imperfections. T1 data is consistent with $\lambda_s \approx$100-200 cm with a 15% *gray*-top reflection. The mean number of photo–electrons (PEs) that

Table 1. Mean number of PEs(standard deviation) over 10000 events in water.

μ-telescope	Data		Simulation	
Configuration	T1	T2	BlackTop	WhiteTop
47.3°, center	-	59.5(13.9)	58.4(14.6)	87.3(18.6)
19.5°, center	41.2(8.5)	-	35.4(8.1)	58.3(11.3)
0°, center	41.3(8.9)	34.7(9.1)	33.2(7.3)	51.7(9.8)
0°, side	40.2(7.9)	29.9(7.1)	31.6(7.1)	49.1(9.1)

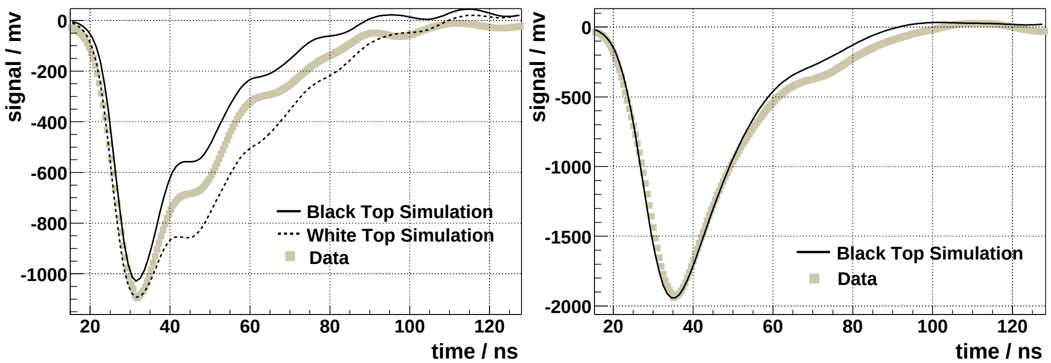

Fig. 1. Comparisons between measured and simulated waveforms for vertical μ-telescope at the tank center in water. T1 tank - lefthand panel, T2 - righthand panel. Each graph is the mean over 10000 events.

reach the PMT in the frozen tank is 82 % of that in water. Another effect of scattering in ice is a small increase of the non-uniformity of signal amplitude depending on the distance to the OM. In the T1 data the mean number of PEs for vertical muon data taken at the side of the tank is lower by 8.3 % (2.7 % in water) from data taken at the center.

Studies of the 2-layer simulation for the T2 tank led to the conclusion of a bad ice layer with thickness of 40 cm and $\lambda_s \approx 10$ cm. The simulated signals are somewhat wider than the measured ones, most probably because of the oversimplified ice model. The mean number of PEs in the bad ice for central muon tracks is 32 % higher than in water, most likely because of scattering from the bad ice in the vicinity of the PMT. The T2 tank is less uniform - the mean number of PEs in side of the tank data is 77 % lower (3.8 % in water) than at the center.

5. Summary

We are able to understand and reproduce the response of the detector filled with water in great detail. This provides us with a powerful tool for the final detector design and for tank calibration as a function of the zenith angle of the detected particles.

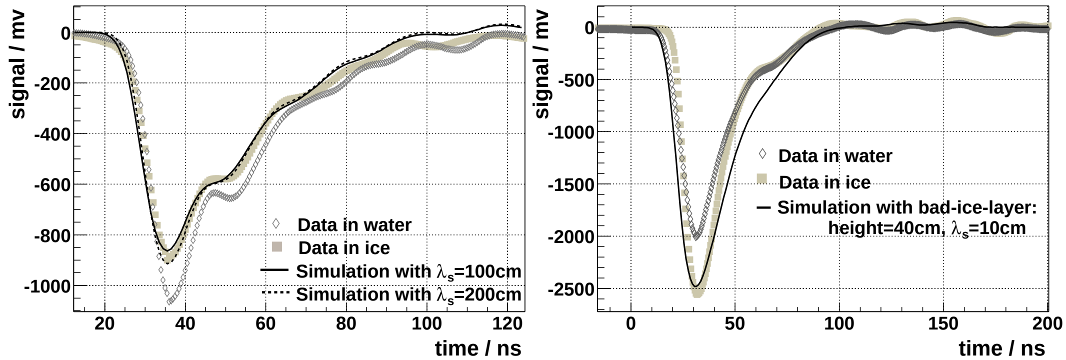

Fig. 2. Comparisons between measured and simulated waveforms of vertical μ-telescope in ice. T1 tank (side) - lefthand panel, T2 (central) - righthand panel. Each graph is the mean over 10000 events.

The data taken in ice could be explained reasonably well. To achieve a better precision we have to develop better models for light scattering and reflection from inhomogeneities and potential ice cracks.

We have started simulations of signals generated by shower electrons and photons. For the completion of the project we will simulate the detector response to the particle densities at different distances from the shower core at a variety of primary cosmic ray energies and primary masses.

Some of the results so far are:

• An absolutely diffuse wall reflection leads to 10 % more PEs compared to directed (Gaussian) reflection for central muon tracks independently of the exact position of the PMT.

• The black top decreases the decay time of the waveform by a factor of two while decreasing the PE yield by 50 %. The waveform fluctuations are also much smaller for a black top.

• The scattering length in the ice should be kept above λ_s =50 cm.

6. Acknowledgments

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7. References

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