Simulation of IceTop VEM calibration and the dependency on the snow layer

THE ICECUBE COLLABORATION[1]
[1]*See special section in these proceedings*

Abstract: Seven years of construction on the IceTop air shower array have culminated in the final detector setup of 162 ice-filled tanks. The tanks are paired as stations over an area of one square kilometer. A continuous and automatic procedure calibrates each tank via the extraction of the vertical equivalent muon peak in the tank charge spectrum. Over the years snow has drifted unevenly on top of the tanks. The overburden of snow influences the charge spectrum as the electromagnetic part of an air shower is attenuated more than the muonic part. The impact on individual tanks affects trigger rates and the air shower event structure. We will present tank response studies with Monte Carlo simulations and compare them to measured IceTop charge spectra in light of the varying thickness of the snow layer.

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1 Introduction

IceTop is the cosmic ray surface detector of the IceCube Neutrino Observatory [1], which is located at the South Pole and was completed in March 2011. The final setup consists of 162 tanks paired in 81 stations on a hexagonal grid with horizontal separations of about 125 m. The array covers an area of one square kilometer at an altitude of 2835 m above sea level, which is equivalent to an average atmospheric depth of 680 g/cm^2. The location together with the geometry and the applied trigger settings make the array sensitive to cosmic rays with energies between 100 TeV and 1 EeV.

An IceTop tank acts as a calorimeter, converting energy deposited by charged relativistic particles into Cherenkov light. The reconstruction of air shower observables such as space angle (zenith and azimuth), core location (x and y) and shower size relies on a good understanding of the light signals in the individual IceTop tanks. A natural way to calibrate and simulate tanks with their individual responses is to use the reference signal - vertical equivalent muon (VEM) - that high energy vertical muons imprint in the charge spectra of each tank.

A schematic of an IceTop tank is shown in Figure 1. The tank is a cylindrical polyethylene vessel 186 cm in diameter and 130 cm in height covered with insulation. The walls are 6 mm thick and the inner part is covered with 4 mm thick diffusely reflective liner of Zirconium[1] fused polyethylene. Each tank is initially filled up to a height of about 90 cm with purified water. Afterwards the water freezes via a controlled top-to-bottom procedure that lasts for about 40 to 50 days. To minimize impurities or contamination and cracks in the ice during the freezing process, a degasser system in combination with a circulation pump extracts air, swirls the water slowly around and removes excess water. At the top of the ice volume, two Digital Optical Modules (DOMs) are mounted to record the Cherenkov light pattern created by through-going and stopping particles. A DOM [2] is an ensemble of a photomultiplier tube (PMT) and digitising, communication and operation electronics inside a glass pressure sphere. In data taking mode the two PMTs inside one tank operate at a different voltage setting, enlarging the dynamic range in linear pulse charge assignment. Moreover, in case one DOM in a tank fails, the tank is not lost in further physics analysis. The ice surface and the two DOMs are covered with perlite, a volcanic ash, that acts as an insulator and prevents light from entering the ice volume and triggering the PMTs.

The tanks are embedded in snow until the snow level equals the surrounding surface. So at installation there is only snow on the sides, but winds blow snow on top of the tanks. Each year some tanks accumulate up to 30 cm of snow on top while others are still in the original setup without a snow layer. This leads to an asymmetry in the behavior of the array and needs to be understood via data and Monte Carlo comparisons.

1. Note that this is true for 150 tanks. The first 8 installed tanks in the year 2005 and 4 out of 16 tanks installed in the year 2010 are different and contain a Tyvek bag that acts as a reflector.

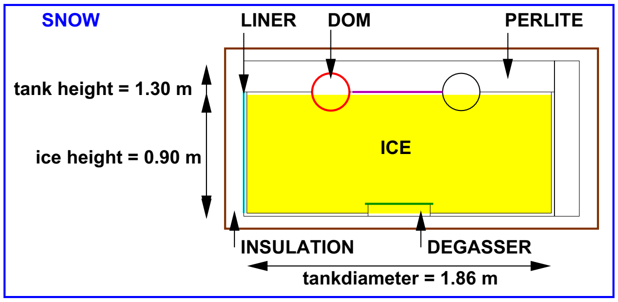

Figure 1: Schematic of an IceTop tank with its dimensions and its most important components. The trench where the tank is installed is backfilled with snow. Winds bring in snow that can accumulate on top of the tank.

2 Calibration

A good handle to study tank dependencies is to use the tank charge spectrum that is naturally generated by the very abundant low energy primary proton showers. Secondary muons within the 1 GeV to 10 GeV energy region leave a very clear and distinguishable signal behind in the tanks. The technique was used to calibrate the water tanks in the Auger experiment [3],[4] and it is also in use in IceTop [5] since 2005. An example of a charge spectrum (expressed in number of photo-electrons (PE)) of one single tank can be seen in Figure 2. The data was recorded between the 15th and the 22nd of January 2011. The overall spectrum is fit by the sum (solid) of a signal part (dashes) attributed to muons and a background part (dots) generated by electrons, positrons and gammas. The exact formula [6] reads:

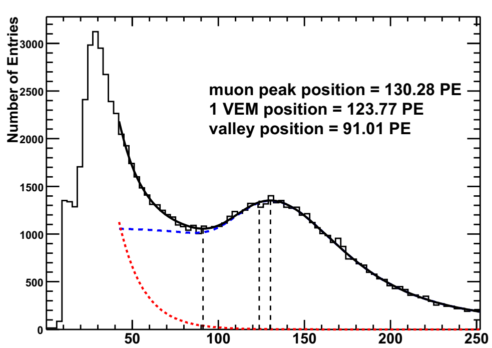

Figure 2: This is an experimentally measured charge spectrum of DOM 61-61 running in calibration mode. The total fit (solid) is the sum of the muon (dashed) and electromagnetic (dotted) contributions. The three extra lines visualize the positions given by the legend.

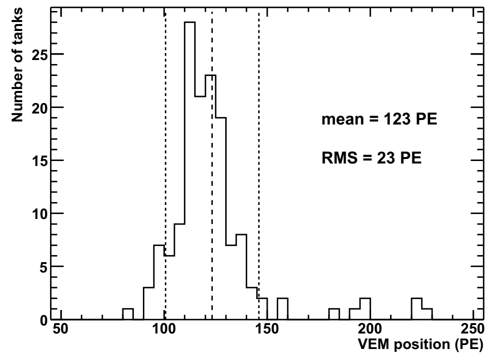

Figure 3: This histogram represents the VEM values of all the 146 (high gain) DOMs running between the 15th and the 22nd of January 2011. The lines visualize the mean and the root mean square region.

$$
\begin{aligned}
f(x) &= p_0 \left(\frac{1.85}{p_1} \frac{1}{\exp(\frac{x-p_1}{p_2})+1} + \mathrm{L}(x,p_1,p_2) \right) \\
&+ p_3 \cdot \exp(p_4 \cdot x) \quad ,
\end{aligned}
$$

where the first term in the summation describes the muon part: on its own a sum of a step function that describes corner clipping muons and L(x,p_1,p_2) a Landau function with p_1 the most probable value and p_2 a scale parameter that describes the bulk of through-going muons. So the signal part describes muons of all energies and incoming directions. Muon telescope measurements have pointed out that vertical muons build up charges around 95 % of the overall muon peak. The last term in the equation describes the exponential electromagnetic contribution. The three dashed vertical lines visualize the position of the valley, the muon peak and the 1 VEM unit.

Since June 2009 all the tanks of the IceTop detector are calibrated via an automated online procedure based on the fit described above. The muon calibration data is collected simultaneously with the physics data and hence both DOMs are evaluated at their running[2] gains. The calibration data is taken via a dedicated trigger that records every 8192nd hit per (high gain) DOM that is not in local coincidence with the other tank in the same station, i.e. there was no activity in the other tank within a short time window of 1 μs.

Each IceTop tank responds in an individual way to air shower particles due to small differences in size, ice quality, liner reflectivity, snow coverage and interfaces between the ice and DOM, the ice and the liners, the ice and the perlite and the ice and the degasser. The size of the ice block is important as more/fewer photons will be generated for longer/shorter tracks. Reflectivity and transmission

2. In the old method calibration was performed on a different set of data where both DOMs were adjusted to the same gain.

will depend on the amount of impurities and cracks in the ice, the quality of the liner and the interface between the ice and the surrounding material. The snow on top insulates the tank and so the PMTs in different tanks operate at different temperatures and hence gains. Snow also blocks the low energy electrons, positrons and gammas and so the energy threshold differs. Figure 3 shows the variety in PE per VEM for the 146 (high gain) DOMs operational between January 15th, 2011 and January 22nd, 2011. The average number is about 123 PE per VEM with a root mean square of 23 PE per VEM. The outliers with higher values belong to tanks lined with the higher reflectivity Tyvek.

3 Simulated VEM Spectrum

The VEM spectrum is the result of the convolution of two components: the ground particles created in air showers and the detector response for each of the particles. The air showers in this study are produced via CORSIKA (v6900) [7]. The high energy hadronic interactions are treated via SIBYLL (2.1) [8] while the low energy interactions are taken care of by FLUKA (2008) [9]. The transition between the models is set at center of mass energy of 80 GeV. The electromagnetic interactions are treated via EGS4 [10] parametrisations. The detector response to each particle is simulated via the official IceTray software [11] of the IceCube Collaboration. The IceTop tanks are modeled in a GEANT4 [12] environment that also tracks the ground level particles. The amount of Cherenkov photons that are generated inside the optical volume is used to assign the measured number of photo-electrons. The DOMs allocate a charge via an experimentally measured single photo-electron charge distribution.

The air showers are generated according the following conditions: only protons are assumed; the zenith angle θ ranges from 0 to 89 degrees and the azimuth angle from 0 to 360 degrees. The azimuth angle is sampled uniformly while the zenith angle is sampled from a $\cos(\theta)\ \sin(\theta)$ relation, the flat detector approach. The lowest triggering primary energy is given by the minimum amount of energy needed to create a muon in the atmosphere that can possibly arrive at the surface. At the South Pole this energy is about 3 GeV. The high energy limit is restricted by the calibration trigger condition that deletes hits from the calibration stream when there is activity in the nearby tank. Simulations point out that the upper limit is situated around 30 TeV. Moreover, Figure 4 shows that it is sufficient to simulate up to 10 TeV as the integrals of the muon spectra saturate. The x-axis is expressed here in units of VEM/0.95, so that the muon peak is situated at one. In the threshold region [0;0.4] the highest energies contribute a bit more than in the muon peak region [0.8;1.2]. This is also visible in Figure 5 where the integrals of the former spectra are shown as a function of the maximum energy in the dataset. Between 10 TeV and 30 TeV the integral increases about one to two percent, see therefore the solid line. The other markers give the integrals for the intervals

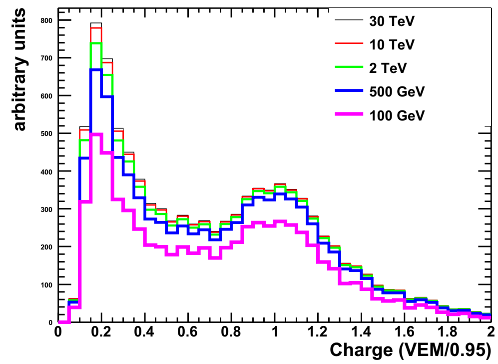

Figure 4: Different simulated muon spectra (weighted to $E^{-2.7}$) where the maximum energy that has been simulated changes. From bottom to top the maximum energy goes up between 100 GeV and 30 TeV as written in the legend.

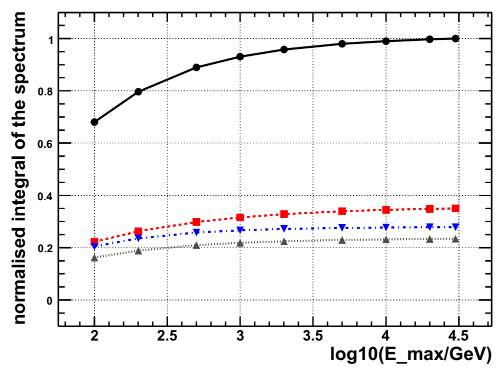

Figure 5: The same as Figure 4, but here the integrals of the muon spectra are plotted as a function of the maximum energy E_{max} used to build up the muon spectra. The solid line represents the whole integral. The dashed, dotted, dash-dotted lines are the integrals in following intervals [0;0.4], [0.4;0.8] and [0.8;1.2].

[0;0.4] (squares), [0.4;0.8] (triangles) and [0.8;1.2] (inverse triangles).

The VEM spectrum technique is used to calibrate the air shower simulations for high energy analysis. The simulated charge signals are calibrated in VEM units such that the simulated calibration muon peak is at the same position as in the corresponding experimental calibration data. The simulations perform well. All systematic checks completed and listed in Table 1 exhibit a stability in the 1 VEM position within two to three percent. The first (second) column gives the shifts of the 1 VEM position for simulations weighted to $E^{-2.4}$ ($E^{-2.7}$). The checks included tests on stability of random numbers, hadronic interaction uncer-

Check	$E^{-2.4}$	$E^{-2.7}$
different seeds	0.2 %	0.5 %
July vs January atmosphere	1.6 %	2.7 %
SYBILL vs QGSJET01c	0.7 %	2.9 %
10 cm to 200 cm of snow	0.4 %	0.7 %
different tanks/DOMs	1.5 %	–

Table 1: Results of systematic checks for the shift of the muon peak and according 1 VEM position due to a variety of effects listed. Two primary energy weightings are presented.

tainty, daily variations of the atmosphere, the accumulation of snow and the differences of all (high gain) DOMs.

4 Snow Dependency

Over the years, snow drifts unevenly on top of the tanks. As can be seen from Figure 6, the overburden of snow influences the charge spectrum as the electromagnetic part [0;0.75] of an air shower is attenuated more than the muonic part [0.75;1.25]. The ratio (S/B) between integrals of the muonic (M(h)) and the electromagnetic fit (EM(h)) in Figure 2 and expressed in the following formula:

$$(S/B)(h) \quad = \quad \int_{0.3\mathrm{VEM}}^{2.0\mathrm{VEM}} M(h) / \int_{0.3\mathrm{VEM}}^{2.0\mathrm{VEM}} EM(h) \quad ,$$

is a function of snow depth h. This is shown in Figure 7. The markers represent simulations where the primary energy is weighted via different differential spectral indices. The dotted and dashed lines are extrapolations to indices of -2.6 and -2.7 respectively. Direct weighting to these more realistic values of the differential spectral indices was not possible due to low statitics and large fluctuations. In comparison the experimental relation is given by the solid line which shows a bit stronger dependency on the thickness of the snow layer.

5 Summary

The VEM spectrum can be efficiently generated with an uncertainty of 2-3%. This leads to an absolute charge calibration in simulation. The snow dependency of the signal to background (muon versus electromagnetic) ratio in experimental data is slightly stronger than the one found in simulated data and has to be further investigated.

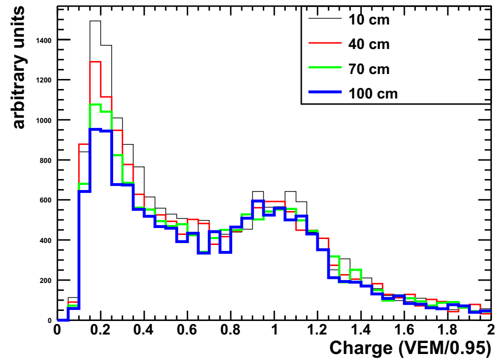

Figure 6: The four histograms represent the ($E^{-2.7}$) simulations of DOM 61-61. The only difference is the amount of snow on top of the tank lids. From top to bottom the snow thickness amounts to 10 cm, 40 cm, 70 cm and 100 cm.

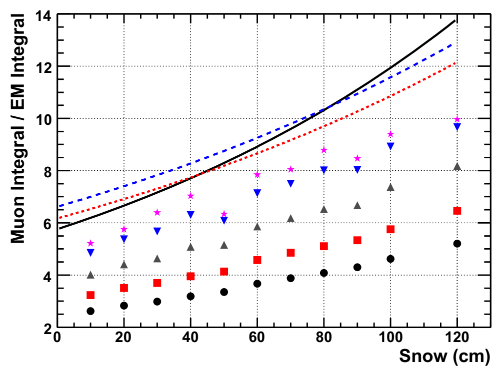

Figure 7: The snow dependency of S/B (see text). The markers represent the simulation weighted with different differential spectral indices: -1.6 (circles), -1.8 (squares), -2.0 (triangles), -2.2 (inverse triangles) and -2.4 (diamonds). The solid line is the relation found in experimental data. The dotted and dashed lines represent extrapolated results for differential spectral indices of -2.6 and -2.7 respectively.

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