

The Effect of Snow Accumulation on Signals in IceTop

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Abstract: IceTop, the surface component of the IceCube Observatory at the South Pole, measures both the electromagnetic and muon components of cosmic ray air showers. Although initially deployed level with the snow surface, drifting snow buries the IceTop tanks under a layer of matter which attenuates the electromagnetic component and whose thickness changes slowly over time. Accounting for this attenuation is an important factor in correctly reconstructing the shower, but it is dependent on the shower's energy, composition, and zenith angle, as well as distance from the shower core. This work studies the attenuation of air shower particles and the effect of this attenuation on IceTop signals.

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1 Motivation

IceTop [?] is the surface detector component of the IceCube Observatory [?]. IceTop's 81 cosmic ray detector "stations" are positioned near the top of IceCube's deeply-buried strings. Each station is composed of two tanks of frozen water; each tank contains two Digital Optical Modules (DOMs), one with high gain and one with low gain, which detect the Cherenkov light from charged particles passing through the tank. IceTop is sensitive to both electromagnetic particles and muons from cosmic ray air showers. The total charge deposited in each tank (which is measured in calibrated units of "vertical equivalent muons" or VEM) is used to reconstruct the properties of the shower, by fitting the distribution of charges to an expected functional form.

The IceTop site is the geographic South Pole, a high-altitude plateau where the snowy surface is ever-changing. Precipitation is minimal, but snowdrift driven by a prevailing wind slowly buries the IceTop tanks over time, especially those near buildings or structures, or which are located on sloped terrain. Figure ?? shows the depth of the snow layer above Station 40, which was deployed in January of 2007, as a function of time. Snow depth increases at an average rate of about 20 cm/year over the entire array. But the coverage of snow on the detector also builds unevenly; tanks deployed early in IceTop's construction history generally have accumulated the most snow, due to a combination of time, sloped terrain, and proximity to structures, as shown in Figure ?. In between regular *in situ* measurements of snow depths, the snow depth of a tank can be estimated using "VEMcal" calibration data in which the amount of signal from muons (which does not attenuate) is compared to the electromagnetic signal (which does) [?, ?].

The accumulated snow is *part* of the IceTop detector, as the particles observed will be attenuated by the layer above, affecting the charge observed in the tank and thus also the measured shower "size" S_{125} . Since S_{125} is used by multiple IceTop analyses [?, ?, ?] to measure primary energy, accounting for snow is critical. In fact, uncertainty in snow

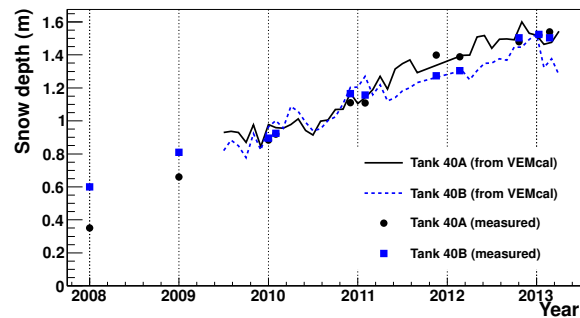


Fig. 1: Example of the accumulation of snow over time, for the two tanks in Station 40. Solid symbols are direct measurements of snow depth performed by scientists on-site. Lines are indirect measurements using VEMcal data taken weekly and smoothed monthly.

correction is the dominant source of systematic uncertainty for the spectrum measurements in these analyses.

2 A simple snow correction

The attenuation of electrons through matter is well-studied. A single (MeV) electron loses energy with a radiation length X_0 of about 37 g/cm² in ice [?]. High energy electrons can generate electromagnetic (EM) cascades in matter, which obey cascade equations [?]. So the electrons in an air shower experience attenuation which is a convolution of the particles' energy spectrum with the energy loss (according to cascade physics) at each energy. In particular, if the electrons have a $E^{-2.7}$ spectrum, the population as a whole is expected to be attenuated exponentially with the distance into the matter, with an effective attenuation length of approximately 85 g/cm² [?]. Using the average density of

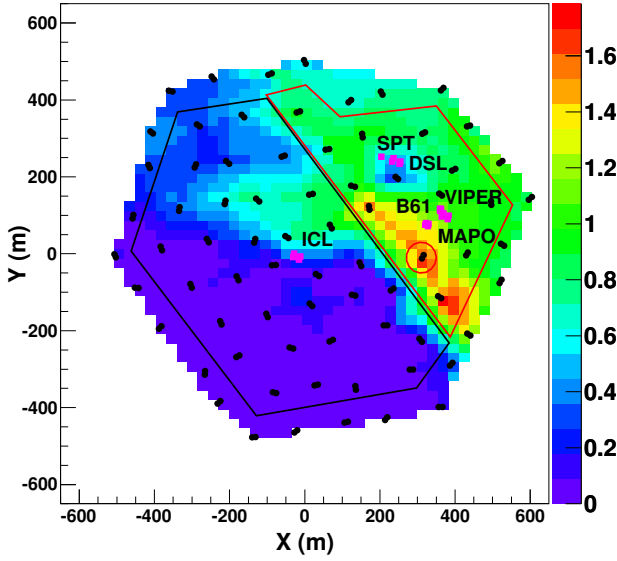


Fig. 2: Map of the snow coverage (in meters) over the IceTop tanks (black dots), during February of 2010. Pink squares labeled with acronyms are structures. The two outlined regions are the “old” subarray and “new” subarray used for optimizing a simple snow reconstruction [?]. The circle indicates Station 38, a very snowy station studied in this paper. Station 40 is two stations grid east of Station 38.

snow at the South Pole (measured on-site) which is 0.38 g/cm^3 [?], this effective attenuation length λ_s should be about 2.1 m.

A simple exponential snow correction in reconstruction of air showers was first used in the analysis of 40-string IceTop-IceCube coincidence data for cosmic ray composition [?]. A shower’s core location, direction, and S_{125} are reconstructed by maximizing the likelihood that the track hypothesis (which predicts an expected signal, in the absence of snow) gave rise to the observed signal (details in [?]). To account for the attenuation by snow, the no-snow expected signal S_0 in a particular tank is reduced by an exponential factor:

$$S_{corr} = S_0 \exp(-X/\lambda_s) \quad \text{where} \quad X = d_{snow}/\cos(\theta)$$

before being compared to the observed signal in that tank. Here, “ X ” is the slant depth that particles must travel to a tank at a depth d_{snow} . Monthly tables of the snow depths of all the tanks, derived using VEMcal data, are used for this correction so that it changes appropriately over time. This simple treatment is also being used in current IceTop analyses such as: measurement of the all-particle spectrum with 73 IceTop stations alone [?] and with coincidence events which also pass through IceCube [?]. The correction was optimized by comparing the “old/more snow” subarray of the IceTop detector to the “new/less snow” subarray. A selection of these subarrays is shown in Figure ?? . The best λ_s is the one which brings the measured S_{125} distributions from the different subarrays in line, as shown in Figure ?? . In these studies, a λ_s of 2.1 m fits the old/new subarray to each other well, but this number has a systematic uncertainty estimated at ± 0.2 m.

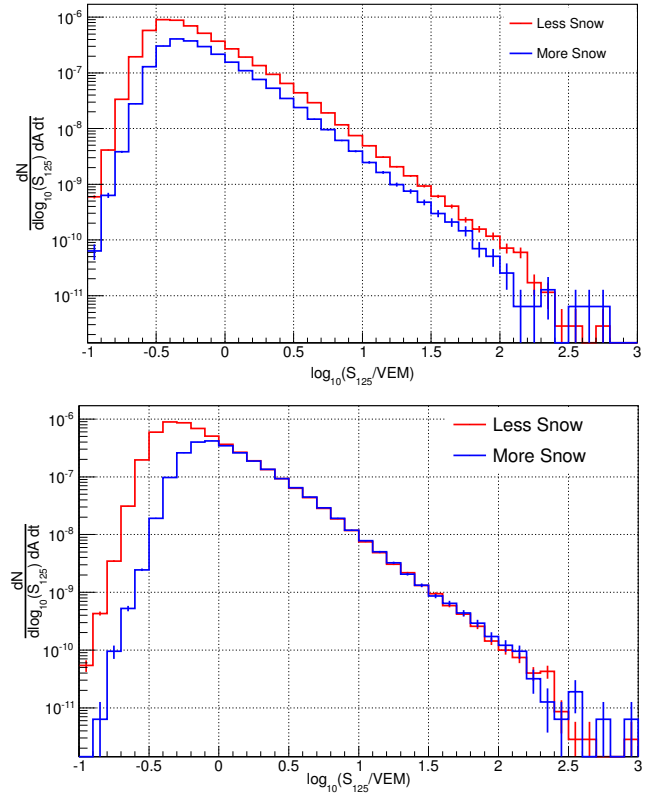


Fig. 3: S_{125} distributions without any snow correction (above) and with an optimal snow correction (below).

3 Toward a more advanced snow correction: studies using IceTop data

Although an average λ_s can be derived using some simplifying assumptions, the behavior of air shower signals in the real IceTop detector is expected to be more complicated. The fraction of the signal coming from unattenuated muons will vary (as a function of distance from the shower core, primary energy, primary composition, and zenith angle) Also, the shape of the spectrum of particles may vary from the assumed $E^{-2.7}$, with these same parameters.

Attenuation as a function of radius from the core was first studied using IceTop data itself. In particular, in IceTop-73 data (from 2010), many of the tanks were newly-deployed and covered with very little snow. These “no-snow tanks” can be used as a reference against which to compare signals in “snowy” tanks. A sample of events was collected for which the core position and direction was well-reconstructed, using quality cuts. For each tank, a normalized lateral distribution function (LDF) of signals was computed, in which each signal S measurement in the histogram was divided by the S_{125} of the event in which the tank was participating. These “normalized S distributions” were made for both snowy and no-snow tanks; the distributions are systematically lower for snowy tanks due to the attenuation. Figure ?? shows the logarithm of the ratio between the normalized S distribution of the tanks in a snowy station to that of the normalized S distribution of the no-snow baseline, in several different regimes of energy (as estimated by S_{125}). The more negative this value, the greater the attenuation of the total signal. The reduction of attenuation with increasing distance can be attributed to a changing muon

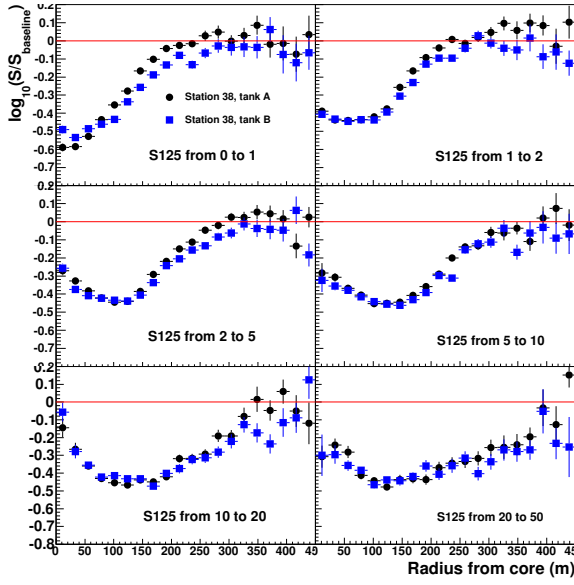


Fig. 4: Log of the ratio of normalized S_{snowy} to normalized S_{nosnow} as a function of distance from reconstructed core, for the two tanks in Station 38. The six panels represent a rough breakdown by energy. Near-vertical (0° to 20°) events only are selected.

content in the shower (further away, the shower becomes more dominated by muons and thus less effectively attenuated).

Muons do *not* explain the “upturn” in this ratio at small distances to the core, which indicates less attenuation (an enhancement) of signal close to the core. The effect grows more pronounced, and out to larger distances, at higher energies. Since real IceTop data suffers from reconstruction errors, unknown muon content, and effects from thresholds and saturation of PMT’s, such a measurement is difficult to interpret on its own.

4 Toward a more advanced snow correction: a ring simulation

To explore these effects further, vertical CORSIKA[?] showers were simulated (both proton and iron primaries), at fixed energies (0.1, 0.316, 1, 10, and 100 PeV). In order to isolate the effect of snow on the EM component of the showers, all muons were stripped out of the CORSIKA files. The modified showers were then propagated through a simplified toy model of an IceTop-like detector, with single tanks (containing two DOMs each) spaced at sixteen different radii from the shower axis (5, 10, 25, 50, 75, 100, 125, 150, 200, 250, 300, 400, and 500 m). Each tank at each radius was simulated under 10 different snow depths, ranging from 0.0 to 1.8 m. The snow and the toy tanks were simulated using an IceTop simulation tool based on GEANT4 [?]. Photons arriving at the toy DOMs’ photocathode were counted; details of the detector response beyond this were not simulated.

The number of photoelectrons registered in each toy tank as a function of snow depth for 1 PeV protons is shown in Figure ??, in which each of the 16 panels represents a dif-

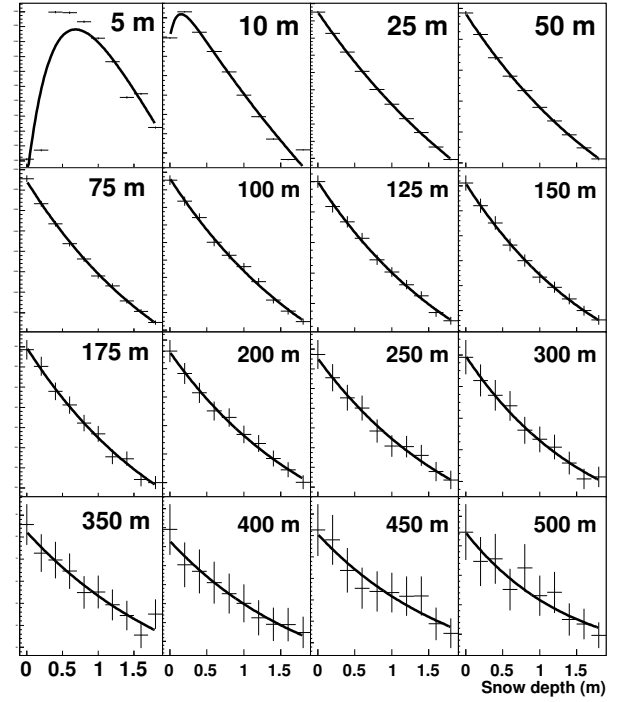


Fig. 5: Number of photoelectrons (arbitrarily normalized) hitting toy DOMs in the “ring simulation” as a function of snow depth, for various radii from the shower core. The showers are from 1 PeV vertical proton primaries. Each of the fit curves is a decaying exponential plus a short-range exponential rise.

ferent radius from the shower core. There are some interesting features, namely: a) that attenuation is exponential (as expected), and the slope of the attenuation slowly changes as a function of radius, and b) that at very small radii (5 and 10 m from the core), snow causes an enhancement in signal at first, followed by attenuation. Corresponding plots for iron showers, and showers of other energies, show similar qualitative behavior.

Production from EM cascades of the highest-energy shower particles in the snow explains the enhancement feature at small distances. Figure ?? shows the spectra of electrons for various distances from the core, for 1 PeV proton showers. At most distances, the spectra have approximately the same shape, but very near the core (10 m and less), the harder electron spectrum stretches to higher energies. The particles in high-energy tails of the spectrum will cause EM cascades of their own in the snow, producing an increase in the number of particles at first, followed by a decrease as the now lower-energy particles attenuate away. To test this interpretation, particle distributions from CORSIKA at discrete core distances (such as those shown in Figure ??) were convolved with the Greisen function for EM cascades:

$$N_{e\gamma} = \frac{0.31}{\sqrt{\beta}} \exp(t(1 - \frac{3}{2} \log(s)))$$

where $\beta = \log(E/83\text{MeV})$, t is the slant depth X in meters divided by X_0/ρ (i.e. measured in radiation lengths), and $s = 3t/(t + 2\beta)$ [?]. The convolution produces an expected

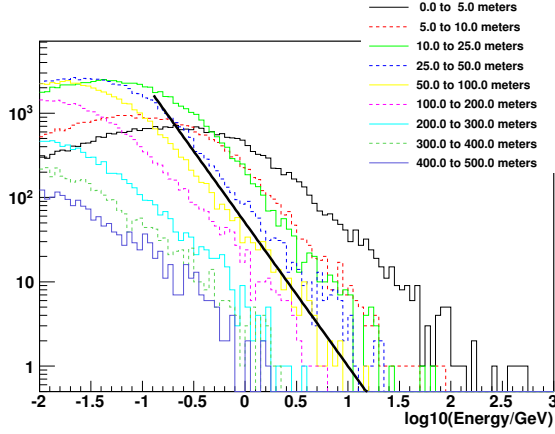


Fig. 6: Spectra of electrons from a 1 PeV proton event from CORSIKA. The different colors represent different distances from the shower core. The solid line is the shape of $E^{-2.7}$, to guide the eye.

number of particles as a function of snow depth; the resulting distributions look qualitatively very similar to Figure ??, with similar enhancement features at 5 and 10 meter distances in particular.

5 Results and Conclusions

Each of the 16 panels of Figure ?? was fit to a decaying exponential plus an EM-cascade “turnover”. Similar fits were performed on all the CORSIKA sets (the different energies, and both protons and iron), all of which show similar qualitative behavior. A summary of the fitted exponential slope (which is $-1/\lambda_s$) as a function of radius to the shower core is shown in Figure ??.

Different primary energies and compositions show different attenuation lengths, especially at small distances where high-energy particles complicate the cascade physics. Most of the curves settle near a slope of around -0.5 (which is a λ_s of about 2 m) at distances beyond 100 m. Since the IceTop hits that contribute most to an event reconstruction are generally at distances of 100-200 m, it is not surprising that the simple snow correction technique currently in use works well. However, this result also shows that improvement is possible; instead of one attenuation length λ_s at all tanks, the attenuation response could be a function of a tank’s position relative to the core, as well as other variables such as hypothesis energy, composition, or zenith.

One must also keep in mind that this attenuation behavior describes the EM shower component only, not the muons. One must also study the fraction of IceTop signals due to muons (either from theory or as part of the reconstruction itself), and attenuate only the EM fraction. So, in the future, a more advanced snow-corrected signal expectation will have a form like:

$$S_{corr} = S_{muons} + A(X)S_{EM}$$

where the attenuation function of slant depth $A(X)$ may be exponential ($A(X) = \exp(-X/\lambda_s)$), but may also include EM cascade effects for tanks very near the core.

This study still faces a number of unresolved issues. A different optimal λ_s is found for Monte Carlo and data. The

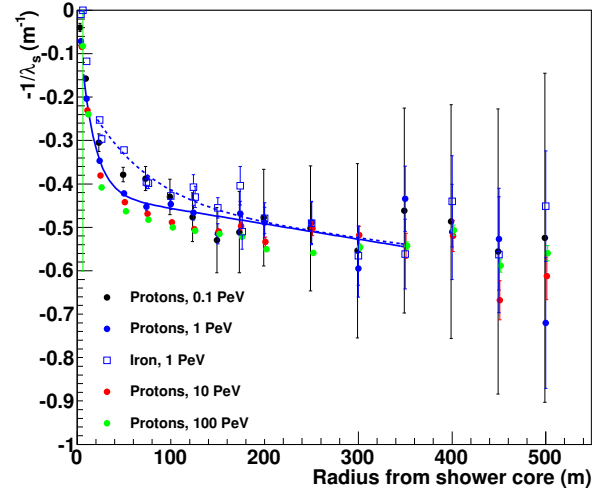


Fig. 7: Slope of an exponential fit to the sixteen curves such as in Figure ??, which is negative $1/\lambda_s$. Different colors represent different simulated proton primary energies, and 1 PeV iron is also shown for comparison. The 1 PeV data points have been fit to curves (protons = solid, and iron = dashed).

ring simulation studies vertical events only, and yet it is known that the behavior of the snow correction depends on zenith angle. A full simulation of IceTop under different snow depths will be necessary to study the effect of threshold and saturation settings, and hopefully to lead to a generalized snow correction technique which will improve reconstructions for all.

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