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Air showers with IceCube: First Engineering Data

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1. Introduction

The IceTop km^2 air shower array of 80 pairs of ice Cherenkov tanks is an integral part of the design of the IceCube neutrino telescope at the South Pole. The neutrino telescope will consist of 80 strings, each instrumented with 60 digital optical modules (DOMs) between 1450 and 2450 m depth. Thus IceCube will be a three-dimensional air shower detector as well as a neutrino telescope. The power of a surface array for calibration and background studies for the neutrino telescope, as well as the physics potential for cosmic-ray studies of the combined detector, are described in Ref. [1]. At ultra-high energy, where the Earth is opaque to neutrinos from below, the surface array will give IceCube a significant ability to discriminate between downward or horizontal neutrinos and cosmic-ray induced background. With the full detector we anticipate study of the primary composition to EeV energies where the transition from galactic to extra-galactic cosmic rays may occur.

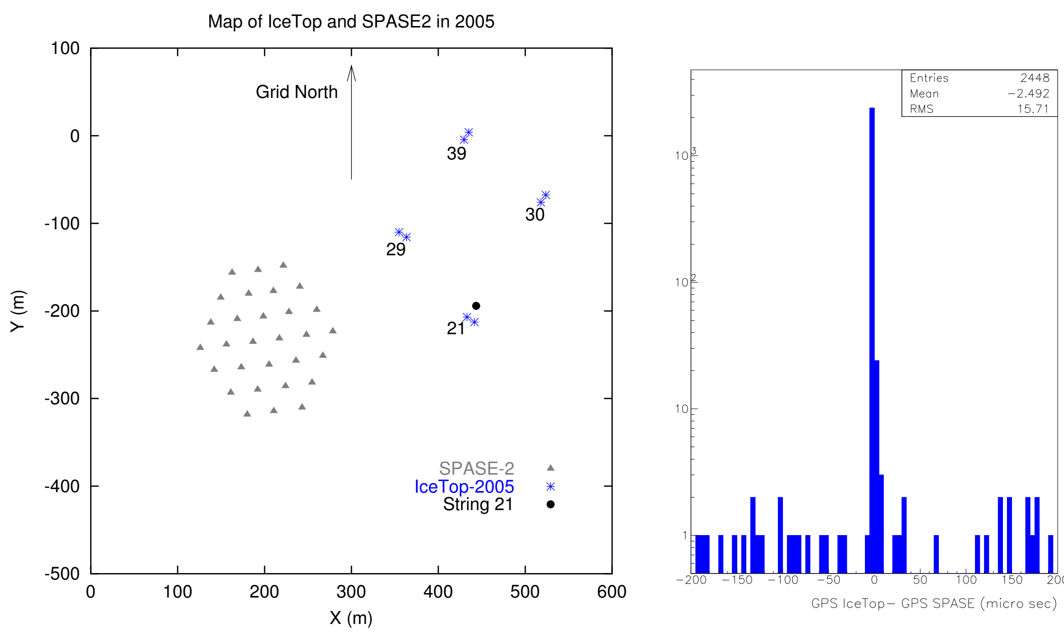

Figure 1. Map of IceTop and SPASE in 2005. The peak in the distribution of time differences between IceTop and SPASE triggers contains events seen by both arrays.

Deployment of IceCube at the Amundsen-Scott South Pole Station began in the 2004/2005 Austral summer season with the installation of one string of 60 DOMs in the deep ice and four IceTop stations on the surface. Fig. 1 shows the configuration of the first four stations relative to the existing South Pole Air Shower Experiment (SPASE) [2], which is still in operation. In this paper we present engineering data from the first four surface stations of IceCube, including coincidences with SPASE. Initial data from the deep string, including coincidences between surface and deep detectors, are presented separately [3].

2. The IceTop Array

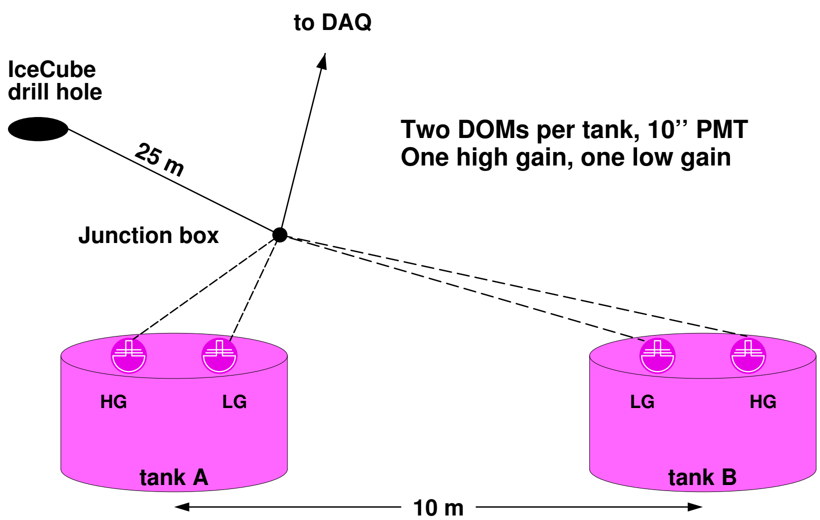

Figure 2. Diagram of an IceTop station.

Each pair of IceTop tanks is associated with an IceCube string. The result is a surface array in a triangular pattern with a grid spacing of approximately 125 m. Each IceTop station consists of two ice Cherenkov tanks separated by 10 meters, as shown schematically in Fig. 2. The two DOMs in each tank face downward and respond primarily to light reflected from the diffusely reflecting, white liner of the tank. The ice surface is in contact with granulated insulation, so that the top inner surface is partially reflecting. The tanks are cylindrical with surface area $2.7\,\mathrm{m}^2$ and ice thickness 90 cm.

Operation of the DOMs (which is described in more detail in [3]) is controlled by digital electronics, which can be set remotely. The tanks currently operate with one DOM set at low gain (5×10^5) and one at high gain (5×10^6). Three channels of the analog transient waveform digitizer (ATWD) on the DOM main board sample the waveforms at 3.3 ns with different amplification, for a dynamic range of more than 5000.

The rate of events detected per tank depends on trigger and threshold settings. The amplitude threshold is currently set at a voltage corresponding to ten times the peak voltage of a single photo-electron. At this threshold and with no coincidence requirement, the rate per DOM is about 3 kHz. This rate includes approximately 1 kHz of muons. Simulations [4] show that the balance is due primarily to low energy electrons and to gamma-rays converting in the tank. The characteristic shape of the spectrum of single hits, which has a prominent muon peak, is shown in the left plot of Fig. 3.

For comparison with the air shower waveform shown below in Fig. 4, we also show in Fig. 3 the average waveform of a throughgoing muon in a high-gain DOM. This is obtained by averaging over a sample of waveforms corresponding to events in the muon peak of the distribution of signals shown on the left panel of Fig. 3. With 90 cm of ice thickness, typical energy-deposition by throughgoing muons is 160 to 200 MeV, depending on zenith angle. Comparison of integrated single photo-electron waveforms with the integral of the average muon waveform allows us to estimate that the typical through-going muon produces enough light to generate approximately 160 photo-electrons in the photomultiplier. The data shown in Fig. 3 were taken during initial fast calibration runs at the South Pole in January. High statistics calibration runs currently underway will provide the basis for detailed calibration of amplitude and integrated charge. Periodic sampling of the single tank spectra will also serve to monitor performance of each tank. In addition, calibration runs with events tagged by a muon telescope are planned for next season.

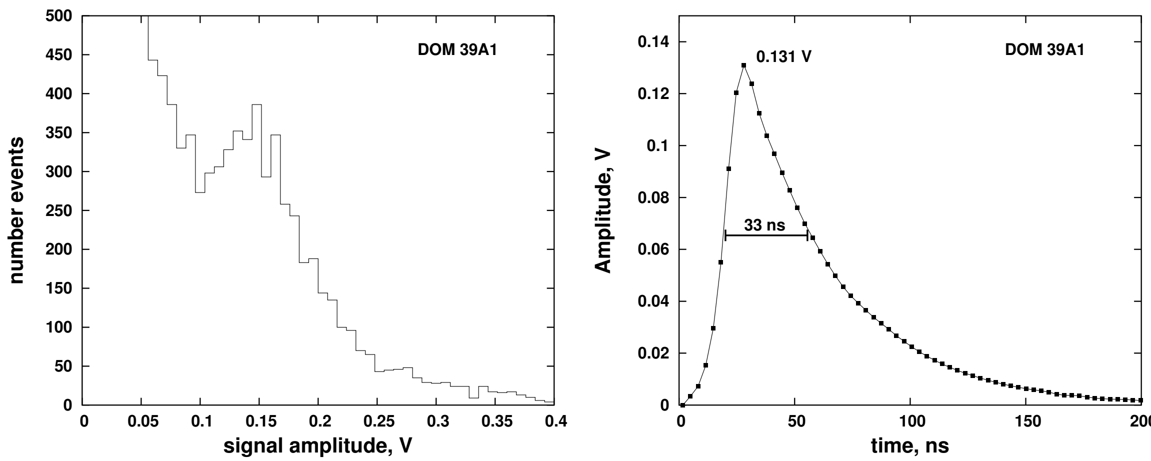

Figure 3. Left: Peak amplitudes of single-tank signals showing a muon peak (high-gain DOM); right: average μ waveform.

The spacing between detectors at a station is chosen so that a coincidence of two tanks at a station without hits in adjacent stations corresponds to small showers from cosmic-ray protons with primary energies in the few to ten TeV range. Such events have a high probability of producing only one muon that reaches the deep detector. Tagging such events will be useful for understanding the principal background of atmospheric muons in the deep detector.

3. Air Showers in IceTop

For a series of runs taken February through May of 2005 the IceTop trigger was set to require 10 DOMs above threshold within 2 μsec. During these initial runs there was a local coincidence requirement within a station such that a DOM only reported if at least one of the DOMs in the other tank at the station was hit. With this setup, only air showers with at least three stations reporting were recorded. The rate of air showers with this trigger is 0.7 Hz, divided approximately 60/40 between 3-station events and 4-station events. This rate is consistent with the expected threshold of 300 TeV and is due to events in the PeV and sub-PeV energy range.

With only 4 stations, most triggers are from air showers with cores outside the perimeter of the array, and the core locations cannot therefore be determined. External events typically have one station with a much bigger signal than the others. Events with cores inside the array will display a more symmetric pattern. Fig. 4 shows a waveform display for one such "contained" event. In this figure the upper row shows the high-gain DOMs and the lower row the low-gain DOMs. Solid lines show tank A and broken lines tank B at each station. Successive panels (from left to right) show the event passing across the array from station 30 to 29. Low-gain waveforms generally track the high-gain waveforms. Shower-front fluctuations can cause significant differences between tanks at the same station (e.g. 39), and details of particle location and DOM response within a tank also cause differences. When all high-gain channels saturate, the low-gain channels may be used to extend the dynamic range of the tank response to beyond that achievable with the three ATWD channels. We expect an overall dynamic range for the tank response of approximately 10^5.

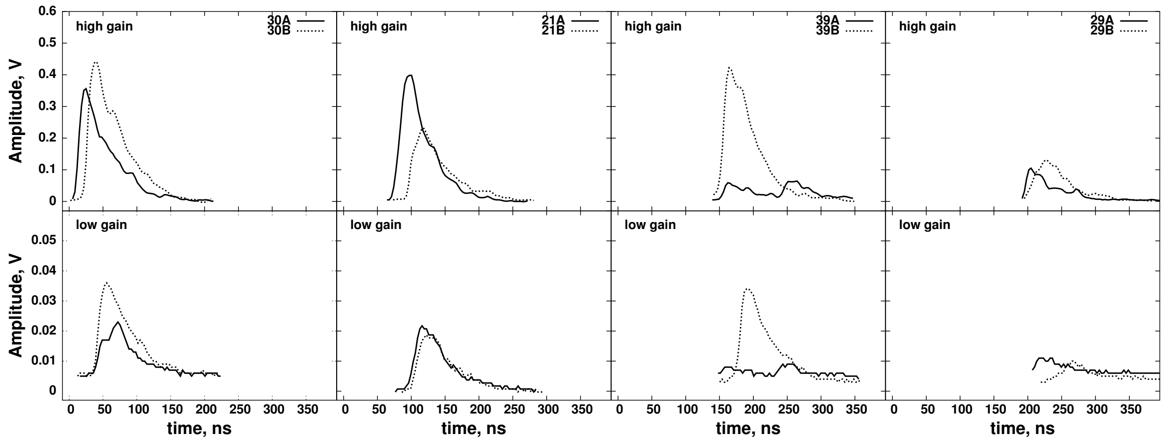

Figure 4. Waveforms for a 16-fold event with a reconstructed zenith angle of 23°.

Off-line we can find coincidences with the SPASE array by matching up GPS times, as shown in Fig. 1b. The rate of coincidences between IceTop and SPASE triggers is about 1 per minute, which corresponds to showers in the 10 PeV range.

4. Conclusion

The four IceTop stations are recording air shower data. During the remainder of this season, tank calibration will be performed using the muon peak in the spectrum of inclusive single tank hits. In addition, fluctuations in the shower front will be studied by comparing signals in tanks at the same station, and detector fluctuations will be studied by comparing DOMs set to the same gain in one tank.

The plan for the coming season at the South Pole is to deploy 12 additional stations grid north of the present array. The result will be a 16 station air shower array with an enclosed area of $0.12\ \mathrm{km}^2$. For operation during 2006 we therefore expect to cover a range of primary cosmic-ray energies from 300 TeV to 100 PeV. Approximately 10% of IceTop triggers will also give hits in the deep detectors, giving a significant potential for calibration of the neutrino telescope with the surface array, as well initial analysis of composition in the knee region of the primary cosmic-ray spectrum.

References

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