29th International Cosmic Ray Conference Pune (2005) **8**, 303–306

IceCube: Initial Performance

D. Chirkin[a] for the IceCube Collaboration

(a) Lawrence Berkeley National Lab Berkeley, CA 94720-8158, U.S.A.

Presenter: D. Chirkin (dchirkin@lbl.gov), usa-chirkin-D-abs1-he15-oral

The first new optical sensors of the IceCube neutrino observatory - 60 on one string and 16 in four IceTop stations - were deployed during the austral summer of 2004-05. We present an analysis of the first few months of data collected by this configuration. We demonstrate that hit times are determined across the whole array to a precision of a few nanoseconds. We also look at coincident IceTop and deep-ice events and verify the capability to reconstruct muons with a single string. Muon events are compared to a simulation. The performance of the sensors meets or exceeds the design requirements.

1. Introduction

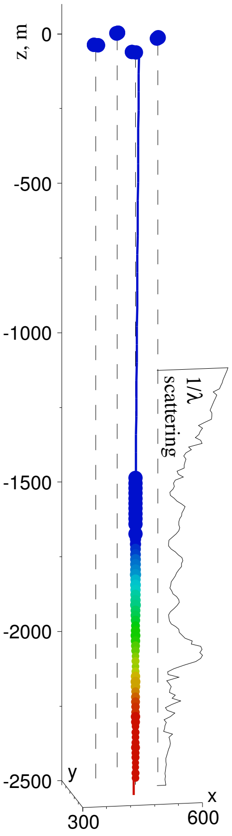

Figure 1. IceCube event

The IceCube neutrino observatory at the South Pole will consist of 4800 optical sensors - digital optical modules (DOMs), installed on 80 strings between the depths of 1450 to 2450 meters in the antarctic ice, and 320 sensors deployed in 160 IceTop tanks on the ice surface directly above the strings. Each sensor consists of a 10 in. photomultiplier tube, connected to a waveform-recording data acquisition circuit capable of resolving pulses with sub-nanosecond precision and having a dynamic range of at least 250 photoelectrons per 10 ns. This year 76 such sensors were installed as a first part of the IceCube and IceTop [1] arrays.

After a sensor acquires and digitizes an event trace, it transmits the data to the surface electronics. The events are time-stamped locally with an internal (to each sensor) clock, which has an estimated drift time of $\sim$ 1 ns/s. All of the DOM clocks are time-calibrated with a special procedure, which involves sending an analog pulse from the surface to the DOM, where this pulse is received, digitized, and recorded. A similar analog pulse is sent from the DOM to the surface, where it is, in turn, digitized, and analyzed together with the pulse recorded by the DOM (which is transmitted to the surface digitally after the main "round trip" calibration procedure finishes). In this report we demonstrate that events are time-stamped with a nanosecond-scale precision over the network of 76 deployed DOMs.

Fig. 1 shows an event involving all 76 DOMs. The circle size is proportional to the signal amplitude, while the color (from blue to red) indicates relative times of the hits recorded in the DOMs. All hits are consistent with an air shower on the surface coincident with a deep-ice muon, traveling down at a zenith angle of $3 \pm 2°$.

From the ice scattering-length profile shown next to the detector string, one sees that most of the detector is located in very clear ice. In fact, the lower 25 DOMs are in ice that is up to 2 times clearer than that available to the AMANDA [2] sensors located at depths of 1500-2000 meters.

2. Time resolution and muon track reconstruction

As a part of each sensor's time calibration, round trip times of the time calibration pulses are measured (Fig. 2). The times are larger for progressively deeper sensors on the string (DOMs with numbers 1-60), and are essentially the same for the IceTop sensors (shown as DOMs with numbers 61-76). Calibrations are done automatically every few seconds. The round trip time varies slightly from one calibration to the next, and the size of the variation provides the basic measurement of the precision of the time calibration procedure (Fig. 3).

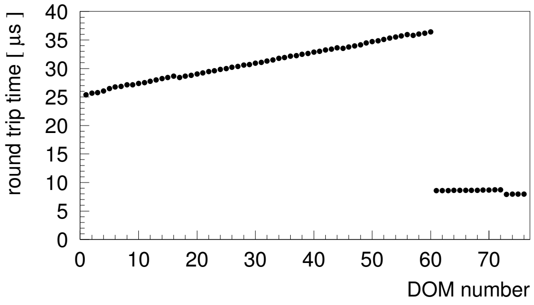

Figure 2. Round trip time of the time calibration pulse (IceTop DOMs are shown with numbers 61-76)

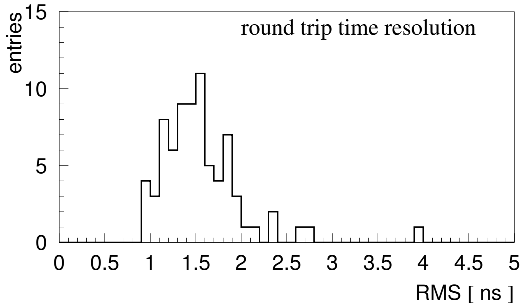

Figure 3. The rms resolution of the round trip time of the time calibration pulse

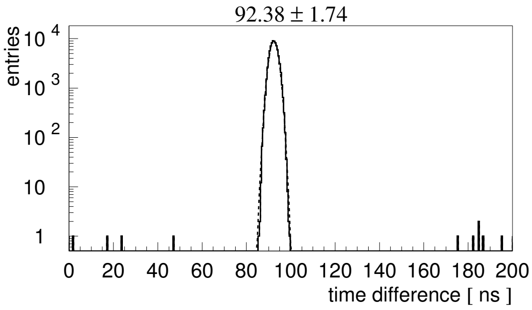

Figure 4. Hit time difference between 2 DOMs directly above the one flashing in clear ice

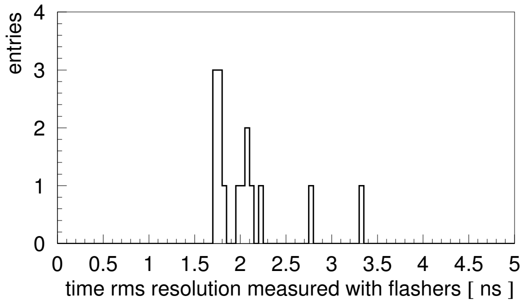

Figure 5. Hit time resolution measured with flashers for 15 DOMs on the IceCube string

Each DOM contains an array of photodiode "flashers", which can be used for many types of calibrations. We used these to find the differences between the photon arrival times at a few DOMs directly above the ones flashing. Fig. 4 shows the distribution of such a difference for DOMs 59 and 58, when DOM 60 was flashing. The rms values for several such DOMs are shown in Fig. 5 and are best (∼ 2 ns) for the DOMs located in clearer ice.

A typical waveform captured by an IceCube sensor is shown in Fig. 6. The waveforms are described very well by a waveform decomposition procedure, which yields single photon hit times.

A likelihood minimization algorithm for one-string track reconstruction in multi-layered ice was used to reconstruct the deep-ice data. The scattering and absorption values used were those measured with AMANDA and extrapolated to deeper ice using available ice core data and data collected by a dust measuring device used during the string deployment.

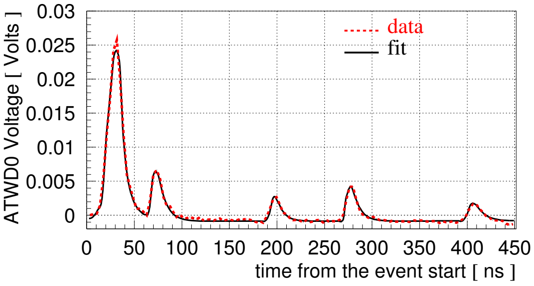

Figure 6. Captured hit event waveform

The track-fitting algorithm was tested on a simulated data sample of downgoing muons (Fig. 7) and was found to reconstruct it rather well (Fig. 8). The rms resolution of the muon track zenith angle reconstruction is 9.7° with an event hit multiplicity of 8 or more. The resolution improves rapidly as the multiplicity increases (3.0° at multiplicity 20, and 1.6° at multiplicity 40). This is similar to the one-string AMANDA analysis results [3].

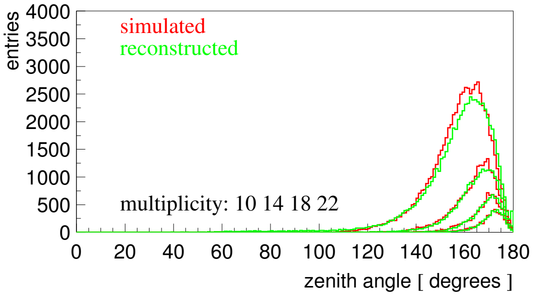

Figure 7. Zenith angle distribution of simulated downgoing muons (red) vs. reconstructed tracks (green)

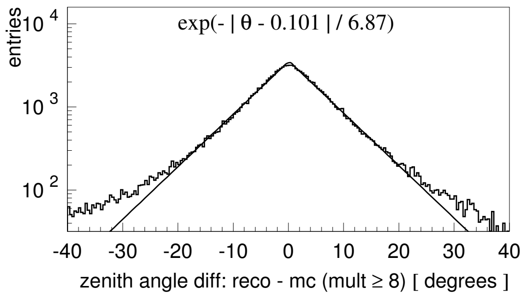

Figure 8. Zenith angle difference distribution of reconstructed and simulated tracks

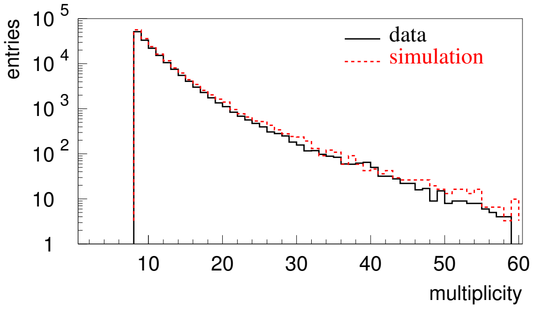

Figure 9. Muon hit multiplicity distribution of data and simulation

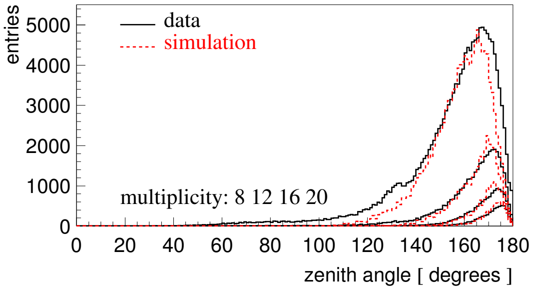

Figure 10. Muon zenith angle distribution of data and simulation

Fig. 9 compares the hit multiplicity distribution for 8 hours of data and a similar amount of simulated data. The zenith angle distribution of the reconstructed tracks in data is compared to the simulated data in Fig. 10. The simulated data used in Fig. 7-10 was produced with standard AMANDA simulation, which was not tuned to the somewhat different trigger logic, ice conditions and different sensors of the deeper IceCube string. As the IceCube simulation matures, the apparent discrepancy observed in Fig. 10 is expected to become smaller.

Coincident deep-ice and IceTop events with a combined hit multiplicity of at least 14+14 hits collected during March, April, and May were reconstructed with both the IceTop shower reconstruction and the one-string muon track reconstruction discussed above. The resulting zenith angle distributions are compared in Fig. 11. The directions obtained with the string reconstruction seem to be systematically closer to the vertical, which may indicate the need to improve the likelihood parameterization used in the track reconstruction. Alternatively it may be due to the shower front being curved and muons originating from a different part of the shower than that seen by IceTop. We measure a systematic offset of 2.1° with an rms deviation of 4.1° (Fig. 12).

To measure systematic time offsets in the IceCube string we applied the one-string reconstruction to one day's worth of data 60 times. Each of the 60 DOMs was removed once during the reconstruction, and the time residuals of the hits in those DOMs to the expected direct (unscattered) hit times from the reconstructed tracks were evaluated. The residual time distributions are consistent with the expected distribution of hits coming from nearby muons (Fig. 13). The maxima of such distributions indicate the time residuals of the most probable (in the current setup, direct) hits. In addition to systematic time calibration offsets these can be systematically removed from zero due to features of the DOM geometry still unaccounted for and scattering affecting photon propagation even at small distances. Most of these residuals are within 3 ns of each other, except for DOMs 35-43, which are located in dustier ice (Fig. 14). This indicates that the DOM clock times for the whole array (currently 76 DOMs) are calibrated to within 3 ns of each other. An apparent large time offset of DOM 60 is currently under investigation.

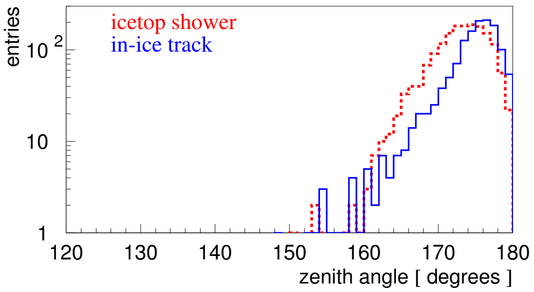

Figure 11. Zenith angle distribution of string-reconstructed tracks (blue) and IceTop-reconstructed coincident showers (red)

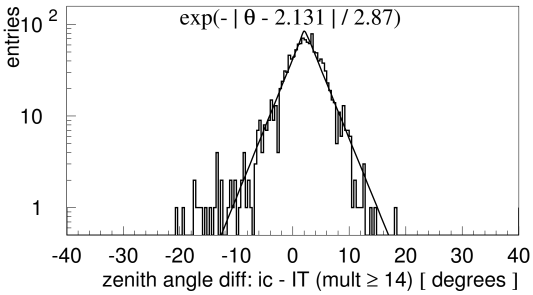

Figure 12. Zenith angle difference distribution between string-reconstructed tracks and IceTop-reconstructed coincident showers

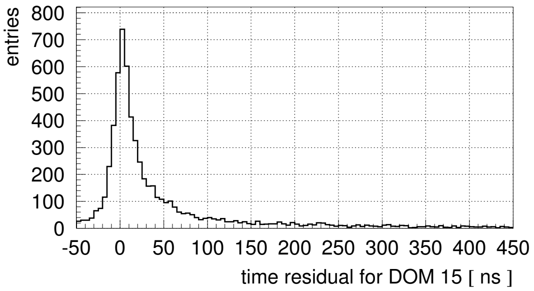

Figure 13. Distribution of time residuals between the hits recorded by a DOM and time expectation for direct (unscattered) hits from nearby tracks reconstructed with the rest of the string

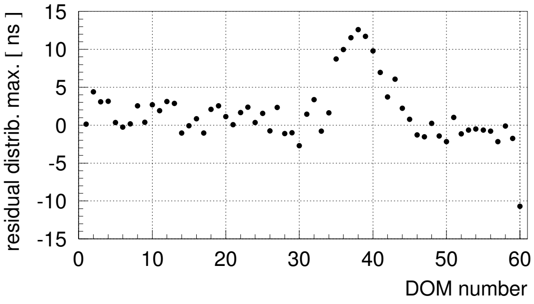

Figure 14. Distribution of direct hit time residuals for all DOMs on the deployed IceCube string

3. Conclusions

We have demonstrated that the newly deployed IceCube string is capable of detecting muons and muons coincident with IceTop air showers. The observed muon flux is compatible with the expectation from the simulation. The global detector time calibration uncertainty is 3 ns, which is better than the design requirement of 7 ns.

References

[1] T.K. Gaisser, these proceedings
[2] E. Andres et al., Nature 410, 441 (2001).
[3] M. Ackerman et al., submitted to Nucl. Instrum. Meth. A