Time calibration and functionality verification of the IceCube instrumentation

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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 1400 to 2500 meters in the antarctic ice, and 320 sensors deployed on the ice surface directly above the strings. Each of these sensors consists of a 10 in. photomultiplier tube, connected to a waveform-recording digital data acquisition circuit capable of resolving pulses with sub-nanosecond precision and having a dynamic range of at least 250 photoelectrons per 10 ns. The first new sensors of the IceCube neutrino observatory - 60 on one string and 16 at four IceTop stations - were deployed during the austral summer of 2004-05.

The photon hit events are time-stamped locally with an internal (to each sensor) clock, which has an estimated drift time of ~ 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, and sending back a similar pulse 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).

We analysed data collected during the pre-deployement testing of the DOMs at the several facilities around the world as well as light calibration, muon, and shower data collected by the IceCube array during the few months following the deployment. Several time calibration algorithms were developed and extensively tested. We concluded that achiving time resolution of ~ 2.0 ns (using laser as a light source in the laboratory conditions, and flasher data in-ice) was possible. We developed a suite of error-correction algorithms, which can recover from all error conditions that we observed (from temporary failure to aquire a valid GPS clock timestamp to mistakenly triggering on noise instead of a time calibration pulse).

A typical waveform captured by an IceCube sensor is shown in fig. 1. The waveforms are described very well by the IceCube waveform decomposition (feature-extraction) procedure, which yields single photon hit times.

Computer code was developed that reads event data, applies time and other types of calibrations (amplitude, charge, etc.), feature-extracts waveforms acquired by DOMs, forms off-line triggers, and reconstructs muon tracks, position of point-like sources (e.g., cascades and built-in photodiod "flashers"), and IceTop showers. This code is available as a stand-alone software program, and as a suite of plug-in modules for the standard IceCube software.

By analysing time delays from reconstructed muon tracks to the IceCube DOMs, we have demonstrated that hit times are determined across the whole array to a precision of a few nanoseconds. We also looked at coincident IceTop and deep-ice events and verified the capability to reconstruct muons with a single string (fig. 3). We also demonstrated a good

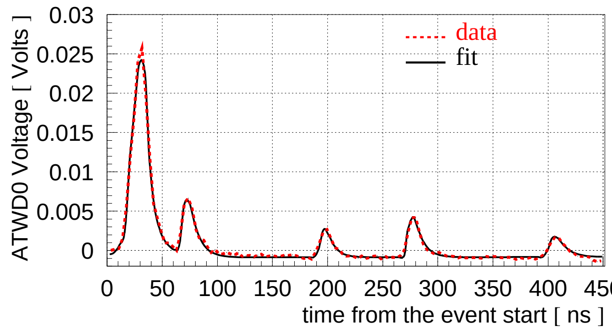

FIG. 1: Reconstruction of single photoelectron hits in the waveform data acquired by DOMs.

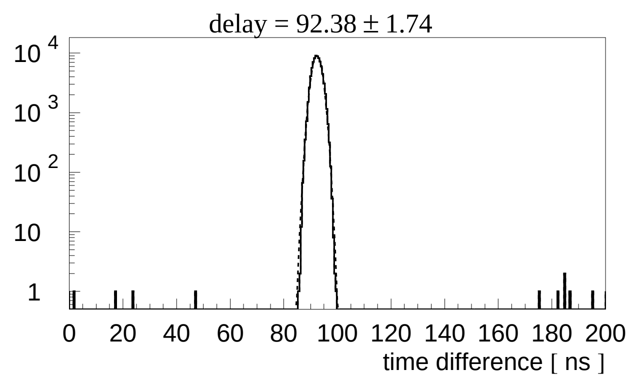

FIG. 2: Hit time difference between 2 DOMs closest from above to the one flashing in clear ice

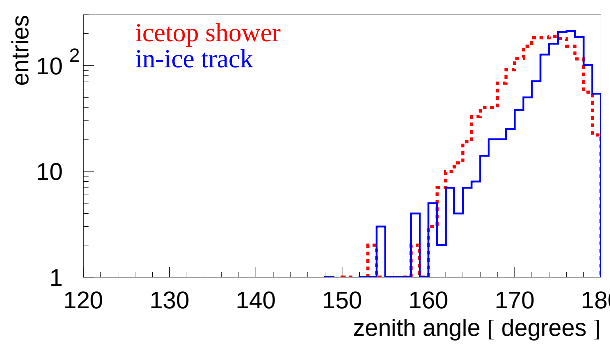

FIG. 3: Zenith angle distribution of string-reconstructed tracks (red) and IceTop-reconstructed coincident showers (blue)

agreement of muon events in data with the simulation.