IceCube Performance with Artificial Light Sources: the Road to Cascade Analyses

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Abstract: The IceCube one km^3 neutrino observatory will collect large samples of neutrino interactions, allowing for observations with small statistical errors. To make maximum use of this statistical power, it is also being designed to minimize systematic errors, via a variety of different calibration techniques. LED and laser light sources are a key part of many of these calibration techniques. To a significant extent, they mimic cascade (ν_e) interactions, allowing fairly direct tests of cascade reconstruction techniques. This contribution will survey the light sources and discuss selected calibration studies.

Introduction

The main goal of IceCube [1] is to detect cosmic neutrinos of all flavors in a wide energy range, from ∼100 GeV to ∼100 EeV and search for their sources. When complete, the IceCube detector will be composed of up to 4800 Digital Optical Modules (DOMs) on 80 strings spaced by 125 m. The array covers an area of one km^2 from 1.45 to 2.45 km below the surface [2].

High energy neutrinos are detected by observing the Cherenkov radiation from secondary particles produced in neutrino interactions inside or near the detector. Muon neutrinos in charged current (CC) interactions are identified by the final state muon track [3]. Electron and tau neutrinos in CC interactions, as well as all flavor neutrinos initiating neutral current (NC) interactions are identified by observing electromagnetic or hadronic showers (cascades). For example, up to ∼10 PeV, electromagnetic showers initiated by the final state electron can be approximated as expanding light spheres originating from a point source. A 10 TeV cascade triggers IceCube optical modules out to a radius of about 130 m [4]. Cascade reconstruction is expected to have limited pointing capability but good energy resolution, 0.11 in $\log_{10}(E)$ [5]. The good energy resolution and low background from atmospheric neutrinos makes cascades attractive for diffuse extraterrestrial neutrino searches [6].

Artificial light sources are of particular importance in IceCube. Each DOM includes 12 LEDs (flashers) as a calibration source. As shown in Fig.1, one string also holds a nitrogen laser with absolute calibration that serves as a "standard candle". The flashers and standard candle (SC) are used for a wide variety of purposes: timing, charge amplitude and geometry calibrations, to measure the optical properties of the ice (a key problem for IceCube), and to mimic cascades. The flasher light output is comparable to cascades with energies up to about 500 TeV, while the standard candle output is comparable to cascades with energies up to about 30 PeV. For the ice studies, the availability of flashers at different depths is critical, allowing comparisons of ice properties at different depths. These studies build on the lessons learned from AMANDA, which pioneered the use of artificial light sources [7].

In this report we present the results of a few selected studies performed with the flashers and standard candle: geometry and timing calibrations, and

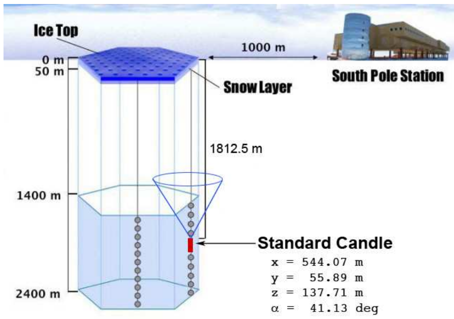

Figure 1: Schematic of the IceCube detector showing the location of the Standard Candle. For clarity, only two out of 80 strings are shown.

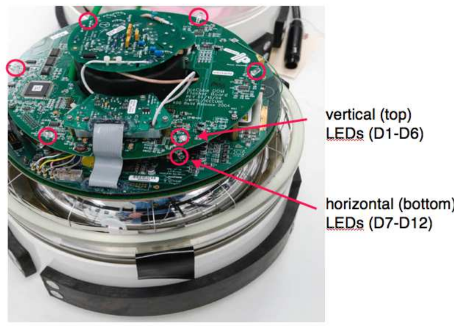

Figure 2: Digital Optical Module with six horizontal and six vertical LED flashers.

the position resolution of cascade algorithms. This work uses data collected during 2006 with 9 strings that had been deployed in IceCube at that time.

LED Flashers

Each DOM contains a flasher board which holds twelve 405 nm LEDs. Six of them point horizontally outward and six point upwards at $\sim$48 degrees. They are mounted on the top and the bottom of the flasher board respectively, cf. Fig.2. The LEDs are individually flashed with a programmable pulse width and amplitude. Typical flasher runs last 500 s with the LEDs firing at 10 Hz at full brightness, with nominal width of 10 ns.

Geometry Calibration

The LED flashers were used to calibrate the position of the DOMs. Figure 3a) shows a schematic of one study that was used to measure the relative depth of DOMs on different strings. The LEDs in a DOM on one string were pulsed and arrival times for nine nearby DOMs on a neighboring string were analyzed. The time of the earliest hit t_0 was derived from the photon arrival time distribution, cf. Fig. 3b), by fitting a Gaussian in the turn-on region: $t_0 = \mu - 3\sigma$, where μ and σ are the mean and sigma of the Gaussian. The uncertainty is determined by propagating the errors on the fit parameters. The arrival times of the earliest hits are

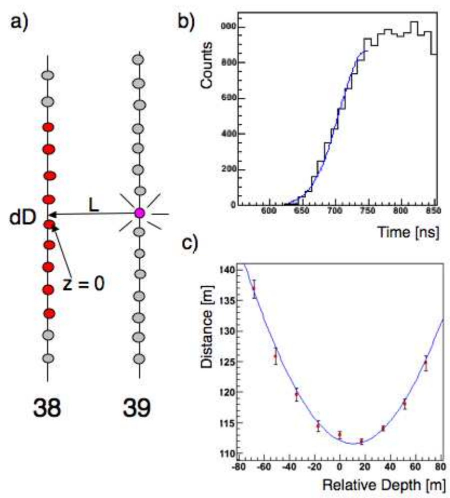

Figure 3: a) Schematics of the interstring detector geometry measurement. The flasher light from LEDs on DOM 39-15 is seen on a neighboring string. b) The earliest hit time distribution for light detected at DOM 38-10. c) The earliest hit time observed at DOMs on string 38 shown as a function of the relative depth between the observing DOMs and the flashing DOM.

converted to distances (assuming that there is no scattering, appropriate for the first photon seen). Figure 3c) shows these distances versus the relative depth from the deployment records. This distribution was fitted with a hyperbola to determine the relative depth and lateral separation between the two strings. The position of the minimum gives the relative depth and is used to correct the string position determined from deployment and survey data. Systematic uncertainties in the determination of the lateral separation are under study.

Timing Calibration

Flasher data are used also to verify the system timing resolution. The method is to flash an LED on a DOM and measure the arrival time of light reaching a nearby DOM, as shown in Fig. 4a). The earliest photons are likely not scattered, hence the difference in timing between the two DOMs reflects the time in ice. The distance between DOMs on the same string (∼17m) is smaller than the light scattering length in ice (∼25m) and the light intensity is high enough so that direct light is seen on neighboring DOMs. The resolution is dominated by electronics and timing uncertainties. A distribution of the first photon arrival time for a single receiving DOM is shown in Fig. 4b). The resolution for most DOMs was found better than 2 ns, as shown in Fig. 4c), confirming the precision of the time synchronization procedure. The results are consistent with an alternative method which uses muon tracks [2].

Standard Candle

The Standard Candle (SC) is an in-situ calibrated N_2 pulsed laser, which emits light with a wavelength of 337 nm. It is used to study cascade reconstruction, and to provide a method for calibrating the cascade energy scale which is independent of Monte Carlo simulations. At 100 % intensity, the SC generates $(4.0 \pm 0.4) \times 10^{12}$ photons which are emitted at an angle of 41° with respect to the candle axis, as is shown in Fig. 1. The 41° angle was chosen to approximately match the Cherenkov radiation from a cascade. Although the light distribution initially matches that of a cascade, the wavelength of 337 nm is shorter than most of the

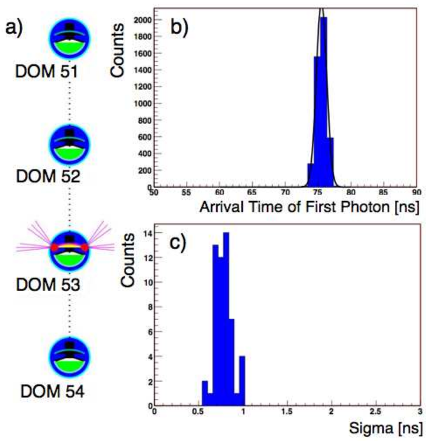

Figure 4: a) DOM 53 is flashing. b) Photon arrival time delay at DOM 52 when DOM 53 is flashing. c) RMS variation of time delay measured with flashers for 59 DOM pairs on an IceCube string.

Cherenkov radiation observed in IceCube. This results in ∼10 % shorter absorption and scattering lengths, and requires adjustments to the amplitude calibrations. Pre-deployment calibration and internal power measurement contribute to 10% uncertainty in light output. The light intensity is determined on a pulse-by-pulse basis.

The SC is equipped with an adjustable attenuator that can reduce the light output down to 0.5% of the full scale. This is used to study detector (especially photo-multiplier tubes) non-linearities. We plan to deploy one additional standard candle, which will point downwards or to the side, allowing different cascade geometries to be studied in future.

Reconstruction Results

Figure 5 shows an event with the SC at full laser intensity. Results from the SC laser events reconstruction as cascades are shown in Fig. 6. The dashed histogram shows the center-of-gravity (COG) x position. The COG is calculated for each event as the signal amplitude weighted mean of all hit DOM positions. The mean COG x position, about 512 m, is about 30 meters from the actual SC x position of 544 m (shown as a dashed-dotted line). The reason for this discrepancy is that the SC

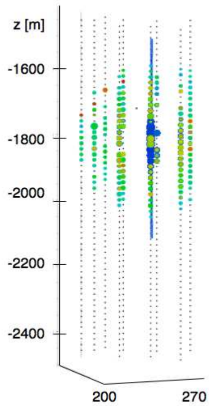

Figure 5: Standard Candle event display with 162 DOMs hit. The size of the circles is proportional to the signal amplitude, while the color distinguishes between relative photon arrival times in the DOMs.

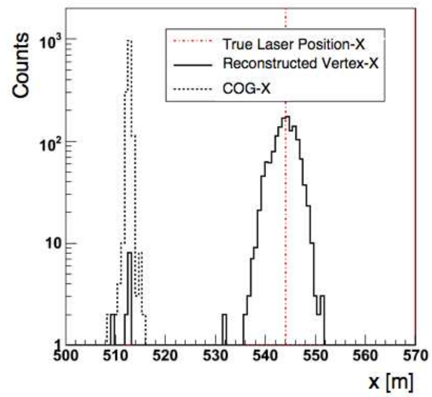

Figure 6: The reconstructed x-vertex position of 'cascades' from SC events. The dashed histogram shows the center-of-gravity (COG) position, and the continuous histogram shows the reconstructed vertex position. The dashed-dotted line is the 'true' SC laser position in the detector ($x = 544.1$ m).

is on a string at the edge of the 9 string array, and the COG is pulled toward the center of the array. The COG is used as a first approximation for a full maximum-likelihood reconstruction algorithm [8]. This algorithm considers the photon arrival times at all of the other DOMs. It finds an x position (continuous histogram) within 10 m of the actual SC position for about 99% of the events. Similar results have been obtained for y and z vertex positions. The fact that the algorithm can find the position so well for asymmetric events (with DOMs on only one side of the SC) gives us confidence in the reconstruction algorithm accuracy.

Summary

The IceCube flasher LEDs and standard candle laser are used for a variety of calibration and verification studies, including geometry and timing calibrations, and studies of ice properties. It has been demonstrated that for most DOMs the timing resolutions is better than 2 ns and the DOM positions are known to 1 m. These studies will help IceCube reduce the systematic errors for various physics analyses. Artificial light sources have also been used to study the position reconstruction performance of cascade reconstruction algorithms, and to study the absolute energy scale of the detector. In future, they will be used to study also the energy and directional reconstruction of more advanced algorithms.

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