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Construction Status and Future of the IceCube Neutrino Observatory

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Abstract. The IceCube neutrino telescope nears the end of its second running season having collected a sample of over $2 \times 10^9$ triggered events. While the majority of these events are cosmic ray muons, the detector is already sufficiently well understood to allow identification of neutrino-induced muon candidate events from the CR background. The production of optical module instrumentation is now well-established, the modules themselves are functioning properly with low failure rate, and it has been proven that the hot water drill can deliver the holes needed for deployment of these instruments. The project plans to deploy 12-14 strings each year during the next several austral summers to bring the detector volume to 1 km$^3$.

1. Introduction

High-energy neutrino astrophysics is entering the era of kilometer-scale observatories. The IceCube neutrino telescope will be the first detector with an integrated exposure volume to reach 1 km$^3 \cdot$yr. The detector includes a deep array of digital optical sensors deployed at depths between 1500 m and 2450 m in holes drilled in the glacial ice sheet at the geographic South Pole. These deep sensor modules detect the Cherenkov light radiated by passing charged relativistic particles in transit through the ice medium. The optical properties of this medium have been measured with \textit{in situ} light sources [1] deployed with the predecessor detector array, AMANDA [2, 3]: below 1500 m the ice becomes bubble free where long absorption and scattering lengths are found ($\ell_{\text{abs}} \sim 100$ m, $\ell_{\text{scatt}} \sim 25$ m).

The IceCube deep array is optimized for the detection of muons produced by high energy ($E \gg 1$ TeV) neutrinos from astrophysical point source emitters such as active galactic nuclei or transient sources such as gamma ray bursts [4]. The muon is produced via charged-current interactions of the neutrino with ice nuclei ($\nu_\mu + N \rightarrow \mu + X$), typically exterior to the detector volume due to the long range of muons with energies in excess of 1 TeV. Ice is also an ideal calorimetric medium due to the long optical absorption lengths and so the visible energy of contained neutrino events can be reconstructed with $\pm 20\%$ resolution in the exponent. In addition to these high-energy phenomena of cosmic origin, IceCube may observe signals from dark matter annihilations and will collect a high statistics sample ($O(10^6)$) of atmospheric neutrinos relevant to particle physics topics such as Lorenz invariance tests in regions unreachable by other techniques. At the low energy end, IceCube presents an effective volume of approximately $2.0 \times 10^6$ tons to MeV neutrinos from supernovae.

An array of the same sensors deployed in the ice holes are frozen into tanks at the top of each hole, providing an airshower detector component for IceCube. Called IceTop, this
instrumentation may be used as a trigger veto to assist in rejection of cosmic ray event backgrounds in the deep detector. Furthermore, combining its data with data from the deep-ice array provides a unique opportunity to study cosmic ray composition in the region of the “knee,” extending earlier measurements performed using the combination of the SPASE and AMANDA detectors [5, 6].

2. Status of IceCube instrument deployment
The first IceCube string (#21) and the first four IceTop stations (#21, #29, #30, and #39) were deployed in January 2005 at the end of the deployment season and were operated during the austral winter of that year. The survivability of the digital optical modules during deployment and subsequent refreeze of the drill hole was established (all DOMs deployed during this season continue to function properly), useful performance data were gathered throughout the year of operation of the string [7, 8], and neutrino candidate events were selected from this data run.

During the following austral summer season, from December 2005 to January 2006, eight more strings (#29, #30, #38, #39, #40, #49, #50, and #59) and twelve more IceTop stations (#38, #40, #47, #48, #49, #50, #57, #58, #59, #66, #67, and #74) were deployed bringing the count to 9 strings and 16 surface stations and a total enclosed ice volume of 0.1 km³. Of the 604 sensors deployed to date, 597 of them communicate and 592 are producing high quality data.

A current view of the IceCube detector installation is shown in Figure 1. The deployment plan calls for 12-14 strings and 10 surface stations to be deployed this year (2006-2007) to be followed
by an average of 14 strings and IceTop stations in the following years until 2011 when the full complement of instrumentation will have been deployed, approximately 70-75 strings (60 DOMs per string) and 80 surface stations (4 DOMs per station). IceCube will be operated throughout the construction, achieving an integrated exposure of 1 km$^3$·yr by 2009 and 4 km$^3$·yr by the second year of operation with the completed detector. We anticipate that the total operating lifetime of the experiment will be 20 years.

3. Drilling and deployment

The Enhanced Hot Water Drill (EHWD) system delivers 2.5 km × 60 cm holes to the deployment team for insertion of the optical sensor hardware. The system includes self-contained heating and electrical powerplants with a combined power of approximately 5 MW, pumping systems, a control facility, and drilling towers. Each year the drill camp is moved into place near the target holes. The towers then operate as mobile field facilities served by the central drill camp and towed into position atop each drill hole (Figure 2). During operation, the drill supplies 200 gallons per minute of 190 °C water at 1000 psi. The average fuel consumed per hole is 7200 gallons. The entire operation of drilling a hole and deploying the optical module instrumentation takes approximately 50 hours.

![IceCube drill camp with drill tower image inset in lower left corner. The tower sits atop a drill hole. Two icetop tanks forming a station are visible in trench to the right of the drill tower.](image)

Figure 2. IceCube drill camp with drill tower image inset in lower left corner. The tower sits atop a drill hole. Two icetop tanks forming a station are visible in trench to the right of the drill tower.

4. The IceCube digital optical module

The IceCube digital optical module (DOM) (Figure 3) is the central detector element used throughout the array, both in the deep ice and at the surface. It is a self-contained optical detector and data acquisition device. The analog optical device is a 10$^7$ photomultiplier tube running at 1.0 × 10$^7$ gain into a ∼ 50 Ω front-end load impedance. PMT high voltage bias is supplied internally by a DC-DC converter module that is powered from the +5 V line on the DOM mainboard and can produce a programmable HV from 0 to +2048 V. A classical resistive divider bleeder distributes voltages to the PMT dynodes. The DOM also contains a PCB containing 12 405 nm LEDs which may be flashed in the ice to provide a known optical
source for studying ice properties or performing geometrical calibrations of the sensor array. All components are housed inside a 0.5" thick glass pressure sphere rated to 10000 psi external pressure. The power and digital communication lines exit the DOM via the penetrator cable which attaches to the main communication cable bundles. DOM digital communication signals travel to the surface over copper quads contained within the 45 mm cable bundles.

DOMs are assembled at three production and test facilities worldwide within the IceCube collaboration: University of Wisconsin, Stockholm University / Uppsala University, and DESY Zeuthen. Following assembly each DOM undergoes a 2-3 week test at various temperatures from +25 \degree C to −55 \degree C in order to evaluate its performance at low temperature and to characterize various optical and electronic operational parameters [9]. All data thus far obtained with DOMs manufactured at all sites supports the claim that all sites are producing equivalent sensor hardware. To date 2000 of a total 5000 DOMs have been built. First pass yields are nearing 90% and the shipping yields are in excess of 95%.

5. Data acquisition
The PMT pulses are converted into digital waveforms by one or more digitizer chips at speeds up to 3 \times 10^8 \text{ samples/s}. Each DOM runs in self-triggered mode with the option to monitor digital trigger lines connected to its neighbor DOMs which it may use to influence the trigger decision. DOM-level triggers force a digitization and readout of the digitizers into local memory on the DOM (the DOM has a capacity of 16 MB) and each readout is time stamped with a counter value derived from the 40 MHz local DOM oscillator. Upon command from a surface controller, the DOM will transfer the contents of its memory buffers to the surface at a bit rate of 1 Mbit/s per copper pair.

At the surface, DOMs are readout by specialized PCI cards plugged into industrial PCs running Linux. Software running inside these computers must translate the DOM timestamp to a global quantity since each DOM oscillator is free running. Therefore the time stamp generated in the DOM is only locally relevant. The time transformation is achieved by a process
called RAPCal wherein the DOM and the surface digital communication hardware periodically (approximately once per second) exchange analog pulses and stamp the arrival and departure times. This information is used to establish the DOM clock to surface clock mapping. The clocks at the surface are driven from a single 10 MHz master clock signal synchronized to GPS. Measurements in the laboratory and in situ at South Pole demonstrate that DOM-to-DOM time jitter is $O(3 \, \text{ns})$ less than the design specification of 5 ns.

Once the digitized PMT pulses have been stamped with a global time, they are merged and sorted into a stream which is sent over ethernet to a cluster of trigger and event processor computers. The triggering and event packaging is accomplished entirely in application software. During the 2006 run, two triggers were implemented: a minimum bias trigger (MBT) generating an event trigger every $n$-th hit for system debugging and the main trigger for physics analysis, the simple majority trigger (SMT), requiring coincidence of 8 or more DOMs hit in the deep-ice array or 6 or more hits in the IceTop array within a time window of 5 $\mu$s. The triggers were formed in separate trigger processors for the in-ice and IceTop arrays; coincident triggers were then handled by a global trigger unit. Typical trigger rates from a run in mid-winter operation are listed in Table 1.

|                | MBT   | SMT   |
|----------------|-------|-------|
| In-Ice         | 5.28 Hz | 139 Hz |
| IceTop         | 0.875 Hz | 6.43 Hz |
| IceTop - In-Ice Coincident | 0.25 Hz |

Table 1. Trigger rates from a June 23, 2006 data run.

6. Summary
IceCube is soon to begin its 3rd deployment season after concluding a successful deployment and running season. All indications from data quality verification studies point to the hardware functioning at or above its design specification. The detector will reach an integrated exposure volume of 1 km$^3 \cdot$yr in as little as two years’ time. Future detectors involving acoustic and radio detection techniques are being investigated as potential additions to the IceCube observatory to substantially extend the detector volume, particularly at higher energies.

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