AN OVERVIEW OF THE ICECUBE NEUTRINO TELESCOPE

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Construction of the IceCube neutrino observatory is in progress with a first deployment of digital strings scheduled in little over a year's time. The cornerstone of the detector technology is the Digital Optical Module, or DOM, which digitizes and processes photomultiplier tube pulses stimulated by Cherenkov photons from charged tracks passing in the deep glacial medium beneath the South Pole. The full array will contain some 5000 of these DOMs arranged along strings sunken into the ice, to capture high energy muons and neutrinos, and frozen in surface tanks to monitor airshower events simultaneously. This paper describes the novel instrumentation of and exciting physics made possible by IceCube.

1. Introduction – Neutrino Astrophysics in Ice

Neutrinos are the only known particles that we can directly observe that carry information about the phenomena of ultrahigh-energy particle production at the far reaches of the Universe. Cosmic rays are either bent by galactic and inter-galactic magnetic fields, or are absorbed by resonant scattering with CBR photons. The high energy gammas above several TeV are absorbed by the ISM. Neutrinos neither are charged nor interact strongly with matter and so transit from production site to observation site unaltered in energy or direction.

Observation of ultrahigh-energy neutrinos requires enormous target volumes: the low fluxes predicted by most theoretical models of production, folded with interaction cross-sections measured in picobarns, yield neutrino interaction rates in the range of a few events per cubic kilometer per year.

Large ice or water Cherenkov detectors are a practical means by which to instrument large volumes. The medium is both dense, providing target nuclei for neutrino interactions, and transparent to the Cherenkov light which is emitted by the charged particles resulting from the interactions as they pass through the medium (Figure 1). IceCube distinguishes between three different event topologies: muon tracks and cascades, both depicted in the Figure, and, for a restricted range of energies, tau neutrino "double-bang" events which manifest as two isolated cascade events (the first from recoiling hadronic material in the initial neutrino-nucleus interaction; the second from the decay of the ultra-relativistic tau after it has propagated some tens of meters through the detector volume) separated by a linear track.

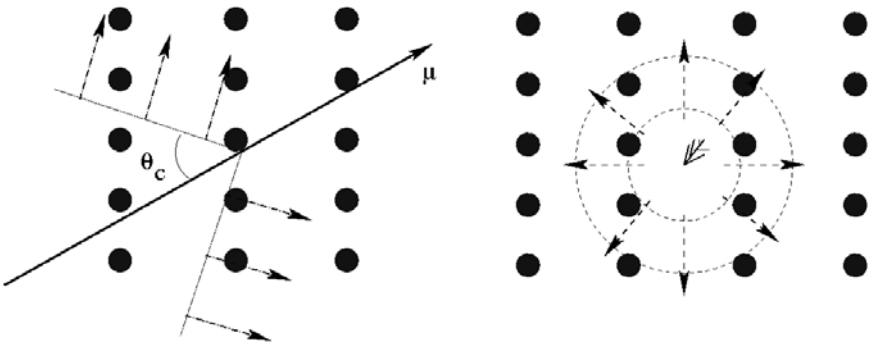


Figure 1. Illustration of Cherenkov light emission from muons (left) and electromagnetic or hadronic cascades (right). The wavefront is depicted as approximately spherical in the case of cascades due to the point-like distribution of charged secondaries followed by light scattering in the ice.

1.1 AMANDA

Much of the technical foundation for deploying and operating large, deep-ice cherenkov telescopes has come from experience gained with AMANDA (Antarctic Muon and Neutrino Detector Array). The currently operated array began taking data in 1996 after deployment of four strings of analog optical modules, known as "AMANDA-B4." The first atmospheric neutrino signals were identified with this array [1]. The following year, six more strings were deployed around B4 to make the AMANDA-B10 array which produced measurements of the atmospheric neutrino flux [2] and several searches for extraterrestrial neutrinos [3, 4]. The last deployment of strings to AMANDA occurred during the austral summer of 1999-2000 and brought the array to the "AMANDA-II" configuration of 19 strings of 677 optical modules, which will continue operation through the construction of IceCube. A completed search for neutrino emission from point sources using the AMANDA-II data has recently been published [5]. No evidence for significant excesses of events from any particular region of the sky has been noted and the flux limits are given in the reference.

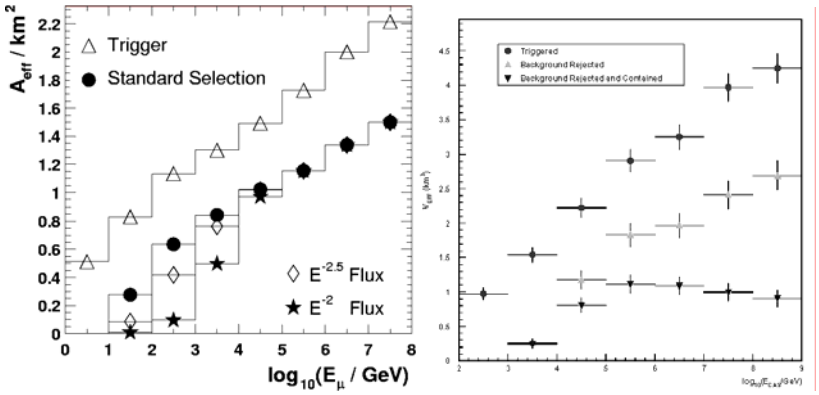


Figure 2. Muon (left) and cascade (right) effective areas and volumes, respectively, versus secondary lepton energy.

2. IceCube Physics Goals and Potential

IceCube is not merely an upgrade or an extension to AMANDA; it will be the first kilometer-scale neutrino telescope with a final instrumented volume a factor fifty-fold larger than AMANDA. In addition, the technology utilized in IceCube which will be discussed in further detail later, will increase the angular and energy resolutions of the array beyond those of AMANDA and therefore result in effective volumes and areas in excess of naïve scaling factors (Figure 2). This will place the sensitivity of IceCube within the range required to detect extraterrestrial neutrino fluxes predicted by current theoretical models. A detailed report of the IceCube physics and the expected array performance is found in reference [6].

3. IceCube Digital Optical Module Instrumentation

The basic detecting element in the IceCube array is the Digital Optical Module or DOM. It is based on the optical module technology deployed in AMANDA which was a large area photomultiplier tube (PMT) housed in a pressure sphere so that it could withstand the immense pressures of the deep glacial ice. In AMANDA, as mentioned, the optical modules (OMs) sent the PMT analog signals up to surface electronics which digitized the signals. The DOM design migrates the critical analog signal processing and digitization from the surface into the optical module which reduces the analog signal path from 2.5 km to 25 cm, with a corresponding increase in the fidelity of the digital signal: pulse rise

and fall times and widths are characteristic of the PMT; noise is greatly reduced; and, by removing the need to drive the long signal transmission lines, the PMTs can be operated at lower gains – 10^7 as opposed to 10^9. This results in an increase in the dynamic range of the module by a factor of 100.

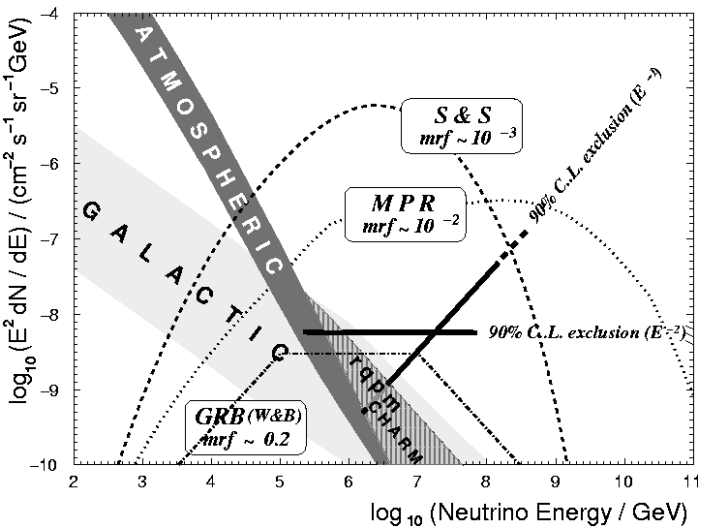


Figure 3. IceCube projected sensitivity to diffuse neutrino fluxes. See reference [6] for details.

A 3-D CAD representation of the DOM which nicely illustrates the various sub-components is shown in Figure 4. The DOM is shown with the upper glass hemisphere of the pressure vessel removed.

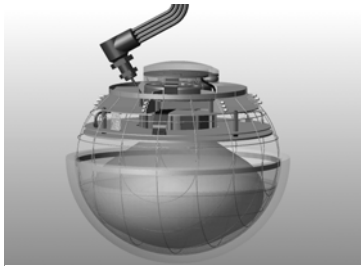


Figure 4. CAD depiction of the DOM. See text for description.

Signals and power are carried into and out of via a penetrator assembly located at the top of the DOM. Three annular PCBs which host the flasher calibration unit, the DOM mainboard, and a signal delay line are mounted around the neck of the PMT which seats in the bottom hemisphere of the pressure vessel, fixed into place and optically coupled to the hemisphere by low temperature silicone rubber gel. The PMT is surrounded by a sparse grid of high permeability metal ("mu-metal") for

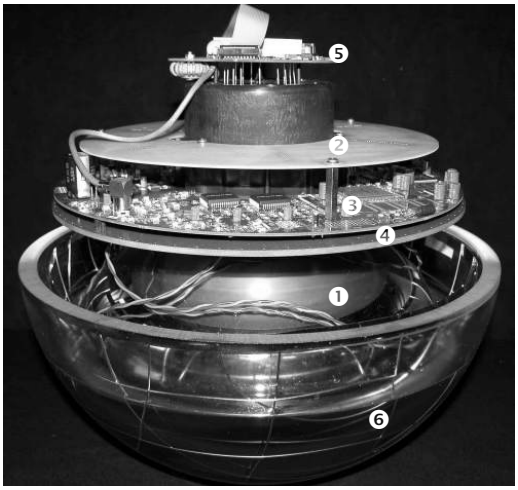


Figure 5. Prototype engineering DOM (Sept 03), showing the PMT ❶, PCB stack ❷❸❹, PMT HV base ❺, and the lower hemisphere of the pressure vessel ❻. The actual flasherboard is not present in this image, rather a mechanical "dummy" has been substituted to provide the necessary support.

magnetic isolation. Finally, the PMT high voltage base, rests atop the PMT, soldered directly onto the flying leads emerging from the PMT envelope.

3.1 Photomultiplier Tube

After an evaluation period of several months, the R7081-02 photomultiplier was chosen as the baseline solution for the IceCube array – both InIce and IceTop. From a list of approximately two dozen functional requirements the PMT darknoise, gain characteristics, and anode signal peak-to-valley ratio were measured from sample units and used to render a final selection. The Hamamatsu tubes by far surpassed samples received from other vendors in the darknoise characteristic; with proper preparation and at temperatures commensurate with the environment of the deep ice these tubes demonstrated rates less than 250 counts per second at nominal gain and using a ¼ photoelectron discrimination threshold.

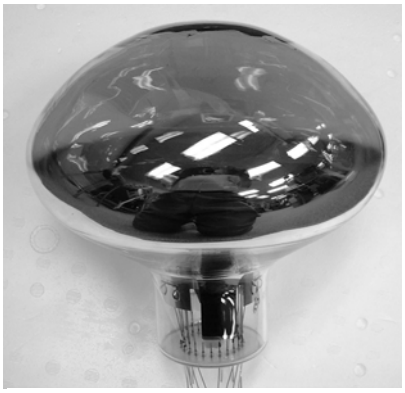


Figure 6. Hamamatsu R7081-02 photomultiplier tube.

The R7081-02, shown in is a 10” diameter PMT with a bi-alkali (Sb-Rb-Cs / Sb-K-Cs) photocathode coating on the borosilicate glass envelope. The electron optics are 10 dynode stages arranged in a box-and-grid configuration providing good collection efficiency and risetimes, falltimes, and transit times all of order a few nanoseconds matching the physics requirements on these tubes.

3.2 Photomultiplier Tube High Voltage Base

The PMTs require between 1300 VDC and 2000 VDC potential difference between the positive anode and the grounded cathode in order to achieve the required gain. This high voltage is generated internally by the DOM from the low-voltage 5 V power rails. There are currently two competing solutions being pursued in IceCube: the “active” and “passive” HV bases. They are both digitially programmable and monitorable in the field and it should be noted that the digital control was designed to have an identical interface in both cases.

The PMT anode is coupled to the analog front end of the data acquisition board through an isolation transformer (apparent as the wound toroids in the images) to block the DC high voltage.

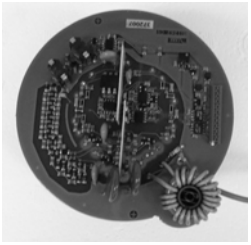
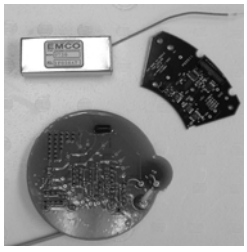


Figure 7. “Active” PMT high-voltage base.

3.2.1 Active Base

The active base includes two Cockroft-Walton high voltage generators: one to supply a constant 600 V (factory fixed) across the PMT’s first dynode, the other supplies the anode-cathode potential difference which is field programmable. This has the advantage of providing a uniform collection field independent of PMT gain at the expense of additional complexity in the circuit. This technology has been deployed previously in some AMANDA-II modules.

3.2.2 Passive Base



The passive base is a modular solution composed of three separate sub-assemblies:

1. A “black-box” HV generator.
2. A digital interface board,
3. A classical resistive-divider bleeder.

This design has the advantage that it is less complex than the dual Cockroft-Walton generators and the switching circuitry internal to the HV generation is

hermetically sealed inside a metal package which provides a good measure of EMI isolation. It however does have a first dynode voltage that tracks the anode-cathode potential at a fixed proportion, which produces sub-optimal electron collection at low values of gain.

3.3 Pressure Vessel

The DOM is completely encased within a ½" thick spherical shell, 13" in diameter and made of borosilicate glass. Its purpose is to protect the internal components of the DOM from pressures up to 10000 psi from the refreezing ice at 2.4 km depth while maintaining an optical transmission profile that matches the wavelengths of the signal photons. The internal environment is kept at 0.6 atm which seals the two mated hemispheres from which the pressure vessel is made and will be backfilled with dry nitrogen to reduce the likelihood of corona from strong electric field gradients in the HV system.

Experience from AMANDA has shown that standard glass contains trace amounts of potassium whose radioactive isotope ^{40}K emits β rays that are above the threshold to produce Cherenkov light in glass. Because of the sizable mass of the pressure vessel, this trace radioactivity can contribute significantly to the rate of non-signal hits registered by the DOM. As a result, IceCube demands low potassium content in the pressure vessel glass, less than 0.075% by weight.

In addition to ^{40}K, recent laboratory measurements point to scintillation in the glass caused perhaps because of trace amounts of cerium as an additional source of background photons which may dominate in low-K glass [7].

Whatever may be its origin, the total rate of background photons emitted by the pressure vessel and seen by the PMT is approximately 600 counts per second above threshold. This number should be compared with the number 25 which is the approximate rate of signal photons in the deep ice: 96% of the hits recorded are background.

3.4 DOM Mainboard

The DOM mainboard houses the analog and digital data acquisition circuitry and is a complete data acquisition system contained on a single 12-layer PCB mounted around the neck of the PMT. A simplified block diagram highlighting the salient functional units and their interconnections is shown in Figure 8.

Fast pulse waveform digitization is performed by one of two ATWD (analog transient waveform digitizers) custom ASICs. Each ATWD chip is capable of digitizing four channels of 128 samples per channel at speeds ranging from 250 MHz to 1 GHz. The digitization frequency is field programmable by means of a DAC on board. Three of the four channels see the same PMT pulse

but at staged amplifier gain levels, 16×, 4×, and 0.66×, and are used to boost the 10-bit instrinsic resolution of each ATWD channel to an effective 14-bit resolution. Two ATWDs are used in order to reduce the tens of microseconds of dead time after one ATWD has captured a waveform and is busy digitizing it.

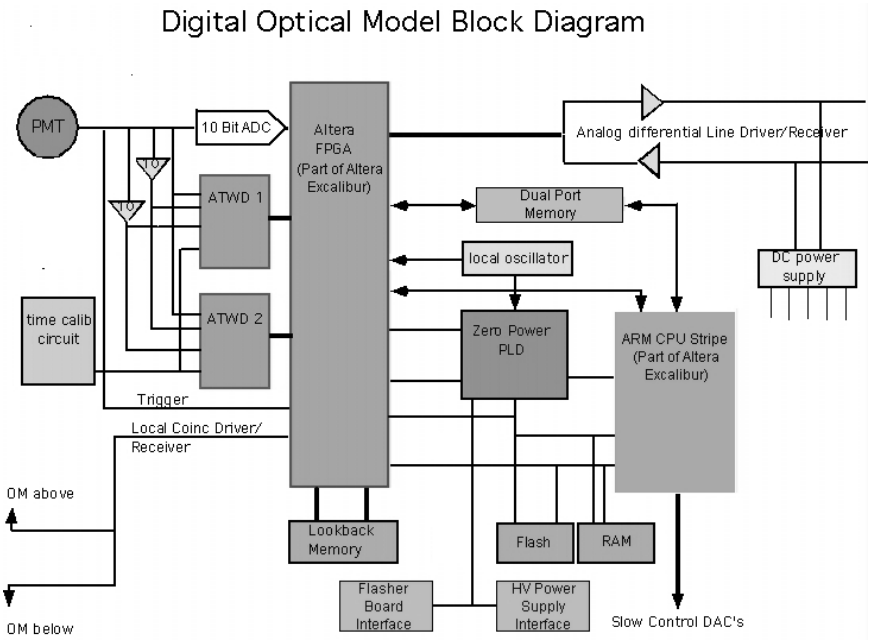


Figure 8. Functional schematic diagram of the DOM mainboard data acquisiton circuit.

The ATWD is well suited to the necessity to have fast but infrequent pulse digitization in a low power environment. It is not a free-running digitizer but rather is started by a discriminator trigger. As a result the PMT pulse must be split so that a prompt pulse can trigger the discriminator and a delayed version of it can be fed into the ATWD.

Because of the limited capture window of the ATWD – in IceCube about 500 ns – and because scattering in the ice can draw out the photon profile of bright but distant showers, the DOM also contains a low-power FADC which is capable of digitizing arbitrarily long capture windows limited only by the available memory, albeit at 40 MHz.

Control of the data acquisition system is effected by the Excalibur chip. It is a 400k gate FPGA and ARM 922T CPU integrated onto a single die. The FPGA controls timing critical operations such as the trigger logic and direct readout of the ATWDs and FPGA into SDRAM and implements the digital

protocol to communicate data to and from the surface. It also will implement the digital signal processing core needed to extract salient features from simple waveforms and record only these features so that the data volume being transferred to the surface does not exceed communication bandwidth. The CPU runs various programs for user interaction, diagnostic and test execution, and data acqusition. Both units are re-programmable at any time allowing for a continuous evolution of the DOM software and firmware.

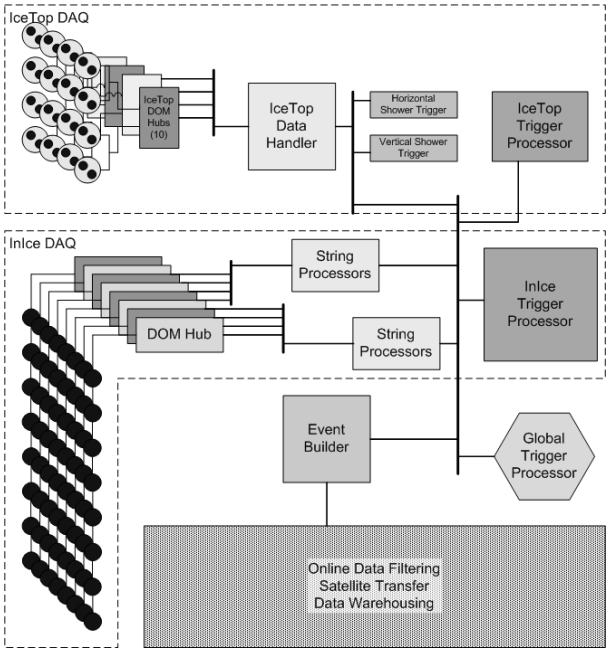


Figure 9. Schematic of surface data acquisition system showing the major functional blocks.

3.5 Surface Readout and Data Acqusition

The IceCube data acqusition system design places a high emphasis on utilization of commercial off-the-shelf (COTS) hardware at the earliest practical stage nothwithstanding the specialized nature of the instrument. This transition from custom to COTS, it was decided, should occur after the digital receiver / transmitter at the surface side of the cable which is the last custom PCB. These boards, known as DOR cards, are PCI cards, designed to fit into a standard industrial rackmount PC – referred to as a DOMHub, requiring 4U of vertical space. Each DOR card is capable of handling 8 DOMs (4 wire pairs, each wire

pair being shared between two physical DOMs), and commericial backplanes are readily available with 8 PCI slots. This allows a convenient segmentation of 1 IceCube string (60 modules) per DOMHub.

The data acqusition schematic is depicted in Figure 9. Data streams collected from a single string by the DOMHubs are forwarded to string processors which apply time transformations and a first level coincidence trigger. The string processors transmit trigger information to downstream trigger processors which apply additional trigger criteria not available at the string level. A final trigger signal is sent to an event builder which collects hits buffered in the string processor, builds them into events and ships the events to the online filter system.

4. Outlook

The IceCube neutrino observatory is on schedule to begin deployment. The first engineering DOMs have already been produced and we anticipate an initial production of DOMs in the Spring of 2004 to support deployment of up to six strings in the ice during the following austral summer. Deployment will continue for the next five years at the end of which time the full cubic kilometer of ice will be instrumented. However, we will reach the important milestone of 1 km^2 – year as early as 2007.

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