Design and Production of the IceCube Digital Optical Module

Kael Hanson and Oxana Tarasova for the IceCube collaboration

BEAUNE 05

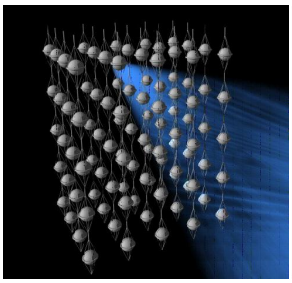
PHYSICS

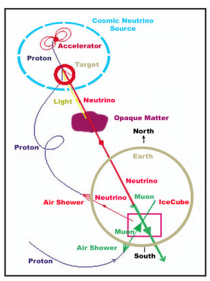
The Detector

IceCube is a kilometer-scale, high energy neutrino detector located at the South Pole in Antarctica. Detector geometry was optimized for detection of TeV-PeV ν's. It consists of:

In-ice array: at depth of 1450 to 2450 m in the ice
- 80 in-ice strings/60 DOMs each
- 17 m DOM spacing
- 125m between strings

IceTop – surface array: 2 frozen water tanks (2 DOMs/tank) on top of every string (280 in total)
- Operate in anticoincidence with the in-ice array: veto for downward going events
- Coincidence mode can synthesize information from both subdetectors to measure the chemical composition of cosmic rays up to 10^{18} eV and additionally is useful for detector cross-calibration.





Physics Motivation

The possibility for IceCube to detect high-energy neutrinos will help test the fundamental laws of physics and learn about the origin of the most energetic cosmic rays. Scientific interests include searches for steady or variable neutrino sources such as
- Active Galactic Nuclei (AGNs)
- Supernova Remnants (SNR)
- Microquasars and Gamma Ray Bursts (GRB)

Due to the low background noise in the ice, IceCube will be sensitive to low-energy (MeV-scale) neutrinos from collapsing supernovae. In addition to high-energy neutrino astronomy questions, IceCube's scientific reach will extend into particle physics by searching for neutrinos from annihilations of weakly interacting massive particles (WIMPs), magnetic monopoles, and other exotic particles like strange quark matter or SUSY Q-balls.

DESIGN

DOM Design

The basic principle of the DOM combines a large area phototube with all of the support electronics for PMT bias power and local digitization of the PMT anode pulses. This is a key concept for IceCube as it overcomes many problems associated with RF analog signal transmission over long distances, up to 3.5 km in the case of the IceCube detector array. DOM technology builds on experience gained with prototype analog and digital modules deployed in the AMANDA-II detector.

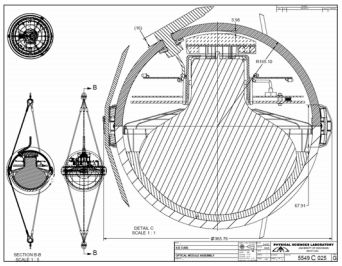


IceCube has chosen the Hamamatsu R7081-02 photomultiplier tube (PMT). Its combination of low noise (200-300 cps @ -40 °C) and high gain as well as fast pulse risetimes and low jitter are well-suited to the IceCube DOM application. PMT high voltage bias is supplied by a HV generator board that is mounted on the PCB stack around the PMT's neck. It produces 0 to +2kV (common cathode), controllable from the surface through commands sent to the DOM. The divider circuit is a high impedance (130 MΩ) resistive bleeder (I_{bias} = 10 μA nom.) with a toroidal transformer coupling to the analog front end.

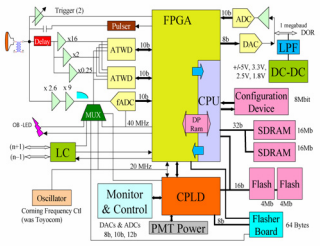


The PMT is potted into 13" dia., 0.5" thick glass pressure housing using a clear RTV gel that serves both to mechanically hold the PMT and its electronics in place as well as match indices to maximize optical transmission from the ice through to photocathode. The PMT is enclosed in a μ-metal cage also potted in the gel at the interior surface of the pressure sphere.

Optical properties of the surrounding ice and geometrical calibration information is obtained using the DOM flasher board. The uppermost PCB mounted around the PMT, it contains 12 high-brightness LEDs (405 nm) which are capable of emitting >10^{10} photons per flash in 10 ns to 100 ns pulses.

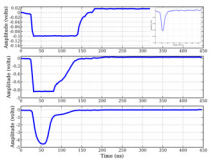


Digital Optical Module Block Diagram



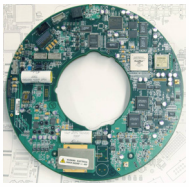
The DOM Embedded DAQ

The DOM Mainboard is the core of the IceCube data acquisition system (DAQ). It contains logic responsible for controlling every aspect of the DOM and reading out, digitizing, processing, and buffering the PMT signals. These signals travel to the front end where they are branched into several independent waveform capture channels. A 40 MHz, 10-bit fADC digitizes slow waveforms from distant high-energy events. Two custom, mixed-signal ASIC Analog Transient Waveform Digitizer (ATWD) chips capture fast waveforms with 10-bit resolution and sampling rates from 250 MHz to 1 GHz. Each ATWD contains 3 separate gain paths, 16×, 2×, and 0.25×, giving an effective 14 bits of resolution to span the PMT dynamic range.



ATWD capture of 2000 pe PMT waveform on 16× (top), 2× (middle), and 0.25× (bottom) channels. The inset plot shows a typical single photon pulse.

Digitization is controlled by the Altera Excalibur FPGA and hardcore ARM CPU on a single die. The FPGA interfaces to the digitizers, various on-board electo-optical calibration devices, the flasher board, the communication subsystem, and executes DSP on PMT signal waveforms. The CPU on the other hand runs application code such as DOM self-test and self-calibration applications and data acquisition programs that buffer waveform data from the digitizers, package it with time stamps from a local oscillator and other state information, and send the data packets to the surface DAQ which merges such packets from all DOMs in the array. Both FPGA and CPU code can be downloaded to the DOM at any time in the field.



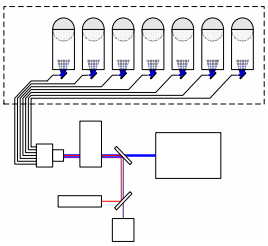
PRODUCTION AND TESTING

DOM Integration

DOM integration is supported at 3 production sites among the IceCube collaborating institutions: UW - Madison (USA), DESY-Zeuthen (Germany), and University of Stockholm (Sweden). Each site receives DOM subcomponents ready for assembly, then:
- The PMT neck is covered with a molded plastic collar to provide a base for installation of the circuit board stack
- This sub-assembly is placed into the lower hemisphere of the glass pressure vessel along with the magnetic shield and the RTV gel, properly mixed and degassed
- In 24 hours the gel is cured and the PCB stack (delay board, mainboard, HV control board, and flasher board) is installed
- Finally, the glass sphere is sealed under a pressure of 0.5 atm. Now the DOM is ready to go through Final Acceptance Test.

Modules passing FAT are outfitted with a harness assembly for attachment to the main cable and shipped to South Pole. The 3 production sites together are capable of integrating and testing approximately 50 DOMs per week.





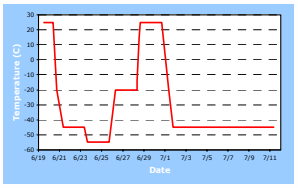
DFL Light Source Description

DOM test stations are arranged on shelves inside the DFL. Each DOM is placed on a plastic cylinder which is foiled on the inside to reflect more light and compensate for the bias towards illuminating the center. Three light sources are used in FAT:
- 405 nm diode laser
- monochromator-tuned tungsten lamp
- fast LED pulser.

Light is distributed to the station via optical fibers. A filter-wheel attenuator is installed just in the front of the bundle to regulate overall intensity. At the station end, the light exiting the fiber is diffused using a holographic diffuser material to distribute light evenly over the cylinder.

Final Acceptance Testing (FAT)

A post-assembly, pre-ship test is performed on all DOMs to find failing or poorly-operating units. Additionally, optical sensitivity calibration information is obtained using a precision optical fiber measurement system. The FAT is performed in special dark freezer laboratory (DFL) facilities co-located or nearby each production site. The DFL capacities range from 64 DOMs at the European sites to 150 DOMs at the US site and is tuned to the site production rate. Each FAT lasts approximately 3 weeks during which time DOMs experience two temperature cycles over the range -55 °C to +20 °C and are soaked at -45 °C for at least 180 hours. At each temperature plateau tests of basic functionality, PMT calibration, dark noise, optical sensitivity, time resolution and DOM pulse linearity are run.



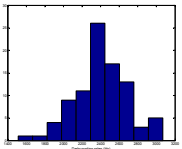
Temperature vs time profile of FAT.

Testing Results

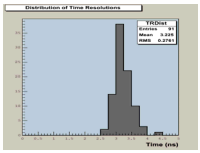
For all test performed during a FAT HV for each DOM was set for PMT gain of 1e7 and discriminator level at 0.25 of peak for SPE.

One of the basic characteristics of the optical module - **dark noise rates** – are monitored for each temperature soak including the long 5 day soak at -45ºC. Due to optical coupling and educed CR activity deep in the ice, ice rates in deployed DOMs are a factor of 3 lower.

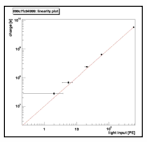
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To characterize nonlinear behavior of each PMT **linearity test** was performed during a FAT. For this test LED optical waveform generator was used producing short 30 ns and long 1μs pulses. To attenuate the light input a set of five filter wheels was used.



Another important test **time resolution** was performed where all DOMs simultaneously were illuminated with a short (~75 ps) laser pulses. Measuring the recorded time of the signal from DOMs and using electrical synchronization pulses as a reference the extent of the uncertainty in this time, i.e. time resolution was calculated.



SOUTH POLE

South Pole Deployment

IceCube holes are drilled using a hot water drill capable of making a 60 cm hole 2.5 km deep in slightly under 50 hours. After the hole is formed, a deployment team attaches DOMs to the electrical cable as it is lowered into the hole, a process which takes 20 hours. The hole is fully refrozen in 3 weeks.

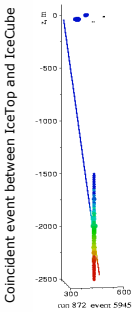


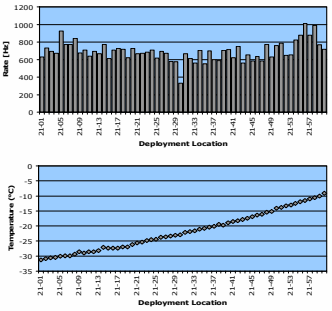
Aerial photograph of drill camp, January 2005. The IceCube hole is being drilled under the Tower Operations Structure (TOS) center, right. Two IceTop tanks are visible in the trench at right.

During the last austral summer season, IceCube deployed a single deep-ice string and 8 IceTop tanks making a total of 76 deployed DOMs all of which are operational and continue to produce physics-quality data. The plan for the next year is to deploy up to 10 strings and 32 IceTop tanks and following this, IceCube deployments will continue at the rate of 16 to 18 strings (32 to 36 IceTop tanks) per year.



DOM attached to cable being deployed.





IceCube Institutions

Chiba University, Chiba, Japan
CTSPS, Clark Atlanta University, Atlanta, GA, USA
DESY, Zeuthen, Germany
Humboldt Universität, Berlin, Germany
Imperial College, London, UK
Institute for Advanced Study, Princeton, NJ, USA
Lawrence Berkeley National Laboratory, Berkeley, CA, USA
Pennsylvania State University, University Park, PA, USA
Amundsen-Scott Station, Antarctica
Southern University and A & M College, Baton Rouge, LA, USA
Stockholm Universitet, Stockholm, Sweden
Universität Dortmund, Dortmund, Germany
Universität Mainz, Mainz, Germany
Universität Wuppertal, Wuppertal, Germany
Universite Libre, Brussels, Belgium
Universite de Mons-Hainaut, Mons, Belgium
University Gent, Gent, Belgium
University of Alabama, Tuscaloosa, AL
University of California-Berkeley, Berkeley, CA, USA
University of Canterbury, Christchurch, New Zealand
University of Delaware, Newark, DE, USA
University of Kansas, Lawrence, KS, USA
University of Maryland, College Park, MD, USA
University of Oxford, Oxford, UK
University of Wisconsin-Madison, Madison, WI, USA
University of Wisconsin-River Falls, River Falls, WI, USA
Uppsala Universitet, Uppsala, Sweden
Utrecht University, Utrecht, Netherlands
Vrije Universiteit Brussel, Brussels, Belgium

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