Design and status of IceCube

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Abstract

IceCube is a kilometer-scale high-energy neutrino detector that builds on the wealth of experience accumulated with its smaller predecessor, AMANDA. An international collaboration has begun construction of key components of the IceCube detector and deployment operations at the South Pole will begin in late 2004.

The underlying design of the IceCube detector and of the DAQ system are presented here, emphasizing the digital optical modules (DOMs) as the smallest discrete IceCube building block. The event reconstruction critically relies on a relative timing accuracy from DOM to DOM of a few nanoseconds over inter-DOM separations of up to 1 km.

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1. Physics goals

Through the detection of very high-energy neutrinos (threshold a few 100 GeV), IceCube [2,3] will open a new window on the universe. By viewing astronomical sources with neutrinos as astronomical messengers, it will address fundamental questions in high-energy astrophysics, particle physics and cosmology. Through the detection of surface electrons and muons, the associated IceTop surface array will allow us to study the chemical composition of high-energy cosmic rays ($E \sim 10^{18}$ eV) and will also help calibrate IceCube and provide a background veto. IceCube and underwater neutrino telescopes [4] share scientific interests, such as searches for steady or variable neutrino emission from point-like source candidates like active galactic nuclei (AGN), supernova remnants (SNR), microquasars and gamma ray bursts (GRB). By virtue of the low ambient noise level in the ice, the ability to detect low-energy supernova neutrinos as an increase in the overall trigger rate is unique to IceCube among all UHE neutrino detectors. On the more speculative side, searches for neutrinos from annihilations of weakly interacting massive particles (WIMPs), for magnetic monopoles and other exotic particles like strange quark matter or SUSY Q-balls can be listed (see e.g. Refs. [5,6]).

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2. Detector design and status

IceCube will consist of 4800 digital optical modules (DOMs), organized in 80 strings, each with 60 DOMs attached, buried in the ice at depths of 1450–2450 m. DOMs will have a vertical spacing of 17 m and the strings will be regularly spaced horizontally by 125 m. At each string location two IceTop tanks, each containing two DOMs frozen in ice, will be deployed. The buried DOMs will have an effective surface area of around 1 km^2, promising optimal sensitivity for neutrinos in the energy range of 1–10 000 TeV while being able to trigger on all higher- and on some of the lower-energy neutrinos, including MeV bursts [8]. The positions of IceCube strings, and the IceTop tanks deployed above them, are shown in Fig. 1. Simulations have shown that IceCube's sensitivity to possible signals is roughly constant for a wide range of feasible configurations.

DOMs form the fundamental building blocks of the IceCube detector. Each DOM contains a 10″ Hamamatsu R-7081 photo multiplier (PMT). The high voltage for the PMT is converted in the DOM from its 48 V DC power supply to achieve the design gain of around 5×10^7. Within a DOM, the PMT signal is split into two copies, with one used for triggering and the other delayed and then digitized if the threshold condition is met. Digitization occurs in two types of DOM-resident digitizers, to extend the digitization time while keeping the resolution high at early times. There is

a set of two four-channel ASIC analog transient waveform digitizers (ATWDs) and a commercial 40 MHz FADC with up to 256 samples and 16-bit resolution available. The two ATWDs operate at 300 MHz and at none, 16, 32, 64 or 128 sample depths with 8- or 16-bit resolution. The two ATWDs are fed signals in a ping-pong manner, reducing DOM dead time to less than 1%. The first three channels of each of the ATWDs are fed signals that have been amplified with factors of 16, 4 and 2/3. This combination of ATWDs and FADC ensures the design dynamic range of up to 200 photo electrons (p.e.) within the first 15 ns and up to 2000 p.e. within the first 5 μs. The fourth ATWD channel can be connected to various inputs like the DOM-clock ticks or LED driving currents, creating a versatile diagnosis and calibration tool. The DOMs further contain a 405 nm LED flasher board, producing programmable light flashes of various intensities detectable by other modules in the array. This capability is useful for studying ice properties and calibrating the relative positions of DOMs. A preliminary version of a DOM, deployed in an IceTop tank in January 2004, is shown in Fig. 2.

The DOM mainboard has a free-running timer which needs to be synchronized with nanosecond accuracy to GPS time, requiring re-calibration roughly every minute. As shown in Fig. 3, a surface circuit sends a bipolar signal at a GPS-latched time t_1, received at a time t_2. After a certain, fixed time interval δ_t, an identical circuit in the DOM sends an identical bipolar pulse to the

Fig. 1. Aerial view of South Pole and positions of the IceTop tanks resp. the IceCube strings (black), Spase-2 stations (grey, dense, regular foreground pattern [7]) and the AMANDA strings (larger grey pattern). Courtesy V. Papitashvili.

Fig. 2. The first DOM frozen into a prototype IceTop tank at South Pole (January 2004). Photo by John Kelley/NSF.
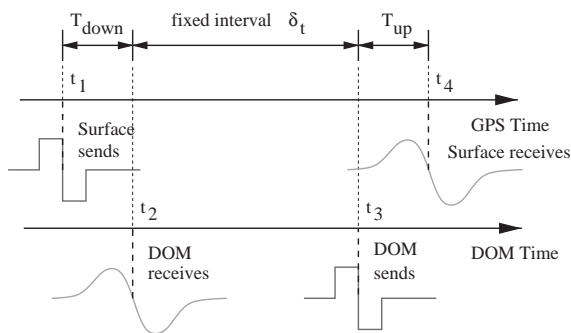

Fig. 3. DOM time calibration, see text.

surface, detected at a time t_4. The cable transmission time is then: $t_{Down} = t_{Up} = (t_4 - t_1 - \delta_t)/2$. This calibration reduces signal time spread to the inevitable contribution from light scattering in the Antarctic ice.

Currently a fully digital, TCP/IP-based approach for the DAQ system is under development, following closely the modular structure of the experimental setup: each *String Processor* stores DOM-data and passes trigger primitives on to the *InIce Trigger*, which, after examining trigger primitives from all *String Processors*, sends its trigger decisions to the *Global Trigger*. The *Global Trigger* combines *InIce Trigger*, *IceTop Trigger* and other (external) information to form its decision. If positive, the *Event Builder* is instructed to retrieve DOM data from the *String Processors*

and assembles them to IceCube events that get passed to the *Online Filter Cluster* for further processing. All of these DAQ system elements are implemented in commercial computers.

The drilling process has been improved in several aspects compared with the AMANDA procedure: setup time for a season will be only 3–5 weeks; 60 cm diameter holes will be drilled with water of 90 °C from a number of heaters with a total power of 5 MW (vs. 2 MW for AMANDA), a larger hose diameter will reduce drill time to 40 h, and the fuel consumption will be lowered by about 30%. With an estimated string drop time of around 20 h, it should be possible to deploy 16 or more strings per austral summer season, leading to a construction time of 5–6 years for the entire detector.

3. Summary

With the assembly and testing of the first batch of DOMs under way, the IceCube collaboration is on track for deployment of the first set of strings at the end of 2004. The digital approach to readout and triggering, together with the sophisticated time calibration, will help to overcome the challenges posed by the sheer size of the detector and the time spreads induced by the Antarctic ice as a detector medium, enabling IceCube to produce useful data for scientific purposes just after the first few deployments.

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