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IceCube - construction status and performance results of the 22 string detector.

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Abstract: The IceCube neutrino observatory is a cubic-kilometer ice-Cherenkov detector being constructed in the deep ice at the geographic South Pole. After a successful construction season ending in February 2007, IceCube consists of 22 strings and 26 IceTop stations with a total of 1424 Digital Optical Modules (DOMs) deployed at depths up to 2450m. Together with the commissioning of the central laboratory building and central DAQ electronics, this allowed IceCube to begin early operations and data analysis. The goal is to complete construction of the final configuration of 80 strings and IceTop stations in 2011. First results from the 22-string configuration and an overview of the project will be presented.

Overview

The IceCube neutrino observatory is a kilometer-scale neutrino telescope currently under construction at the South Pole. The existing AMANDA-II array, the precursor of IceCube, will be surrounded by and integrated into the IceCube array [1]. IceCube is designed to detect astrophysical neutrino fluxes at energies from a few 100 GeV up to the highest energies of 10^9GeV [2], [3].

Project Year	Strings deployed	IceTop stations	# of Sensors
2004/05	1	4	76
2005/06	8	12	528
2006/07	13	10	820
2007 total	22	26	1424

The IceCube neutrino observatory at the South Pole will consist of 4800 optical sensors - digital optical modules (DOMs) - installed on 80 strings at depths of 1450 m to 2450 m in the Antarctic Ice, and 320 sensors deployed in 160 IceTop [4] detectors in pairs on the ice surface directly above the strings. Each sensor consists of a photomultiplier tube connected to a waveform-recording data acquisition circuit capable of resolving pulses with nanosecond precision and having a dynamic range of at least 250 photoelectrons per 10 ns. Construction started at the South Pole in November 2004. A total of 1424 sensors have been installed to date

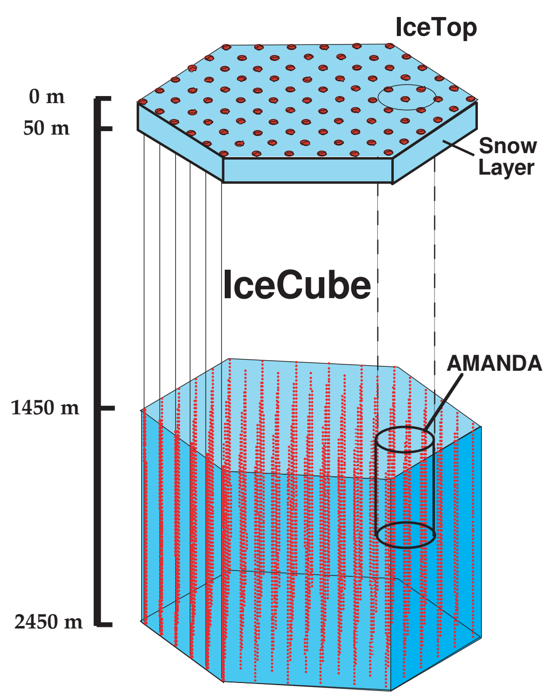

Figure 1: Schematic view of the IceCube array consisting of 80 strings with 60 sensors on each string. The surface array IceTop consists of 160 detectors, two of which are associated with each string.

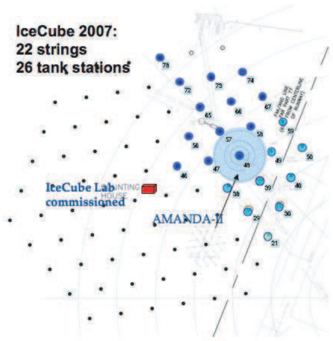

Figure 2: Schematic view of current geometry

on 22 strings and in 26 IceTop surface detector stations. The table below summarizes the construction status as of February 2007.

Electrical and mechanical structure

It was a design goal to avoid single point failures in the ice, as the sensors are not accessible once the ice refreezes. High reliability and ease of maintenance were other design goals. A string consists of the following major configuration items: a cable from the counting house to the string location, a cable from the surface to 2450 m depth, and 60 optical sensors. 30 twisted-pair copper cables packaged in 15 twisted quads are used to provide power and communication to 60 sensors. To reduce the amount of cable, two sensors are operated on the same wire pair, one terminated and one unterminated. Neighboring sensors are connected to enable fast local coincidence triggering in the ice.

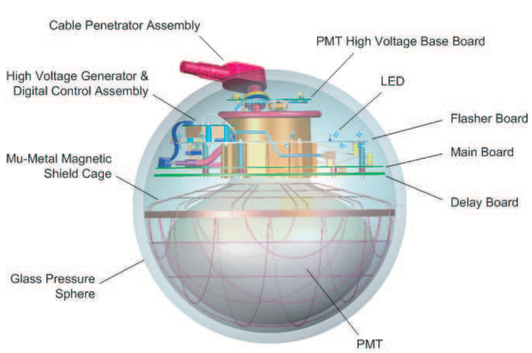

Figure 3: Schematic view of a Digital Optical Module.

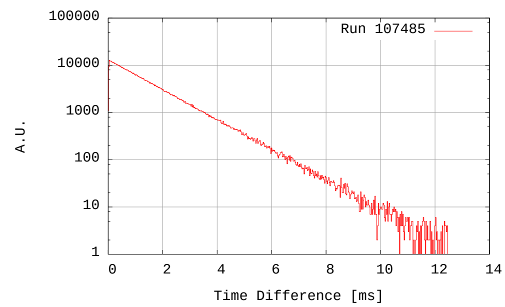

Figure 4: The time difference between subsequent events is shown for one run.

A schematic view of an optical sensor is shown in Fig. 3. An optical sensor consists of a 25-cm-diameter photomultiplier tube (PMT) embedded in a glass pressure vessel of 32.5-cm diameter. The HAMAMATSU R7081-02 PMT has ten dynodes, allowing operation at a gain of at least $5 \cdot 10^7$. The average gain is set to $1.0 \cdot 10^7$, providing a single photoelectron amplitude of about 5 mV. The signals are digitized by a fast analog transient waveform recorder (ATWD, 300 MSPS) and by a fADC (40 MSPS). The PMT signal is amplified by 3 different gains ($\times 0.25$, $\times 2$, $\times 16$) to extend the dynamic range of the ATWD to 16 bits. The linear dynamic range of the sensor is 400 photoelectrons in 15 ns; the integrated dynamic range is of more than 5,000 photoelectrons in 2 μs. The digital electronics on the main board are based on a field-programmable gate array (FPGA) which contains a 32-bit CPU, 8 MB of flash storage, and 32 MB of RAM. A small communications program stored in ROM allows communication to be established with the surface computer system and new programs to be downloaded to the DOM.

The flasher board is an optical calibration device which is integrated in each DOM. The amplitude of the LED pulses can be adjusted over a wide range up to a brightness of $9 \cdot 10^{10}$ photons at a wavelength of about 405 nm.

Data acquisition and online data processing

All digitized photomultiplier pulses are to be sent to the surface. A local coincidence (LC) trigger scheme is used to apply data compression for isolated hits, which are mostly noise pulses. Every string is connected to one server called a stringhub, which includes 8 custom PCI cards. They provide power, communication and time calibration to the sensors. The stringhub sorts the hits in time and buffers them until the trigger and eventbuilding process is complete. The digital architecture allows deadtime-free data acquisition (Fig. 4) with the exception of runstop and start times and maintenance times. A joint eventbuilder combines signals from the AMANDA-II array with IceCube data. The raw data rate is on the order of 100 GB/day, which are written to tapes. An online processing and filtering cluster extracts interesting phenomena, such as all upgoing muons, high-energy events, IceTop-In-ice coincidences, cascade events, events from the direction of the moon, events that are interesting for dark matter search and events in coincidence with GRB. The filtered data stream (of order 20 GB/day) is then transmitted by satellite to the Northern Hemisphere to be stored and archived in the data center. The data will then be prepared for physics data analysis by the working groups in the collaboration.

Drilling and detector installation

The strings are installed in holes which are drilled using the enhanced hot-water drill (EHWD). The drill consists of numerous pump and heating systems, hoses, a drill tower and a complex control system. It delivers a thermal power of 5 MW. The average time required for drilling a hole 60 cm in diameter to a depth of 2450 m was

$\sim$34 hours in the most recent construction season. The subsequent installation of a string with 60 DOMs required typically 12 hours. Overall, the construction cycle time between two strings was 3 days, which allowed the installation of 2 strings per week. With some optimizations in set-up time and an improved technique for drilling through the firn layer, we expect to install up to 18 strings between December 2007 and January 2008. Based on the past season, the long-term construction schedule remains unchanged with completion expected in January 2011.

All sensors undergo a final acceptance test at their production sites before being shipped to the South Pole. They are again tested briefly on the ice prior to deployment. The installation and the subsequent freeze-in process (with temporary pressures up to more than 400 bar) places unusual demands on the string hardware. Yet, the survival rate of optical sensors is very high. For 1424 optical sensors deployed to date, only 16 (1.1%) are not usable; another 18 (1.3%) have developed minor issues, some of which are expected to be resolved. 97.6% of all sensors have been commissioned with full functionality and are in operation to date. Only two sensors failed after they were frozen in and commissioned. A total of 1000 DOMyears of integrated operation has been accumulated as of May 2007.

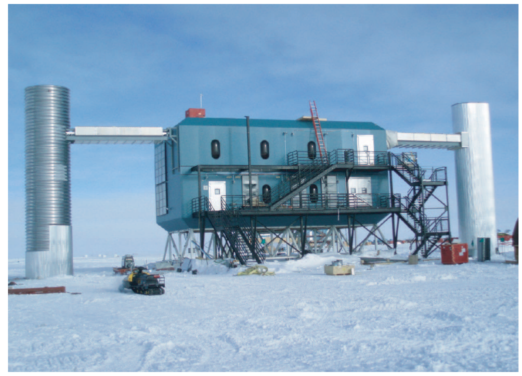

Figure 5: The IceCube Laboratory contains all surface electronics and server farms for data acquisition and online data processing.

Operation and performance characteristics

The detector electronics and software are designed to require minimal maintenance at the remote location. For example, the time calibration system, a critical part of any neutrino telescope, is designed to be a self-calibrating, integral part of the readout system (in contrast to the AMANDA detector, which required manual calibration of all analog detector channels). The strings are calibrated as soon as they are frozen in, allowing for gradual commissioning of the instrument.

All sensors have precise quartz oscillators to provide local clocks, which are synchronized every few seconds to the central GPS clock. Using LED flashers, it was possible to verify the time resolution to a precision of less than 2 ns on average. Studies with muons and flashers have shown that the timing is stable over periods of months [5]. Another important performance parameter is the dark-noise rate of the sensors. There is no known natural background of light in the deep ice other than light generated by cosmic particles. The noise rates for DOMs in the deep ice are ≈700 Hz. The rate is ∼320 Hz with an applied dead time of 50 μs. The very low noise rates of the sensors are critical for the detection of the low energy neutrino emission associated with supernova core collapse.

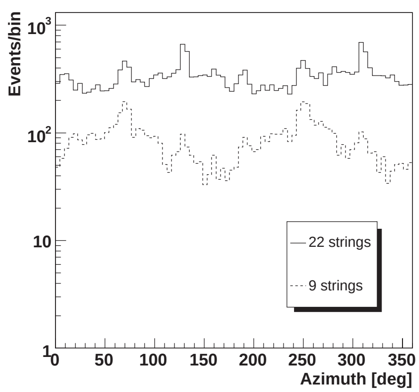

Figure 6: Azimuth distribution of atmospheric muons observed in the 9-string array in 2006 and the 22-string array in 2007.

The 9- and 22-string arrays trigger on atmospheric muons at a rate of 140Hz and 520Hz, respectively. The 22 string trigger condition requires an 8-fold coincidence within 5 μsec. Several characteristic figures of AMANDA-II, IC9, IC22 and IC80 are compared in table 2. The 22-string configuration has a significantly higher effective area and overall sensitivity. Fig. 6 shows the azimuth distribution of cosmic-ray muons for one hour of livetime of the 9- string array and the 22-string array for events with at least 20 DOMs and 3 strings hit. The azimuth distribution for IC22 is more even, and the overall rate is visibly higher as the detector is now sensitive in all directions.

First physics analyses have already been performed using data of the IceCube 9 string array[6, 7, 8]. The start of regular science operations with IC22 is scheduled for May 2007 and will continue in this configuration until March 2008.

-	A-II	IC9	IC22	IC80
Instr. Volume/km^3	.016	0.044	0.18	0.9
# of sensors (in ice)	677	540	1320	4800
$\mu_{Atm.}$/Hz	80	140	550	1650
Ang. res./$^\circ$ (10TeV)	2.0	2.0		0.7

Table 1: Some performance parameters for the AMANDA-II and IceCube 9-, 22- and 80-string detector configurations. Rates are given for cosmic ray muons at trigger level. The rate for the 80-string array is based on simulations [9].

Acknowledgments

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