Design and Performance of the IceCube Electronics

• High Energy Neutrino Astronomy
• IceCube Detector
• DAQ and Electronics
• Performance
• Summary and Outlook

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Goals of High Energy Neutrino Astronomy

• Discover the origin of H.E. Cosmic Rays
  C.R. with energies up to $10^{20} \text{ eV}$ are observed.
  Where are they accelerated?

  Candidate C.R. sources:
  • SNe remnants, $\mu$Quasars
  • Active Galactic Nuclei
  • Gamma Ray Bursts
  • Exotic Higgs (R, etc.)

  Guaranteed sources of $\nu$'s (from Cosmic Rays):
  • Atmosphere
    C.R. induced $\pi$ & K decay
  • Galactic plane:
    C.R. interacting with ISM
  • Cosmology:
    C.R. interacting with CMB
    UHE $p \gamma \rightarrow \Delta^{+} \rightarrow n \pi^{+}(p \pi^{0})$

• Searches for exotica:
  Wimps, Monopoles, …
H.E. Neutrino Detection

Event reconstruction by Cherenkov light timing

\[ \Theta_{\nu} \approx 0.7^\circ \cdot \left( \frac{E}{T_{eV}} \right)^{0.7} \]

*Longer absorption length => larger effective volume

Large volume + shielding => deep water/ice

Detectors for High Energy Neutrino Astronomy

- AMANDA
- ANTARES
- BAIKAL
- ICECUBE
- NEMO
- NESTOR
- KM3Net

AMANDA skyplot 2000-2003

3329 events below horizon

3438 events expected from atmospheric \( \nu \)'s
IceCube

- 70-80 Strings
- 4200-4800 PMTs
- Instrumented volume: \( \sim 1 \text{ km}^3 \) (1 Gton)
- IceCube will detect neutrinos of all flavors at energies from \( 10^{11} \text{ eV} \) to \( 10^{20} \text{ eV} \), and low energy \( \nu \)'s from supernovae
The drilling site in January, 2005

Each 2 m dia. IceTop tank contains two Digital Optical Modules. The freezing of the water is done in a controlled manner to produce clear ice.
IceCube’s First String: January 28, 2005

27.1, 10:08: Reached maximum depth of 2517 m

28.1, 7:00: Preparations for string installation start.

9:15: Started installation of the first DOM

22:36: Last DOM installed

12 min/DOM

23:48: Start drop

29.1, 1:31: String secured at depth of 2450.80 m

20:40: First communication to DOM

Ice Drives the Design

• Surface temperatures \(-20^\circ C \leftrightarrow -70^\circ C\)
• At-depth temperatures \(-35^\circ C \leftrightarrow -10^\circ C\)
• Freeze-in subjects cables, connectors, optical modules to high stress
• Inaccessibility requires reliability, remote operation
• Once modules are deployed, have stable environment
• No radioactivity in ice \(\Rightarrow\) PMT rate < 1kHz
• Optical scattering relaxes timing requirements
• Prototype string (41 Digital Optical Modules) deployed in Jan. 2000 (AMANDA -“String-18”)
‘Electronic’ Requirements

- Quality data, maximum information, high information/noise (identify, analyze rare events)
  - Timing (ability to reconstruct tracks, locate vertices)
    - <7ns rms  3 ns
  - Waveform capture (all photons carry information)
    - 300 MHz (for 400 ns), 40 MHz (for 6.4 μsec)
  - Charge dynamic range (energy resolution)
    - >200PE/15ns  ~400 PE/15 ns
  - Onboard calibration devices
    - LEDs for int. & ext. calibration. Electronic pulser
  - Hardware local coincidence in the ice
    - Nearest and next-nearest neighbor
  - Communications signaling rate to surface
    - 1 Mbaud/twisted pair

‘Environmental’ Requirements

- Robust equipment for a harsh environment
  - copper cable, rugged connectors
- Effective operation (reduce manpower at S. Pole)
  - automatic, self-calibration; remote commissioning
- Low power (fuel expensive at S. Pole)
  - ≤ 5 W/DOM
- Insensitivity to interference from other experiments at S. Pole: VLF, Radar
  - Common mode rejection
- Long life time > 10 years after completion
  - Design for reliability
- Minimize cost
  - Two DOMs per twisted pair
The DAQ is based on the Digital Optical Module, a semi-autonomous sensor/processor with high functionality.

"Real-time" DAQ Elements

GPS Master Clock

Hub

SP (String Processor)

DOMs (60/string)

DOM: “local time units”

Hub: “master time units”

SP: transforms local time stamps to master time
Key Components

**Analog Transient Waveform Digitizer - ATWD**
- Custom ASIC having high speed and low power consumption
- Switched capacitor array
- 4 channels x 128 samples deep, acquisition on launch
- Digitization: 10 bit, 30 μs /channel
- Variable sampling speed: 250 - 800 MHz
- Power consumption 125 mW
- Design - S. Kleinfelder ~1996 (also used in KamLAND, NESTOR)

2 ATWD/DOM: 0.25 W
DOM MB Block diagram

Key Components, cont.

Very stable crystal oscillator

- Provides time stamp for launch of ATWD
- Clock for FPGA, CPU, FADC, DACs, ADCs
- Allan Variance typical ~1 x 10^{-11}
- Toyocom 16.6 MHz $7 used in AMANDA prototype
- Vektron/Corning 20 MHz $70 chosen for reliability, specs
- 10^{-10}, -40°C, tested
DOM MB Block diagram

Key Components, cont.

FPGA + CPU

- Altera EPXA 4
- System On a Programmable Chip
  - FPGA
    - 400,000 gates
    - 20, 40 MHz
  - CPU
    - ARM922T 32-bit processor
    - Single Port SRAM 128 Kbytes
    - Dual Port SRAM 64 Kbytes
    - 80 MHz
- Power consumption 0.5 - 0.7 W

Supports: control, communications, ATWD readout, data compression, calibration, …..
DOM MB Block diagram

Key Components, cont.

Local Coincidence

- Reduce Data Rate
- Rate without LC ~1KHz
- Rate with LC <15Hz
- Dedicated Full Duplex LC connection
- Transmit and Receive go through FPGA
- LC functionality can be reprogrammed
Digital Optical Module Mainboard

Mainboard design, fabrication and testing by Lawrence Berkeley National Laboratory
Digital Optical Module

DOM assembly facilities at U.Wisconsin, DESY-Zeuthen, U. Stockholm

Key Components, cont.
The ~ 3km Cable

- 0.9 mm copper wire
- Twisted quad configuration
- 145 Ohm impedance DC resistance < 140 Ohm/2.5km (cold)
- low cross talk between twisted pairs is essential
  - > 50 dB suppression near end cross talk
  - > 30 dB suppression far end cross talk
- Requires careful mechanical construction.
Surface Front-End Readout Card
("DOR" card)

Comm. Ch0
ADC / DAC

Comm. Ch1
ADC / DAC

Comm. Ch2
ADC / DAC

Comm. Ch3
ADC / DAC

Comm. FPGA

Power Control Ch0, Ch3
On, Cur, Vol

PLL
10MHz

Osc. 1PPS

Timestring

96 V

SRAM
1 MByte

FLASH
2 MByte

JTAG

PLD

PCI

FPGA

Mem. Bus

Local Bus

In0

In1

Osc.

10MHz

DOM
quad cable

Readout Card design, fabrication, testing by DESY-Zeuthen

DOR (Digital Optical module Readout)

Surface front-end readout card

DOM Communication
DOM Power Input
GPS Master Time Input

Main Cable Connector
PCI interface
DOM Power Distribution
DOM Hub
services 1 String = 60 DOMs

~300 W running 60 DOMs

RELIABILITY

• Goals and constraints
  ▪ 10 years operation after construction
  ▪ <0.2%/yr complete failure, <1%/yr partial failure
  ▪ Inaccessibility of components after deployment
  ▪ Cost vs component quality (comm., indust., mil.)

• Use sound reliability & design practice
  ▪ Parts selection
    ▪ Derating
    ▪ Preferred, qualified vendors
    ▪ Special attention to key components
  ▪ Quality fabrication (IPC 610 class 3 - used for medical, satellite applications)
  ▪ Testing, Testing, and more Testing
Some reliability design consequences

- Used industrial parts spec’d to -40°C
- Tin-lead solder used wherever possible
- Electrolytic caps replaced with higher reliability plastic caps
- High stability crystal oscillator (~$7 Toyocom replaced by ~$70 Corning)
- Found and replaced component types that did not operate properly at low temperature.

Testing Sequence

- Mainboard Design Verification Testing
  - Small number of boards tested
  - Software test suite resident on Mainboard
  - Extreme conditions - determine range of operation
    - -80°C to +80°C, 30 G rms vibration
- Mainboard Production Testing
  - All boards tested
  - Temperature cycling (+65°C to -50°C), vibration 7 G rms
  - Burn in 24 hours at +65°C 24 hours at -50°C
  - Integration testing with other DOM components
    - 3 km cable
    - PMT
    - Flasher board
Testing Sequence, cont.

- Final Acceptance Testing of assembled DOMs
  - 14 days at temperatures down to -55°C
    - Communications
    - Calibration
    - Timing with laser, fiber optic distribution

  Transport to South Pole

- Retest all DOMs before deployment
  - Ambient temperature -25°C to -35°C

Performance

- Time calibration
- Detector verification with LED flashers
- Muon reconstruction
- Timing verification with muons
- Coincidence events
  - IceCube - IceTop
  - IceCube - AMANDA
Time Calibration

Automatic, every few seconds

Time Calibration for 76 DOMs

In-ice DOMs
IceTop

1.74 ns rms

Timing verification with flashers

All 60 DOMs

1.74 ns rms
Timing verification with flashers

Some typical high-multiplicity muon events
Time calibration verification using muons

The random and systematic time offsets from one DOM to the next are small, \( \leq +/- 3\text{ns} \)

IceCube muon data reconstruction

- Data and simulation comparison for multiplicity
- Data and simulation comparison for zenith angle
IceTop and in-ice coincidences

The difference is due to shower curvature.

AMANDA and in-ice coincidences

Off-line search through GPS time-stamped AMANDA and IceCube string- 21 events.

iceTop shower
in-ice track
The difference is due to shower curvature
Summary

• The first IceCube string and four IceTop stations have been successfully deployed

• All 76 DOMs function well

• The overall detector timing uncertainty was measured to be <3 ns

• Muons and air showers have been analyzed

• The observed muon flux is consistent with the expectation from simulations

• The first components of the IceCube detector perform as expected, or better.

OUTLOOK

• 2005-06 up to 10 strings
  (IceCube > AMANDA)

• 2006-07 14-16

• 2007-08 16-18

• 2008-09 16-18

• 2009-10 14-18
  71-79 strings
THE ICECUBE COLLABORATION

USA:
Bartol Research Institute, Delaware
Pennsylvania State University
UC Berkeley
Clark-Atlanta University
IAS, Princeton
University of Wisconsin-Madison
Lawrence Berkeley National Lab.
Southern University and A&M College, Baton Rouge

Sweden:
Uppsala Universitet
Stockholm Universitet

UK:
Imperial College, London
Oxford University

Netherlands:
Utrecht University

Germany:
Universität Mainz
DESY-Zeuthen
Universität Dortmund
Universität Wuppertal
Universität Berlin

Japan:
Chiba university

Belgium:
Université Libre de Bruxelles
Vrije Universiteit Brussel
Universiteit Gent
Université de Mons-Hainaut

New Zealand:
University of Canterbury

(The IceCube Collaboration now includes AMANDA)
Optical Scattering in S.P. Ice
Time calibration verification using muons

- reconstruct muon tracks without DOM X
- plot the time residual for DOM X for nearby reconstructed tracks
- if optical scattering length is longer than the distance cut (10 m) the most likely residual should be 0, otherwise residual will show delay increasing with the amount of scattering.

\[
\text{Time residual} = (\text{photon arrival time} - \text{reconstructed time}^*)
\]

\(^*\text{assuming no scattering.}\)

Inside the DOM Hub

- Power Supplies
- Fans
- Monitors
- From Master Clock Unit
- 10 MHz (Twisted Pair)
- 1 Pulse per Second (Twisted Pair)
- RS-232 Time String (Twisted Pair)
- For GPS distribution

- CPU
- DSB Card
- DOR card
- DOR card
- DOR card
- DOR card
- DOR card
- DOR card
- DOR card
- DOR card
- DOR card
- DOR card
- 10 MHz, 1 pps. Time String