Design and Performance of the IceCube Electronics

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

IceCube

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DESY, November 21, 2005

Goals of High Energy Neutrino Astronomy

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

Candidate C.R. sources:

- SNe remnants, μQuasars
- Active Galactic Nuclei
- Gamma Ray Bursts
- Exotica (decays of topological defects...)

Guaranteed sources (from Cosmic Rays):

- Atmosphere:
  C.R. induced (π & K decay)
- Galactic plane:
  C.R. interacting with ISM
- Cosmos
  C.R. interacting with CMB
  UHE $p\gamma \rightarrow \Delta^+ \rightarrow n\pi^+ (p\pi^0)$

- **Searches** for exotica:
  Wimps,
  Monopoles,
  …

MAP THE NEUTRINO SKY

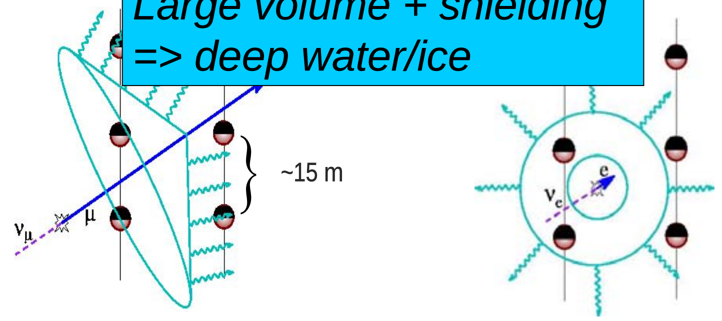
H.E. Neutrino Detection

Event reconstruction by Cherenkov light timing

~ km-long muon tracks* from ν_μ

~10m-long cascades, ν_e ν_τ neutral current

Large volume + shielding => deep water/ice



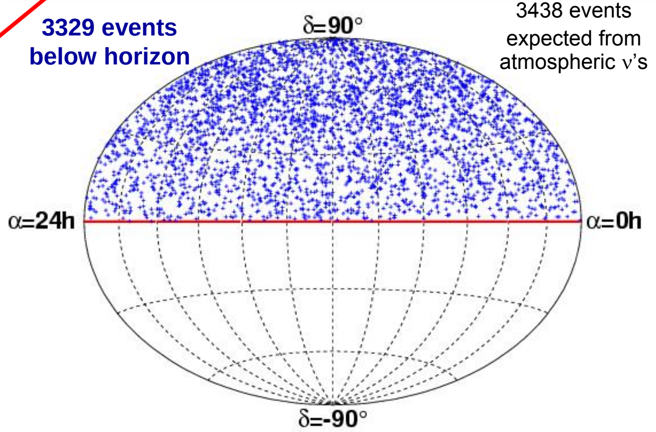
$\Theta_{\mu\nu} \approx 0.7° \cdot (E_\nu / \mathrm{TeV})^{-0.7}$

*longer absorption length => larger effective volume

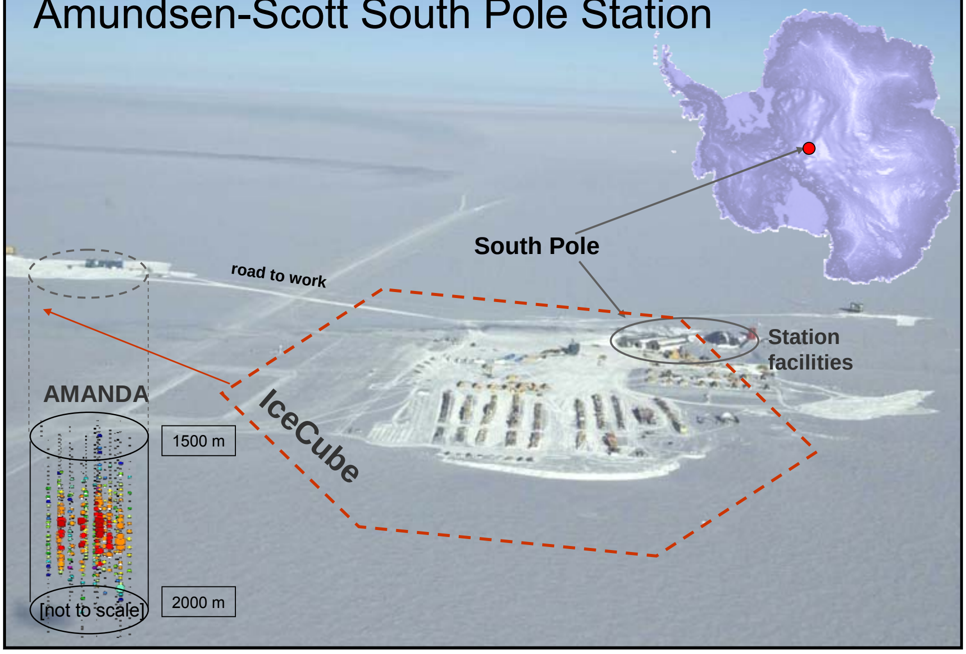
Detectors for High Energy Neutrino Astronomy

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

AMANDA skyplot 2000-2003

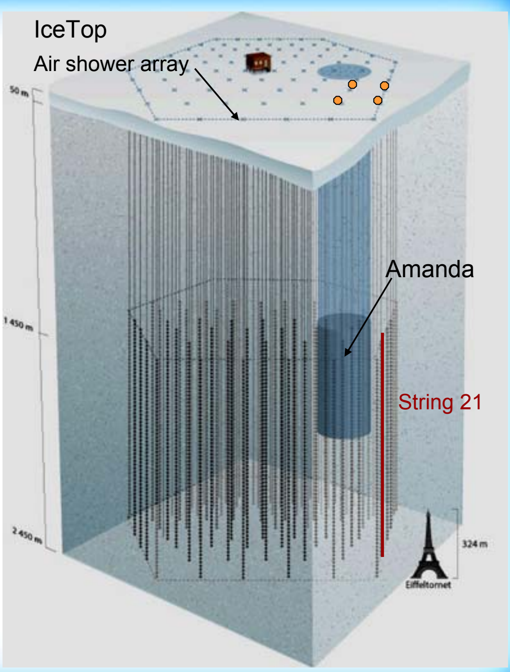


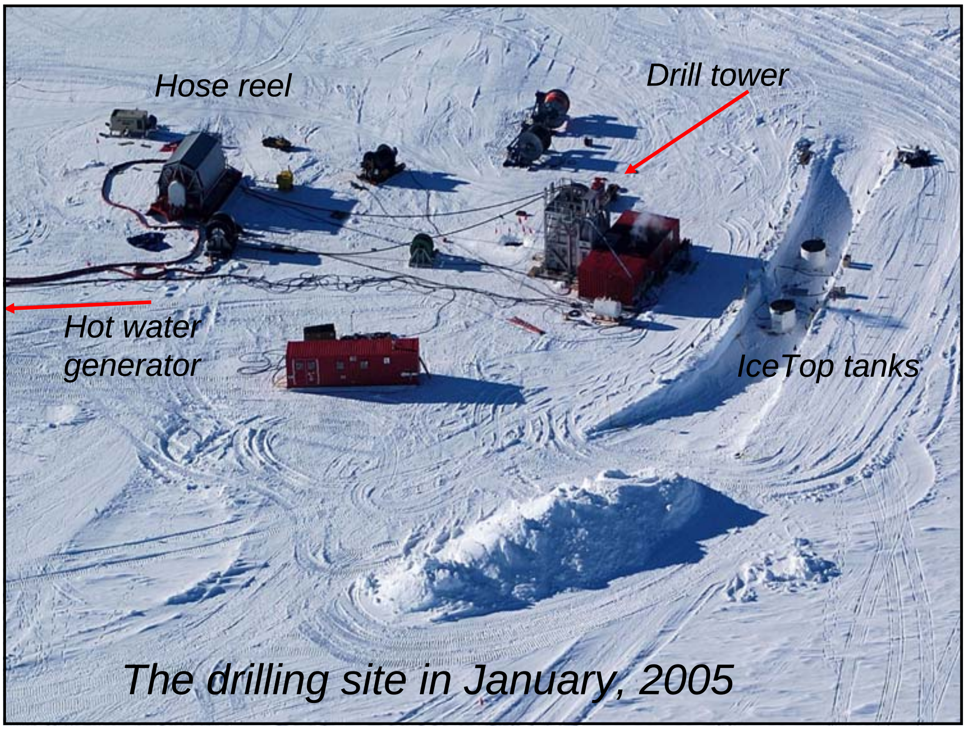
Site of AMANDA and IceCube: Amundsen-Scott South Pole Station



IceCube

- 70-80 Strings
- 4200-4800 PMTs
- Instrumented volume: ~1 km3 (1 Gton)
- IceCube will detect neutrinos of all flavors at energies from 10^{11} eV to 10^{20} eV, and low energy ν's from supernovae




Hose reel
Drill tower
Hot water
generator
IceTop tanks
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

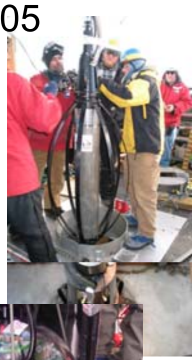
9:15: Started installation of the first DOM

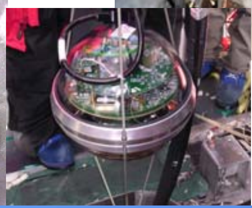
22:36: last DOM installed
12 min/DOM

22:48: 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^{o}C $\leftrightarrow$ –70^{o}C
- At-depth temperatures -35^{o}C $\leftrightarrow$ –10^{o}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")

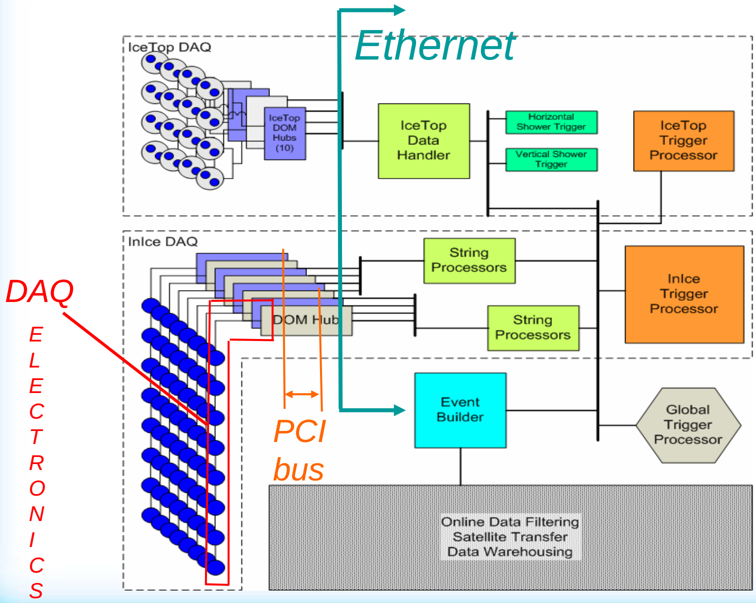
‘Electronic’ Requirements

- 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

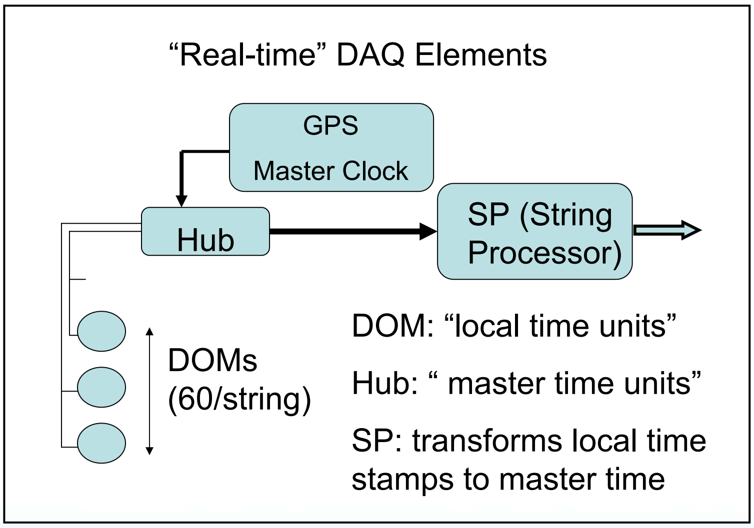
‘Environmental’ Requirements

- 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

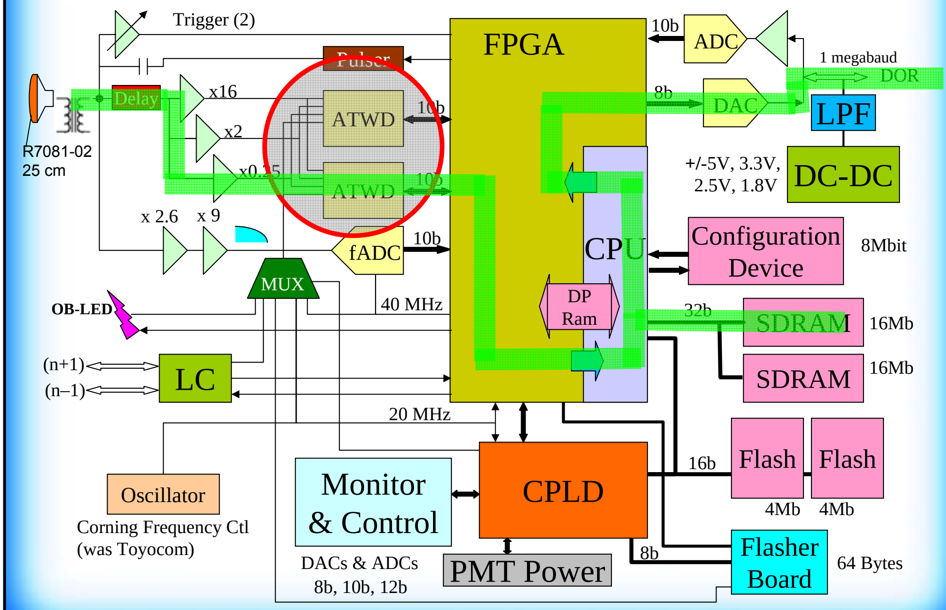
IceCube DAQ Block Diagram



The DAQ is based on the **D**igital **O**ptical **M**odule, a semi-autonomous sensor/processor with high functionality.



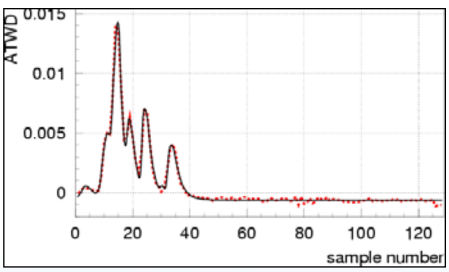
DOM MB Block diagram



Key Components

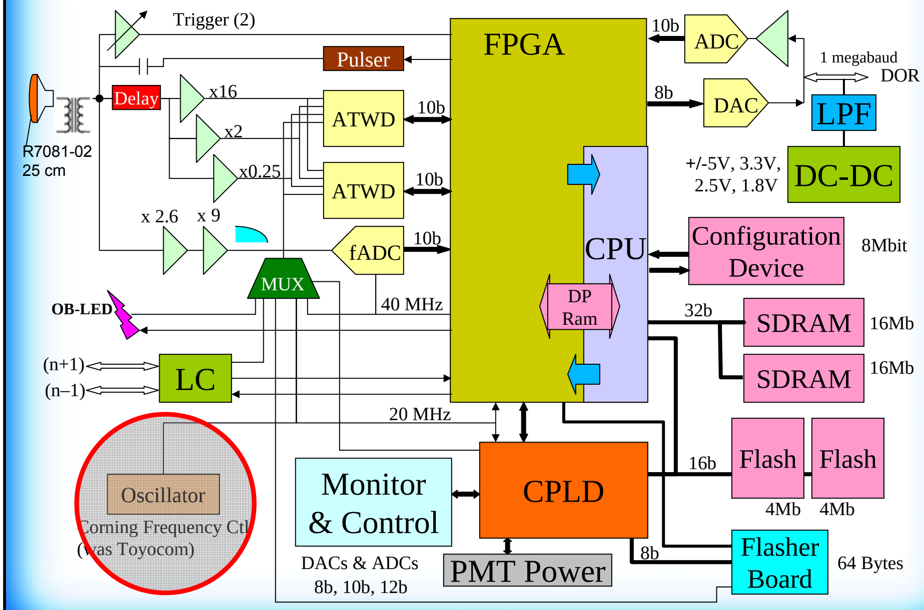
Analog Transient Waveform Digitizer - ATWD

- 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

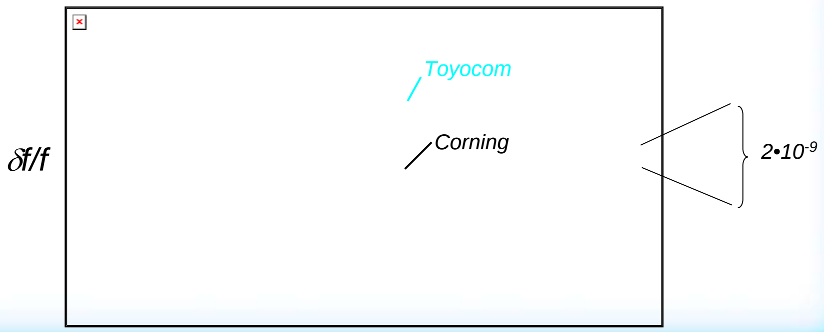
DOM MB Block diagram



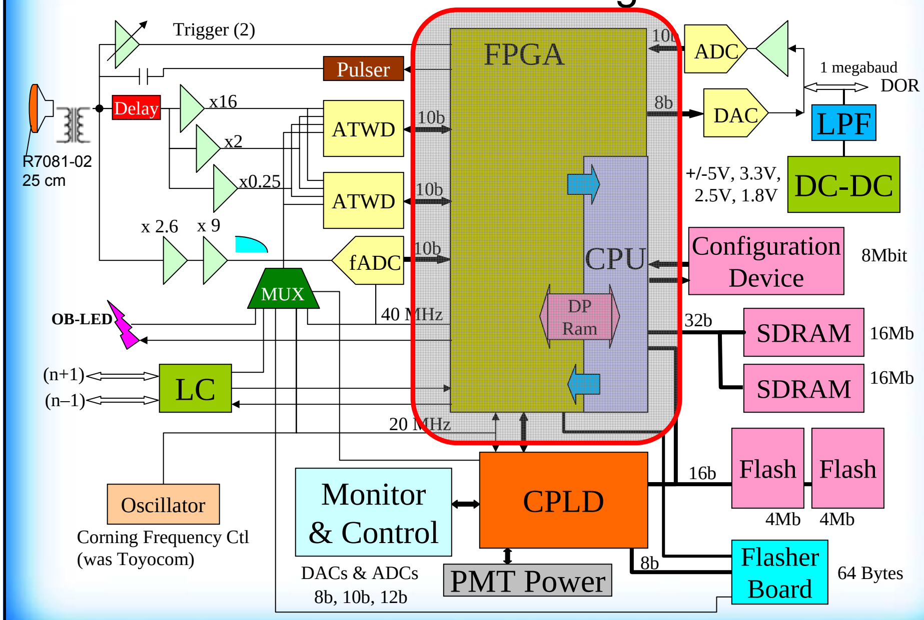
Key Components, cont.

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



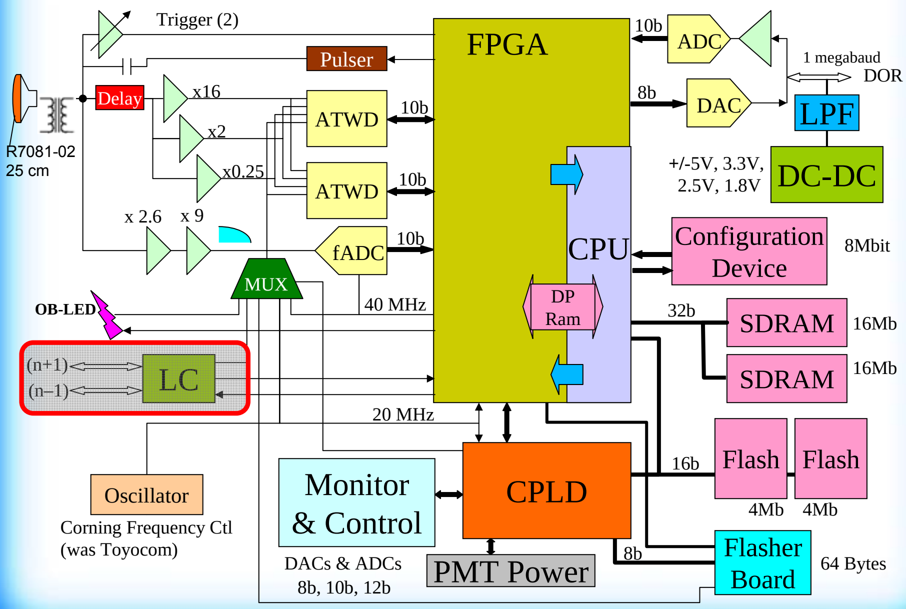
Key Components, cont.

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, …..

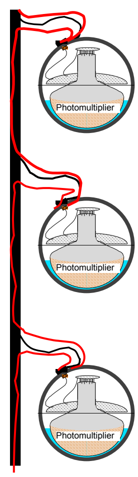
DOM MB Block diagram



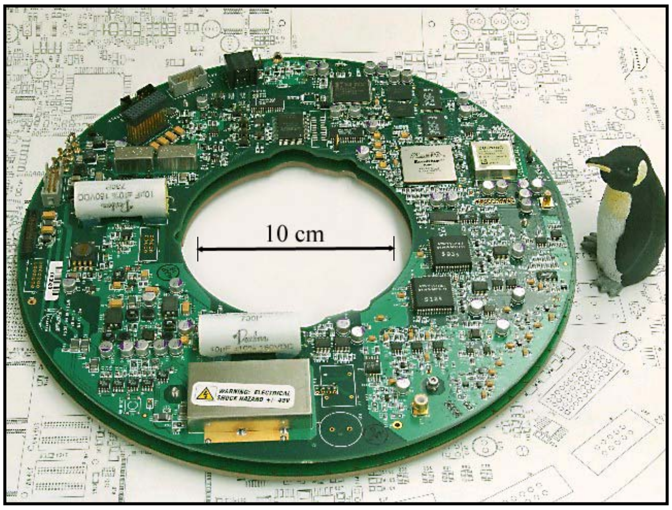
Key Components, cont.

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

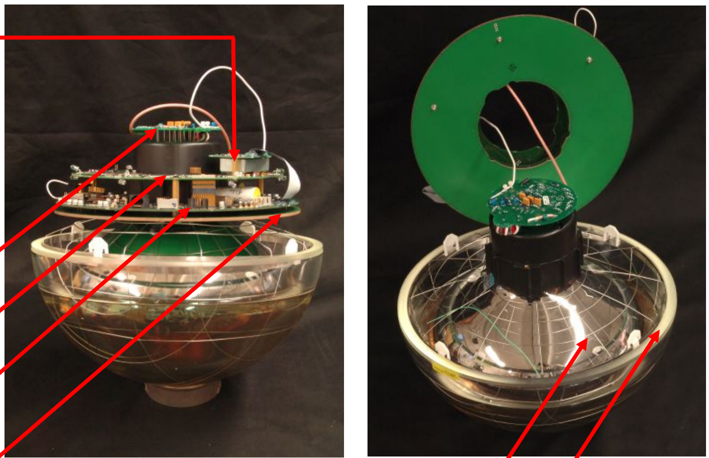


Digital Optical Module Mainboard



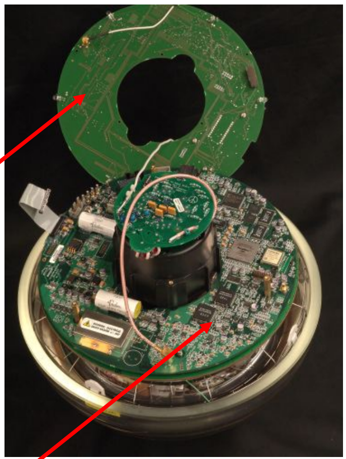
Mainboard design, fabrication and testing by
Lawrence Berkeley National Laboratory

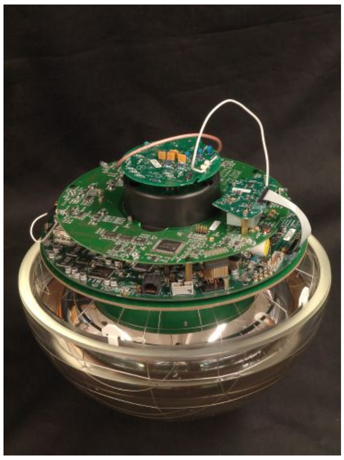
Digital Optical Module



Digital Optical Module

LED flasher board





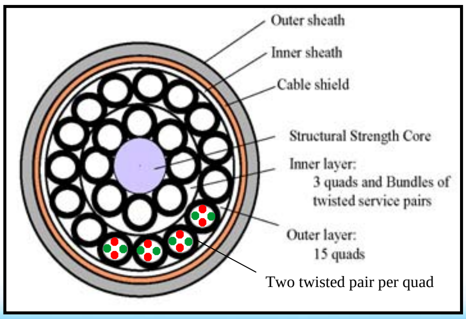
main board

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

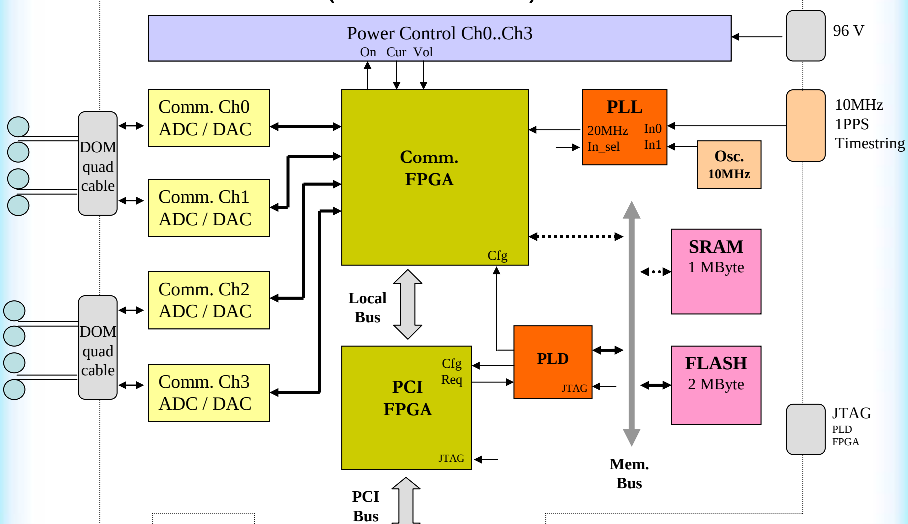
Key Components, cont.

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.



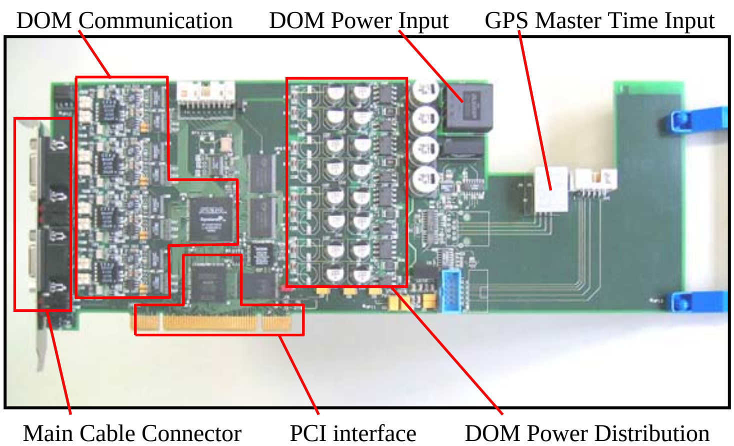
Surface Front-End Readout Card ("DOR" card)



Readout Card design, fabrication, testing by DESY-Zeuthen

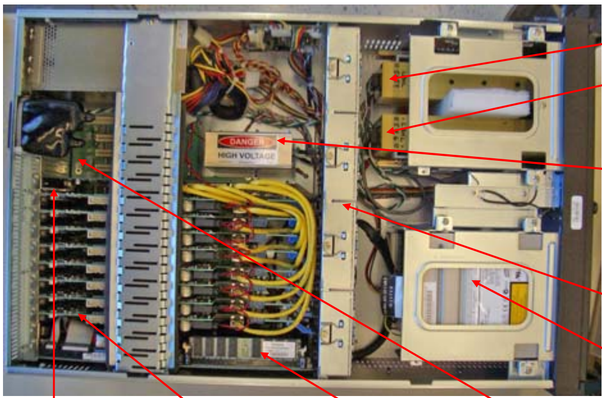
DOR (**D**igital **O**ptical module **R**eadout)

Surface front-end readout card



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^{o}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^{o}C to +80^{o}C, 30 G rms vibration
- Mainboard Production Testing
  - All boards tested
  - Temperature cycling (+65^{o}C to -50^{o}C), vibration 7 G rms
  - Burn in 24 hours at +65^{o}C 24 hours at -50^{o}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

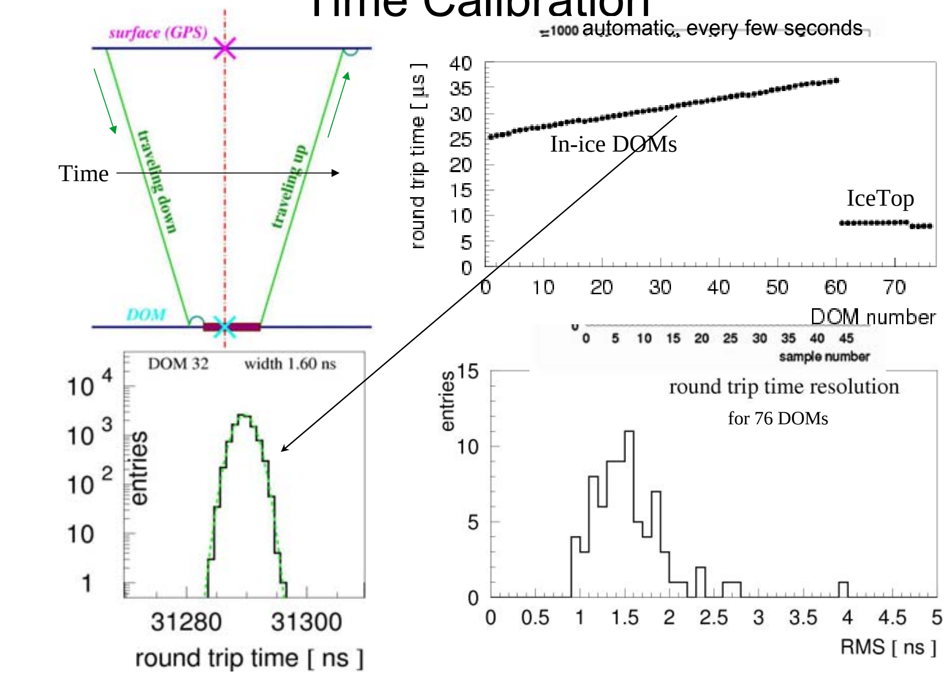
Transport to South Pole

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

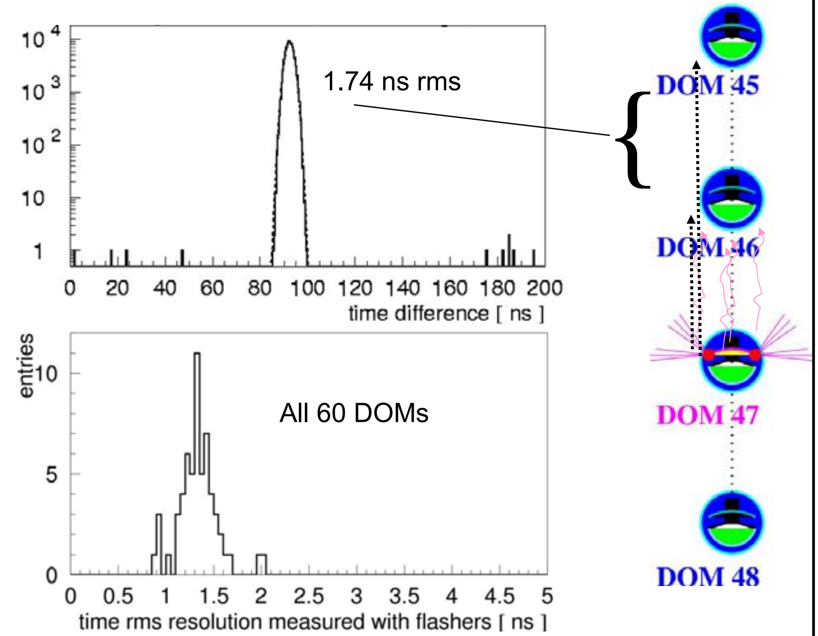
Performance

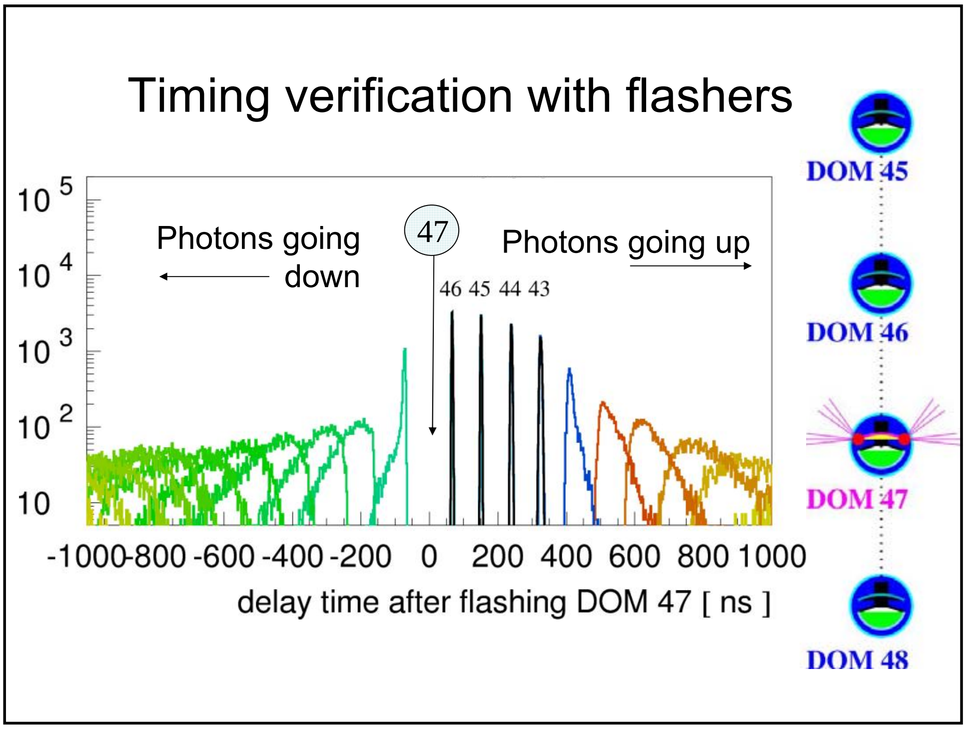
- Time calibration
- Detector verification with LED flashers
- Muon reconstruction
- Timing verification with muons
- Coincidence events
  - IceCube - IceTop
  - IceCube - AMANDA

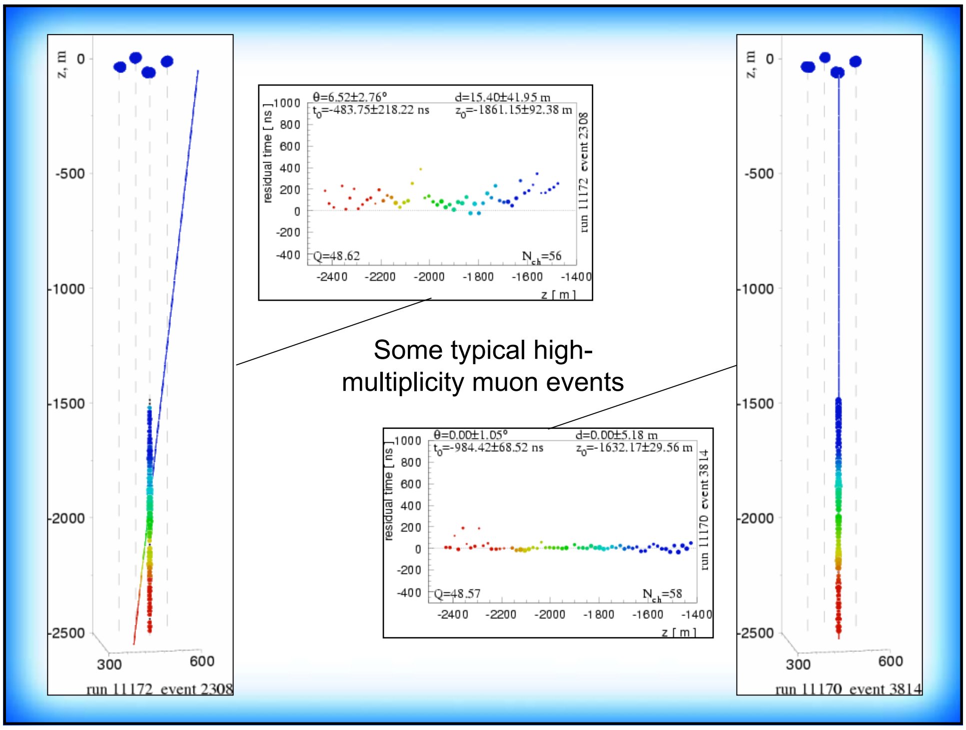
Time Calibration



Timing verification with flashers

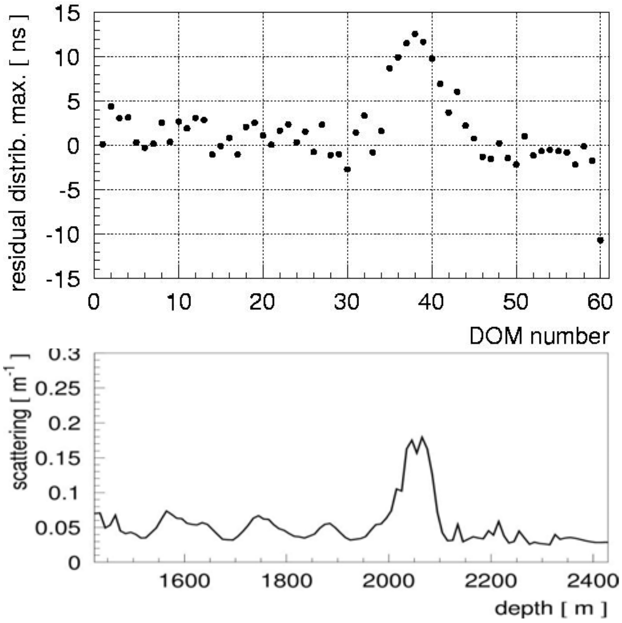



Timing verification with flashers
Photons going down
47
Photons going up
46 45 44 43
DOM 45
DOM 46
DOM 47
DOM 48
delay time after flashing DOM 47 [ns]

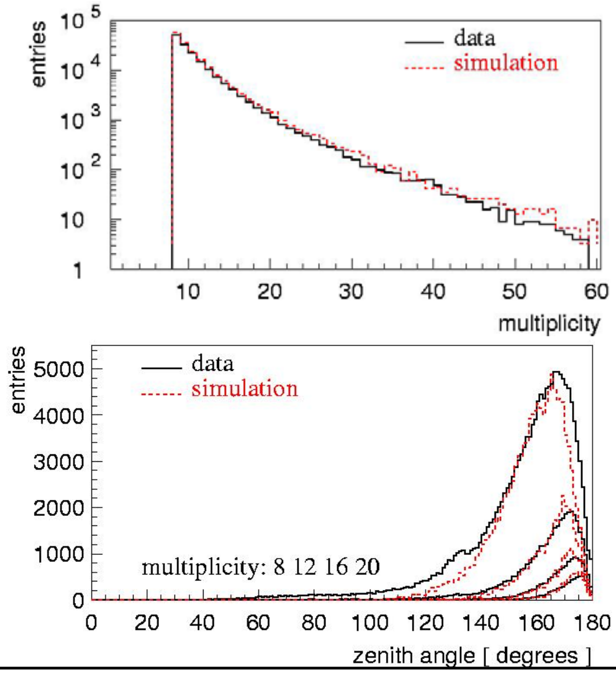

Some typical high-multiplicity muon events
run 11172 event 2308
run 11170 event 3814
residual time [ns]
z [m]

Time calibration verification using muons

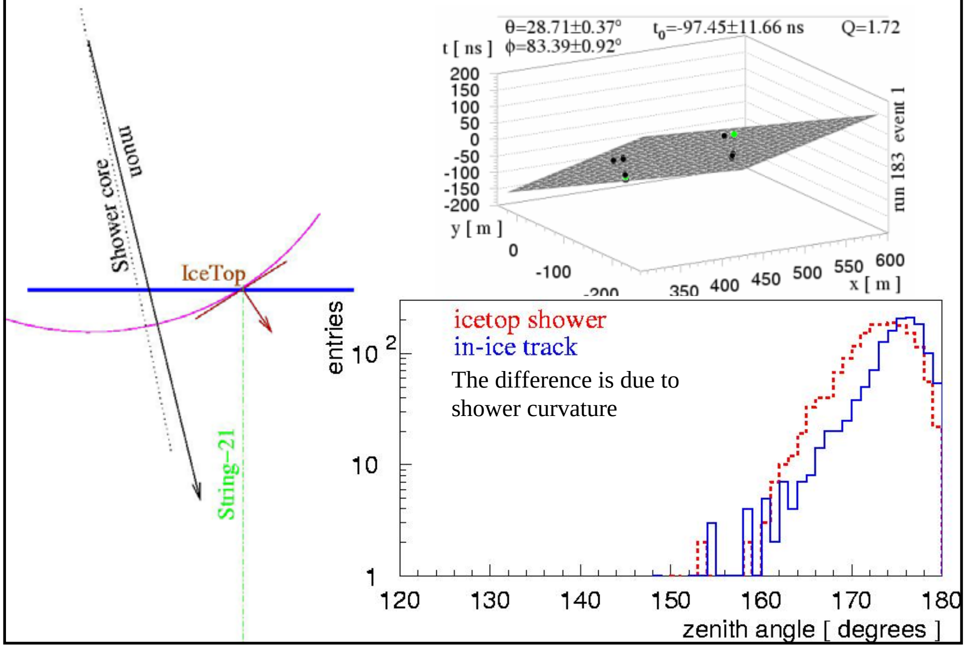
The random and systematic time offsets from one DOM to the next are small,
≤ +/- 3ns



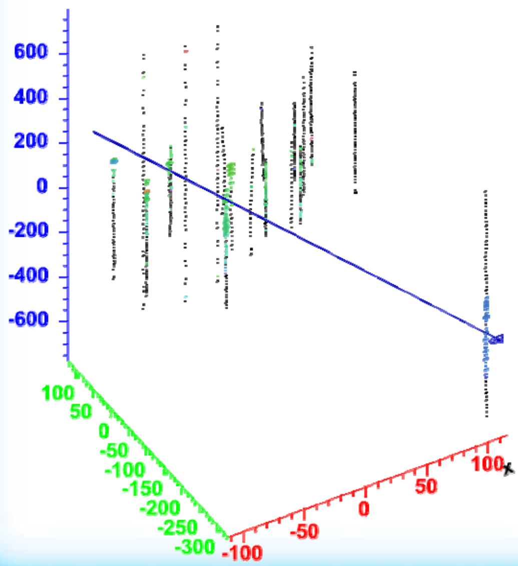
IceCube muon data reconstruction



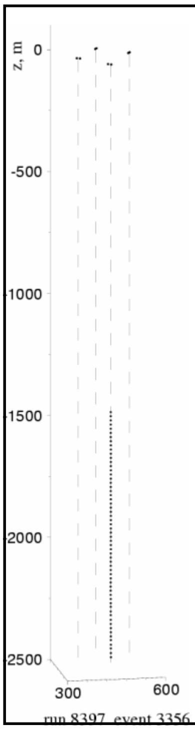
IceTop and in-ice coincidences



AMANDA and in-ice coincidences



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



Summary

- The first IceCube string and four IceTop stations have been sucessfully 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.

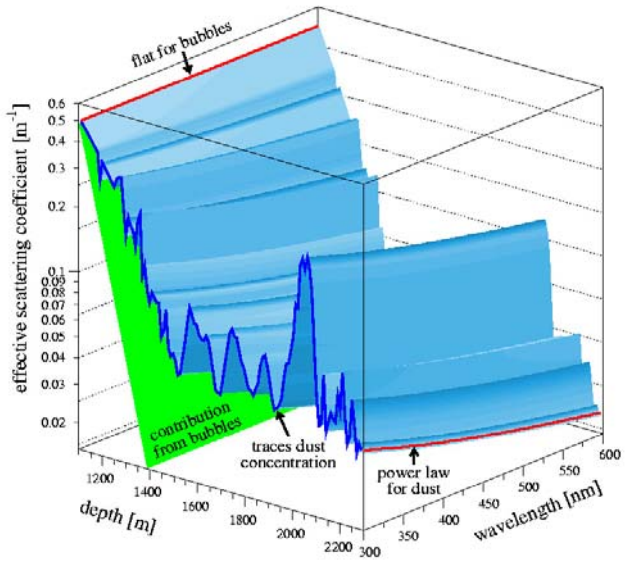
OUTLOOK

- 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

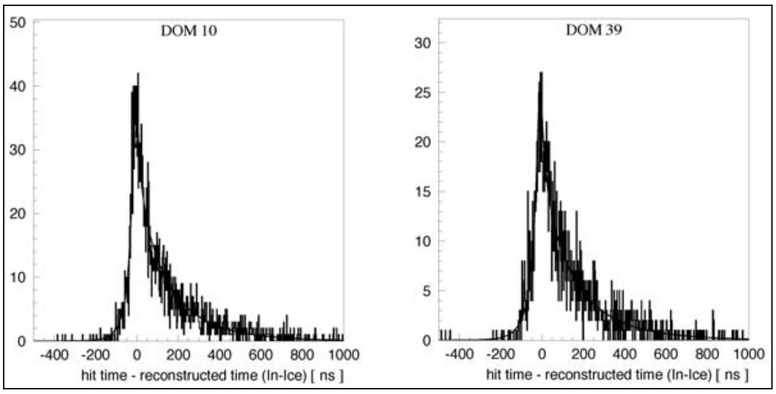
(The IceCube Collaboration now includes AMANDA)

Optical Scattering in S.P. Ice



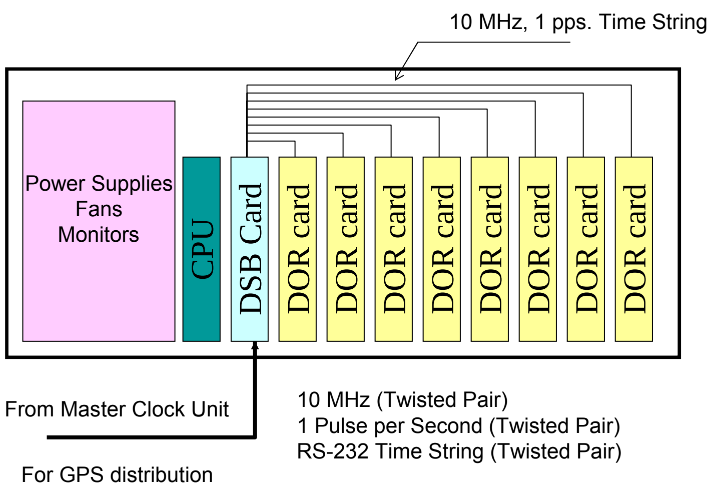
Time calibration verification using muons

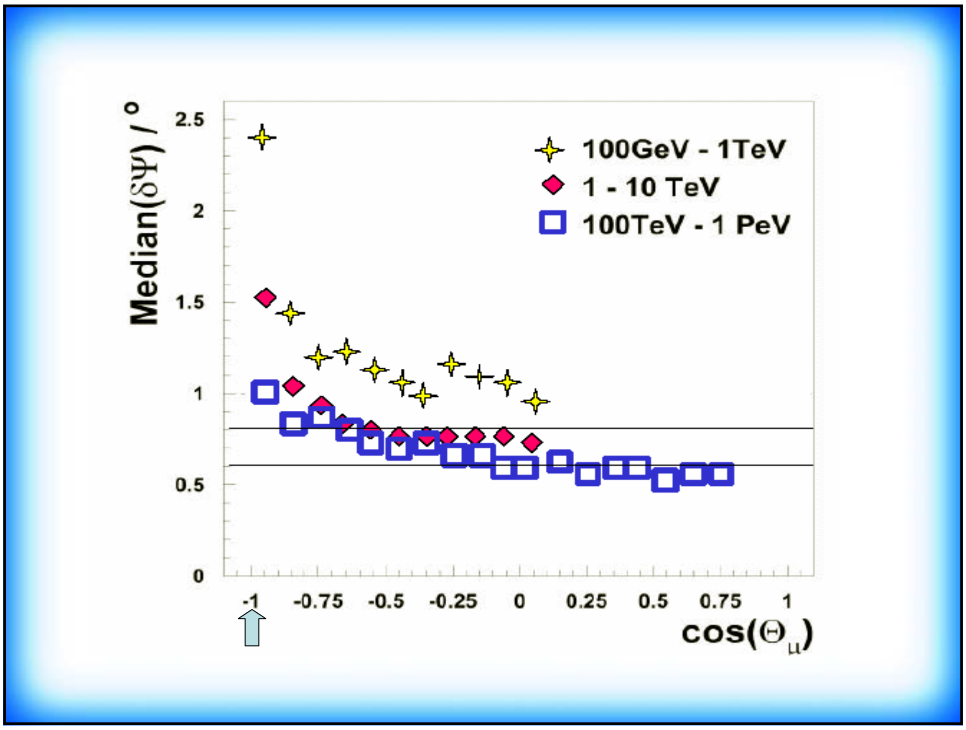
- reconstruct muon tracks without DOM X
- plot the time residual for DOM X for nearby reconstructed tracks
- if optical scattering length is longer than the distance cut (10 m) the most likely residual should be 0, otherwise residual will show delay increasing with the amount of scattering.



Time residual = (photon arrival time - reconstructed time*)
*assuming no scattering.

Inside the DOM Hub





Median(δΨ) / °
2.5
2
1.5
1
0.5
0
100GeV - 1TeV
1 - 10 TeV
100TeV - 1 PeV
-1
-0.75
-0.5
-0.25
0
0.25
0.5
0.75
1
cos(Θμ)