The Digital Optical Module -- How IceCube will Acquire Data

R.G. Stokstad*

for the IceCube and AMANDA Collaborations

Very large detectors for high-energy cosmic neutrinos have long distances between the photomultiplier tubes and a high-level signal processing center. In the case of AMANDA, which uses the ice cap at the South Pole, the distances are ~ 1.5 km to 2.5 km so that it was possible to connect the anodes of the PMTs by coaxial cable with analog electronics in the surface counting house. The completed AMANDA-II detector (~600 optical modules on 19 strings) represents an evolution of technologies from coaxial cable to twisted copper pair to optical fiber (**Fig. 1**). In all these cases, the analog signals are brought to the surface where they are digitized and processed.

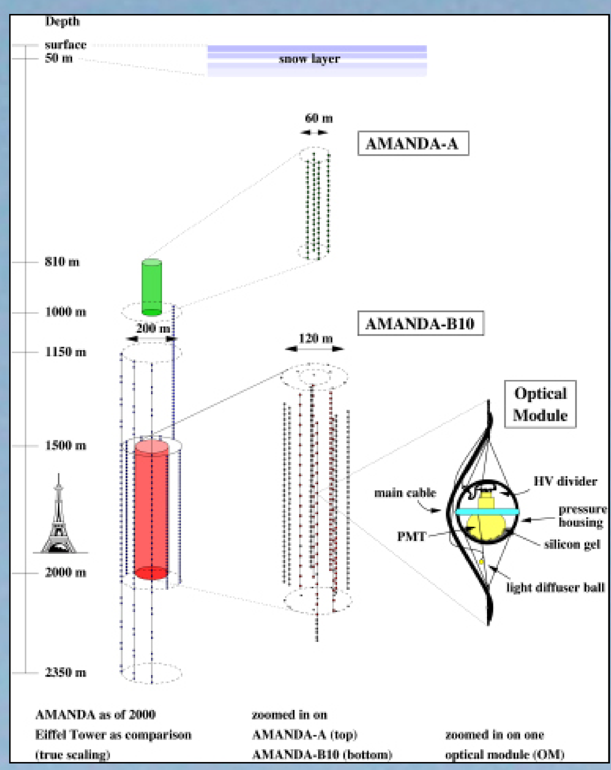

Fig. 1. The completed AMANDA-II detector.

IceCube (**Fig. 2**, Ref 1.) is a km-scale detector and the successor to AMANDA-II. It will consist of 4800 optical modules on 80 strings of 60 modules each. Its longer cable lengths and the much larger number of PMTs has led to the development of a data-acquisition technology with the following desirable features: 1. The robustness of copper cable and connectors between the surface and the modules at depth. 2. Digitization and time-stamping of signals that are unattenuated and undispersed. 3. Retention of a maximum amount of useful information. 4. Calibration methods (particulary for timing) that are appropriate for a very large number of optical modules. The PMT anode signal is digitized and time-stamped in the optical module. Waveform digitization, in which all the information in a PMT anode signal is captured, is incorporated. The time calibration procedure is both accurate and automatic.

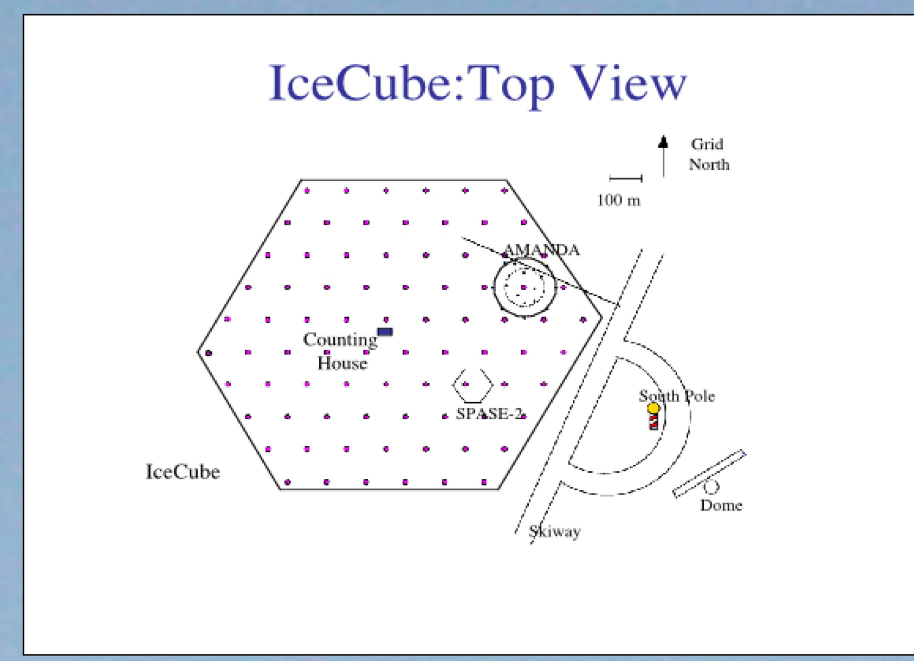

Fig. 2. The size of IceCube.

A system (Ref. 2) having these features has been tested in AMANDA. **Fig. 3.** shows a schematic diagram of the prototype system that was deployed in January, 2000 as the 18th of AMANDA's 19 strings. Each of the 40 optical modules includes the regular AMANDA data transmission system (analog signals over fiber optic cable) and the prototype digital system. String 18 thus contributes to the AMANDA trigger and data stream while the digital portion of the system can be operated independently and used for development and testing. The cables connecting adjacent modules make possible a local time coincidence, which eliminates most of the ~1 kHz of dark noise pulses that would otherwise be transmitted to the surface.

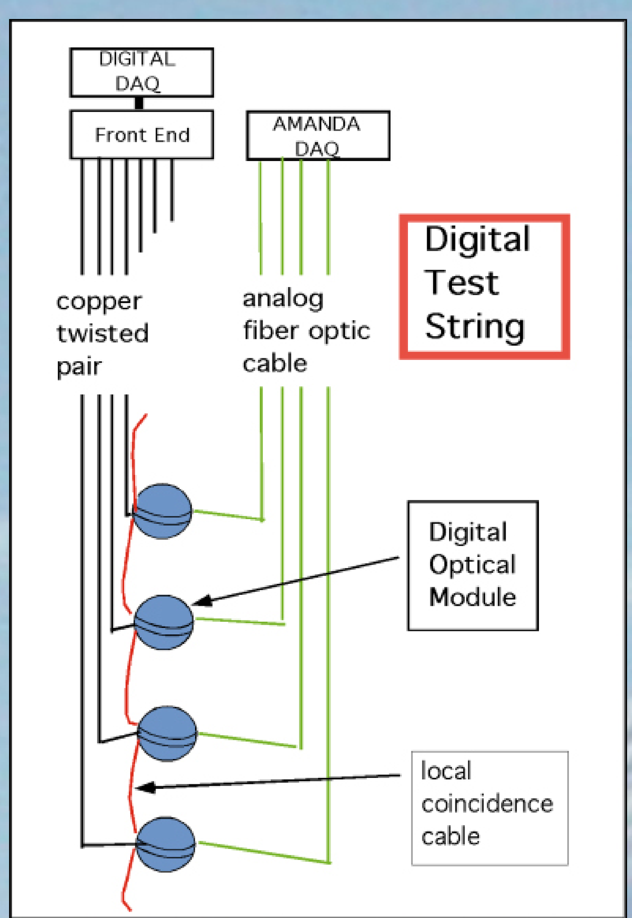

Fig. 3. The configuration of String 18.

A block diagram of the Digital Optical Module (DOM) signal processing circuitry is shown in **Fig. 4**. The principal components are: the analog transient waveform digitizer (ATWD), a low-power custom integrated circuit that captures the waveform in 128 samples at a rate of ~500 Megasamples/s; a "fast" ADC operating at ~30 Megasamples/s over an interval of several microseconds; a FPGA that provides state control, reads out the ATWD, time stamps events, handles communications, etc. a low-power 32-bit ARM CPU, which takes care of higher level operations via a real time operating system; the 16.8 MHz oscillator, made by Toyocom, is free-running, very stable ($\Delta f/f \sim 5 \cdot 10^{-11}$ over ~5s.) and provides clock signals to several components. The communications ADC and DAC are also used in the time calibration procedure. The surface DAQ (**Fig. 5**), which supplies power to, and communicates with, the DOM, has a front end that mirrors the DOM communications hardware. In December 2001, the surface DAQ was upgraded to service all of the DOMs on String 18 and resulted in improved performance. Downloading of new firmware and software via the internet to the deployed DOMs and to the DAQ is done as needed.

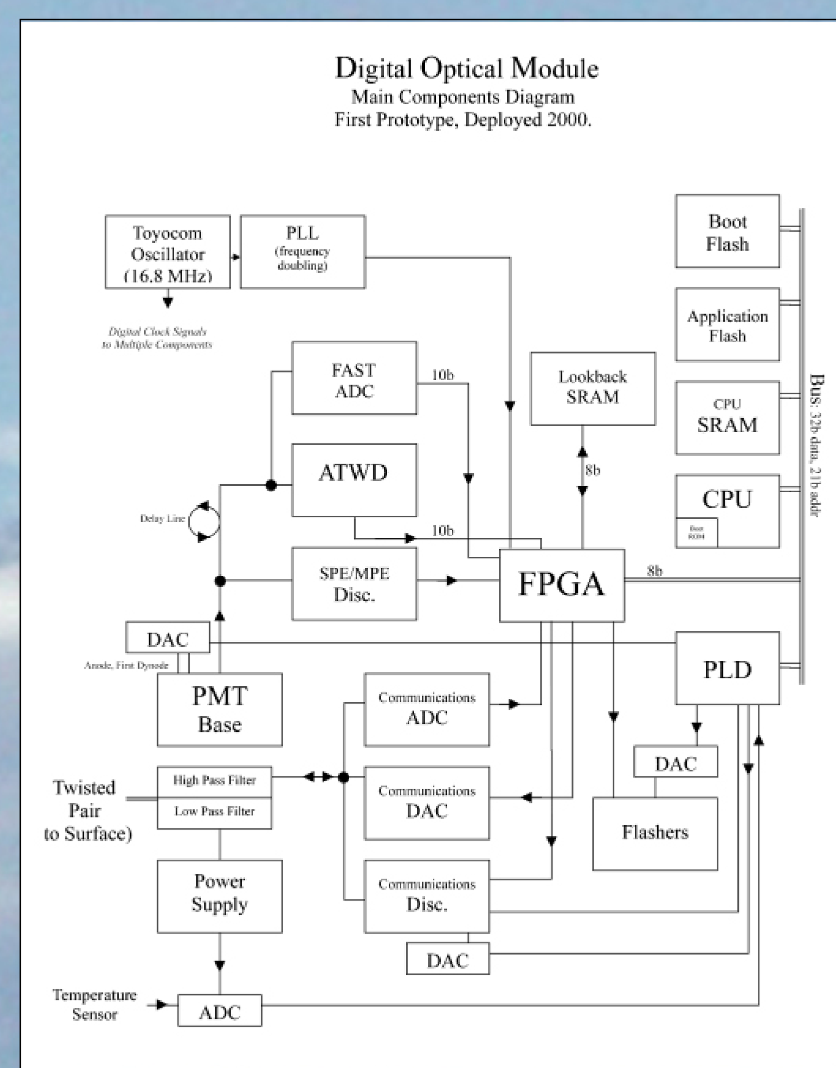

Fig. 4. Block diagram of the DOM main board.

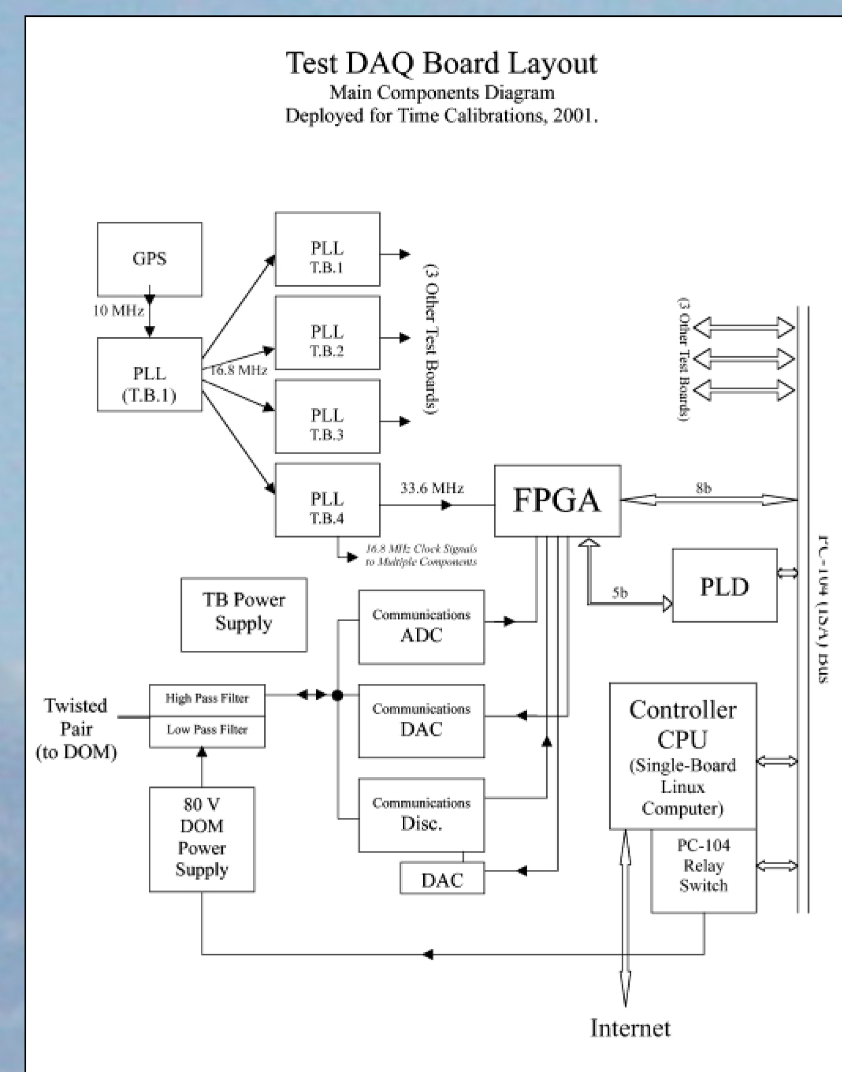

Fig. 5. Block diagram of an early the surface DAQ board.

A critical requirement for the digital system is the ability to calibrate the DOM oscillator against a master clock at the surface. There are two main elements in the determination of the frequency and off-set of a DOM oscillator relative to the master clock. In essence, timing pulses sent in one direction at known time intervals can be used to determine relative frequency, and the round trip time of pulses sent in both directions can determine the offset. See **Fig. 6.** At the tick of the clock, a timing signal is sent from one end of the cable to the other, digitized by the communications ADC, and a leading edge or crossover time determined with respect to the DOM oscillator. This process is repeated at regular intervals. Comparing the intervals measured on the surface with those measured in the DOM determines the relative frequency of the two clocks. After receiving a timing pulse at the DOM and waiting for a short time, δt, measured on the DOM clock, a pulse is sent from the DOM to the surface. The shapes of the pulses sent down and up are identical and are analyzed in the same way to determine the time mark. In this case, the times up and down are the same and are therefore equal to half the roundtrip time minus half the delay in sending the pulse back up. The offset of the DOM clock can be calculated directly from this one way time. This method of sending identical pulses in both directions to calibrate the one clock against the master clock is called Reciprocal Active Pulsing (Ref. 3).

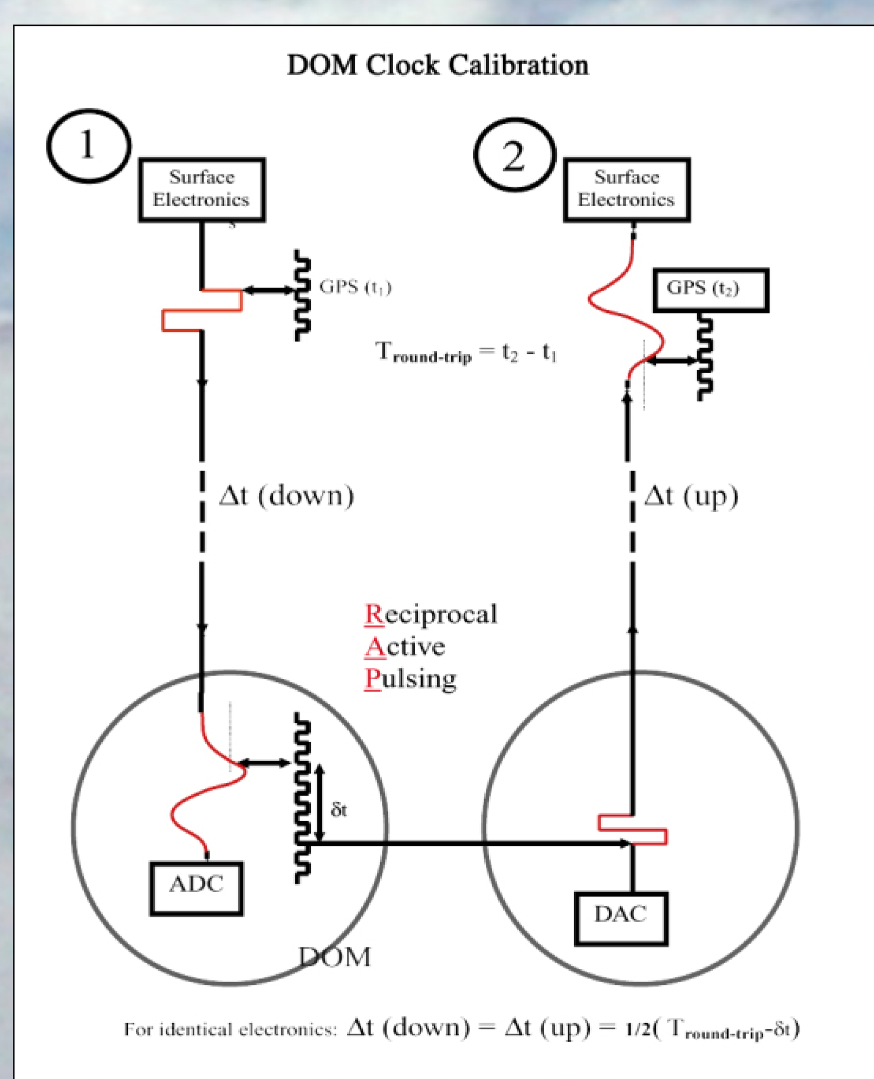

Fig. 6. The method for calibrating the DOM oscillator.

The accuracy with which the two clocks can be calibrated is illustrated in **Fig. 7**. The distributions shown here are the residuals of repeated measurements made at regular intervals of exactly 2.5 seconds. The differences in time intervals for successive measurements $(t_{i+2} - t_{i+1}) - (t_{i+1} - t_i)$ is a measure of the time calibration accuracy and includes contributions from clock drift (over a 2.5 second period), electronic noise, and errors in determining the leading edge of the time calibration pulse. Because the residuals for any two successive intervals are correlated, the intrinsic rms resolution of for a *single* measurement in *one* direction is the standard deviation shown in **Fig. 7** divided by $(6)^{1/2}$. The rms resolution for pulses received at the DOM is 1.8 ns. The resolution for pulses sent upward is 2.8 ns. (The larger value of 2.8 ns arises from the larger ambient electrical noise in the DAQ electronics on the surface compared to that in a DOM.) The systematic errors are estimated to be less than 5 ns.

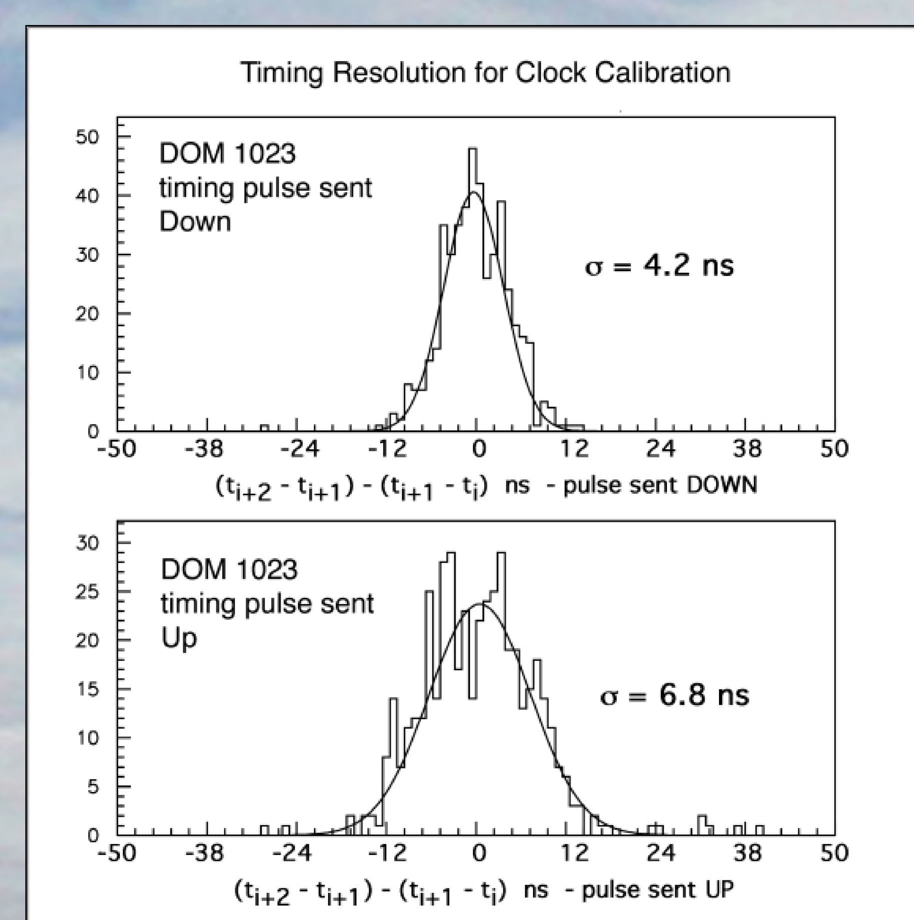

Fig. 7. The measured differences for successive time calibrations

Each DOM contains six LEDs, which can be pulsed at intervals determined by the clock in the DOM. These light pulses are detected in adjacent DOMs, 12 m and 24 m away. Comparing the time intervals for photons detected in the two DOMs determines a value for the overall time resolution for photon detection. This resolution is about 8 ns and includes the effects of light scattering in the ice. **Fig. 8** shows the resolution as a function of the length of time between successive clock calibrations and illustrates how short term drifts in DOM clock frequency can degrade the resolution. Performing clock calibrations every 5-10 seconds keeps these drifts small and consumes negligible bandwidth.

Digitized wave forms are shown **Fig. 9**. Typically, 85 % of all waveforms correspond to a single photo electron. (Only the ~15% of waveforms that are "complex" will be transmitted to the surface.) The ATWD is launched only when a discriminator threshold on the PMT anode signal is exceeded. The launch (or hit) times are sent to the surface DAQ where they are converted to universal time and used in a software trigger to determine whether a muon or cascade event has occurred.

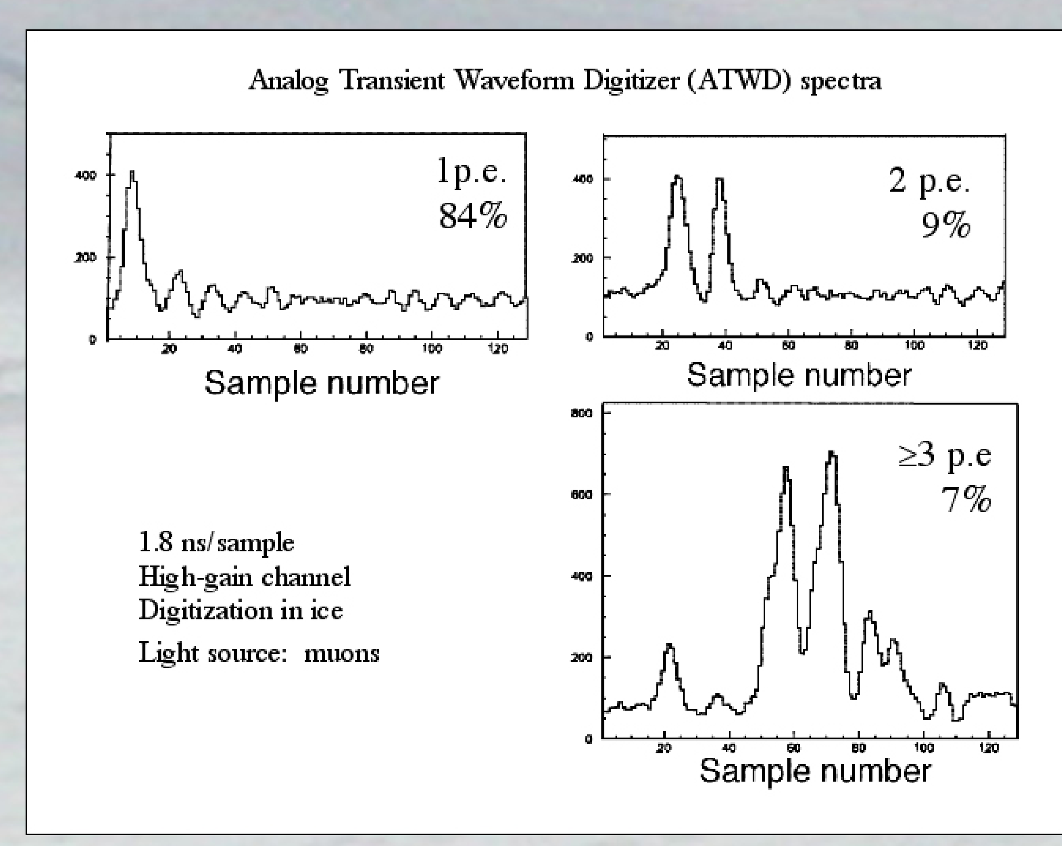

Fig. 9. Examples of PMT waveforms.

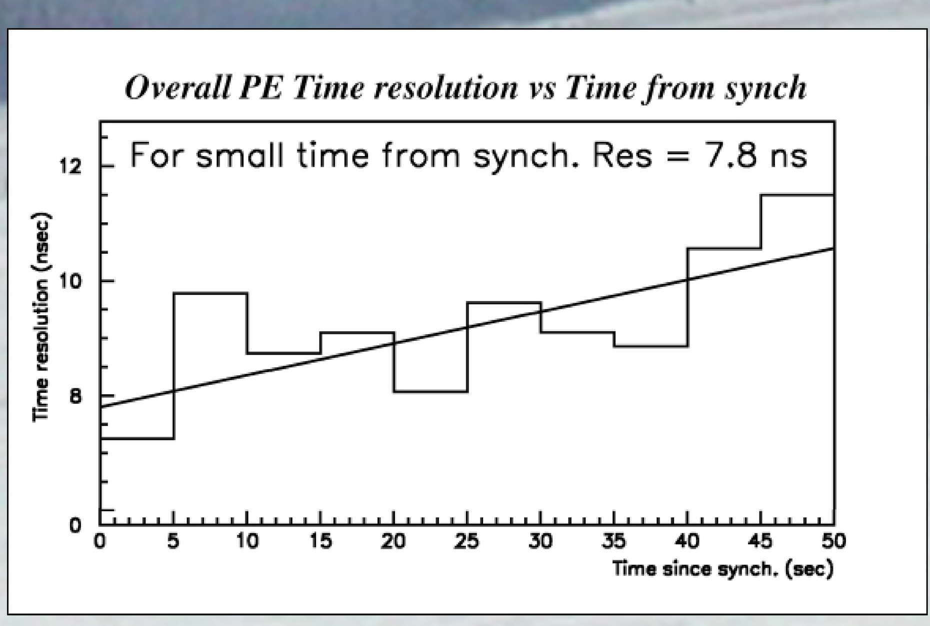

Fig. 8. The time resolution for photons vs interval between calibrations

The general concept for the surface system DAQ for IceCube is shown in **Fig. 10**. There will be two DOMs per twisted pair. Each DAQ front-end HUB will communicate with 8 DOMs. 8 HUBS will service a string of 60 DOMS. All communications after a HUB will be via Ethernet. Each string will have a string processor that time-orders hits and forms “string triggers.” Hits satisfying a global trigger will be built into events. A large capacity disk storage system will retain all events for several days (to search for Gamma-Ray Bursts, for example) and an on-line cluster of CPU’s will filter data for transmission via satellite to North America.

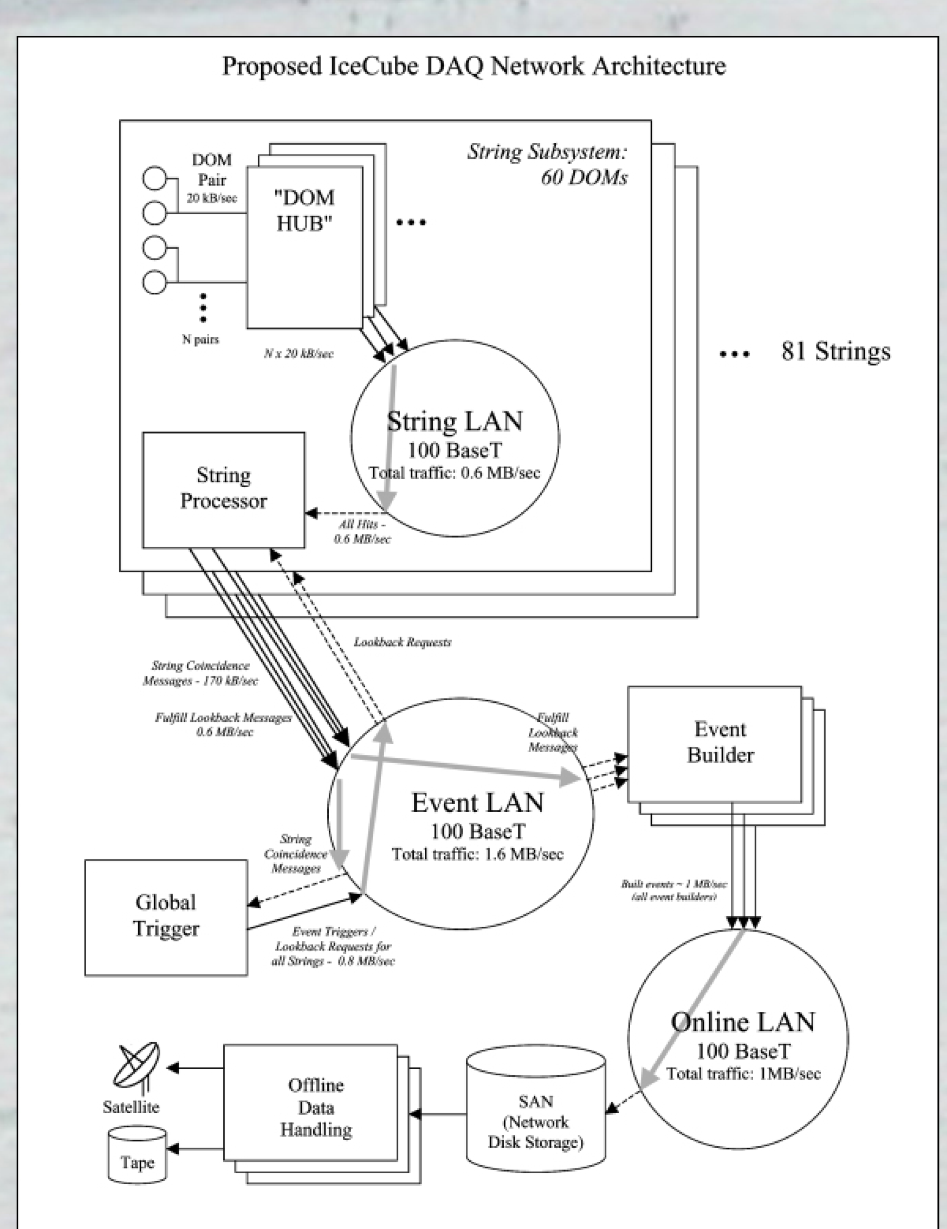

Fig. 10. The concept for the IceCube surface DAQ.

References

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IceCube[1] and AMANDA[2] Institutions

Bartol[1,2] Research Institute, University of Delaware
BUGH[1,2] Wuppertal, Germany
Universite Libre de Bruxelles[1,2], Brussels, Belgium
CTSPS, Clark-AtlantaUniversity[1], Atlanta USA
DESY-Zeuthen[1,2], Zeuthen, Germany
Institute for Advanced Study[1], Princeton, USA
Dept. of Technology, Kalmar University[1,2], Kalmar, Sweden
Lawrence Berkeley National Laboratory[1,2], Berkeley, USA
Department of Physics, Southern University,[1] Baton Rouge, LA, USA
Dept. of Physics, UC Berkeley[1,2], USA
Dept. of Physics, UC Irvine[2], USA
Dept. of Physics, U. Kansas, Lawrence, KS, USA
Institute of Physics, University of Mainz[1,2], Mainz, Germany
University of Mons-Hainaut[1,2], Mons, Belgium
Dept. of Physics and Astronomy, University of Pennsylvania[1,2] Phila., USA
Dept. of Physics, A[3]RI, PSL, SSEC, University of Wisconsin[1,2], Madison, USA
Physics Department, University of Wisconsin[1,2], River Falls, USA
Division of High Energy Physics, Uppsala University[1,2], Uppsala, Sweden
Fysikum, Stockholm University[1,2], Stockholm, Sweden
University of Alabama[1] Tuscaloosa, AL, USA
Vrije Universiteit Brussel[1,2], Brussel, Belgium
Dept. of Physics, Chiba U., Chiba, Japan
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*Institute for Nuclear and Particle Astrophysics
Lawrence Berkeley National Laboratory
Berkeley, CA 94720 USA

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