IceCube Sensor System Calibration Plan

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Abstract

This document presents a high level plan for calibrations performed during and after string deployment in IceCube, and plans for calibration of the IceTop surface array and its use in high-level calibrations of the in-ice array. The techniques to be used are described and for each calibration a plan is presented. Dedicated calibration hardware is discussed and monitoring considerations briefly touched upon.
Contents

1 Purpose and Scope 4

2 Low-level calibrations 4
   2.1 Verification of timing calibration (WBS 1.5.3.2.3) 4
      2.1.1 Requirements 4
      2.1.2 Plan 5
      2.1.3 Status 6
      2.1.4 Monitoring considerations 7
      2.1.5 Major WBS dependencies 7
   2.2 Geometry calibration (WBS 1.5.3.2.4) 7
      2.2.1 Requirements 7
      2.2.2 Plan 7
      2.2.3 Status 10
      2.2.4 Monitoring considerations 10
      2.2.5 Major WBS dependencies 10
      2.2.6 IceTop geometry 11
   2.3 Charge calibration (WBS 1.5.3.2.2) 11
      2.3.1 Requirements 11
      2.3.2 Plan 11
      2.3.3 Status 13
      2.3.4 Monitoring considerations 13
      2.3.5 Major WBS dependencies 13
   2.4 Angular DOM acceptance 13
      2.4.1 Requirements 13
      2.4.2 Plan 13
      2.4.3 Status 14
      2.4.4 Monitoring considerations 14
      2.4.5 Major WBS dependencies 14
   2.5 Optical properties of ice (WBS 1.5.3.2.7) 14
      2.5.1 Requirements 14
      2.5.2 Plan 14
      2.5.3 Status 16
      2.5.4 Monitoring considerations 16
      2.5.5 Major WBS dependencies 16
      2.5.6 Optical properties of ice in IceTop tanks 16

3 High-level calibrations 16
   3.1 Vertex resolution (WBS 1.5.3.2.6) 17
      3.1.1 Requirements 17
      3.1.2 Plan 17
      3.1.3 Status 18
      3.1.4 Major WBS dependencies 18
   3.2 Pointing accuracy and pointing resolution (WBS 1.5.3.2.5) 18
      3.2.1 Requirements 18
      3.2.2 Plan 18
      3.2.3 Status 19
      3.2.4 Major WBS dependencies 19
   3.3 Energy calibration (WBS 1.5.3.2.6) 19
      3.3.1 Requirements 20
      3.3.2 Plan 20
      3.3.3 Major WBS dependencies 21
   3.4 High level calibrations of IceTop 21

4 Summary of calibration devices 22

5 Detector monitoring (WBS 1.5.3.1) 24

6 Calibration database (WBS 1.5.3.2.8) 24
   6.1 Calibration data from low-level calibrations 24
   6.2 Calibration data needed for high-level calibrations 24
7 Calibrating the first four strings

7.1 Low-level calibrations of the first four strings .......................................................... 25
7.2 Calibrating first four strings with IceTop ................................................................. 25
1 Purpose and Scope

This document presents a plan for calibrations to be performed in IceCube during and after string deployment, as covered by WBS element 1.5.3.2. Plans for pre-deployment calibrations of different components in the lab are not included. Requirements imposed by science goals are listed and briefly discussed, but their physics justifications are presented elsewhere (e.g. in [1]). For each identified calibration topic, a plan is presented to meet the requirements and the methods to be used are described. The needs for monitoring of calibration constants are briefly discussed but will be more thoroughly covered by the Monitoring Plan. This document also discusses dependencies on tasks covered by other WBS elements, such as Reconstruction (1.5.2) and AMANDA-IceCube Integration (1.5.4).

The need for dedicated calibration devices (described in more detail in other documents) is discussed where relevant. Calibration data are either generated in the DOM firmware and are part of the normal data stream, or will be generated and triggered by external sources.

The calibrations discussed here can be roughly divided into two categories: low-level calibrations to be applied to the recorded raw data, and high-level, or physics, calibrations. This document is structured according to this division.

2 Low-level calibrations

The DOM records a waveform whenever one or more photons arriving at the PMT convert into one or more photoelectrons (PE). The low-level calibrations are applied to extract basic photon hit parameters from these measurements. The time of the leading edge of each waveform has to be related to the times for all other waveforms in the event; the relation between the integrated charge in the waveform with the number of PEs has to be known; the relative position of the DOM to all other DOMs must be known as well as the absolute position of the array. These parameters must be known at all times for which data is recorded. They are stored in a calibration database and are monitored to detect trends or anomalies that are indicative of problems.

The following subsections discuss the low-level calibrations in turn.

2.1 Verification of timing calibration (WBS 1.5.3.2.3)

2.1.1 Requirements

The overall requirement for knowing when each recorded photon hits a DOM, relative to all other hits in the event, is 7 ns [1]. All hit times, i.e., all waveforms, have to be calibrated individually. The timing requirement is imposed by requirements on track reconstruction and cascade reconstruction.
2.1.2 Plan

Timing calibration in IceCube is done in two stages: (A) the calibration of DOM hit times in the DAQ and (B) the higher-level verification of the time calibration using physics data (from muons and in-situ light sources).

A. Time calibration with RAPCAL

Timing calibration is performed by DAQ software in a number of separate steps:

1. Each recorded waveform, or hit, is time-stamped by a free-running local clock in the DOM, using a two-stage method that produces a coarse and a fine time stamp. When a PMT signal triggers the discriminator, the resulting pulse is synchronized to the next DOM clock edge at which time it causes the ATWD to launch. The coarse time stamp is the clock value at the instant of ATWD launch. The fine time stamp marks the position of the leading edge of the waveform within the resulting ATWD record.

2. These local times are then translated to master clock times at the surface, and ultimately linked to GPS times. The conversion between the local clock time and the master clock time is provided by an automated time-synchronization procedure. The surface DAQ periodically transmits bipolar time-mark signals, synchronized to the master clock, to each DOM where the arriving dispersed and attenuated pulses are digitized and time-stamped locally. This procedure provides knowledge on local clock frequency and phase, relative to the master clock.

3. Slightly differing physical properties of the twisted quads introduce an offset to the measured clock phase by introducing differences in the signal propagation time through the cables. A Reciprocal Active Pulsing calibration (RAPCAL) method is used to measure the relative signal propagation times, or cable electrical lengths. The RAPCAL method performs symmetric round-trip measurements with identical time-mark pulses that are sent in both directions, initialized either by the DAQ or in the DOM, and separated by a known wait period.

RAPCAL will be invoked repeatedly at periodic intervals, nominally every 10 s, as part of normal DAQ operations, and the results from these measurements will be stored in the calibration database. Initially, RAPCAL data will also be stored in a database. Cable round trip times should be stable with time once the water column in the hole is refrozen and has reached ambient temperature.

One part of the timing calibration, the PMT transit time and its dependence on high voltage, can be measured independently, using the on-board LED. This measurement will be performed both in the lab prior to deployment (and the results stored in the DOM database) and in situ for all DOMs.
B. Verification of time calibration

After implementation of the automated timing calibration procedure (using RAPCAL) in the deployed DOM strings, one crucial task for Detector Characterization is to verify that this procedure works and delivers calibrated times for the recorded waveforms within the required resolution. This will be done with two main methods:

1. Data from dedicated flasher runs will be used to study time differences between calibrated hit times in neighboring DOMs. On every string, the flasher on every DOM $k$ will be run at a brightness sufficiently high for the two closest neighbors (DOMs $i = k - 1$ and $j = k - 2$) above the flashing DOM to record light levels of at least 5 photoelectrons per pulse on average. For each such pair of receiver DOMs, the distribution of time difference $(\Delta t)_{ij}$ is determined and its width $\sigma_{ij}$ and mean $\Delta_{ij}$ are calculated. The width depends on the overall time resolution for the two DOMs, and the mean should be zero unless there are systematic shifts in the timing calibration. Given individual time resolutions $\sigma_i$ and $\sigma_j$ for the two DOMs, and an inherent resolution $\sigma_{\text{syst}}$ (which depends on flasher brightness) for the method, the width of the time difference is given by

$$\sigma_{ij} = \sqrt{\sigma_i^2 + \sigma_j^2 + \sigma_{\text{syst}}^2}.$$  

(1)

If data is acquired for every neighboring pair of DOMs on a string (i.e., with every flasher except the two top ones), the individual resolutions $\sigma_i$ can be calculated (except for the lowest and the highest DOM) from a set of equations like (1), provided $\sigma_{\text{syst}}$ is known from simulations. When the $\Delta t$ distributions are determined, only the first hit in each pulse is used for each of the two DOMs. This makes the distribution narrower, i.e., $\sigma_{\text{syst}}$ smaller, and the method more sensitive. Brighter flashes also decrease $\sigma_{\text{syst}}$ by increasing the mean number of photoelectrons recorded for each pulse and thereby narrowing the time spread for the first hit.

2. The timing calibration will also be verified by studying residual hit times (after position calibration and reconstruction) in data from down-going muon tracks or from the in-situ flasher boards. Simulations of such data with realistic ice properties will be used for comparison of these time distributions and their dependence on distance from the source (muon track or flasher). Based on experiences with the use of down-going muons for timing calibration in AMANDA, this method is expected to detect systematic shifts in the timing calibration for individual DOMs or groups of DOMs to an accuracy of 5 ns.

2.1.3 Status

RAPCAL is a new calibration method, not routinely used in AMANDA, but partially introduced and tested on the string 18 DOMs. The individual parts of this timing calibration have been demonstrated to work in-situ on string 18 and have shown to give a combined
uncertainty under 7 ns. The procedure will be automated and incorporated into the DAQ. Control and monitoring software has to be written and plenty of testing has to be performed. Software for verification using the two methods (time differences between neighbors and time residuals) has to be developed and tested with simulated (flasher and muon) data.

2.1.4 Monitoring considerations

For each DOM, the local time stamp can be translated to global time by a linear transformation, say \( t_{\text{global}} = a \cdot t_{\text{local}} + b \). The two parameters \( a \) and \( b \) are time dependent and their values need to be stored in the calibration database and monitored. Since \( a \) and \( b \) are functions of clock drift and electrical cable length is may be conceptually simpler to monitor these parameters instead.

We also need to monitor the performance of RAPCAL at a higher level. For this high-level monitoring, we will use in-situ data from the flasher boards, where the location of the source and the timing of the light pulses are known, as well as reconstructed data from down-going muons. Parameters to monitor could include time residuals from muon track fits as function of impact parameter and track direction, and time residuals as function of distance to and brightness of flasher source.

2.1.5 Major WBS dependencies

The main dependency for timing calibration is on DAQ software (1.3.4) for implementation and automation, and on Reconstruction (1.5.2) for verification with muons and flasher data. The development of verification tools depends on the availability of software and simulations under Data Systems (1.4).

2.2 Geometry calibration (WBS 1.5.3.2.4)

2.2.1 Requirements

The relative positions of individual DOMs, and the absolute depth and orientation of the entire array, must be known to within one meter. This requirement ensures that the systematic uncertainty from position calibration is smaller than the 7 ns timing requirement (for event reconstruction these two uncertainties are complementary). The speed of light in ice is 4.4 ns per meter. The requirement is imposed by requirements on track and cascade reconstruction and by requirements on pointing accuracy of the array.

2.2.2 Plan

Determining the detector geometry involves a number of methods which are combined to yield an accuracy in absolute position of individual DOMs of better than 0.5 meters (shown in AMANDA). Some measurements must be done during deployment, while others can be repeated and improved after deployment. The elements of the position calibration are:
• The absolute locations of individual holes, and therefore the orientation of the array in the horizontal plane, will be determined with a **GPS survey** of the positions of the hole centers on the surface, using control points on “permanent” station structures. All holes will first be surveyed prior to drilling, and then again after deployment since the position of the actual hole will not necessarily coincide with the pre-surveyed position within the required accuracy. The centers of the holes, i.e., the actual (so-called *as-built*) locations that are surveyed, will be clearly marked on the surface to ensure that any future surveys will use the same points. Individual hole centers can be surveyed to within 10 cm, but the somewhat irregular profiles of the holes in the firn layer (the top 40-50 m of the ice) impose larger uncertainties. The GPS survey will also provide absolute elevations for all surveyed holes so that variations in the elevation of the snow surface between holes can be correctly accounted for when the relative vertical string locations are determined.

• The absolute depths will be based on **pressure sensor readings** during deployment. Each string will have one high-precision, temperature-compensated pressure sensor located at the bottom end, just below the deepest DOM. This sensor will also be used to monitor the depth of the string during deployment and to make sure the target depth is reached. In addition, each string will be equipped with a second pressure sensor in the upper part of the instrumented section which will serve as backup for deployment monitoring and will be used for a cross-check of final depth and to monitor string stretching.

• The **well depth**, i.e., the vertical distance between the top of the hole (whose elevation is measured as part of the GPS survey) and the water level in the hole (which is the point from which depth is measured with the pressure sensors) is measured at the time of deployment with three complementary methods (for redundancy). 1. **Up-hole pressure logging.** A dedicated pressure sensor will be lowered into the hole a few tens of meters below the water surface, at a known distance from the top of the hole. Its pressure reading will be monitored with the deployment monitoring system and the data collected and saved with the down-hole pressure readings. 2. **Optical ranging.** A laser distance meter will be used to measure well depth at the close of deployment of the string. If the water level is relatively unperturbed, the laser device can measure well depth to within a few centimeters. 3. A **manual measurement** of the well depth will be made from the top of the hole with a tape measure. For all three methods, a final measurement must be simultaneous with the final depth reading from the down-hole pressure sensors since refreezing of the water column continuously changes these complementary quantities (well depth and pressure adds up to total depth at bottom of string).

• The LED flasher boards [3] will be used to record time-of-flight data to neighboring strings. **Interstring data** will be taken for a large set of emitters (at least five on each string) and receiving DOMs on all nearest-neighbor strings. A global, over-constrained
fit to these time distributions is then used to determine relative string locations in three dimensions. This gives a relative array geometry, but only for entire strings, not individual modules. For this method to work, we need the LED flashers to be bright enough to get sufficiently high data rates (i.e. well above the noise rates) on at least nine (four above and four below the one closest to the emitter) DOMs on all the nearest strings (i.e. up to six for strings not on the perimeter of the hexagonal string arrangement). With a string spacing of 125 m and a vertical DOM spacing along the strings of 17 m, the light has to be seen at sufficient levels at least 150 m from the emitter. This leads to light level and power requirements for the LED flashers boards [3]. The optical interstring method for measuring the relative geometry gives an accuracy of better than 1 m in the horizontal plane and better than 0.5 m vertically.

- The cable spool will be equipped with a payout system that measures the length of cable deployed in the hole. Since stretching will be similar for all cables and therefore predictable, this enables a cross-check on the depth measurements and provides backup in case all pressure sensors fail on the string. The payout readout will also be used in combination with the pressure readout to monitor string deployment.

- The drill logs will be used to extract horizontal drifts of the holes from a vertical line from data recorded during drilling. Hole profiles, i.e., horizontal drifts versus depth, reconstructed from this data are used to adjust the positions of individual DOMs from the interstring fits (which only gives string positions, i.e., averaged DOM positions).

- A muon tomography method is being developed and tested on AMANDA data which uses down-going muon data to determine the relative positions in space of individual modules. A high-statistics sample of minimum bias data, effectively consisting entirely of down-going cosmic-ray induced muons, is processed and track reconstructed with a nominal geometry determined by a combination of the above techniques. Each DOM is then moved around virtually in three dimensions around the nominal position and the changing contribution of its hits to the likelihood function is recorded to create a likelihood grid. The minimum in this grid is taken as the corrected position of the DOM.

- Some strings will be equipped with an acoustic televiewer that will be used to map the contour of the hole during deployment, providing calibration data for drilling.

- IceTop can be used to make a geometry survey of the in-ice DOMs by looking at coincident events. With the coverage provided by the large IceTop surface array, a significant fraction of the downward muons passing through the in-ice detector will have been tagged at the surface by making a coincidence event in one IceTop station. The directions of these events are thus constrained externally by the fact that their impact points at the surface are defined to within half the station spacing (< 70 m). Such single station hits will most often correspond to single muons in the in-ice detector. In addition, for air showers which trigger the surface array, the trajectory of
the corresponding muon bundle will be determined externally by the direction assigned by the surface array. Use of such events for muon tomography has been developed (on a much smaller scale than will be possible with IceCube) by SPASE-AMANDA [11]. For both classes of events the trajectories can be further constrained (independently of the in-ice muon reconstruction algorithm) by using the centroid of hits in the deep detector.

All of the above methods (except acoustic hole logging and optical well-depth logging) have been developed and used successfully in AMANDA. Application of the muon tomography method showed that positions of individual OMs can be determined to within the radius of the hole, i.e., 30 cm. This precision makes it possible to study glacial ice flow. A recent study [4] concludes that the ice sheet at South Pole is frozen down to bedrock, and estimates that its horizontal velocity is $\sim 10$ m/yr from the surface down to $\sim 2000$ m and then monotonically decreases down to zero at bedrock, around 2800 m deep. The best estimate from this study is that the deepest AMANDA modules (at $\sim 2300$ m) will lag behind the bulk of the detector (which is shallower than 2000 m) by $\lesssim 1$ m/yr. In IceCube the effect could be even larger for the deepest modules. The muon survey method should be sufficiently sensitive to verify this effect and to calibrate the geometry periodically to track these possible drifts.

2.2.3 Status

The methods to be used for geometry calibration are mostly known and tested, and we have lots of experience from AMANDA. The main work is to adapt these methods to IceCube data which includes developing software within the IceTray framework. Flasher boards have to be designed according to calibration requirements, and their control software integrated into the DAQ system.

2.2.4 Monitoring considerations

The geometry should only change very slowly, if at all. There is no apparent need for geometry monitoring beyond an annual comparison of results from the muon tomography method.

2.2.5 Major WBS dependencies

The main dependency for geometry calibration is on Reconstruction (1.5.2) and In-Ice Devices (1.3.1) for the interstring method, on Deployment (1.2.3) and Drilling (1.2.2) for the non-optical preliminary geometry calibration, and on Reconstruction (1.5.2) for the muon tomography method. The development of verification tools depends on the availability of software and simulations under Data Systems (1.4). Geometry verification with coincident IceTop events also depends on IceTop (1.3.2).
2.2.6 IceTop geometry

Locations of IceTop sensors will be determined by a one-time survey. Each tank has two fiducial points, a vertical pipe on the side and a mark on the center of the outside top cover of each tank. Locations of two DOMs in each tank relative to the tank center and to the pipe are recorded at installation. Spatial coordinates \((x, y, z)\) of the two fiducial points for each tank are obtained by survey after tanks are closed. The \(z\) coordinate (elevation) of the snow surface at the pipe is obtained annually by survey from a fixed control point (e.g., the top of the counting house). From this information we obtain the depth of snow, which is stored in the data base. Extensions to the pipe can be added as needed due to snow accumulation.

2.3 Charge calibration (WBS 1.5.3.2.2)

2.3.1 Requirements

A crucial part of track and energy reconstruction will be to know the number of photo-electrons (PE) corresponding to the charge measured in each waveform for each DOM. The global requirement from science considerations on the absolute charge calibration for DOMs is 5\% [1]. The range and degree of linearity of the DOM response must also be measured, as well as saturation characteristics. The dynamic range of the PMT alone and of the fully assembled DOM will be measured in the lab for all modules.

2.3.2 Plan

This calibration task, like the timing calibration, can be divided into two parts: implementing and executing a charge calibration procedure (A and B in this section), and verifying its performance at a higher level (C below).

Charge calibration characteristics (ATWD calibration, SPE peak, linearity, saturation) will be measured for all DOMs in the dark freezer lab (DFL) prior to deployment, and the results stored in the database. These calibrations, performed with DOM-resident software such as DOMCal, will be repeated in situ. They consist of two separate procedures: (A) ATWD calibration and (B) gain calibration.

A. ATWD calibration

A1. Pulser calibration. First, the discriminator level is set to a known level (the threshold voltage is obtained from a known relationship between the discriminator DAC and the bias DAC). The SPE trigger rate is then monitored as the pulser amplitude is adjusted until half of the pulses are over threshold. This is repeated for different discriminator levels, and the correlation between the pulser amplitude DAC setting and the pulser amplitude in volts is determined with a linear fit whose output (which is stored) is a slope, an intercept, and an \(R^2\).
A2. ATWD bin calibration. In this step, the front-end bias voltage is first set to a known value (which can be varied to shift the overall baseline of the ATWD waveform, decoupled from any channel amplifier effects), and the average ATWD pedestal is recorded. The bias voltage is then varied, and linear fits of ATWD value vs bias voltage are performed for every bin (0-127) and channel (0-2). The output from this procedure consists of a fitted slope, intercept, and $R^2$ for every channel and every bin for both ATDWs, and these parameters translate ATWD values into voltages before channel amplification. Note that the individual fits automatically account for the unique pedestal pattern.

A3. Amplifier calibration. The pulser is set to a known amplitude which can now be translated to a voltage. Pulses are sent into ATWD0, channel 0-2, and the peak position is determined and converted to a voltage with the ATWD bin calibration parameters. The channel gain is then calculated by dividing the ATWD voltage by the pulser voltage. The result is the (mean) gain, or amplification, for channels 0-2 and the corresponding uncertainties.

A4. Sampling speed calibration. For this calibration, the sampling speed DAC is first set to a given value. The 20 MHz (40 MHz in Rev3) clock signal is fed into ATWD channel 3. The average number of clock waveforms (positive zero-crossings) in the ATWD window is measured. The sampling speed DAC is then varied, and a linear fit is applied to the measured correlation between sampling speed in multiples of clock oscillations and sampling speed DAC value. The fit parameters translate a sampling speed DAC into ATWD sampling frequency as a multiple of the 20/40 MHz clock, for both ATDWs.

B. Gain calibration

The DOMCal software also calibrates the gain for every DOM. Using noise data, SPE waveforms are integrated (and the charge converted to pC) to build SPE charge histograms. Each spectrum is then fitted to determine the SPE peak charge and the peak-to-valley ratio, and the gain is calculated from the former. This procedure is repeated for different high voltage (HV) settings and a linear fit is applied to the correlation between log(HV) and log(gain).

The SPE peak location will be known to within 5%, but the spread of the peak, which depends on PMT characteristics, dominates the uncertainty in the calibrated charge. The SPE peak, linearity, dynamic range and saturation behavior of every DOM will be measured in the lab as function of temperature and high voltage applied to the PMT and the results will be stored in a DOM database [9, 10]. Some of these measurements (SPE peak and width) are then repeated in the ice at regular intervals.

C. Verification of charge calibration

The charge calibration will be verified at a higher level (after position calibration and event reconstruction) using data from down-going muons and from flasher boards, e.g., by
studying the distribution of calibrated charge around reconstructed tracks or pulses from in-situ light sources.

Such data can also be used to perform the in-situ charge calibration: muon data can be used to get SPE parameters and the flashers can be used to measure linearity and saturation effects. Part of the verification task is to compare results from these in-situ calibrations with the corresponding parameters from the DFL calibrations which are stored in the database.

2.3.3 Status

The procedure used for in-situ charge calibration is relatively straightforward. Software for SPE peak fitting and extraction has already been developed as part of DOMCal. Method and software for verification have to be developed and tested with simulated data.

2.3.4 Monitoring considerations

The calibration parameters resulting from the periodic charge calibrations will be stored in a calibration database, monitored and compared to the corresponding parameters from measurements in the lab which are retrieved from the DOM database. Relevant parameters to be monitored include: SPE peak position and width, DOM temperature, linearity range, and saturation level.

2.3.5 Major WBS dependencies

The main dependency for charge calibration is on DAQ software (1.3.4) for implementation and automation, and on Reconstruction (1.5.2) for verification with muons and flasher data. The development of verification tools depends on the availability of software and simulations under Data Systems (1.4).

2.4 Angular DOM acceptance

2.4.1 Requirements

The angular dependence of the DOM acceptance must be known to a high degree of accuracy for reliable reconstruction and simulations. In addition, the expected range of variations between individual DOMs must be known.

2.4.2 Plan

In the lab, the intrinsic angular dependence will be measured prior to deployment by mapping the response of fully assembled DOMs to light from different sources (beamed lasers? plane wave?) at all possible incident angles [?]. The angular dependence of the photon detection efficiencies for the DOMs measured in the lab differs from the effective angular acceptance in the ice due to the optical properties of the refrozen water column, the so-called hole ice, in which the DOMs are embedded. The optical properties of the hole ice differ from those of
the bulk ice because of tiny trapped air bubbles that modify the angular acceptance of the
modules.

There are a number of possible approaches to measuring the angular acceptance in the
ice which could be explored:

- If the optical properties of the hole ice (mainly the reduction in scattering length
  introduced by the trapped air bubbles surrounding the DOMs) are measured in situ, the
  effect on the angular (and absolute) DOM acceptance can be estimated from detector
  simulations.
- The effective angular dependence can be measured in the ice, using known signals from
  light sources (such as the flashers) or by studying the response to cosmic ray muons.

These measurements are inherently difficult and any effects on optical data (from muons or
flashers) introduced by the hole ice are very difficult to disentangle from effects in the bulk
ice.

A different approach would be to freeze a block of ice with trapped air bubbles around
a DOM in the lab and directly measure (with light sources as above) how the angular
acceptance is altered. Bubble concentration and configuration can be varied in these mea-
urements.

2.4.3 Status

Although there are some schematic ideas on how to (possibly) measure the angular accep-
tance (or the hole ice properties) in situ, they are at a speculative level and need much more
thought. There is currently no definitive plan for such measurements.

2.4.4 Monitoring considerations

As the angular acceptance is not expected to change over time, no monitoring is required.

2.4.5 Major WBS dependencies

As there is no plan for in-situ calibrations of the angular DOM acceptance, no dependencies
have been identified.

2.5 Optical properties of ice (WBS 1.5.3.2.7)

2.5.1 Requirements

In order to accurately simulate the propagation of photons through the ice, the basis for most
IceCube physics simulations, the optical properties of the ice must be known to a sufficient
accuracy for all relevant wavelengths and over the entire instrumented depth range. The
relevant optical properties are absorption length and effective scattering length (sometimes
expressed as their reciprocal coefficients), the mean scattering angle (which is used to define the effective scattering length in a Mie scattering scenario) and the refractive index of the ice.

2.5.2 Plan

AMANDA has measured absorption and scattering properties between 340 and 540 nm for depths between 1000 and 2400 m to within 10% [5]. The wavelength dependence of both absorption and scattering have been determined, as well as the depth dependence. The optical properties are dominated by impurities in the form of dust particles, deposited in horizontal bands with varying composition. In the studied depth range the effective scattering coefficient varies by up to a factor 4, and absorption by slightly less.

The current knowledge of the ice properties is already at a level which is nontrivial to implement into detector simulations in full detail, but a number of open questions relevant to IceCube remain:

1. The horizontal scale of IceCube, \( \sim 1 \) km, is an order of magnitude larger than for AMANDA. Deeply penetrating radar surveys of South Pole ice have shown that over this scale the vertical locations of the dust bands that determine the optical properties can have variations of up to several tens of meters. Such possible horizontal variations in the dust bands would cause significant variations in the optical properties and must therefore be measured so they can be included in the simulation and reconstruction. Optical loggers [6], continuously measuring the level of emitted DC light scattered back into the logger, can be used to roughly determine the vertical locations of the most significant dust bands. In this way a three-dimensional map of the dust bands is recorded. This is done during deployment with the dust logger attached to the end of the string. Loggers will be used on strings along the detector perimeter and on some in the central part to cover the entire detector area. The dust loggers can resolve cm-thick ash bands corresponding to volcanic deposits.

A complementary method is to use down-going muon data and look at hit rates versus depth for individual strings. The varying ice properties will translate into large variations in hit rates, thereby enabling the identification of dust bands. This method, used initially in AMANDA, has a resolution of a few tens of meters.

2. In case pressure spheres are used for the DOMs which are more transparent further down in the UV, the region below 340 nm, for which no pulsed AMANDA data exists, should be probed in IceCube. This can be done with the same methods used in AMANDA, using in-situ pulsed light sources with wavelengths down to the cutoff. Fitting time-of-flight distributions between known emitter and receiver locations with simulations of photon propagation yields scattering and absorption independently.

3. As mentioned in the previous section, the properties of the hole ice could be relevant for event reconstruction and simulation. In addition to the ideas outlined in that section, a
dedicated camera module could be used to obtain information on bubble distributions around the DOMS. Using a dual-camera module, it could be looking up to see bubbles between the module and the DOM above, and looking down to see bubbles on its surface.

2.5.3 Status

On the hardware side, there is ample experience within the project in building and operating dust loggers (used in Antarctica and Greenland) and pulsed light sources (used in AMANDA). The main tasks will be to design, build, and test such devices for IceCube, and these tasks will affect cable design, DAQ design, software etc.

The analysis techniques used to extract optical properties from pulsed light source data are highly refined in AMANDA. There is also plenty of experience with analyzing and interpreting dust logger data.

2.5.4 Monitoring considerations

The ice properties are not varying within the geologically very short time scales pertaining to the IceCube project. The mapped optical properties will be stored in a database for use in simulations and event reconstruction, but there is no apparent need for monitoring of these properties.

2.5.5 Major WBS dependencies

The main dependencies for ice properties are on In-Ice Devices (1.3.1) and Deployment (1.2.3) for the dust loggers, and on In-Ice Devices (1.3.1) for the fits to flasher data. The development of calibration software tools depends on the availability of software and simulations under Data Systems (1.4).

2.5.6 Optical properties of ice in IceTop tanks

Tank ice requirements will be understood by comparison of the spectrum of signals from single particles (as described in section 3.4) for each tank in the field with the spectrum of signals in an identical water-filled tank in the IceTop test station in the lab. This will require use of simulations to interpret any variations in the single particle spectrum from tank to tank in terms of scattering, reflections and absorption in the ice. Triggering on single muons with a portable muon telescope may also be used to study response as a function of location of the muon track.

3 High-level calibrations

Once the recorded raw data, the digitized waveforms, have been calibrated as described in the previous section, i.e., their properties translated into time, charge and position for each
hit, the events can be reconstructed. At this stage attempts are made to fit hypotheses for a number of event types (single and multiple muon tracks, cascades) and the likelihoods for these possibilities are determined. The aim is to determine the direction and energy of muon tracks and cascades as precisely as possible. Some elements of the high-level calibrations will be performed online, e.g., some calibration data is acquired periodically during normal data taking through the DAQ. Other high-level calibrations are made off-line, after reconstruction, and are not part of normal DAQ operations.

In general, most of these high-level calibrations are conceptually part of WBS 1.5.1 Detector Verification and will be described in more detail in that framework. Here follows a description at a higher level of these physics calibrations.

3.1 Vertex resolution (WBS 1.5.3.2.6)

The vertex resolution for cascades will be measured with data from pulsed in-situ light sources located at known positions in the ice. The energy dependence of the vertex resolution will be studied for cascade energies from $\sim 1$ TeV to 10 PeV by varying the light output of these sources and by combining data from the flasher boards (405 nm) with data from the even brighter nitrogen laser Standard Candles (337 nm).

3.1.1 Requirements

Accurate vertex reconstruction for cascades is required for optimal energy reconstruction. AMANDA experience has shown that it is possible to reconstruct point-like sources (cascades, lasers, LEDs, etc) with a resolution of 2-5 m. For double-bang $\nu_\tau$ events individual vertices must be identified and properly reconstructed.

3.1.2 Plan

- Calibrated LED flashers [3] and lasers [12] can be used to emulate the light output of a cascade. Calibrations must be performed at various depths and at varying distances from the vertical axis of the detector to account for variations in optical properties of ice and to study fully and partially contained cascades.

- The calibration of double bang events can be done in two ways: 1) Firing two LEDs with a time delay corresponding to the tau time of flight. This imposes specific design requirements on the DAQ and hardware. 2) Data from two different LEDs can be combined offline in software by introducing the appropriate time delay. This can be done since the waveforms are available. However, this method does not allow triggering effects to be studied since the data that are combined come from different events. Another disadvantage is that effects like saturation are not properly taken into account.

- Monte Carlo simulations of neutrino induced cascades (both single and double bang) will predict the performance of the detector.
3.1.3 Status

Single vertex calibration has been performed with lasers (532 nm, 337 nm) and LED flashers (370 nm, 470 nm) with AMANDA. This method is well tested. Double-bang vertex calibration has not been performed. Either of the proposed methods is not possible with AMANDA hardware. Software has to be written. Flashers, lasers, etc designed with these requirements in mind.

3.1.4 Major WBS dependencies

The main dependency for vertex resolution calibration is on Reconstruction (1.5.2) for software and In-Ice Devices (1.3.1) for hardware (standard candles and flashers). The development of calibration tools depends on the availability of software and simulations under Data Systems (1.4).

3.2 Pointing accuracy and pointing resolution (WBS 1.5.3.2.5)

3.2.1 Requirements

The accuracy to which the direction of muon tracks can be determined has a limit given by the uncertainty in the scattering angle in the neutrino-nucleon interaction. For low energies, $E < 1$ TeV, this is about 1 degree, decreasing with higher neutrino energies.

For point-source searches, the separation of two or more neutrinos must be maximized. This should be smaller than the sigma in the neutrino-nucleon scattering angle at low energies, and as small as possible at higher energies.

For double bang ($\nu_\tau$) events the angular resolution is dictated by the lever arm between the bangs and the position resolution of the vertices. For example, two vertices separated by 250 m and with a resolution of 5 (3) m results in an angular resolution of 2.3 (1.4) degrees.

3.2.2 Plan

- Events that simultaneously trigger IceTop and IceCube constitute a data sample with well-defined track directions (as the result of the long lever arm) that can be used to calibrate IceCube’s angular response and pointing accuracy. IceTop will determine the location of shower cores at the surface to TBD accuracy, and the direction of muon bundles to TBD. The details of this calibration will be presented in a separate document [?].

- A complementary measurement of the angular response can be done by tracking the shadow of the moon by measuring the accompanying depletion in muon flux. This method is restricted to angles close to the horizon. The advantages of this method over using IceTop-tagged muons are (1) that zenith angles below the horizon, down to about 25 degrees, can be studied, and (2) the air showers are lower energy than those
triggering IceTop and thus single muon events can be more easily found (IceTop events in coincidence will be dominated by muon bundles).

3.2.3 Status

A similar technique was successfully used by AMANDA with SPASE-2 data. Moon tracking is a novel idea, currently being explored by AMANDA.

3.2.4 Major WBS dependencies

The main dependencies for pointing calibration are on IceTop (1.3.2) and Reconstruction (1.5.2). The development of calibration tools depends on the availability of software and simulations under Data Systems (1.4).

3.3 Energy calibration (WBS 1.5.3.2.6)

The energy of the secondary lepton (e, \( \mu \), or \( \tau \)) created in a neutrino-nucleon interaction can be measured only to a certain degree, by sampling the energy deposited in the detector, which can then be related to the secondary lepton energy, which in turn is related to the initial neutrino energy. Energy calibration divides into three sub-categories: (a) cascade energies, (b) single muon energies, and (c) energies of muon bundles. These energies are calibrated with different techniques.

Reconstructed muon events are divided into four types, depending on where the neutrino-nucleon vertex is located relative to the detector: through-going, contained, stopping and starting. Contained muons have both the creation vertex (the start) and the point where they have lost all their energy (the stop) within the effective detector volume, so their entire energy is deposited inside it. This enables the energy to be measured on an event-by-event basis. Through-going muons start and stop at unknown points outside the detector and so deposit an unknown fraction of their energy in the detector.

Electrons will lose their entire energy in electromagnetic cascades very close to the hadronic showers at their points of creation.

Muon and cascade energy is calibrated in a number of ways:

- Detailed detector simulations are used to establish the probabilistic connection between detected energy, energy deposited in the detector volume and the actual energy of the lepton in the event. From these simulations the energy can be estimated on an event-by-event basis (for certain kinds of events).

- Atmospheric neutrinos can be used as a test beam with known energy spectrum by making a comparison to the neutrino spectrum measured with IceCube. Normalize to a known flux, e.g., the down-going flux of atmospheric muons.

- Use calibrated light sources, standard candles [12], with well-defined light output. These can be calibrated in the lab before deployment.
3.3.1 Requirements

Various low-level quantities serve as fundamental building blocks for the energy calibration. All of these quantities must be measured in the lab, i.e., prior to deployment. Some must also be measured and/or monitored in-situ. Energy calibration also depends on the ability to measure other high-level quantities, such as the event vertex or track direction.

No calibration source may produce spurious signals in the detector, such as crosstalk, at a level which impairs the ability to reconstruct any cascade vertex, direction, or energy by more than TBD, as measured by TBD (e.g., Monte Carlo simulations).

3.3.2 Plan

All low-level calibrations will be performed during PMT and DOM testing in the Northern hemisphere. The results of these calibrations will be stored in a database for convenient future access.

The subset of low-level calibrations which can be performed without specialized equipment will be repeated prior to deployment, and the result compared to those stored in the database. These quantities comprise the measurements of relative gain, saturation behaviour and dynamic range.

After deployment, the relative gain, saturation behaviour and dynamic range of each DOM are measured with a frequency sufficiently high to enable us to track changes in the energy response to 10%.

Low-energy cascade energy calibrations are performed using the following techniques. All techniques are checked against one another for consistency.

1. Down-going muon bremsstrahlung events deposit amounts of energy which are compared with the prediction from Monte Carlo simulations.

2. The energy spectrum of atmospheric electron and/or tau neutrino events is compared with the prediction from Monte Carlo simulations.

3. DOM LEDs are flashed at predetermined light levels to simulate cascade signals.

4. Up-going atmospheric muon neutrino events which have a starting vertex contained in the detector fiducial volume provide an energy spectrum which is compared with the Monte Carlo prediction. Cascade direction is determined from the outgoing muon.

High-energy cascade energy calibrations are performed using the following techniques. All techniques are checked against one another for consistency.

1. DOM LED flashers (see above) will be used for energies up to 10 TeV.

2. In-situ nitrogen lasers with well-defined light output, “standard candles” [12], will be used for the highest energies, in the TeV-EeV range.
3. The lasers will be located throughout the array in such a way that the maximum number of physics processes can be simulated. Examples of such processes are fully contained cascades and various kind of partially contained cascades. The shape and direction of the emitted light pulse will vary.

4. The lasers will be operated at varying light levels, digitally controlled through the DAQ. Relative light levels will be known to 10% accuracy, and absolute light level to TBD%. Light levels will be calibrated in the lab prior to deployment for each laser individually, and monitored in-situ.

5. Cross-talk created during operation of the lasers must not exceed TBD in order not to compromise the integrity of the data and interfere with event reconstruction.

6. Tau double-bang events are simulated with time-correlated firings of LED flashers in widely separated DOMs and/or widely separated laser modules.

3.3.3 Major WBS dependencies

The main dependency for energy calibration is on Reconstruction (1.5.2) for software and In-Ice Devices (1.3.1) for hardware (standard candles and flashers). The development of calibration tools depends on the availability of software and simulations under Data Systems (1.4).

3.4 High level calibrations of IceTop

Tank signals in showers will be characterized by total charge in units of vertical equivalent muons (VEM). VEM is defined as the signal generated by a muon passing vertically through 90 cm of ice in a tank. Preliminary estimates show that one VEM contains a total charge equivalent to approximately 60 PE. This number will be confirmed by measurements in the test station at UD and by measurements in tanks to be deployed in the 04/05 South Pole season. Calibration with muons requires monitoring the spectrum of hits in each tank. The spectra will be dominated by signals generated by single particles incident on the tanks. Electrons and gamma-rays dominate at small signal-size and muons at larger size. The muon contribution gives a peak which will be related (by simulations and/or by use of a muon telescope) to the VEM. There is also a high energy tail in the distribution of tank hits due to air showers (multiple coincident particles). The particle fluxes that generate the tank signals are nearly constant in time, with only small seasonal and pressure variations, which are the same for all tanks. This steady signal (approximately 2.5 kHz for signals above a threshold of 10 PE) will be used to set the PMT voltages so that the muon peak is at the same signal size (as measured by total charge or by peak voltage, TBD) for the high-gain DOM in each tank. The VEM signal will be related to the charge in PE, which will be determined in special calibration runs for each DOM in the same way as described in section 2.3.2. The operating range of the low-gain DOM will have sufficient overlap with the that of the high-gain DOM to allow it to be calibrated in terms of PE as well.
In addition, other aspects of the response of the IceTop array will be calibrated in a number of ways:

- For air showers in which more than three stations are hit, the total charge will be available from the signal in each DOM, either via a compressed report for simple waveforms or from the entire waveform that will be reported by DAQ in case of complex signals.

- Following standard air shower reconstruction procedures, shower direction will be reconstructed from the times at which the tanks are hit.

- Core location will be determined from the pattern of signal sizes in the stations included in the event. Determination of direction and core-location are coupled because the shower front is not a plane.

- Variations in response of a tank to a given signal will be measured experimentally by comparing signals in the two tanks at the same station with each other for events binned by shower size and direction.

- Similarly, variations in arrival time can be measured experimentally using the paired detectors and correcting for their local (10 m) separation as compared to the 125 m separation between stations.

- Shower-front curvature will be fitted from the data itself in an interactive manner as a function of shower size and core distance.

- Showers will be characterized by a single global quantity (TBD) that is well-correlated with primary energy (e.g., VEM per m$^2$ in the shower front at 125 m from the shower core).

The experimental determinations of detector response will be confirmed by understanding the results by comparison with simulated data.

4 Summary of calibration devices

This section summarizes the dedicated in-situ devices needed for calibrations that are to be deployed with the strings. It also lists some of their properties.

1. DOM on-board LEDs are needed for (a) charge calibrations of individual DOMs in the lab and in the ice. They should have adjustable light output for linearity measurements and be possible to attenuate down to a low light level for SPE measurements.
2. LED flasher boards [3] are needed for (a) interstring geometry measurements, (b) simulations of cascades for energy and vertex calibration. These flasher should have adjustable light output over a wide energy range, give pulses of TBD ns width, and operate at a wavelength close to (1) the average wavelength of detected photons and (2) the optimal ice properties. The light should be emitted with a known angular distribution to enable accurate simulations.

3. Powerful standard candles [12] (presumably nitrogen lasers) are needed for (a) energy calibrations in the high-energy region, (b) vertex reconstruction studies. These laser modules should have calibrated (to within TBD%) and stable light output levels, adjustable in well-defined steps over six orders of magnitude in corresponding cascade energy. Energy range above that of the flashers, up to EeV. Controlled digitally through the DAQ. Known angular distribution to enable accurate simulation. Three different orientations (in separate modules): up, down, sideways, or adjustable orientation (with mirrors) to enable simulation of cascades in different directions.

4. Dust loggers are needed to (a) map the locations of the dust bands over the full horizontal range of IceCube. The dust loggers are used for real-time optical logging of dust concentration during deployment, and have sensitivity for unambiguous identification of main characteristics of dust structure.

5. Pressure sensors (Paros, Kellers) are needed to (a) calibrate the absolute depth of the detector, (b) calibrate the relative depths of the strings, (c) monitoring during deployment to detect if the string gets stuck, (d) reach the target depth.

6. Thermistors are needed to (a) map out the temperature profiles, (b) to tell us when ambient temperature is reached after refreezing. Should cover entire instrumented depth range.

Calibration devices used at the surface during deployment:

1. Cable payout monitoring system (part of cable spool). Real-time readout for immediate detection of stuck string (readout synched with pressure sensors).

2. Optical sensor (laser distance meter) for manual well-depth measurements.

In addition, the IceTop air shower array on the surface can be used for a number of calibrations: (a) to measure the pointing accuracy for reconstructed muon tracks and (b) its angular dependence, (c) to measure the energy in muon bundles penetrating the ice down to the IceCube sensors, (d) to provide a set of tagged down-going muon events.

For calibration of the IceTop array itself, we plan to develop a portable muon telescope to provide a trigger on vertical muons. This will be used to clarify understanding of the tank response to single particles, for example, by studying the response to single muons entering the tank at different points.
5 Detector monitoring (WBS 1.5.3.1)

Detector monitoring is discussed in detail in a number of separate documents, e.g., the Monitoring Plan [7] and a document discussing requirements [8]. Some monitoring considerations have been discussed in the sections above.

6 Calibration database (WBS 1.5.3.2.8)

Each calibration produces a number of calibration constants, which are to be stored in a calibration database (calDB). Here follows a preliminary list of constants delivered by low-level calibration and needed for high-level calibrations.

6.1 Calibration data from low-level calibrations

- The geometry calibration delivers coordinates \((x, y, z)\) for each DOM.
- The timing calibration delivers constants \((a, b)\) used for the linear translation of local times into universal times. It also gives PMT transit times vs high voltage, both measured in the lab and in the ice.
- The charge calibration delivers, for each DOM: SPE peak and width and linearity curves containing the saturation behavior.
- The ice properties calibration gives a map of scattering and absorption coefficients as functions of depth and wavelength.

6.2 Calibration data needed for high-level calibrations

- All of the high level calibrations depend on timing, charge and geometry calibration through the use of reconstructed data.
- Energy calibration at very high energies, where many PMTs are saturated, relies on PMT linearity and saturation behaviors measured in the lab and stored in the calDB.
- All high level calibrations that use reconstruction or detector simulations also depend on the optical ice properties.

7 Calibrating the first four strings

In January 2005, the first four IceCube strings are deployed. This section presents a brief step-by-step plan for how they will be calibrated (w.r.t. timing, charge, and geometry) in the first field season.
7.1 Low-level calibrations of the first four strings

The geometry calibration of the first strings will follow the procedure described above. The following calibrations will be carried out during the Pole season:

1. Deployment data (pressure, well depth) will be combined with a surface survey and drill data to get a preliminary geometry for the new strings.

2. As soon as the DAQ is operational, the RAPCAL timing calibration will be implemented, and a first charge calibration will be performed.

3. Once RAPCAL works, flasher data will be taken for the interstring geometry measurements. On each of the new strings, ten flashers will be run and data collected on all new strings.

4. Depending on how far along AMANDA-IceCube integration has gotten, we can (a) run flashers on string 18 and record data on the new strings, and (b) take data with AMANDA during the IceCube flasher runs. This will give us a valuable cross-calibration and determine the absolute geometry.

Back in the real world, the final stages of the low-level calibrations are performed:

1. Minimum bias muon data is used to determine the position of each DOM individually through muon tomography. This requires that the basic DOM calibrations (timing, charge) are working and that the reconstruction is up and running.

2. The timing calibration is verified using flasher data and down-going muon data.

3. The charge calibration is verified using flasher data and down-going muon data.

7.2 Calibrating first four strings with IceTop

With a 4-string/4-station array, we expect a rate approaching 0.1 Hz per IceTop station for events with exactly one station hit and a muon inside the volume contained by the 4 strings. The geometry of the event is approximated by a line from the hit station to the centroid of the event in the strings. The geometry will not be as good in year one as in future years because of the contamination of the single-station hits by higher-energy events with trajectories that pass outside the 4-station array. In future years such events will be identified as large showers by hits in surrounding stations.

The rate of air showers hitting all four stations and having trajectories pointed at the 4-string volume will be about 15-20 per hour. These events will typically have two or more muons at the in-ice detector. The direction can be determined by the reconstructed direction of the shower using the surface stations only. As with SPASE-AMANDA, the geometry can be improved if the air shower fit is constrained by the centroid of the hits in the deep detector (but without using the full deep-ice reconstruction algorithm). Because these are multi-muon events, they can be used for study of response of the deep detector to large depositions of energy as well as for calibration of direction.
References


[7] Detector Wide Monitoring Proposal for Year One, WBS 1.5.3.1, I. Taboada.

[8] Requirements for the IceCube Monitoring System WBS Element 1.5.3.1, R. Porrata.


