Outline for DOM acceptance testing in the DFL

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Preliminary draft

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Changes from last draft (Nov.10):

Addressed issue of readout dead-time by requesting truncated events or local coincidence

All tests except those listed in “STF Tests” section are done in DOMTest framework.

Modified nonlinearity scan test to include droop test (suggested recently; still needs to be discussed by the group).

Added descriptions and illustrations of hardware setup.

From discussions at the Production Workshop at PSL in December 2003:

- Primary light source: N2 laser with dye laser for selecting other wavelengths
- Reference module provided with electrical synchronization pulse, to be used for improving the time resolution test and the optical sensitivity test
- Second reference module provided with small, well understood PMT (yet to be selected)
- Removed flasher light output test
- Stability test is run steadily all day after other daily tests are done

In its draft form, the purposes of this document are:

- Specify possible DFL tests in sufficient detail to reveal problematic issues.
- Provide a reference guide to tests for development of test software
- Provide a concrete basis for discussion so the collaboration can move toward agreement on specifics of tests

Parts of this document still in flux:

- Equipment overview (not written or illustrated yet)
- Text describing hardware layout, partly done but not complete
- Light spreader boxes still being designed, lab tests are pending
- Schedule of tests is not completely worked out, i.e. how many days at each temperature and so on
- The cold soak test needs to be modified so that dark noise is monitored continuously, to detect corona discharge or whatever might cause spiking of the rate. This was discussed at the December production workshop but I forgot…

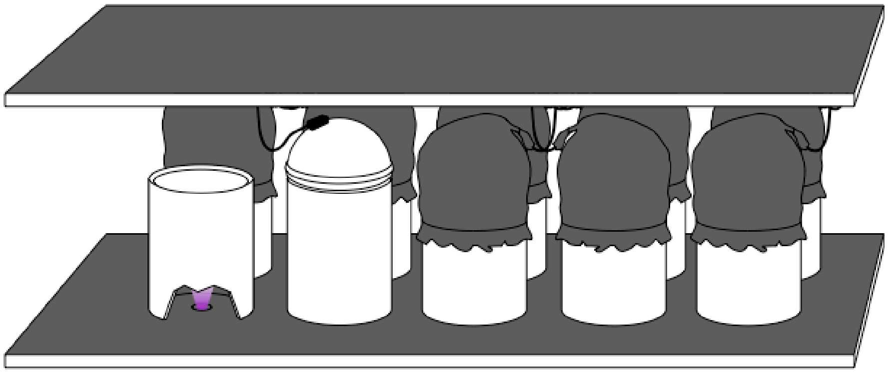
1. Equipment

1.1. Overview

1.2. Test Stations

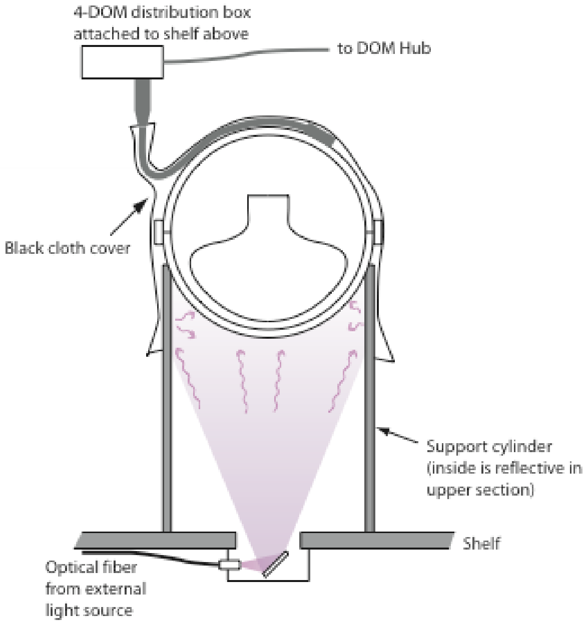
DOM test stations are arranged on shelves, two rows per shelf and three units high. The DOMs are placed on plastic cylinders which are then brought to the shelf and slid into place. The shelf surface is lined with Teflon or other material to allow easy sliding without generating dust. The cylinders are aligned on center with holes in the shelf by pushing horizontally against removable dowel pins which are installed in the shelf. Illumination is provided by means of light distribution boxes mounted under the shelf at the center holes of each station.

Electrical signals to each test DOM are made at a distribution box mounted to the underside of the shelf above. This configuration allows for the very short cords fitted to half of the DOMs.

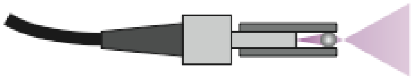


The inside of the support cylinder is made reflective near the equator of the DOM, to reflect more light onto this region and compensate for the bias towards illuminating the center. This upper region of the cylinder may be painted with reflective paint or covered with metal foil. Shiny foil would reflect more light into the DOM than paint, which tends to reflect in all directions. The bottom interior of each station is kept non-reflective to avoid creating an artificial tail in the photon time distribution from light bouncing around too many times.

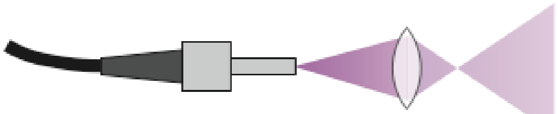
A black cloth is tied around the DOM to avoid light getting from one test station to another. It does not need to be perfectly light-tight, since this is not expected to be a big problem.



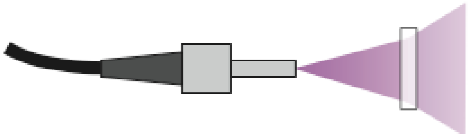
Light exits the optical fibers in a cone of half-angle 9° (distribution is flat out to 6° and falls to nearly zero by 12°). This is too narrow to illuminate the equator region of the PMT, so the light has to be spread out. There are a number of options, some of which are shown below. Lenses and diffusers that work with UV light tend to be fairly expensive ($100), but sapphire ball lenses are available for only $2, so if this works well enough it would be the preferred option. As shown, the ball would be mounted in a sleeve that fits onto the end of the optical fiber connector.



Ball lens (1/8" DIA)



Convex or concave lens (1/2" DIA)



Diffuser (1/2" DIA)

1.3. Electrical signal distribution

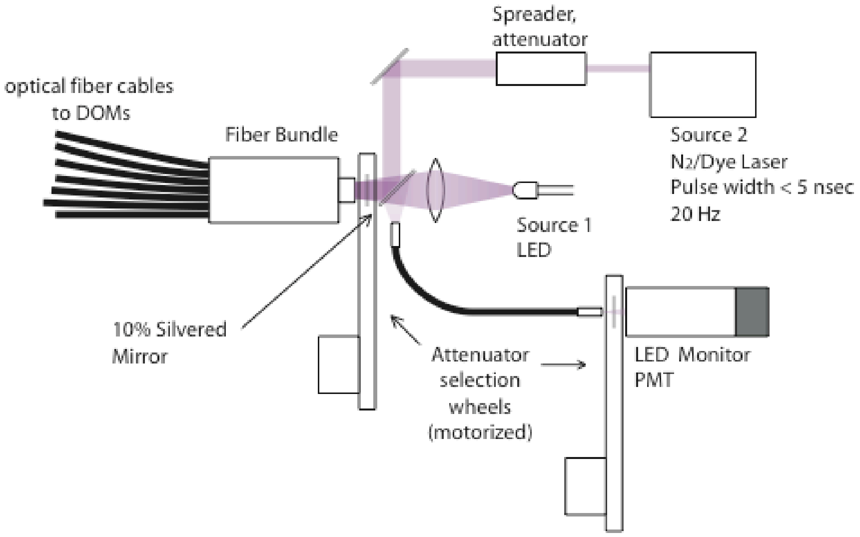
Each distribution box provides for connecting four DOMs. Twisted pairs carry signals from these boxes to the DOR cards at the DOM Hub computer.

The distribution boxes also provide for connecting local coincidence signals from each test DOM to its neighbor.

1.4. Fiber optic light distribution

At input end, all optical fibers are packed together into a tight bundle (just bare fiber, no jacket) to allow for even illumination by laser and LED sources. The fibers are UV grade (high OH-), all silica, 200um diameter, exemplified by Romack Fiber Optics part number 211210-0200. Attenuation in this fiber is less than 0.1 dB/m for wavelengths of 337nm to 700nm. Maximum fiber lengths for the PSL freezer are 18 meters.

Light from the LED is focused directly onto the fiber bundle, and a partly silvered mirror allows for combining the laser signal as shown. A computer-controlled attenuator selection wheel is installed just in front of the fiber bundle. (The other attenuator selection wheel is associated with the LED optical waveform generator feedback loop, see below.)



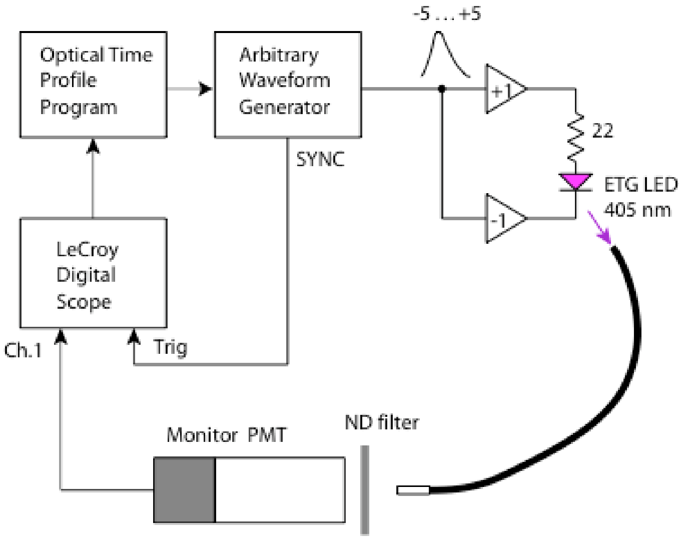
1.5. Nitrogen and Dye Laser

Pulse width 5 nsec or better. Pulse rate 20 Hz or better. Electrical synchronization output with a stable relationship to the optical output (less than a few nsec drift over the course of an hour).

1.6. LED Optical Waveform Generator

The optical waveform generator is a program, which controls an LED driver signal and a filter wheel placed between the LED and the optical fibers. The motorized filter wheel selects between calibrated neutral density filters, an empty space, and an opaque disk. The program monitors light output through a separate path involving another filter wheel and a PMT connected to a digital storage oscilloscope. Based on commands received from the sequencer, it activates one of several pre-programmed time profiles scaled to the specified intensity. The first three standard profiles are “rectangular” (quotes allow for rise and fall time) with widths of 5 nsec, 10 nsec, and 1 μsec. The next three are characteristic of light expected from EM cascades at distances of 50m, 100m, and 200m from a DOM (TBD). The seventh profile is characteristic of light expected from a 50 nsec flasher LED pulse from a neighboring DOM (i.e. 17 meters away). When appropriate filters are in place and the waveform is stable, a ready signal is sent back to the sequencer.

The LED driver circuit has an electrical synchronization output signal, and is also provided with a trigger input to allow flashing at a fixed time after every laser pulse (for event tagging).



For purposes of labeling data, the following pulse types are defined:

0	Laser pulse
1	Laser followed by bright LED marker pulse 100nsec later
10	LED short pulse, about 5 nsec
11	LED 10 nsec rectangular pulse
12	LED 1 μsec rectangular pulse
20	LED, profiled like cascade 50m away
21	LED, profiled like cascade 100m away
22	LED, profiled like cascade 200m away
23	LED, profiled like flasher 17m below

1.7. External Reference Modules

Both reference modules will be operated outside the freezer, preferably near +25°C.

Reference Module 1

Reference Module 1 employs a small PMT, selected to have well understood optical sensitivity vs. wavelength, insensitive to ambient magnetic fields. It must also have well understood transit time.

This PMT is illuminated by a fiber just like all the others that go to test stations in the freezer, and it is connected to a standard MB for readout along with test DOMs. This PMT-MB module is used for correlating measurements of optical sensitivity and transit time between different test batches. The number of hits is translated into a light level illuminating the test DOMs, and the timing of hits serves as a well defined timing reference.

Reference Module 2

In Reference Module 2, an electrical synchronization signal is connected in place of the PMT input. The synchronization signal is generated in time with optical pulses from the laser or LED. The attached MB is read out in the same data stream with test DOMs. It is used during data analysis to distinguish deliberately-induced hits from noise hits in the test DOMs. It is also used as a timing reference during the time resolution and transit time measurements, with the aid of the PMT-MB reference module for removing effects of electrical cable and logic delays.

2. Tests

Prerequisites:

Before running the acceptance tests, the following setup tasks should be completed:

- Determine approximate time offset “Laser_Sync_Offset”, describing how much later light pulses are detected in typical test DOMs compared to electrical synchronization pulses recorded in reference module 2.
- Determine approximate time offset “Laser_Sync_Offset_Ref1”, describing how much later light pulses are detected in reference module 1 compared to electrical synchronization pulses recorded in reference module 2.
- Measure relative illumination levels in each test station with precision of 5% or better.
- Calibrate each attenuator setting by observing the change in response of reference module 1 when attenuator setting is changed. Illumination level needs to be set low enough that PMT is operating in the linear region.
- Determine attenuator settings for each laser wavelength to yield about 1.5 PE detected in typical DOM, per pulse.
- Determine attenuator settings for N_2 laser to yield about 0.1 PE detected in typical DOM, per pulse (for time resolution test).
- Calibrate the LED light source; this procedure sets the operation point for the LED light feedback PMT, and also determines the scale factor for illumination level in a typical testing station.
- Determine LED and attenuator settings resulting in very narrow pulses with 0.01 PE detected in typical DOM.
- Determine operating parameters for flashing LED at 20 PE level after each laser pulse, adjusting synchronization delay so that LED flash is observed 100 nsec later than the laser flash at testing stations.

Time sequence of acceptance tests:

An outline of the sequence is shown in the table. After a few measurements at +25°C, the temperature is lowered to –45°C and kept there for a number of days. This is the major period in which measurements are made and stability is monitored. After this, the temperature is lowered briefly to –55°C for a functionality check and then raised briefly to –20°C for another check. To stress the tested DOMs, the temperature is then raised to +25°C and lowered again to –45°C. This temperature is maintained for just a few days before bringing the freezer back to room temperature for the final optical sensitivity test.

The first optical sensitivity measurement at +25°C is not strictly necessary, but is provided for comparison with the final measurement at the same temperature. The final measurement should occur after all other temperature cycling because a subset of DOMs will subsequently be measured for absolute sensitivity at +25°C, setting the scale for all DOMs tested. These absolute measurements do not need to be performed on DOMs from every test batch, because there are reference PMTs to maintain batch-to-batch consistency. If no DOMs from a given batch are to be sent for the absolute sensitivity test, then all of the +25°C tests can be omitted from the schedule.

T=+25°C	
Boot Test	1 hour
STF Tests	2 hours
Gain vs. HV Scan	2 hours
Optical Sensitivity Test	2 hours
T=–45°C Daily schedule:	
Boot Test (first day only)	1 hour
STF Tests	2 hours
Gain vs. HV Scan	2 hours
Dark Noise Test	1 minute
Optical Sensitivity Test	2 hours
Time Resolution Test	1 hour
Nonlinearity Scan Test (first day only)	3 hours
Stability Test	Remaining time
T=–55°C (PSL freezer only)	
Boot Test	1 hour
STF Tests	2 hours
Gain vs. HV Scan	2 hours
Dark Noise Test	1 minute
Time Resolution Test	1 hour
Stability Test	Remaining time
T=–20°C (maybe slowly varying in some freezers)	
Boot Test	1 hour
STF Tests	2 hours
Gain vs. HV Scan	2 hours
Dark Noise Test	1 minute
Time Resolution Test	1 hour
T=+25°C (just for stressing DOMs, but the schedule could be changed to an overlapping one, with half the stations unloaded and reloaded at this point)	
T=–45°C (check that results match after temperature cycle) Daily schedule:	
Boot Test (first day only)	1 hour
STF Tests	2 hours
Gain vs. HV Scan	2 hours
Dark Noise Test	1 minute
Optical Sensitivity Test	2 hours
Time Resolution Test	1 hour
Nonlinearity Scan Test (first day only)	3 hours
Stability Test	Remaining time
T=+25°C	
Boot Test	1 hour
STF Tests	2 hours
Gain vs. HV Scan	2 hours
Optical Sensitivity Test	2 hours

2.1. Boot Test

Summary:	Check Main Board boot sequence operation in cold state, then allow MB to reach normal operating temperature and check again.
Special hardware:	none
Temperature:	T= –20C, –45C, –55C
Time required:	1 hour, once DOM power has been off over 1 hour
Pass/Fail criteria:	Successful boot as indicated by signal from DOM.

Sequencer:

If DOMs were powered, turn off and wait 1 hour for temperature equilibration.

Restore power to DOMs, check for valid response.

Send reboot command, check for valid response.

Wait 1 hour to allow MB to reach normal operating temperature.

Cycle power to DOMs, check for valid response.

Send reboot command, check for valid response.

Notes:

Waiting 1 hour after the test is mostly to ensure that following tests are done at normal operating temperature. Testing reboot operation after this wait is a “freebie”.

2.2. STF Tests

Summary: Within the STF framework, check functionality of main board, high voltage control, and flasher board. Optimize main board DAC settings. Measure scale factor for digitization (ADC counts per mV).

External light source: none

Temperature: T= +25C, –20C, –45C, –55C

Time required: 2 hours

DOM state: STF

Quantities recorded: MB electronic noise
Optimized MB DAC settings for digitization range (?)
ADC counts per mV for each ATWD channel

Pass/Fail criteria: Logic tests pass
Pedestals in range TBD
Analog input noise less than TBD
ADC counts per mV in range TBD
Optimized MB LED intensity between 0.01 and 0.1 PE

Sequencer:

- Reboot all DOMs into STF mode.
- Perform MB logic tests, documented in “Tests for IceCube DOMs”, by A. Goldschmidt and A. Jones. These tests include communication on interfaces with the high voltage controller and the flasher board.
- Perform MB amplifier/digitizer tests and calibrations. Optimize DAC settings for digitization range (?). Calibrate on-board pulser using discriminator threshold scan. Check operation of front end amplifiers and digitizers using on-board pulser, and record scale factor (ADC counts per mV). Measure pedestals and noise at low HV setting (TBD), and compare with requirements.
- Observe PMT signals resulting from pulsing MB LED, and determine whether an intensity setting can be found that yields between 0.01 and 0.1 PE per pulse.
- Scan the high voltage from 1200-2000 volts, and check ADC for agreement.
- Test flasher board LED operation based on current monitoring through ATWD 3. For each LED, scan pulse widths over the range 10, 20, 30, 40 nsec (nominal) and pulse heights over the range 5, 10, 15 volts (nominal). Set limits on observed width and height of the LED current pulse to verify that the control circuit works.
- Reboot all DOMs into DOMApp mode.

2.3. Gain vs. HV scan

Summary:	Generate events with zero or 1 PE detected, using external light source. Measure PMT gain, pulse height, P/V ratio as a function of HV.
External light source:	LED, narrow pulse, approx 0.01 PE detected, 10 kHz
Temperature:	T= –20C, –45C, –55C
Time required:	2 hours There are 9 high voltage settings, and each requires about 5000 events accumulated at 100 Hz times the live-time fraction. The live-time fraction will be worse than usual (estimate 10%) because the discriminator threshold needs to be set very low.
DOM state:	TestDOMApp
Quantities recorded:	PMT gain, pulse height and P/V ratio at 1200,… 2000 volts
Pass/Fail criteria:	Gain > 5e7 at 2000 volts P/V ratio > 2 when gain = 1e7

Sequencer:

Send commands to LED controller for minimal pulse width (5 nsec FWHM), intensity 0.01 PE level and 10 kHz rate.

For each HV setting (1200, 1300, … 2000 volts):

- send HV set command to DOMs
- acquire 1000 pedestal triggers, first 32 samples of ATWD 0 only
- set discriminator to appropriate low level TBD
- acquire 50000 discriminator triggers (of which about 5000 are expected to be from LED pulses), first 32 samples of ATWD 0 only

Send "off" command to LED controller.

Analysis:

For pedestal trigger events, histogram ADC counts in each time bin.

Fit the pedestal histograms to determine the pedestal pattern.

For discriminator triggers, determine the hit time by fitting the normalized pedestal-subtracted pulse to a standard SPE shape. Choose only events that are in a narrow time window (±20 nsec, TBD) around hits recorded in the electrical synchronization module, offset by the cable delay constant LED_Sync_offset. Histogram the pedestal-subtracted pulse integral and peak value, accounting for digitization scale factors previously determined.

Require a minimum of 2000 events in the histograms. Fit the pulse integral histogram to determine gain and P/V ratio. Fit the peak value histogram to find the most probable peak value, from which the discriminator threshold will be determined for subsequent tests.

2.4. Dark Noise Test

Summary: Measure dark noise rate at gain 1e7.

External light source: none

Temperature: T= –20C, –45C, –55C

Time required: 1 minutes

DOM state: TestDOMApp

Quantities recorded: Count rate at gain = 1e7

Pass/Fail criteria: Count rate < 1 kHz at gain = 1e7 (TBD)

Sequencer:

- HV should already be set for gain = 1e7 (otherwise need to settle at new value).
- Set discriminator level at 0.25 of peak for SPE.
- Set artificial deadtime for supernova scalers to 6.4 microseconds.
- For a period of 1 minute, write monitor records containing supernova scaler values.

Analysis:

Read the monitor records and accumulate counts for each DOM until the test is complete. Record average count rate for each DOM and compare with requirements.

2.5. Optical Sensitivity Test

Summary: Illuminate all PMTs simultaneously with external light pulses of various wavelengths. Each light pulse is followed by a bright LED flash to ensure triggering, allowing occupancy to be determined even in the presence of significant readout dead-time.

Compare occupancy in each DOM to occupancy in external reference DOM, account for characteristics of reference PMT and test stations, and thus determine optical efficiency for each DOM. The efficiency measured includes glass and gel transmission, PMT quantum efficiency and PMT collection efficiency, at PMT gain = 1e7.

External light sources: N_2 (337 nm) and dye laser (xxx nm – yyy nm TBD): 1.5 PE

LED: 10 nsec wide pulse, 20 PE, 100 nsec after laser pulse

Temperature: T = +25C, –45C

Time required: 2 hours
The laser pulses at 20 Hz. With truncated events, live-time should be over 50%. Therefore acquiring roughly 10000 real events per wavelength requires about 20 minutes. For measurements at six different wavelengths, the complete test takes 2 hours.

DOM state: TestDOMApp

Quantities recorded: Relative efficiency and statistical uncertainty for each wavelength

Pass/Fail criteria: Efficiency > 15% for wavelengths over 350nm (TBD)

Sequencer:

HV should already be set for gain = 1e7 (otherwise need to set it and wait for settling).

Set discriminator threshold to 25% of SPE height.

Acquire 1000 pedestal triggers, truncated to first 32 samples of ATWD 0 only.

For each available wavelength:

- Set laser system to specified wavelength.
- Adjust attenuator for correct illumination level at this wavelength.

- Turn on the laser and configure the LED flasher to trigger on laser sync output, with appropriate delay.
- Add external monitor records to the data stream specifying illumination conditions.
- For 30 minutes, acquire discriminator triggers from all DOMs, truncated to first 32 samples of ATWD 0 only. This will result in approximately 10^6 triggers per DOM.
- Turn off the laser.

Analysis:

For pedestal trigger events, histogram ADC counts in each time bin.

Fit the pedestal histograms to determine the pedestal pattern.

For discriminator triggers, determine the hit time by fitting the normalized pedestal-subtracted pulse to a standard SPE shape. Check whether the hit occurred in a narrow time window (±20 nsec, TBD) around the closest synchronization pulse, offset by the cable delay constant Laser_Sync_Offset (or Laser_Sync_Offset_Ref1 for hits in Reference Module 1); such events are tallied as laser hits (N_H). Otherwise, check whether the hit occurred in a similar time window 100 nsec later; such events are really just triggered on the bright LED flash, so tally these as laser misses (N_M). The ratio of hits to misses, defined in this way, is insensitive to dead time. Define the total number of events:

$$N = N_H + N_M$$

The mean number of PEs observed from each light pulse (μ) can be calculated from the number of laser hits (N_H) and the total number of events (N):

$$\mu = -\ln(1 - N_H / N)$$

The fractional uncertainty in μ is:

$$\frac{\sigma_\mu}{\mu} = \frac{1}{\sqrt{N}} \frac{1}{\mu} \sqrt{e^\mu - 1}$$

The overall efficiency of each DOM relative to Reference Module 1 may then be computed from μ, dividing by the μ value for Reference Module 1 and accounting for previously measured relative light levels at each test station.

Record results and statistical uncertainties.

Notes:

The minimum fractional uncertainty in μ occurs at μ=1.6, for which the fraction of events with at least one PE is 80%. At this light level, 10000 events will give a fractional uncertainty of 1.2%. A similar uncertainty is expected for Reference Module 1, leading to a combined statistical uncertainty of 1.7% (or slightly worse if the optical coupling in Reference Module 1 does not match that of the test stations).

(Improved precision could be obtained by using a light source that pulses at rates around 1kHz. Another high precision option is to provide steady illumination at the 1kHz level, in which case it would be necessary to subtract the dark count rate and filter out afterpulses with a dead-time after each hit; also one would need to determine the readout dead-time fraction by comparing supernova scalers with tallies of recorded events. Lastly, one could consider using brighter pulses with about 100 PE, still at 20Hz, in order to reduce statistical uncertainty; if the PMT gains could be measured to better than 1%, then the overall uncertainty would be improved relative to the occupancy measurement method described above.)

To normalize the efficiency results, a subset of tested DOMs will also be measured in a special lab test at one wavelength and room temperature. The connection to other temperatures and wavelengths is solely via the DFL tests. For this reason, the wavelength dependence of the Reference Module 1 PMT needs to be well understood. The illumination levels in each test station also need to be measured as a function of wavelength, relative to Reference Module 1.

Because orientation of the DOMs in the earth's magnetic field is not controlled, and this is expected to cause changes in collection efficiency at the several percent level, it is not necessary to measure relative illumination levels beyond this level of precision.

The illumination pattern in the cans surrounding each DOM should be optimized as much as possible to be isotropic and uniform over the face of the PMT, but it is understood that a true isotropic distribution is difficult to attain while also avoiding multiple-bounce time smearing of optical pulses (Time Resolution Test). Painting the inside of the cans white near the equator, which is not well illuminated from directly below the DOM, may be a good compromise.

The fraction of coincident hits due to noise is expected to be about (1000 Hz / 10 Hz)*(40 nsec / 0.05 sec)=10^{-4}, which is much smaller than the statistical uncertainties.

2.6. Time Resolution Test

Summary:	Illuminate all DOMs simultaneously with short (< 1 nsec) light pulses, about 0.5 PE level. PMT gain = 1e7. Using electrical synchronization pulses as a reference, calculate time resolution. Check for any unexpected tail in the measurement time distribution. Also check the average pulse shape for anomalies in rise or fall time. Measure transit time relative to reference PMT transit time.
External light source:	N_2 laser (337 nm) Approximately 0.1 PE illumination level. This leads to about 5% of events with multiple PEs superimposed.
Temperature:	T = –25C, –45C, –55C
Time required:	1 hour The laser pulses at 20 Hz. With truncated events, live-time should be over 50%. Therefore acquiring roughly 4000 real events requires about an hour.
DOM state:	TestDOMApp
Quantities recorded:	Time resolution PMT transit time relative to reference module Fraction of times more than 15 nsec from mean Rise time, fall time
Pass/Fail criteria:	Time resolution < 5 nsec Transit time in range TBD Fraction of times beyond 15 nsec < 0.01 TBD Rise time < 3 nsec TBD (20%-80%) Fall time < 8 nsec TBD (80%-20%)

Sequencer:

HV should already be set for gain = 1e7 (otherwise need to set it and wait for settling).

Set discriminator threshold to 25% of SPE height.

Acquire 1000 pedestal triggers, truncated to first 32 samples of ATWD 0 only.

Set laser wavelength and optical attenuator. Enable laser pulses.

For 60 minutes, acquire discriminator triggers from all DOMs, truncated to first 32 samples of ATWD 0 only. This will result in approximately $3\cdot10^6$ triggers per DOM.

Turn off the laser.

Analysis:

For pedestal trigger events, histogram ADC counts in each time bin.

Fit the pedestal histograms to determine the pedestal pattern.

For discriminator triggers, determine the hit time by fitting the normalized pedestal-subtracted pulse to a standard SPE shape. For inclusion in histograms, consider only hits in a narrow time window (±50 nsec, TBD) around the synchronization pulses recorded in Reference Module 2, offset by the approximate cable delay constant Laser_Sync_Offset (or Laser_Sync_Offset_Ref1 for hits in Reference Module 1).

For each hit, histogram the time relative to the synchronization pulses.

Also average the pedestal-subtracted pulse shapes, after normalizing to unit area and shifting in time so the rising edge of the shifted pulse is always in the same bin. The bins for the hit time and pulse shape histograms should be 1 nsec wide. In the case of the pulse shape averaging, this means each ATWD sample will be divided among several histogram bins.

Fit the hit time histograms with a Gaussian peak plus smooth background to determine the time resolution. Calculate the fraction of hits more than 15 nsec from the peak position. Compute relative transit time by subtracting the reference PMT peak position from each test PMT's peak position. Compare quantities with requirements and record results.

Determine the rise and fall times from the average pulse shape histograms. Compare with requirements and record results.

Notes:

Assumes RAPCAL is in place. The measured time resolution includes contributions from RAPCAL, PMT, and electronics. This test is effectively a RAPCAL verification.

The light level chosen is a compromise between test duration and wanting mostly single-PE events.

2.7. Nonlinearity Scan Test

Summary: Using short (10 nsec) rectangular pulses, determine onset of nonlinearity (5% level) and compare with requirements at gain 1e7. Check pre-pulsing and after-pulsing levels at 100 PE and gain 1e7.

Using long (1 μsec) rectangular pulses, check response droop vs. brightness (at gain 1e7) and compare with requirements.

It is also valuable to characterize the full nonlinear behavior of each PMT and archive the information for later reconstruction and analysis of events observed in the ice. For this purpose, illuminate DOMs with light pulses covering the dynamic range of the PMT and with time structures characteristic of scattered light originating from several representative distances in the ice. For each case, average and save the observed waveforms in an archive, including variation with gain.

External light source: LED Optical waveform generator

Temperature: T = –45C

Time required: 3 hours
Most of the this is determined by the allocation of 30 seconds per gain, pulse shape, and intensity. Additional time is allowed for gain stabilization at each HV, pedestals, and gain check.

DOM state: TestDOMApp

Quantities recorded: Linearity limit of PMT response (5% deviation), 10 nsec pulse
Pre-pulsing relative charge, 10 nsec pulse
After-pulsing relative charge, 10 nsec pulse
Maximum pulse height at saturation vs. gain, 10 nsec pulse
Response droop after 1 μsec rectangular pulse vs. brightness
Observed waveform shape vs. gain and vs. intensity/shape

Pass/Fail criteria: PMT linear within 5% for signals < 200 PE at gain 1e7 (TBD)
Pre-pulsing fraction < TBD PE at 100 PE, gain 1e7
After-pulsing fraction < TBD PE at 100 PE, gain 1e7
Response droop after 1 μsec < 10% for pulse intensity TBD

Temperature: T = –45C

Sequencer:

For each HV setting, previously determined to give gains 5e6, 1e7, 2e7, 5e7:

- Send HV set command to DOMs.
- Allow 10 minutes (TBD) for PMT gain to stabilize.
- Acquire 1000 pedestal triggers, with full waveform information.
- Perform gain check procedure (see Time Stability Test for details).
- Set discriminator to 0.25 times the SPE maximum pulse height, as determined from previous measurements, adjusted for actual gain vs. expected gain at this HV.
- Set trigger mode to discriminator plus local coincidence with either neighbor.
- Set readout for full waveforms, including ATWD channels 0-2 and the FADC.
- Send commands to LED optical waveform generator to start runs with a selection from 6 pulse shapes and scanning maximum pulse intensity from 1 to 1000 PE/nsec in approximately 10 logarithmic steps. Pulse frequency will be varied at the same time from 500 Hz to 1 Hz. Each setting will be allowed 30 seconds of acquisition time, or longer if needed for statistical noise to be less than a few percent per 10 nsec bin around the main peak. (The largest pulses will be generated at only 1 Hz, resulting in a small number of events, but PMT response to such pulses tends to be very consistent and requires little averaging.) Special monitor records must be generated in the data stream, indicating the illumination conditions.
- Send "off" command to LED controller.

Restore HV to nominal value for 1e7 gain. Allow 10 minutes (TBD) for PMT gain to stabilize before beginning the next test.

Analysis:

For pedestal trigger events, histogram ADC counts in each time bin. Fit the pedestal histograms to determine the pedestal pattern.

For discriminator triggers associated with gain measurement, i.e. with short and dim pulses (type 10): Use the procedure described under "Time Stability Test" to determine the PMT gain.

For discriminator triggers associated with saturation measurements, i.e. pulse types 11-12 or 20-23: Determine the hit time from the point on the pedestal-subtracted ATWD channel 0 waveform where the amplitude rises above 50% of SPE peak height at current gain. For inclusion in histograms, consider only hits in a narrow time window (±50 nsec, TBD) around the synchronization pulses recorded in Reference Module 2, offset by the approximate cable delay constant LED_Sync_Offset.

For each good hit, choose the ATWD channel which resolves the entire pulse best without being saturated. Calculate the observed time profile relative to the hit time expected from the synchronization pulse and LED_Sync_Offset. Convert this waveform to mV units using ATWD digitization scale factors. Accumulate the average resulting waveform over all events for each DOM.

Average the FADC waveforms in a similar way.

Process averaged pulses for each run as follows.

From the lowest intensity 10 nsec rectangular pulses, determine a scale factor for each DOM between the number of PEs and the illumination level recorded in external monitor records. The number of PEs is obtained from the average pulse integral, using previously measured gains and assuming the PMTs are linear.

For all other pulse intensities and shapes, use these scale factors to determine the number of PEs from the illumination level.

For the 10 nsec rectangular pulses at gain 1e7, plot main peak area vs. pulse intensity, with both axes in units of PEs. Find the point where the curve deviates by 5% (TBD) and compare with requirements.

Also for the 10 nsec rectangular pulses at gain 1e7, and when illumination is at approximately 100 PE, record the integral of the after-pulse and integral of the pre-pulse, relative to the integral of the main pulse. Compare with requirements.

For the 10 nsec rectangular pulses, find the maximum pulse amplitude at each gain, and record it. This information can later be translated into a maximum gain for each PMT beyond which pulses are clipped by the ATWD input protection circuit.

For the 1 μsec rectangular pulses, examine the average FADC waveform, and plot relative droop (after slightly less than 1 μsec) vs. number of PEs. Check that the droop is consistent with requirements.

Record the actual average waveforms for every run, along with information describing HV, gain, pulse shape and number of PEs.

Notes:

The rectangular pulses allow good resolution of pre-pulses and after-pulses, and the shoulder on the main peak. They also allow comparison with simple laboratory measurements.

The dead-time for DOM readout needs to be small, otherwise the tests will take a very long time. The preferred way to ensure this here is to require total observed charge greater than several SPE before sending full events out. This would eliminate most of the single-hit noise. A high discriminator threshold would be a poor substitute in the case of pulses that turn on slowly, since the early part of the pulse could get lost. As for the time resolution test, another solution would be to hard-wire a synchronization signal through the local coincidence inputs.

2.8. Time Stability Test

Summary:	Measure dark noise, pedestals, gain and P/V repeatedly, without changing high voltage. Check for unexpected instability.
External light source:	LED, narrow pulse, approx 0.01 PE detected, 10 kHz
Temperature:	T=–45C
Time required:	10 minutes per iteration Dark noise measurement takes 1 minute. Pedestals are measured for all ATWD time bins, so 1000 events requires about 1 minute. The gain measurement requires about 5000 events accumulated at 100 Hz times the live-time fraction. The live-time fraction will be worse than usual (estimate 10%) because the discriminator threshold needs to be set very low. That gives about 8 minutes for gain measurement.
DOM state:	TestDOMApp
Quantities recorded:	Dark noise rate, pedestal pattern, PMT gain, P/V ratio.
Pass/Fail criteria:	Dark noise rate < 1kHz TBD Pedestal values not more than TBD counts from time average PMT gain does not deviate more than 10% (TBD) from 1e7 P/V ratio more than TBD

Sequencer:

Dark noise test:

- Set discriminator level at 0.25 of peak for SPE.
- Set artificial deadtime for supernova scalers to 6.4 microseconds.
- For a period of 1 minute, write monitor records containing supernova scaler values.

Pedestal stability:

- Acquire 1000 pedestal triggers, with full ATWD waveforms.

Gain measurement:

- Send commands to LED controller for minimal pulse width (5 nsec FWHM), intensity 0.01 PE level and 10 kHz rate.
- set discriminator to appropriate low level TBD
- acquire 50000 discriminator triggers (of which about 5000 are expected to be from LED pulses), first 32 samples of ATWD 0 only
- Send “off” command to LED controller.

Analysis:

Dark noise:

- Read the monitor records and accumulate counts for each DOM until the test is complete. Record average count rate for each DOM and compare with requirements.

Pedestals:

- Histogram ADC counts in each time bin. Fit the pedestal histograms to determine the pedestal pattern. Record the pedestal pattern.
- At the end of all iterations, examine the individual bins from recorded pedestal patterns, as a function of test time. Compute the maximum deviation from the time average and compare with requirements.

Gain:

- Determine the hit time by fitting the normalized pedestal-subtracted pulse to a standard SPE shape. Choose only events that are in a narrow time window (±20 nsec, TBD) around hits recorded in the electrical synchronization module, offset by the cable delay constant LED_Sync_offset. Histogram the pedestal-subtracted pulse integral, accounting for digitization scale factors previously determined.
- Require a minimum of 2000 events in the histograms. Fit the pulse integral histogram to determine gain and P/V ratio.