1 Water Cherenkov Detector Calibration Tasks

1.1 Scope of work

We propose to significantly contribute to the design of the calibration and monitoring systems for the large Water Cherenkov Detector option for LBNE. These systems are an essential feature in a Water Cherenkov detector because the properties of the water change with time and position due to temperature and water quality variations. In fact, in the Super-Kamiokande experiment the water attenuation length was observed to vary as much as 20 m within a month and even twice that when comparing year to year [**?**]. It is possible that in a larger water Cherenkov detector the water circulation of a larger mass of water will make this a more significant issue. In addition, the attenuation coefficient is a function of wavelength as it is subject to Rayleigh and Mie scattering as well as absorption terms.

These variations potentially have an impact on physics quantities such as vertex and angular resolution and consequently particle identification efficiency. Every effort will be made to measure each factor individually and eventually input it into the simulation, in addition measuring the physical quantities for different particles types provides more direct access to the final uncertainties as a function of time and position in the detector. These uncertainties have direct consequences on the final sensitivity of this experiment.

1.2 Interested Groups

The work here proposed is organized within the calibration task for the water Cherenkov detector option for LBNE. The goal of the group is to develop all of the calibration systems required to achieve the level of uncertainties needed to obtain the desired sensitivity of this experiment given other design constraints such as the size of the detector, the PMT density and quantum efficiency, etc. The group includes 8 sub-tasks including: measurement of transparency of the water, the calibration of photomultiplier tubes (both timing and pulse height), the calibration of the energy scale and resolution, the calibration of particle identification efficiencies, vertex reconstruction accuracy and angular resolution of the WCD, and the monitoring of the environment within the WCD. Groups that are participating in these tasks from the EPSCOR proposers are: Hawaii, LSU, ISU and SDSMT. Other groups involved include: LANL, RPI, Irvine and Drexel.

1.3 Specific Goals

The specific goals are to contribute to specific aspects of the Water Cherenkov calibration system design:

- **Water Transparency Monitoring:** The development and investigation of systems that monitors the transparency of water.

  – In-situ water monitoring: This would include measurements of the stratification within the Water Cherenkov Detector. The measurement of the effective attenuation length and the monitoring of overall optical quality using relative measurements of cosmic muons.

- **Photomultiplier Calibration:** The development and investigation of the systems that calibrate the response of the photomultipliers including any light collectors that may part of the optical system.

  – Timing calibration: The development of a system that calibrates the timing response of the photomultipliers to better than 1 ns. This system includes the laser, the electronics to trigger the laser, the fiber optic system used to introduce light into the detector.

  – Pulseheight calibration: The development of the system that calibrates the gain of the photomultipliers to 1%. The system includes a laser, a system to vary the light level introduced in the detector, the fiber optic system and the electronics to trigger the laser.

- **Energy Calibration:** The development of the system that calibrates the energy scale of the detector. This includes systems to determine the energy scale and resolution at high energies applicable to the neutrino beam events.

  – High-energy calibration: The development of the system that calibrates the energy scale between 100 MeV and 1-2 GeV based on naturally occurring sources. This system must determine the energy scale to within 2% and determination of the energy resolution to within xx% between 100 MeV and 2 GeV.

  – Low-energy calibration: It includes the development of various radioactive gamma and beta sources, a low-energy linac (5-16 MeV) and the use of Michel electrons as calibration sources. Some radioactive sources that may be used are 16N (6 MeV), 8Li (up to 14 MeV), a Cf-Ni source, and a pT source (19.8 MeV).

- **Particle Vertex and ID Calibration:** The development and investigation of the systems and procedures to calibrate vertex and angular resolution and particle identification efficiency at high energies applicable to the neutrino beam events.

  – High-Energy Particle Vertex and ID: The development of the system that establishes the effectiveness of the particle vertex and identification performance in the detector for energies between 100 MeV and 2 GeV.

  – Low-energy calibration: The development of the system that establishes the effectiveness of the particle vertex and identification performance in the detector for energies below 100 MeV. It includes the development of various radioactive sources and the use of Michel electrons to determine vertex resolution and particle ID. A LINAC option will also be investigated for electron energies 5-16 MeV.

- **Detector Environmental Monitoring:** The development of the system that monitors the environment within the detector volume.

  – Water Parameter monitoring: The development of the system that monitors temperature, level, ph, total dissolved solids, resistivity, biologics, flow rate and flow pattern within the detector.

1.4 Relationship to the Simulation Effort

At this stage of the experiment most of the calibration design is based on assumptions of scalability and transferability from the Super-Kamiokande detector to the LBNE detectors. However, there are significant differences in the design that need to be addressed to confirm such assumptions, such as larger detector size, different PMT type, density, granularity, etc. Another potential concern is the low muon rate at 4850 feet depth of the DUSEL cavern. Thus this effort requires extensive simulation work using the LBNE proposed design as well as the development of dedicated software algorithms to reconstruct, identify, analyze and select suitable subsets of events that can verify and improve the uncertainty in the vertex reconstruction and contribute to improved, more robust particle identification. The water Cherenkov simulation developed by LBNE collaborators at Duke University, which is based on the T2K 2-km water Cherenkov detector, will be used as a starting point. We expect to contribute significantly to the simulation effort and to provide the main link between the calibration and simulation groups.

1.5 Water Cherenkov Calibration Requirements

1.5.1 Water Transparency Monitoring

Cherenkov light is scattered and absorbed before reaching the PMTs. The scattering and absorption for wavelengths between $\sim$340 and 500 nm impact the energy estimation and the event reconstruction. The attenuation length (sum of absorption and scattering lengths) of the water should exceed 100 m between 370 and 450 nm, and must be determined to an accuracy of better than 5%.

Cosmic-ray muon signals provide an important cross-check on other measurements, as well as measurements in and of themselves integrated over the Cherenkov spectrum produced by real particle signals. This approach is based on proven techniques developed in Super–Kamiokande. We can determine the attenuation length by fitting the muon sample and comparing the light-path length and deposited charge observed by a PMT. We correlate the observed changes with the optical quality of the water. While this provides for Super–Kamiokande one of the most effective ways of monitoring this quantity, the challenge for LBNE arises from a significantly lower cosmic-ray rate: 0.05 Hz or 2.7 min^{-1}. *Simulations and reconstruction will be developed to determine the time granularity allowable at these rates.*

1.5.2 Photomultiplier Calibration

The PMT signals are converted to a relative arrival time and incident light level. The timing measurement must be corrected for electronic slewing. The PMT-calibration system will determine the slewing-corrected hit time to better than 1 ns for light levels of 1 – 1000 PE. The gain calibration (conversion of electronic signal to PEs) must be better than 10% over the same range of incident light levels. The calibration system must measure the relative PMT quantum efficiency to 10%.

The PMT calibration system will consist of a pulsed-laser light source, an optical fiber for a light guide, and a light-diffusing ball located near the center of the water volume. To measure the relative quantum efficiency of the PMTs (i.e., against each other) and the response of the PMTs as a function of incident angle, we will need an isotropic light source. We will map the source to correct for any non-uniformities in the angular distribution of its emitted light. The ball will be movable (in the z direction) to enable a cross-check on the light-source uniformity and the angular response of the PMTs. Given the difference in distance from the center of the tank to the PMTs, the light-source system feeding the central diffusing ball requires a dynamic range of roughly 10^6 and must be capable of delivering 10^{12} photons to the ball.

To meet the timing requirement, the laser must be pulsed, with a pulse duration of a few ns or less. We will use multiple lasers to cover the range of wavelengths over which the PMT response will be measured. A set of monitoring PMTs will measure the pulse-to-pulse variation in the light generated by the lasers.

1.5.3 Energy Calibration

In order to determine the neutrino oscillation parameters and reduce the background, the energy response of the detector must be understood. At high energies (above 100 MeV) the energy resolution of the WCD must be $5\%/\sqrt{E_{GeV}}$ or better, while at low energies it must be $50\%/\sqrt{E_{MeV}}$. The absolute energy scale of the detector must be measured to 2% or better.To accomplish this at higher energies, near 1 GeV we will use through-going and stopping muons. At low energies, other naturally occurring phenomena such as Michel electrons and pions from muon interactions) as well as radioactive sources can be used for this calibration.

The energy calibration can be accomplished by a combination of naturally occurring events inside the detector, such as through-going and stopping muons and to some extent neutral pions if these events can be identified with good accuracy and occur sufficiently often. Good reconstruction algorithms and potentially dedicated hardware to identify muons entering into the detector are also required. Uncertainties in track length reconstruction have a critical impact on the ability to determine the energies of stopping as well as through-going muons. For the latter the uncertainty on the muon energy estimate, which can be obtained from a MC simulation also affects our ability to determine the absolute energy scale and resolution.

At the foreseen detector depth of 4850ft or 4290 m.w.e. the expected rate of muons is $(2.3 \pm 0.7) \times 10^{-5}$ $\mathrm{m}^{-2}\mathrm{s}^{-1}$ and the expected average muon energy is around 320 GeV [**?**] For a cylindrical detector with a 50m diameter and height this translates roughly into a muon rate of 0.05 Hz or 2.7 min^{-1}. Hence a muon telescope would have to be large in order to provide a statistically significant muon sample for calibration purposes. However, a muon telescope also serves the purpose of vertex resolution and particle identification.

It is apparent that the low muon rate is a critical factor in determining a calibration strategy. Calibrations with cosmic muons require a combination of muon telescope events which can be used to validate software algorithms *to reconstruct, identify and select suitable events in larger quantities. Estimates on track length reconstruction are not yet available but it is planned to estimate our ability to measure the energy resolution function and scale uncertainty as function of time (e.g. sample size) based on a number of reasonable assumptions for track reconstruction uncertainties and other parameters. The anticipated calibration study will also determine the amount of time required to acquire a statistically significant sample of Michel electrons.*

A secondary physics objective for the WCD is to characterize the detector response in the energy range relevant for solar and SN neutrinos as well as nucleon decay which ranges from a few MeV to hundreds of MeV and even a few GeV. Also detector enhancement which foresees the addition of Gd to the water is possible. Having a well defined energy response is necessary when searching for low multiplicity event clusters while also trying to minimize accidental coincidences since the positron originating from the inverse beta decay reaction tends to have on average a higher energy compared to low background events. As a result the detector's energy response in the region of 5–10 MeV needs to be well understood. Radioactive sources and Michel electrons aim to calibrate the energy region from a few MeV to well below 100 MeV.

1.5.4 Particle Vertex and ID Calibration

Vertex resolution varies as a function of energy and depends on whether the event is e-like or μ-like. Based on experience from similar WCDs such as Super–Kamiokande ([**?**], [**?**]), the vertex resolution for both e-like and μ-like events should be determined with less than 30 cm uncertainty in the high-energy range. As the particle energy decreases, the amount of emitted Cherenkov light decreases as well, increasing the uncertainty in the vertex resolution. Thus the vertex resolution in the low energy range should be better than 100 cm, although this requirement may vary, depending on the detector photo coverage and physics goals (for example Super–Kamiokande at 40% coverage has 100 cm resolution at 7 MeV, that quickly imrpoves to 60 cm at 15 MeV). Another important element for differentiating between e-like and μ-like events and determination of their energy is the angular resolution, which should be better than 3° for e-like and 1.8° for μ-like events in the high energy range. Angular resolution becomes significantly worse in the low energy range for the same reasons as the vertex resolution (for example, Super–Kamiokande detector has 25° angular uncertainty at 10 MeV and 40% photo coverage). Particle misidentification for e-like and μ-

like is crucial for the ν_e appearance search and thus should be better than 1% for all particle types. Finally, the Cherenkov ring finding algorithm should achieve more than 90% efficiency. *While these numbers should serve as a rough guideline for LBNE, other factors may limit the resolution of LBNE. An MC study will be done in several stages. First, by using GLOBES and determine the limits in resolution that will allow us to meet the physics goal. Then, a full LBNE Water Cherenkov detector simulation to determine the resolution (using the reference design as well as alternatives in the detector configuration) and variation throughout the detector volume to ensure that LBNE can meet its physics goals.*

Naturally occurring events in the detector may be used to calibrate vertex resolution. They are available for free in the detector and do not require dedicated calibration run time. However, a veto detector is needed in order to utilize these events for vertex and angular resolution calibration. In the case that a veto detector is not used, a muon telescope on the top of the detector is necessary. Vertex calibration with naturally occurring events in the detector require the development of dedicated software algorithms to reconstruct, identify, analyze and select suitable subsets of events that can verify and improve uncertainty in the vertex reconstruction and contribute to improved, more robust particle identification. *Their use will be preceded by the simulation studies, which should assess the impact of utilizing these naturally occurring events in the detector, on the vertex/ID calibration and achieving the requirement for it with either veto or muon telescope in place (one potential concern is low muon rate at 4850 feet depth of LBNE). The non-exhaustive list, for both high and low energy option includes: cosmic muons (number of photo-electrons as a function of track length, number of photo-electrons as a function of Cherenkov angle for low energy muons, spectrum of Michel electrons, stopping muons) and neutral pions (reconstruction of π_0 invariant mass).*

A second physics baseline objective for the WCD is to characterize the detector response in the energy range relevant for solar and SN neutrinos as well as nucleon decay which ranges from a few MeV to hundreds of MeV and even a few GeV. For a Mega-ton scale water Cherenkov detector to address solar neutrino physics questions it is critical that the energy response in the few to ~20 MeV energy range be mapped out in detail such that spectral distortions can be measured accurately and backgrounds not be misinterpreted as neutrino signal.

A detector enhancement which foresees the addition of Gd to the water is under discussion. The addition of Gd serves primarily to increase the detectors sensitivity to observing the diffuse neutrino background which originates from past supernovae. The relevant energies span the region around a few tens of MeV. Having a well defined energy response is necessary when searching for low multiplicity event clusters while also trying to minimize accidental coincidences since the positron originating from the inverse beta decay reaction tends to have on average a higher energy compared to low background events. As a result the detector's energy response in the region of 5–10 MeV needs to be well understood.

In the energy region from a few MeV to well below 100 MeV, Michel electrons are a well suited naturally occurring calibration source. However, due to the relatively low rate of stopping muons inside the detector the achievable accuracy may be rather limited. *The foreseen calibration study will determine the required amount of time to accumulate a statistically significant sample of Michel electrons. Depending on the outcome, Michel electrons could either be used as a primary calibration source or as a secondary addition to artificial sources.*

The deployment of radioactive sources involves the study of specific source geometries and containers, and of a deployment system that can interface to and deploy a variety of different calibration sources with a positional accuracy of a few cm. Multiple calibration access ports are foreseen and hence it is possible to access various positions inside the detector with a wide range in radius, azimuthal angle and depth by means of a relatively simple single axis vertical deployment system which could be moved from one access port to another. *If further studies reveal variations in the expected detector response (position dependence, angular dependence) to be large and the resulting requirements call for a more fine-grained calibration grid alternatives such as a movable arm with multiple sections or a remotely controlled submarine will be considered.*

1.5.5 Environmental Monitoring

The detector-environment monitoring system will monitor the temperature, level, resistivity, and pH within the water volume during the operational phase of the LBNE WCD. The water treatment system will monitor the total flow rate. If possible, the flow pattern will be measured (on a periodic basis) to minimize the presence of dead zones that may lead to the growth of microbes. We will periodically extract samples from the calibration ports to monitor the biologic activity within the WCD. The radon content of the water must be measured to an accuracy of better than 1 mBq/m^3 on a periodic basis. The magnetic field within the cavern will be measured prior to and after the installation of the magnetic compensating coils.