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Development of Calibration Light Sources for the Pacific Ocean Neutrino Experiment

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The Pacific Ocean Neutrino Experiment (P-ONE) is a very-large-volume neutrino telescope proposed for deployment deep in the northern Pacific Ocean off the coast of British Columbia, Canada. Successful deployment of P-ONE will expand the observable skyline and increase the global detection rate of extraterrestrial neutrinos, expanding our understanding of their energetic sources across the cosmos. The detector will consist of an array of mooring lines instrumented with Precision Optical Modules (P-OMs) which detect Cherenkov light from secondary particles produced in neutrino interactions within the detector volume. For successfully reconstructing incident neutrinos, both the optical properties of seawater and the positions of each P-OM within the detector must be known to high precision. To achieve this goal, P-ONE will be designed to include a variety of calibration light sources for both localized and ranged measurements within the detector. These sources include unique P-ONE calibration modules (P-CALs) which are a combination of the detection elements of the P-OM with a well calibrated nanosecond flasher and small fast light flashers integrated into each P-OM for local calibration. This contribution highlights the current status of optical calibration light source development from initial simulations to results from lab tests of integrated flasher properties.

38th International Cosmic Ray Conference (ICRC2023)
26 July - 3 August, 2023
Nagoya, Japan

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1. The Pacific Ocean Neutrino Experiment

The Pacific Ocean Neutrino Experiment (P-ONE) [1] is a large-volume neutrino telescope which will be deployed in the northern Pacific Ocean off the coast of Vancouver Island, Canada. The detector will consist of an array of one kilometer long mooring lines, each instrumented with optical modules along the length of the mooring. These modules will be used to collect Cherenkov light from secondary particles produced in neutrino interactions. Using these optical signals, P-ONE will be able to measure the energy and direction of high-energy neutrinos and correlate these particles with their sources in the cosmos. P-ONE will complement existing neutrino observatories around the world such as IceCube [2] and KM3NeT [3] to expand the global neutrino sky coverage.

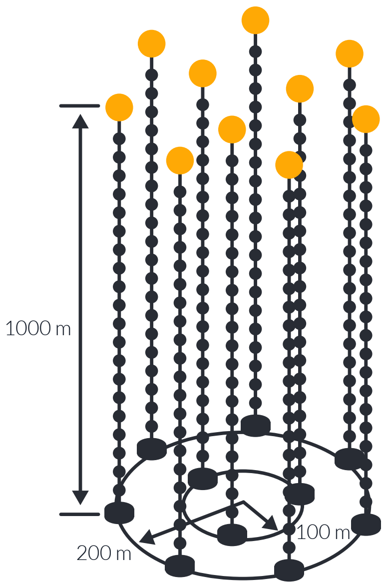


Figure 1: A sketch of a cluster of P-ONE mooring lines. The full scale detector is planned to consist of seven clusters. Figure adapted from Ref. [1]

P-ONE will be deployed in the Cascadia Basin at a depth of 2660 metres. Figure 1 shows an illustration of the initial cluster of ten P-ONE mooring lines, called the P-ONE Demonstrator. Each mooring line will be connected to the NEPTUNE deep sea fiber-optic cable network operated by Ocean Networks Canada (ONC) [4]. This collaboration with ONC provides the backbone infrastructure and oceonographic expertise to make P-ONE possible. The full scale P-ONE detector is planned to consist of a total of 70 mooring lines, each with 20 modules spaced evenly along its length. There are two types of modules integrated into each mooring, P-ONE optical modules (P-OMs) and P-ONE calibration modules (P-CALs). Each module is housed in two 17 inch borosilicate glass hemispheres and attached to the mooring line using a titanium flange. P-OMs hold 16 photomultiplier tubes (PMTs) uniformly spaced over the module to provide nearly 4π solid angle coverage for light detection. The P-CAL has a similar design but replaces eight PMTs with an optical calibration system. The undersea environment is constantly changing with ocean currents impacting the detector geometry, optical properties of the water, and bioluminescent activity. Consequently, the P-CAL will be used to measure the real-time relative positions of P-OMs and absorption, scattering, and dispersion properties of sea water. This document will highlight the design and early development of the P-CAL and its role as a critical component of P-ONE.

1.1 P-CAL Design

The P-CAL is a hybrid module which in addition to light collection and acoustic positioning, provides a light source and optical camera for detector calibration measurements. The current design of this module is shown in Figure 2 and Figure 3. Structurally, this module is like the P-OM with half the PMTs removed in place of a plastic shroud. The shroud provides a mounting platform for the P-CAL calibration components and shields the PMTs from diffuse light flashes.

In addition to the eight PMTs, the P-CAL contains optical light flashers for isotropic or beamed pulses, an acoustic positioning system, self-monitoring sensors, and a camera system, some of which are mounted on the shroud facing perpendicular to the mooring line. Protruding from the centre of the shroud is a white teflon diffuser sphere which allows the module to create isotropic flashes. Using these components, the P-CAL can make real-time *in-situ* measurements of the undersea environment and detector conditions. Each module in P-ONE is instrumented with ten beamed sub-nanosecond light flashers of various wavelengths from 300-600 nm. Mounted close to the glass within the PMT frame, each flasher points up or down the mooring line aimed towards adjacent modules. These beamed pulsers are intended for measuring scattering, dispersion, and inter-module time synchronization. The diffuse flasher system in the P-CAL is made up of a set of five high-power nanosecond light pulsers which sit under the white teflon diffuser. This allows for a choice between the wavelength and pulse properties of the flash. The teflon diffuser is optically coupled to the glass using a fill of optical gel throughout the entire top section of the hemisphere, minimizing unwanted refractions at the glass interface. With a careful choice of shroud geometry and diffuser shape, the P-CAL is able to generate well-calibrated isotropic flashes within the detector. Measuring the intensity and arrival time of a flash at the other modules in the detector, the P-CAL can measure *in-situ* module efficiencies, water optical properties, and perform geometrical calibration of module positions. The optical positioning performed by the diffuse flasher will be cross checked by the the acoustic positioning system within each module. For more information on the acoustic system see Ref. [5]

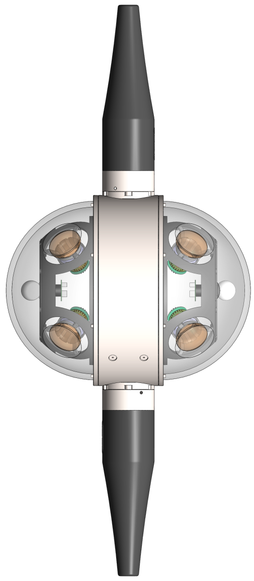
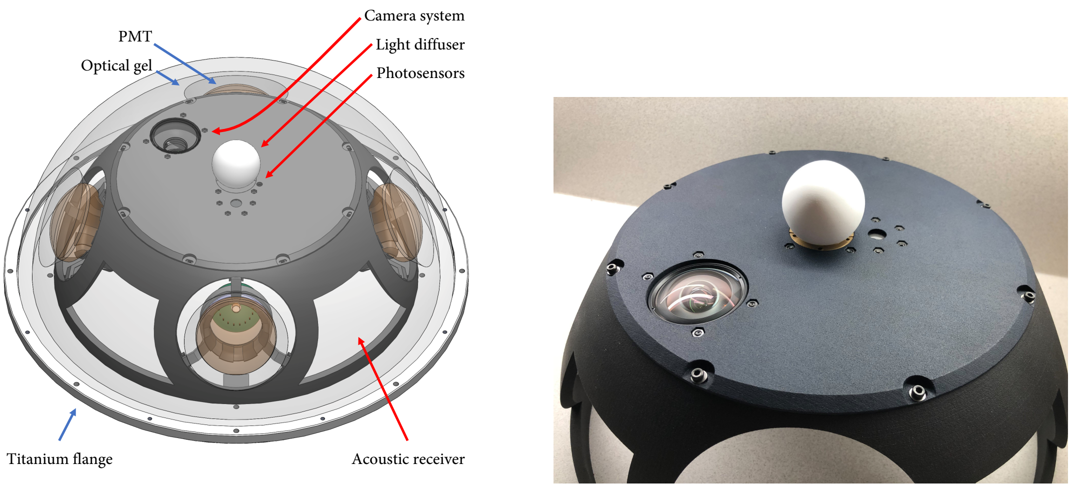


Figure 2: Fully integrated P-CAL. Calibration components are seen facing away from the mooring line.

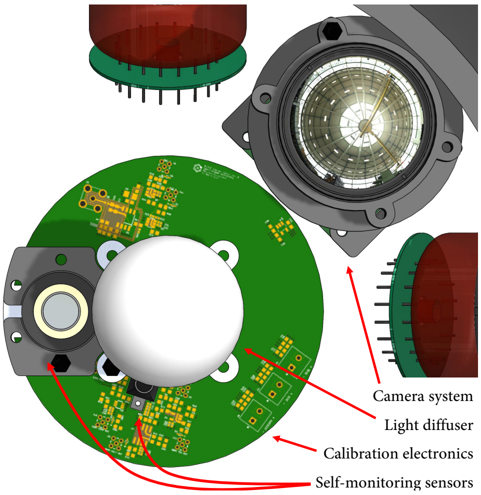


(a) Half P-CAL CAD view. Image taken from Ref. [6]

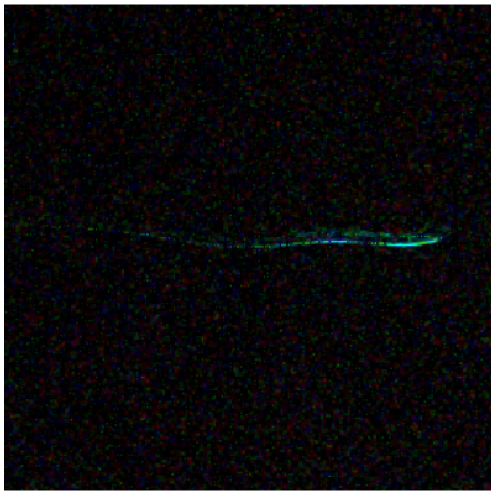
(b) Half P-CAL in-lab

Figure 3: **(a)** shows a P-CAL module in CAD software. **(b)** shows the same module after fabrication. The diffuser, self-monitoring sensors, and camera are all attached to the shroud.

Each P-CAL further contains a photodiode and silicon photomultiplier (SiPM) for self-monitoring. These components are critical to ensure the precise understanding of pulse shape and timing of each flash from the diffuser. This gives a measured benchmark for module efficiency measurements and allows for cross checks of flash timing. The photodiode is clamped and screwed into the flat mounting surface of the P-CAL pointing through a small opening near the diffuser. Similarly, the SiPM sits on the PCB below the diffuser within a plastic shielding. This protects the internals of the P-CAL from unwanted light. A view of the self-monitoring electronics within the P-CAL is shown in Figure 4a.



(a) Top-down P-CAL interior view from Ref. [6]



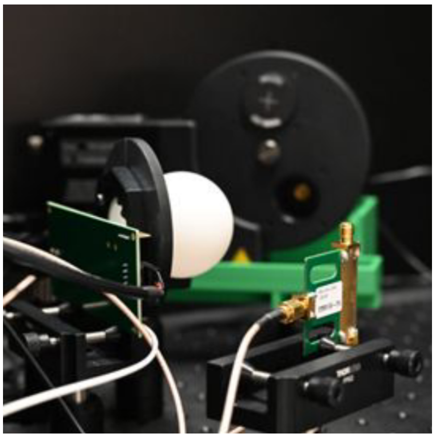
(b) Bioluminescent organism on camera from Ref. [7]

Figure 4: **(a)** shows an interior view of the P-CAL. The self-monitoring photodiode and SiPM are positioned to the left and bottom-left of the diffuser sphere respectively. The camera is mounted in the top right corner of the image. **(b)** is a 60 s exposure image of a bioluminescent organism taken by the a camera in the STRAW-b pathfinder [7].

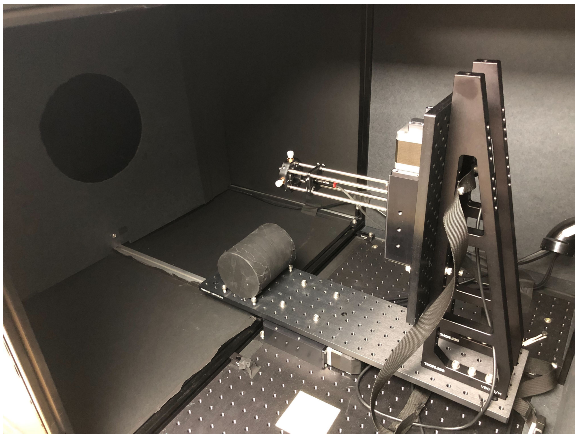
Furthest away from the flasher PCB is the camera system. This consists of a CMOS camera mounted to the surface of the P-CAL shroud, equipped with a fish-eye lens. Using this camera, the P-CAL can take photos of the module from inside to monitor sedimentation and biofouling levels. In addition, the camera can take long exposure images of bioluminescent organisms in the vicinity of the P-CAL. An example of one such organism is shown in Figure 4 which was taken by STRAW-b, a P-ONE pathfinder mission [7].

1.2 P-CAL Testing Infrastructure

Flashers for the P-CAL are characterized in a small dark box containing the light source, teflon diffuser, photodiode, and SiPM. Using this setup, the number of emitted photons, wavelength spectrum, and time profile of the flasher are measured. Figure 5a shows a photograph of the flasher characterization setup. Once integrated, P-CAL hemispheres will be tested in a much larger dark box setup. This larger box is 3.5 metres in length with a photodiode at one end and two rotation stages at the other. Four baffles are placed along the length of the box to shield the photodiode from stray light. P-CAL hemispheres can be mounted on the rotation stages allowing the modules to be rotated across all zenith and azimuth coordinates. This setup is intended to measure isotropy of both individual teflon diffusers and integrated P-CAL hemispheres. Furthermore, this allows for characterization of both the self-monitoring electronics, and camera system in a completely dark environment. The hemisphere rotation mount is shown in Figure 5b.



(a) Flasher characterization setup



(b) P-CAL hemisphere rotation stage setup

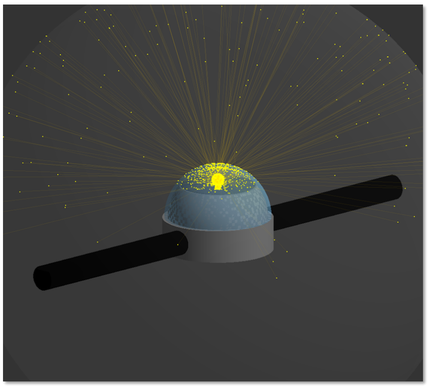
Figure 5: (a) shows the small dark box setup used for flasher characterization. The flasher is positioned behind the white teflon diffuser. Emitted light is measured by a photodiode and SiPM adjacent to the diffuser. **(b)** shows part of the large dark box containing the module rotation stages. The motorized stages currently hold a laser cage system for alignment with the photodiode on the other end of the box.

2. P-CAL Development Simulations and First Measurements

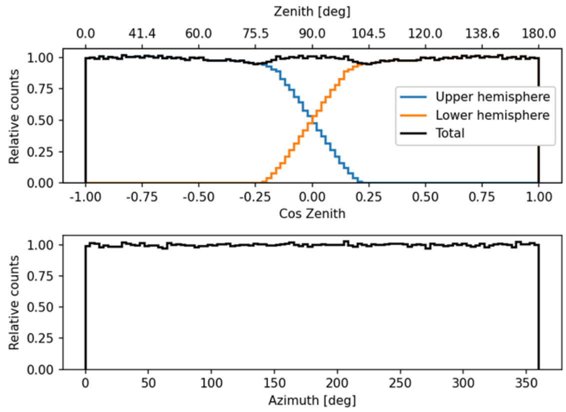
Development of the P-CAL is currently underway. Simulations were used to find preliminary requirements for module design which are now implemented and being tested. Using the testing infrastructure developed, the P-CAL module's optical properties can be fully characterized.

2.1 Simulation

Before development of the P-CAL began, it was necessary to demonstrate a proof-of-concept. Preliminary simulations study the isotropy of diffuse flashes from the module. Using Geant4 [8], a model of the P-CAL was assembled in a spherical world of water. Photons were emitted from within the diffuser system and detected at the spherical world boundary. Isotropy was measured based on the uniformity of photon detections. A picture of the Geant4 simulation setup as well as results from the isotropy simulations are shown in Figure 6. Simulation parameters were tweaked to adjust the simulated isotropy to be within 2%. This involved varying the refractive index of optical coupling gel, shape of the teflon diffuser, and slope of the previously flat P-CAL diffuser mounting surface. A simulation of detector geometry calibration was then performed using the simulated flash isotropy. The number of P-CAL modules per mooring line and position of modules was varied while the photon arrival times at modules across the detector were recorded. Based on these simulations it was determined that 2-3 modules per line should be repllaced with P-CAL modules in order to achieve sufficient optical coverage of the detector. Figure 7 shows a plot of a module cluster flash simulation.



(a) Geant4 isotropy simulation setup



(b) Geant4 isotropy simulation results

Figure 6: **(a)** shows the P-CAL model in Geant4 used to study the isotropy of a calibration device. Photons are emitted from within the diffuser and collected on the spherical world boundary. **(b)** shows the results of this study where the coloured lines represent each individual P-CAL hemisphere and the black line shows the combined flash. Tuning design properties of the P-CAL gives a flash isotropy of within 2%.

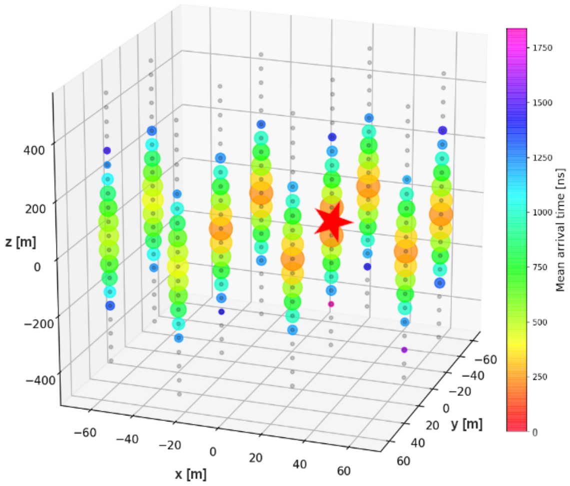
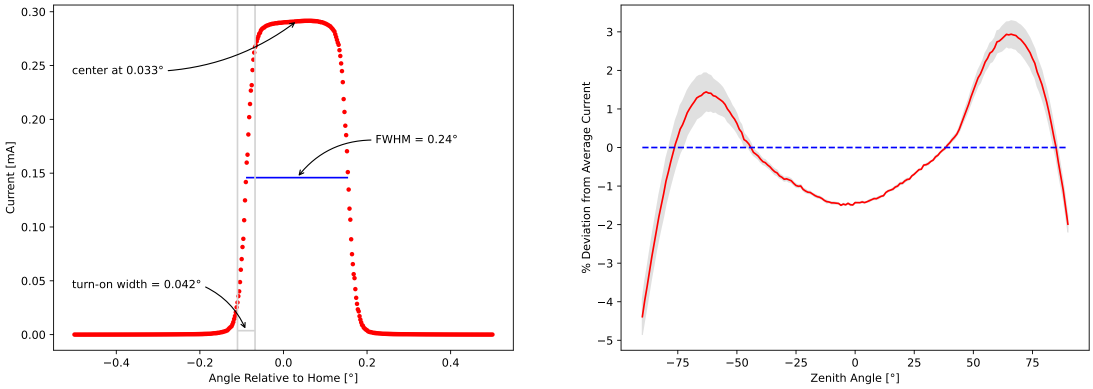


Figure 7: Simulation of a P-CAL flash propagating through a P-ONE cluster. The red star at the origin represents the P-CAL. The coloured dots represent other modules detecting light with arrival time and intensity shown as colour and size respectively.

In addition to ensuring the P-CAL was able to produce isotropic flashes, it was necessary to show that the light emitted would not damage the PMTs on the instrument. Using a setup similar to that used to study isotropy, photons that hit the PMT frame below the diffuser, in the area where the PMTs sit, were recorded. The number of detected photons varied as a function of gel refractive index and slope of the diffuser mounting plane. It was shown that self burn-out of PMTs will not be an issue. A measurement verification of this is currently underway.

2.2 Measurements and Testing

Both nanosecond and sub-nanosecond flashers are measured and characterized in the small dark box. Verification of flasher board designs is currently ongoing. The P-CAL requires flashers with a variety of wavelengths, pulse widths, and pulse intensities all of which need to be well known. Synchronously, the large dark box setup for measuring the isotropy of diffuse P-CAL flashes is being verified. Using a laser pointing down the box coincident with the axis of rotation, the alignment of the photodiode relative to the rotation stages was measured and is shown in Figure 8a. The zero of the motor is re-adjusted according to this measurement to ensure accurate alignment. Before integrated modules are measured, the teflon diffusers themselves need to be characterized to ensure there are no machining defects. An initial isotropy sweep for a bare teflon diffuser illuminated from inside by an LED is presented in Figure 8b. This preliminary result shows an isotropy of within 4%. Moving forward, the diffuse flasher systems will be mounted inside the



(a) Laser alignment of the rotation stage

(b) Diffuser isotropy measured over 180°

Figure 8: **(a)** shows the preliminary result zenith alignment sweep. This indicates a resolution of 0.24° and that the zero angle needs to be readjusted to 0.033°. **(b)** shows a preliminary isotropy measurement of a teflon diffuser. The red line is an average over 12 azimuthal measurements. This first measurement shows a maximum 4% deviation from the average photodiode current over the entire sweep range.

P-CAL shroud and isotropy of the integrated modules will be measured. Mechanical design of the diffuser mounting plane will be varied to provide the best balance between flash isotropy and PMT shielding. Further, the output of the self-monitoring photodiode and SiPM will be observed during isotropy tests to create a baseline for P-CAL self-measurement. The camera system will be studied along with different lenses available. Field of view, sensor noise, and image quality metrics will be used to make a final decision on component selection.

3. Summary and Outlook

Deep below the ocean surface, in an ever changing environment, the P-CAL module is a crucial component for the success of P-ONE. Understanding the optical properties of the sea water, monitoring module efficiencies, and calibrating detector geometry are all achievable through its novel design. P-CAL development is currently underway and testing of the first fully integrated modules will begin in the coming months. With an ambitious deployment timeline for the first mooring line, P-CAL modules will soon be in the water paving the way for the success of P-ONE.

Acknowledgements

We thank Ocean Networks Canada for the very successful operation of the NEPTUNE observatory, as well as the support staff from our institutions without whom P-ONE could not be operated efficiently.

We acknowledge the support of Natural Sciences and Engineering Research Council, Canada Foundation for Innovation, Digital Research Alliance, and the Canada First Research Excellence Fund through the Arthur B. McDonald Canadian Astroparticle Physics Research Institute, Canada; European Research Council (ERC), European Union; Deutsche Forschungsgemeinschaft (DFG), Germany; National Science Centre, Poland; U.S. National Science Foundation-Physics Division, USA; Science and Technology Facilities Council, part of U.K. Research and Innovation, and the UCL Cosmoparticle Initiative.

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