PROCEEDINGS OF SCIENCE

First instrumented line of the Pacific Ocean Neutrino Experiment: status, development and outlook

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The Pacific Ocean Neutrino Experiment (P-ONE) is a planned water-based Cherenkov neutrino telescope that will be located off the west coast of Canada. P-ONE will observe high-energy astrophysical neutrinos, aiming to identify the sources where they are produced, and will allow long-term in-situ studies of bioluminescence in the Cascadia Basin. The detector will be composed of instrumented mooring lines, which, along with the existing deep-sea infrastructure of the NEPTUNE observatory, make the design easily scalable. The first phase of the experiment, called P-ONE-1, is the first complete detector line and is instrumented with 20 modules spanning one kilometer. P-ONE-1 will serve as a test for all the newly developed systems and infrastructure and will pave the way for the future phases. This contribution will give an overview of the current status of the construction of the first line, the expected performance and the recent design innovations.

39th International Cosmic Ray Conference (ICRC2025)
15–24 July 2025
Geneva, Switzerland

ICRC 2025
The Astroparticle Physics Conference
Geneva July 15-24, 2025

*Speaker

PoS(ICRC2025)1087

1. Introduction

The Pacific Ocean Neutrino Experiment (P-ONE) is a planned water-based neutrino telescope located off the west coast of Canada, in the Cascadia Basin (Figure 2). The main science goal is detecting high-energy astrophysical neutrinos in order to identify their sources. With this, P-ONE will complement multi-messenger observations in a new era of neutrino astronomy. The site was already investigated for the feasibility of a neutrino telescope with the pathfinder missions, STRAW and STRAW-b [1, 2], which studied the optical properties of the deep-sea water and the bioluminescent emission that is present in Cascadia Basin. These missions revealed that the attenuation length has its maximum at $27.7^{+1.9}_{-1.3}$ m, and shed light on the background rates of ^{40}K and bioluminescence and on the effect of sedimentation on the performance of the detector. Ultimately, they confirmed that the Cascadia Basin is a suitable site for the P-ONE experiment.

P-ONE will benefit from the existing deep-sea infrastructure from the NEPTUNE observatory present in the Cascadia Basin, an advantage unique to this site. Hosted by Ocean Networks Canada (ONC), the infrastructure provides an 800 km long fiber-optic cable and power network on the seafloor, with several nodes for instrumentation. P-ONE will be connected to one of those nodes at a depth of 2660 m, providing power and network connection to the detector for data transport to shore and ultimately further processing.

The first instrumented line of the telescope, called P-ONE-1 (a model of the line can be seen in Figure 1), is in its construction phase and is planned to be deployed in the 2026 season. P-ONE-1's novelty also resides in the close collaboration with industry partners for the development of several components, such as with the MacArtney Subsea Engineering[a] for the backbone cable, M. I. Montage[b] for the structure that serves as deployment frame and anchor of the line, and with Nautilus Marine Service GmbH[c] for the glass hemispheres of the modules and titanium termination connecting them to the cable. P-ONE-1 will serve as a test for the newly designed systems and as the first step towards the already funded second phase of the experiment, the P-ONE Demonstrator. The Demonstrator is planned to comprise a total of 6 detection lines, following the design of P-ONE-1 and informed by first data.

The final geometry of the full P-ONE array is under optimization, with dedicated simulation being produced currently [3], including segmented and uniform geometry layouts. This design makes the detector easily scalable, while accounting for flexibility and constraints of deep-sea operations.

Figure 1: Simplified model of the P-ONE-1 line.

[a] https://www.macartney.com
[b] https://www.mimontage.dk
[c] https://nautilus-gmbh.com/en

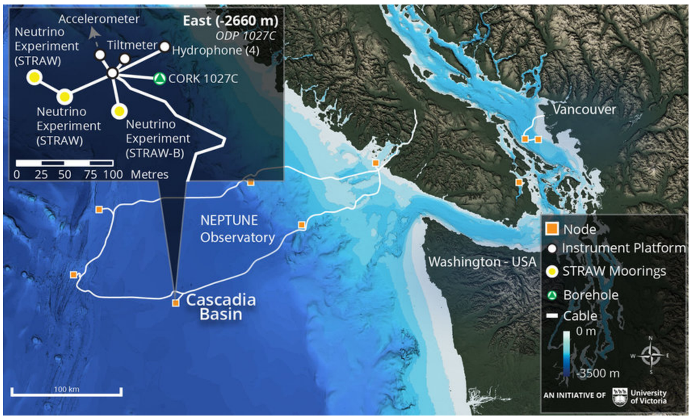


Figure 2: Map of the Cascadia Basin. The NEPTUNE observatory and the experiment lines of the STRAW and STRAW-b pathfinders are shown [4].

2. The P-ONE-1 line

P-ONE-1 is a 1-km long mooring line instrumented with 20 evenly distributed modules, and will pave the way for the future lines of P-ONE. The line is connected to the NEPTUNE Observatory infrastructure through a Junction Box, in which the backbone cable that carries the modules terminates. The Junction Box also contains all the power and communication electronics for the line (shown inside the subframe in Figure 6a). The frame used for the deployment (see Section 3.3 for more details) also serves as the anchor. The whole line keeps a vertical position using a sub-sea float attached to the end, and which is also used for unfurling the spooled-up line after landing on the seafloor.

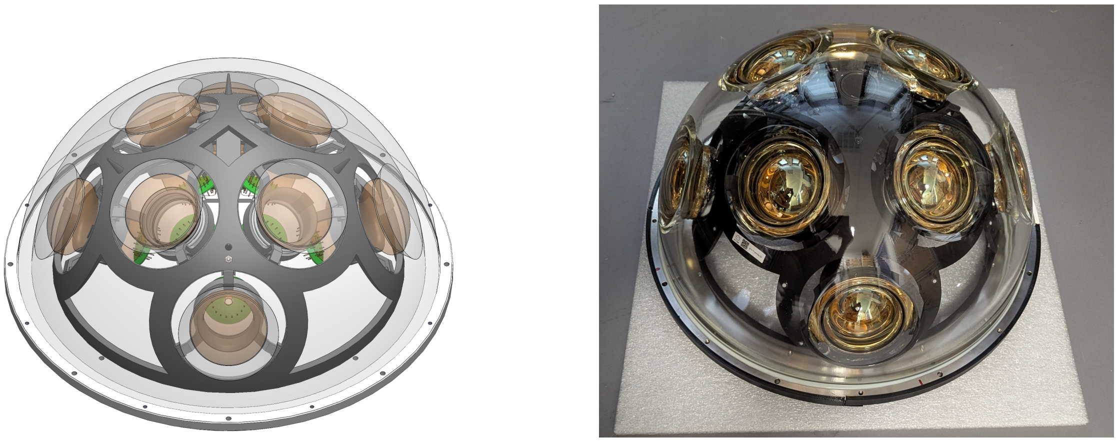
Out of those 20 modules, two are dedicated calibration modules, while the other 18 are regular optical modules. They are all connected to the backbone cable through a titanium termination, where the necessary copper and fiber strands are branched out. At the same time, the rest of the wires continue to the next module. A sealing system ensures that the line keeps functioning even in the case of a cable or instrument failure.

2.1 Common elements in the modules

There are two types of modules in the P-ONE-1 line: the P-ONE optical modules (P-OMs) and the P-ONE calibration modules (P-CALs). They share a common structure consisting of two 17-inch glass hemispheres, 3D-printed frames to which the multiple components are mounted, and titanium flanges that attach to the titanium termination on the line. Each full module contains one mainboard, two interposer boards for communication and power control of the internal components, a Muon In-Situ Tracker (MIST), and two systems for time synchronization: either a clock signal distributed on a dedicated fiber from the central clock or one reconstructed from the Ethernet data stream, both of which feed the onboard phase-locked loop (PLL) that drives the ADC [5]. A variable combination of additional instruments assist for calibration: eight EPC8004 GaNFET flashers [6] emitting in different wavelengths (three looking "upwards", three "downwards" and two horizontally), an axicone that produces a cone of light for monitoring of the line’s inclination and deflection; and acoustic receivers to calculate the position of the line [7]. In addition, an Oceanography Sensor

Interface is planned to be included in a subset of modules to monitor environmental proxies with external sensors, such as temperature and chemical composition of the water, and to observe climatic, spatial and temporal variations.

2.2 The P-ONE Optical Module



(a) Model of the P-OM. **(b)** Real P-OM.

Figure 3: Model of the P-OM module and picture of an already assembled P-OM hemisphere.

The P-OM modules are equipped with sixteen 3-inch Hamamatsu R14374-10 photomultiplier tubes (PMTs), covering a field of view of almost 4π. Each PMT is optically coupled to the glass hemisphere through an individual gel pad made of Wacker Silgel 612 and Wacker Elastosil RT 601[1]. This design allows for a stricter quality control of the optical properties of the gel and of the functionality of the PMTs. Especially, since a faulty PMT, or one with many impurities in the gel pad, could be replaced without affecting the rest. The gel pad geometry also increases the effective photocathode area thanks to the internal reflection. The PMTs are mounted to the frame with a custom spring-mounting mechanism that accommodates compression and vibrational loads due to temperature changes and transportation. Finally, each PMT is equipped with a microBase, originally designed for the IceCube Upgrade [8], that supplies the necessary high voltage.

2.3 The P-ONE Calibration Module

Similarly, the P-CALs have eight PMTs per module with the same configuration of individual gel pads, microBases and spring-loaded mechanical attachment. These modules, however, are optimized for calibration measurements, for which also an isotropic light source and a camera are present. The light source emits sub-nanosecond high-power light pulses through a diffusing sphere and is monitored in-situ with two photodiodes and a SiPM. The camera is the model DFM 37UX265-ML from The Imaging Source[2] with a wide-angle lens, which will allow monitoring of bioluminescence and biofouling. More details on the P-CAL modules can be found in [9].

[1] https://www.wacker.com
[2] https://www.theimagingsource.com

(a) Model of the P-CAL.

(b) Real P-CAL.

Figure 4: Model of the P-CAL module and picture of a P-CAL hemisphere with all the integrated components.

2.4 Anti-biofouling coated hemispheres and optically enhanced hemispheres

One of the main discoveries from the pathfinder missions was the impact of biofouling on the efficiency of the modules. Initial analysis shows this was reduced by up to 65% after 5 years due to sedimentation. To mitigate this unavoidable effect, two different approaches were employed. Four glass hemispheres were coated with an anti-biofouling layer of ClearSignal HL-120, manufactured by Severn Marine Technologies. It is a release coating that modifies the treated surface, either preventing organisms from attaching or weakening their attachment to the point where currents can remove them. This type of coating was chosen since it meets the requirements of being non-toxic, transparent, and long-lived. In addition, two polished glass hemispheres are used along the line, removing surface impurities and weakening potential attachment of biofouling organisms. These hemispheres are equally distributed along the line, with one fully-coated P-CAL, and four P-OMs in hybrid configurations of coated and polished or untreated hemispheres. The data taken at different depths will inform us about the best path forward for future lines. More details on the anti-biofouling coating approach can be found in [10].

3. Current construction status and developments

The basic design of the line was introduced in [11], but some components were re-designed, tested, and calibrated for the upcoming deployment. In this Section, some of the most relevant changes and measurements are discussed.

3.1 Gel pad production and PMT testing at TUM

A dedicated clean room was built for the production of PMT gel pads and the integration in the P-OMs at the Technical University of Munich (Figure 5). Approximately 400 gel pads were produced and underwent several stages of quality control to detect any impurities that might affect their optical properties. Most common reasons for rejections of gel pads are bubbles of >2 mm and an irregular reflecting surface. The information was saved for each individual PMT for later analysis. Some of these PMTs were sent to the Simon Fraser University, where they were integrated into the P-CALs being developed and produced there.

Figure 5: Production site at the Technical University of Munich. The picture shows the clean-room where the gel pads were produced, attached to the PMTs, and subsequently to the hemisphere glass.

After integration of PMTs in the modules, each module was tested in the Optical Module Calibration Unit, where the gain calibration, the saturation curve and the dark rate for each PMT were measured. All of the PMTs were fully functional, with the obtained parameters within the expected range based on the values provided by the manufacturer and on previous measurements. More details on the testing of the integrated PMTs can be found in [12]. The modules are shipped to TRIUMF (Vancouver, Canada), where the final assembly of the full line will happen, and will be checked again as part of the final acceptance test for the deployment readiness.

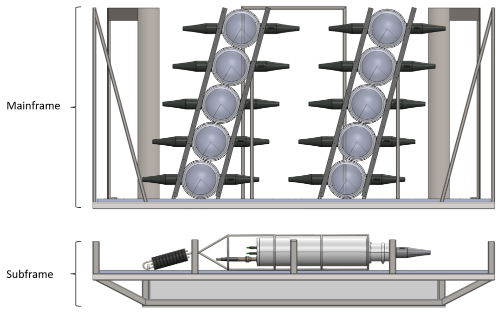
3.2 Module synchronization

To achieve the sub-degree angular resolution required by P-ONE-1, precise synchronization of all module ADC sampling at the 0.1 ns level is necessary. This is ensured by distributing a stable clock signal, a global phase-synchronization marker stream, and time-of-day information. The frequency reference and marker stream generate the sampling clock and the phase-synchronization signal, aligning ADCs across modules. This guarantees overall alignment of PMT data sampling to the accuracy of the frequency reference and phase-synchronization marker stream. Redundancy is built in via two independent systems to ensure timing resilience. Both have been demonstrated to provide the required sub-ns accuracy.

3.3 Deployment details

The deployment of the line will follow a bottom-up approach, as described in [11]. The fully instrumented line is coiled-up inside the deployment frame and will be lowered from a vessel to the sea-floor by a heavy lift operation. A remotely operated vehicle (ROV) inspects the structure and performs the connection to the sub-sea infrastructure. The initial visual inspection and boot-up sequence after the connection allows assessment of the state of the line and its components, and eventually informs if the line can be unfurled. If the status is deemed ok, the ROV will operate a scotch yoke mechanism to trigger the release of the float. The uplift of the float will pull up the line until taut.

The deployment frame is being designed for a WMO sea state of 4, which corresponds to moderate sea conditions with wave heights of 1.25 m to 2.5 m. It is split into two major components. The mainframe, holding the instruments as well as the hybrid backbone cable, and



(a) Model of the frame.

(b) Main frame with spooled backbone cable.

Figure 6: Deployment frame for the P-ONE-1 line.

the subframe, a sub-structure that hosts the Junction Box and provides sufficient distance to the seafloor to accommodate for the sink-in into the sediments on the ground. Appropriate safety factors are required for the dynamic loads that emerge when then line is being lowered from the vessel and transits through the splash zone. Here, the addition of a spreader cage allows to take up compressional loads during on- and offshore lifting. The spreader cage will be removed prior to the unfurling of the mooring to free the path of the instruments.

3.4 Software development

In conjunction with hardware advancements, considerable effort has been invested in developing the necessary software. Comprehensive simulations for a water-based telescope are ongoing, utilizing novel methods that either target P-ONE or are applicable to other neutrino telescopes, such as ambient background simulations and more efficient photon propagation techniques [3]. The data collected during the construction phase (e.g., calibration measurements or hierarchical structure of the line) is stored in a MongoDB database, available for future reference.

The data acquisition system will consist of two components working together: the Maximum Integrated Data Acquisition System (MIDAS) for the detector operation and control, and communication of all non-PMT data to both the ONC database and the P-ONE computing servers; and the fastDAQ system, which handles the high-speed data streams from the PMTs in the modules. The commissioning phase for P-ONE-1 will inform development of different detector run modes and trigger algorithms [13], mainly focused on calibration, as well as K-40 and bioluminescent background characterization.

4. Outlook

The first experimental line of the P-ONE neutrino telescope, P-ONE-1, is in its construction phase and planned to be deployed in 2026 season. Designed for scalability, P-ONE-1 will constitute the first step towards the full array, and will allow us to understand the environmental backgrounds and potential challenges of a deep-sea telescope.

This first line will also guide the next stages of construction with its performance, starting with the P-ONE Demonstrator. In parallel, discussions are underway to explore potential design optimizations for the next phases. The upcoming deployment represents a critical milestone towards a next-generation neutrino telescope, which will aim to address some of the long-standing questions in neutrino astronomy.

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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 this experiment and P-ONE could not be operated efficiently. We acknowledge the support of the Natural Sciences and Engineering Research Council of Canada (NSERC) and the Canadian Foundation for Innovation (CFI). This research was enabled in part by support provided by the BC and Prairies DRI and the Digital Research Alliance of Canada (alliancecan.ca). This research was undertaken thanks in part to funding from the Canada First Research Excellence Fund through the Arthur B. McDonald Canadian Astroparticle Physics Research Institute. P-ONE is supported by the Collaborative Research Centre 1258 (SFB1258) funded by the Deutsche Forschungsgemeinschaft (DFG), Germany. We acknowledge support by the National Science Foundation. This work was supported by the Science and Technology Facilities Council, part of the UK Research and Innovation, and by the UCL Cosmoparticle Initiative. This work was supported by the Polish National Science Centre (NCN).

PoS(ICRC2025)1087