PROCEEDINGS OF SCIENCE

Design of the Pacific Ocean Neutrino Experiment‘s First Detector Line

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The Pacific Ocean Neutrino Experiment (P-ONE) is a planned multi-cubic-kilometer neutrino telescope in the depths of the Northeast Pacific Ocean, offshore of Vancouver Island, British Columbia. Its primary scientific objective is the detection of high-energy neutrinos, which as cosmic messengers, are crucial to complement our understanding of the origin and acceleration mechanisms of cosmic rays. P-ONE will be connected to an existing deep-sea infrastructure, the NEPTUNE observatory, hosted by Ocean Networks Canada (ONC). Following the successful deployment of two pathfinder missions, aiming for the characterization of the proposed deployment location, the P-ONE collaboration with its partners at ONC is working towards the realization of the first detector line of P-ONE. The challenging deepsea environment, ocean dynamics, background variations induced by bioluminescence and ^{40}K decay, as well as the aim for modularity and scalability, require novel approaches to the detector design. The P-ONE-1 line strives to overcome these challenges and ultimately serve as a blueprint for the following installations. P-ONE-1 will comprise 20 optical and calibration modules, enclosed in glass hemispheres and integrated with a novel hybrid cable architecture with a combined length of just over 1000 m.

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1. Pacific Ocean Neutrino Experiment

The Pacific Ocean Neutrino Experiment (P-ONE) will be a next-generation neutrino telescope located in the Northeast Pacific Ocean. Using the deep sea as a Cherenkov medium, P-ONE aims to detect highly energetic astrophysical neutrinos, complementing the existing or currently under-construction neutrino telescopes, such as IceCube [1], KM3NeT [2] and GVD Baikal [3]. The scientific objectives of P-ONE range from advancing the field of neutrino astronomy, unraveling astronomical phenomena and fundamental physics at the PeV scale, to providing complementary input and follow-up observations in multi-messenger astronomy. P-ONE benefits from an already-existing offshore infrastructure, the NEPTUNE observatory, hosted by Ocean Networks Canada (ONC) [4]. This unique oceanographic observatory comprises an 800 km long loop of a hybrid power and communication cable. Experiments can access the infrastructure at different nodes located offshore of Vancouver Island, Canada. The node at the Cascadia Basin in a depth of 2660 m has been selected as the site for P-ONE, following the successful deployment and classification of the optical properties by two pathfinder experiments [5]. These delivered valuable data on the attenuation length, peaking at 27.7 m (+ 1.9 m, - 1.3 m) [6], making it a suitable site for a neutrino telescope. Further, important insights into ambient background rates induced by ^{40}K decays and diffuse bioluminescence, sedimentation, marine growth, and footage and classification of bioluminescence bursts were gathered. See [5] for more details. The pathfinders were successfully deployed in 2018 and 2020, respectively, and have been recovered in July 2023, preparing the site for the deployment of the first detector line of P-ONE, called P-ONE-1. The detector geometry of P-ONE is currently envisioned as a segmented structure, with around ten detector lines in each of seven clusters. The design of the array is scalable, enabling flexible installation in various sizes and facilitating data collection at different stages of construction [7]. A preliminary design is shown in Figure 1. The geometry is under optimization to increase the discovery potential [8] and will also be adjusted based on experiences with the first lines. Currently, the focus lies on developing and constructing the first detector line of P-ONE. Novel detector design approaches are necessary to tackle the challenges of the deep-sea environment, ocean dynamics, and background variations while also targeting a modular and scalable system. New detector concepts also open up significant performance benefits.

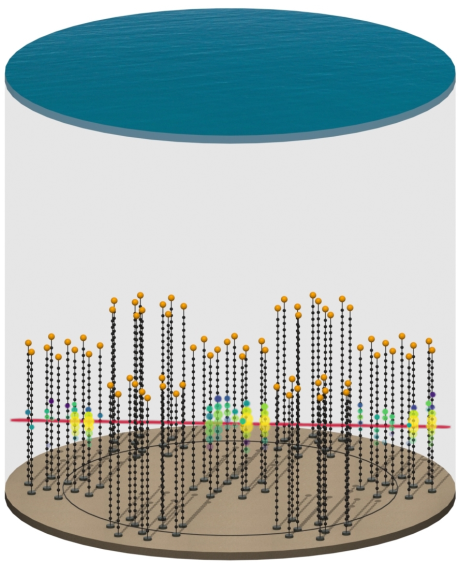

Figure 1: Conceptual illustration of the Pacific Ocean Neutrino Experiment (P-ONE), including a horizontal neutrino event signature.

2. Design overview of P-ONE-1

P-ONE-1, with its anticipated length of just over 1000 m and 20 evenly distributed optical and calibration modules, aims to be the blueprint for the following detector lines, and as such constitutes the

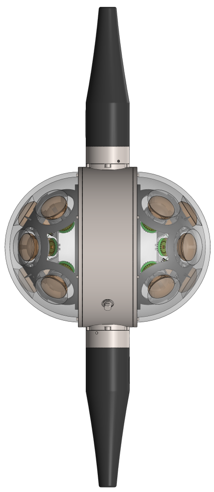

Figure 2: P-OM illustration, the backbone cable terminates in the titanium cylinder. The PMTs are orientated such that their field-of-view is unimpaired.

first construction stage of P-ONE. Of these 20 modules, up to three will be dedicated calibration modules [9]. The integrated backbone cable, which carries all modules, terminates in a mooring junction box (mJB), which acts as the interface to the NEPTUNE network. P-ONE-1 is held in position by an anchor and pulled taut by a subsea float. During the design phase of P-ONE-1, a special emphasis is set on developing the system as a cohesive whole, incorporating modular construction principles, and ensuring a scalable deployment approach. A novel backbone cable system (Fig. 2), combining a load-bearing aramid braid with the hybrid electro-optical power and communication cable, circumvents the need of running wire or dyneema ropes in parallel to communication cables. This streamlines the mooring design and reduces the risk of entanglement during deployment. The connection of the modules is performed by branching out the necessary number of copper and fiber strands via a titanium termination can. The remaining wires are fed through to the next instrument. A sophisticated multi-layered sealing system allows for maintaining a functioning system in case of cable or instrument failures along the line. The titanium cylinders transfer the mechanical load of the structure and are an integral part of the detector line (Fig. 2). The modules are hosted in 17" glass hemispheres which are adhesively connected to titanium flanges and screwed to the termination cylinders. The new backbone technique circumvents the need for subsea connectors and guarantees a free field-of-view for all photosensors. The system has been developed with experienced industrial partners, MacArtney Subsea Engineering[a] and Nautilus Marine Service GmbH[b]. At the time of writing, the first prototype of the instrument assembly is being constructed and prepared for design verification tests. The individual components of the backbone assembly, i.e., titanium cylinders and cable, are stored on the so-called deployment frame. This is used as a mounting structure for the furled-up detector line and allows access to individual instruments. Post-deployment, the frame serves as the anchor of P-ONE-1.

3. P-ONE Optical Module (P-OM)

Each hemisphere of the optical module of P-ONE-1 houses 8 photomultiplier tubes (PMTs) with a diameter of 3.1" (Hamamatsu[c] R14374-10). The PMTs are mounted in a spring-loaded configuration to accommodate temperature

[a] https://www.macartney.com/
[b] https://www.nautilus-gmbh.com/en/
[c] https://www.hamamatsu.com/eu/en.html

gradients, hydrostatic compression, and shock and vibrational loads during deployment and transportation. Optical coupling is provided by silicon-based optical gel pads, which utilize total internal reflection to increase the effective photocathode area (fig. 3). Additionally, photons with low incident angles missing the primary PMT can be collected by adjacent ones. The mounting scheme, together with the easily removable gel pads, offers the possibility to safely swap PMTs during production and testing. The PMT is supplied with high-voltage by the microBase, which was originally developed for the IceCube Upgrade [10] and offers a versatile low-power high voltage supply for the PMTs [11]. An automated calibration and test system for the characterization of PMTs and P-OMs has been developed at the Technical University of Munich. Here, a 405 nm laser serves as a light source, while rotational stages allow angular measurements. Currently, the setup is being upgraded to accommodate a multi-wavelength light source, a robot for angular measurements of an optical module hemisphere, and indirect light sources. The development of the gel pad production scheme and integration in the module has been successfully concluded earlier this year, and reliable procedures for the production are in place. The development and lab work is accompanied by simulation efforts in Geant4[1] where a digital model of the P-OM has been created by reading in construction files (Fig. 4). The simulation toolbox allows investigation of the optics of the instruments, attribution of optical effects, and eventually design optimization (Fig. 5).

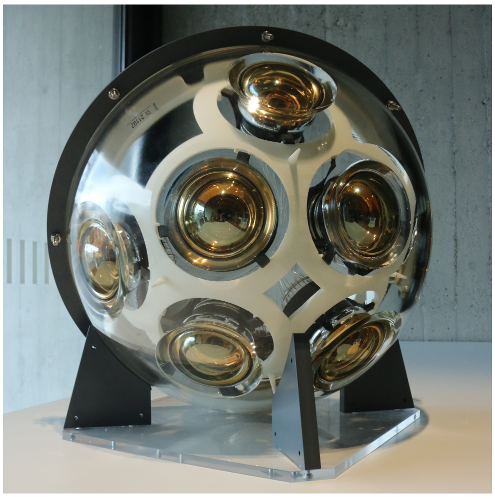

Figure 3: Picture of a mechanical prototype of the P-OM, with 8 PMTs optically coupled to the glass via gel pads.

[1] https://geant4.web.cern.ch/

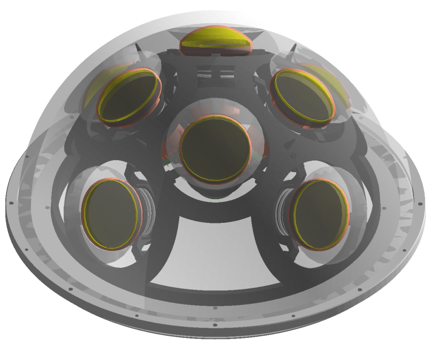

Figure 4: Geant4 visualization of the P-OM used to check the impact of the gel pad and mechanical structure on the collection efficiency of the module.

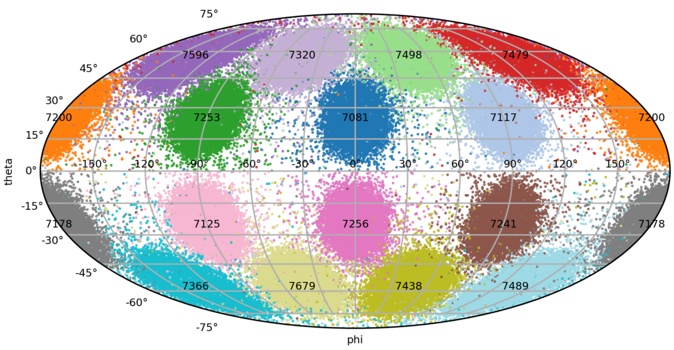

Figure 5: Photon hit heatmap of a homogeneously illuminated digital P-OM. The photon impact spots are attributed to the PMT position where it has been collected (color coding). The simulation was used to identify the effects of the gel pad on the collection efficiency by attributing the impact areas. Similar studies were performed to investigate different gel pad configurations.

The openings in between PMTs will be used to mount additional devices for calibration purposes, including light beacons, axicons for light collimation and acoustic receivers [12]. The calibration module and principles will be discussed in the following section.

4. P-ONE Calibration Module (P-CAL)

P-ONE´s calibration scheme relies on two main systems, optical and acoustic calibration. The optical calibration is based on the emission of in-situ monitored sub-nanosecond high-power light pulses into the detector volume. The pulses are emitted uniformly with the aid of a diffusing PTFE sphere and monitored by the surrounding optical modules. A wide dynamic range ensures that close-by modules are not saturated and far modules can be reached, depending on the selected configuration. The light flashes will be monitored in-situ by a photodiode and a SiPM. These principles are based on developments made for calibration light sources for the IceCube Upgrade [13]. The pulser electronics will also be used for stand-alone flasher beacons integrated in all P-OMs. The 17" form factor of the instrument housings offered additional space to add PMTs in the module, allowing the P-CAL to serve as a hybrid module for calibration and detection. This ultimately avoids blind spots along the detector line while integrating dedicated calibration instruments. The acoustic calibration will rely on acoustic transceivers distributed on the seafloor in reach of P-ONE-1. Their acoustic signals will be detected by piezo-based acoustic receivers, which are acoustically coupled to the glass hemispheres of each module. Additionally, the P-CAL will host a camera to monitor bioluminescence events and sedimentation effects on the instrument. Calibration setups have been constructed for the development, calibration, and testing of the light emitters, in-situ photosensors, cameras, and acoustic receivers. A detailed description of the calibration sub-systems and test setups will be provided in [9] and [12].

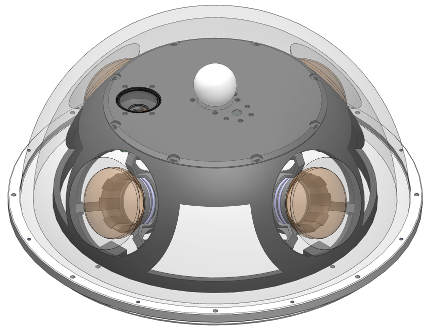

Figure 6: Render of a calibration module (P-CAL) hemisphere. The diffusing PTFE-sphere can be seen in the center and the camera on the left. A neck of PMTs completes the module.

5. Data acquisition and time synchronization

The signals of the 16 PMTs are read out by an analog-to-digital converter (ADC) with a sampling frequency of around 210 MHz and subsequently stored in a local ring-buffer. The ADC readout allows us to collect full waveform data as input for event reconstruction and analysis. Event triggering is performed by tagging time-over-threshold (ToT) values with a PMT handle and time stamp and sending them to the trigger computer integrated in the mJB. After noise differentiation, signals of interest will be requested and sent to shore. The multi-PMT configuration allows to separate bioluminescence events by local coincidence. The development of trigger algorithms is currently ongoing, and optimization will rely on in-situ data collected by P-ONE-1. For this reason, untriggered data will be sent to shore for several months after deployment. PMT time-over-threshold rates will be permanently collected to monitor baseline changes due to seasonal, ocean, or climate variability. Proper event reconstruction requires sub-ns time synchronization within the instruments. To achieve this, a clock will be distributed from the central hub inside the mJB to the individual modules in a star-like configuration. The modules will run with the same clock frequency and re-broadcast via fiber to the mJB. Due to the different fiber lengths, a phase delay will be observed. Precise in-situ measurement of the phase differences allows sub-ns timing reconstruction and synchronization. The first prototype of the time synchronization and communication system, called BlackCat, is operational, and phase differences were measured and attributed in laboratory measurements, see also [14].

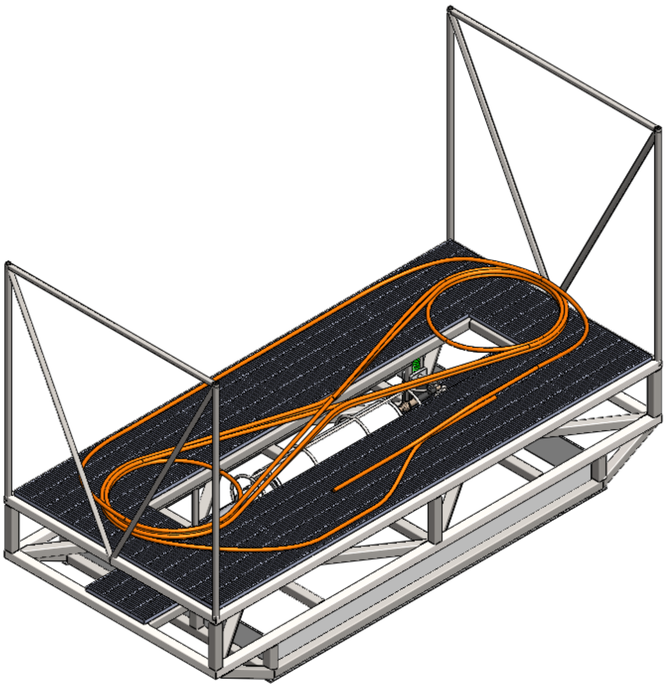

Figure 7: Conceptual illustration of the deployment frame. The design is work in progress. The modules will be stacked in tiles and unfurled by the uplift of the buoy.

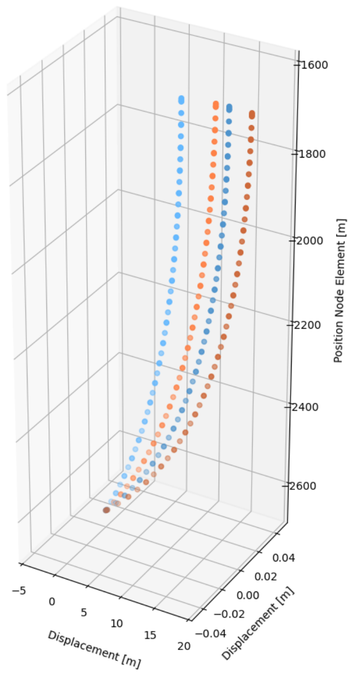

Figure 8: Knockdown simulation of the detector line in the anticipated current with different float configurations.

6. Deployment Concept

For a roughly 1000 m long detector line, a top-down deployment approach, i.e. unfurling and submerging the line from the back deck of the vessel, would take up a considerable amount of time and potentially hands-on work. It depends further on a stable weather window during several hours under daylight conditions. These constraints led to a bottom-up approach. In this process the structure is packed and lowered to the seabed by a heavy lift operation. The line is then released by setting the float free. This approach, however, requires careful engineering and consideration of unfurling dynamics. Here, the streamlined detector line design, enhanced by the hybrid backbone, provides several improvements in terms of deployment flexibility and risk reduction. For the bottom-up deployment of P-ONE-1, a hosting structure is currently in development (Fig. 7). This deployment frame will be used for several purposes: during transportation, deployment, and potentially the line recovery. A preliminary design is shown in Figure 7. At the beginning of the deployment, the frame is lowered to the seabed in a heavy lift operation. After this, a remotely operated vehicle (ROV) will inspect the integrated structure and perform the connection to the NEPTUNE infrastructure prior to the unfurling process. If the line is visually intact and responsive after network connection, the float will be released by the ROV, and the line will be lifted by its buoyancy. The ROV remains at the deployment frame to monitor the unfurling process. With the aid of marine dynamics analysis software (ProteusDS[2]), the effects of varying line designs on stress during deployment, hydrodynamic behaviour and knockdown from current are being simulated (Fig. 8). In order to enhance the accuracy of the simulation, we are currently incorporating additional parameters that specifically address the stress and torsion behavior of the background cable. The reduced form-factor by integrating the detector line on the frame, and the reduced hands-on work during deck operations, allow the deployment of several detector lines during one offshore operation.

7. Outlook and Conclusion

P-ONE-1´s development is in full progress. In this proceeding an update on the design of the first detector line of P-ONE has been provided. We are in the prototyping phase for the optical and calibration module, and the first modules of each are scheduled for production in 2023. Additionally, we are constructing a 1:1 model of the deployment frame to analyze the dynamic behavior of the complex line structure during unfolding. Our objective is to deploy a fully instrumented line by the end of 2024 or early 2025. As part of ongoing developments, we are also integrating oceanography sensors to broaden the scientific capabilities of P-ONE from its initial stages. Based on the insights gained from P-ONE-1, we will refine the design of the P-ONE detector lines and continue constructing additional lines to demonstrate the feasibility and concept of P-ONE [7].

[2]https://proteusds.com/

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