PROCEEDINGS OF SCIENCE

MuonSLab: A plastic scintillator based detector for muon measurement in the deep ocean

Jiacheng Wu[a,b,1,*], Weilun Huang[c,1] and Hualin Mei[c,d,e] for the TRIDENT Collaboration

[a] *School of Computer Science, Shanghai Jiao Tong University, Shanghai, China*
[b] *Zhiyuan College, Shanghai Jiao Tong University, Shanghai, China*
[c] *State Key Laboratory of Dark Matter Physics, Tsung-Dao Lee Institute, Shanghai Jiao Tong University, Shanghai, China*
[d] *School of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai, China*
[e] *Hainan Research Institute, Shanghai Jiao Tong University, Hainan, China*

E-mail: spring5@sjtu.edu.cn, mei.hualin@sjtu.edu.cn

[1] These two authors contributed equally to this work.
[*] Speaker.

Atmospheric muons are important probes for studying primary cosmic rays and extensive air showers. Additionally, they constitute a significant background for many underground and deep-sea neutrino experiments, such as TRopIcal DEep-sea Neutrino Telescope (TRIDENT). Understanding the muon flux at various depths in the deep sea is essential for validating TRIDENT simulations and guiding the development of optimized trigger strategies. This paper introduces a novel device based on plastic scintillators and silicon photomultipliers (SiPMs) named MuonSLab, which is designed to measure muon flux in the deep sea and has the potential to be extended to other atmospheric muon property measurements. We discuss the design and instrumentation of MuonSLab and present results from several muon flux measurements, demonstrating its sensitivity to muon detection and its stability during operations across multiple locations.

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1. Introduction

Atmospheric muons are charged particles produced in cosmic ray (CR) air showers. These particles are the most abundant charged particles reaching sea level and underground due to their low energy loss in the atmosphere, making them essential probes for cosmic ray studies. The number of muons in CR air showers is related to the CR mass composition [1]. Thus, experiments have been conducted to measure the muon number, revealing a deficit in simulations compared with measurements [2]. Furthermore, these particles can reach extremely high energies, allowing them to traverse several kilometers of seawater or ice, thereby constituting a significant background for neutrino telescopes like IceCube [3] and KM3NeT [4].

TRIDENT is a next-generation neutrino telescope proposed to be built in the northeastern region of the South China Sea [7]. During its design phase, understanding the atmospheric muon properties at the relevant site provides valuable inputs for refining the simulation pipeline, improving reconstruction algorithms, and optimizing trigger designs to effectively distinguish neutrino signals from muon backgrounds. To this end, we have developed MuonSLab, an innovative instrument for in-situ atmospheric muon flux measurement.

2. Detector Design

2.1 Mechanics

All components are integrated into a spherical glass vessel and a titanium alloy junction box, connected by an oil-filled cable. The sensors and electronics are enclosed within a 17-inch Vitrovex® glass sphere (Nautilus [10]) with a diameter of 432 mm, which can withstand water pressure up to depths of 6700 m (Figure 1, left). The junction box houses data backup instruments and allows for external charging (Figure 1, right). This design was driven by the need to validate key engineering components for TRIDENT.

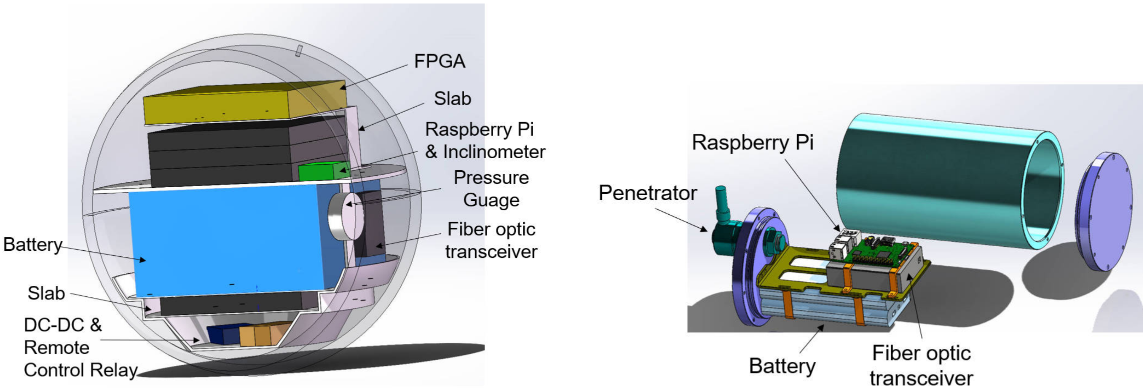

Figure 1: Left: The glass vessel housing the core components of MuonSLab. Right: The junction box for data backup and external charging.

2.2 Sensors and Electronics

The detection core comprises four layers of 200×200×20 mm^3 plastic scintillator slabs (SP101, Hoton [11]), a size chosen to maximize the detection area within the limited volume of the sphere.

Each slab is read out by eight 6×6 mm^2 SiPMs (Onsemi MicroFC-60035 [12]). Signals from four SiPMs on adjacent sides are amplified (x40) and summed by a custom front-end board in a "4-in-1" configuration. This board is fabricated as two flexible strips connected by wires, allowing it to be fixed around the slab, which greatly saves space and simplifies assembly (Figure 2).

The eight resulting analog signals are digitized at 125 MHz by an ALINX ADC board [14] and an ALINX FPGA [13]. A hardware trigger is implemented on the FPGA, requiring coincident signals in at least three of the four layers to identify potential muon events. The system's power and data flow is illustrated in Figure 3. A 2.44 kWh Li-ion battery provides power for about 5 days of autonomous operation.

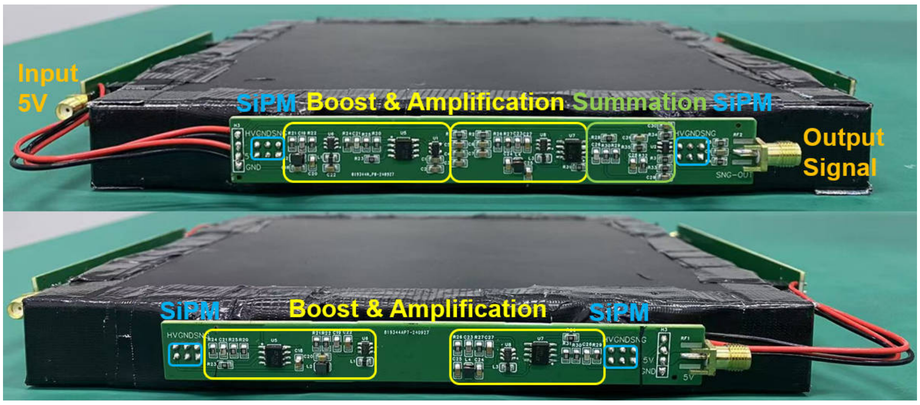

Figure 2: Front-end Electronics for MuonSLab, designed as flexible strips to fit around the scintillator slabs.

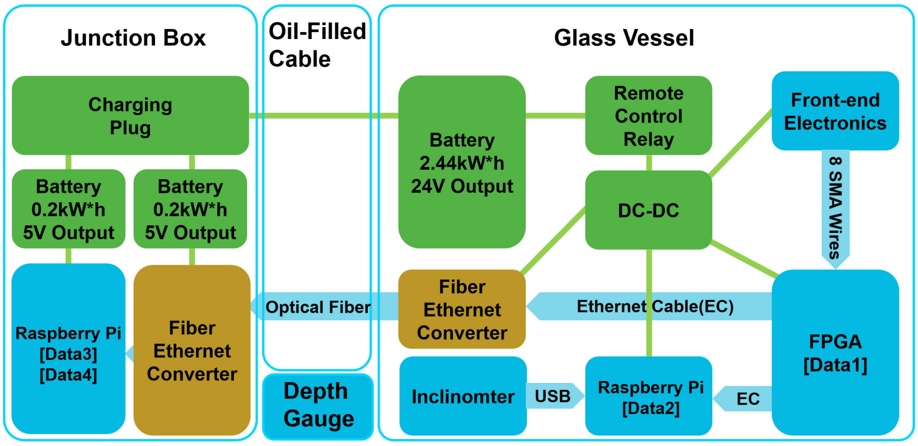

Figure 3: Schematic diagram of the power supply and data flow in the MuonSLab system.

3. Detector Performance

3.1 Sensitivity and Stress Tests

To validate the detector's sensitivity, a laboratory test was conducted. We employed a special trigger requiring only the middle two of the four slabs to fire. This setup selects highly tilted muons, providing an unbiased signal readout for the bottom slab which reveals a two-peak structure(Figure 4). The first peak corresponds to electronic noise, while the second, broader peak is identified as the muon signal. To confirm this, we applied a standard 4-layer coincidence trigger, which exclusively selects through-going muons and isolates the muon peak cleanly. This test confirms that muon signals are clearly distinguishable from the noise background, allowing for an effective trigger threshold to be set between the two peaks.

To validate the device's sensitivity to overburden, MuonSLab was tested in an 8-meter deep ship towing tank. The results (Figure 5) show that muon counts consistently decreased as the detector's depth increased from 1 to 6 meters. Before ocean deployment, the detector also successfully passed a 40 MPa pressure test and a 48-hour low-temperature (2-3 °C) test.

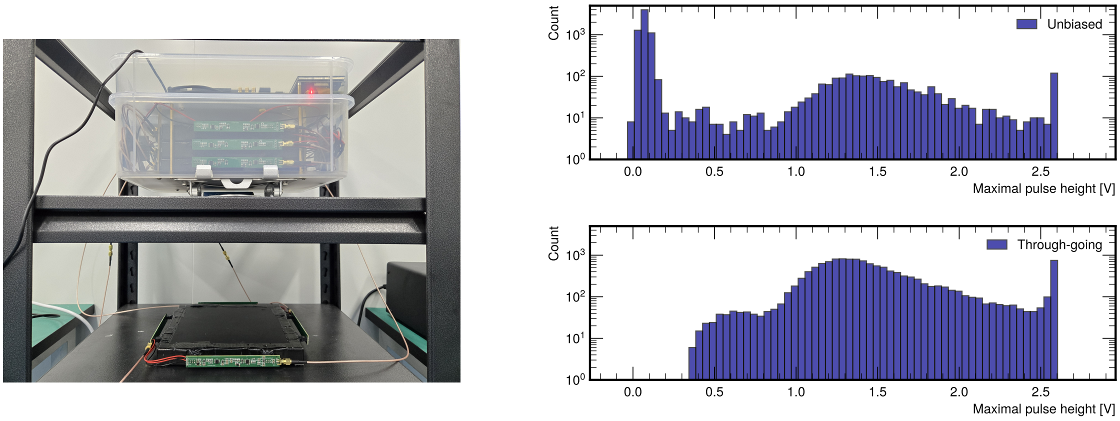

Figure 4: Left: The lab test setup. Right: Amplitude distribution showing the inclusive signal (top) and the clean muon peak after a 4-layer coincidence cut (bottom).

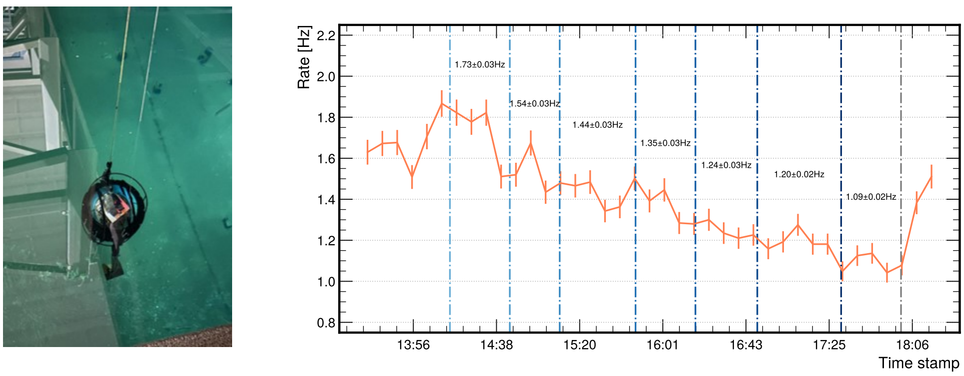

Figure 5: Result of water tank measurement, each interval between two blue dot-dashed lines indicate a certain depth, starting from water surface to 6 meters below the surface, then the MuonSLab was taken up from the bottom of the water tank around 18:00.

4. Measurements and Results

4.1 Sea Trial Measurement

In 2024, MuonSLab was successfully deployed and retrieved during the sea trial in the South China Sea. Two deployments were made, with the vessel attached to a steel cable (Figure 6), reaching depths down to 2.1 km, pausing at specified depths to collect data. The primary result is the measurement of the muon flux as a function of depth, shown in Figure 7 (left). Our data is in good agreement with the reference flux model from Bugaev et al. [17] and data from previous experiments [18]. The flux measurement from this sea trial is still dominated by statistical uncertainty, especially at deep locations. The main systematic uncertainty comes from counting inefficiency due to the choice of threshold and solid angle that MuonSLab could cover during the sea trial, which were estimated to be 11% and 20% respectively. To ensure long-term operation, future work will involve using more corrosion-resistant materials like titanium alloy and integrating dedicated calibration devices (e.g., an LED-based system for monitoring SiPM response).

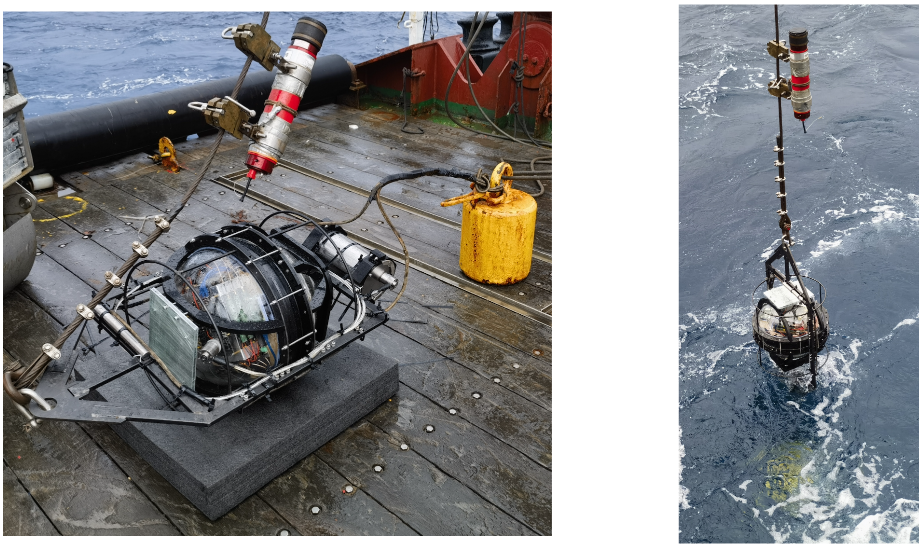

Figure 6: The pressure-resistant vessel on deck before deployment (left) and being lowered into the sea (right).

4.2 Auxiliary Measurements

A portable version of MuonSLab was created by simplifying its support structure and reducing battery size. This unit was operated on a plane from Sanya to Shanghai, measuring muon rate variations up to an altitude of 10,000 meters (Figure 8, left). This device was also operated continuously for a week, yielding stable results (Figure 8, right). These measurements demonstrate the detector's flexibility and long-term stability.

5. Conclusion

MuonSLab, as a compact muon detector, has demonstrated its sensitivity and stability in measuring muons. The successful deployment of this device during T-REX 2024 confirmed our

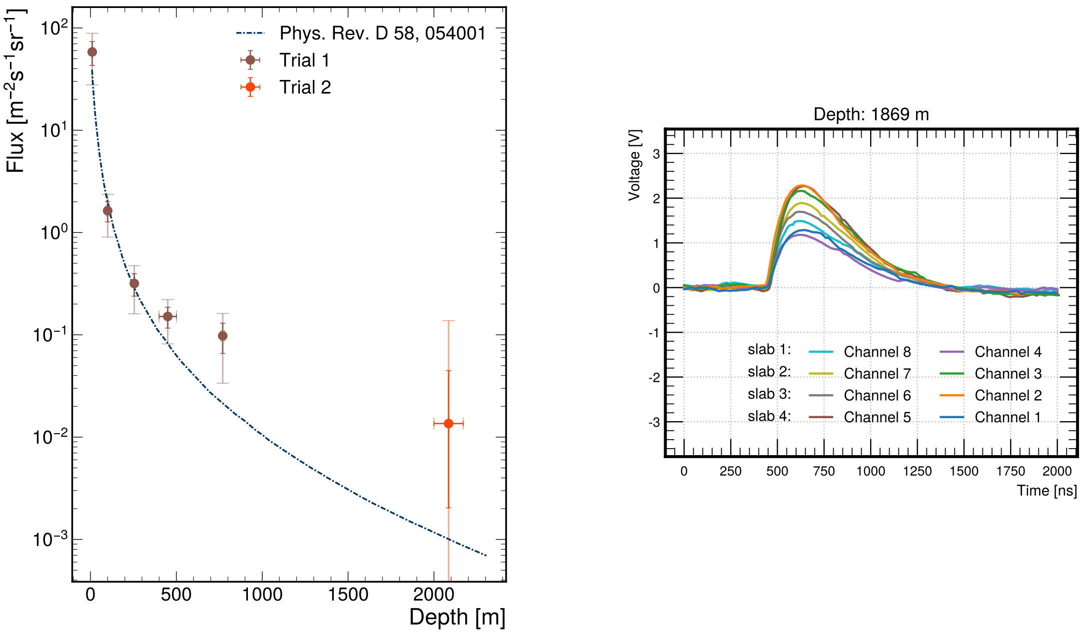

Figure 7: Left: Muon flux as a function of depth is presented using data from the two sea trials. In the first trial, the detector was paused at several depths, while in the second trial, it was paused only at approximately 2.1 kilometers. Reference flux from previous experiments [**?**] has been included for comparison. Vertical error bars represent 1 σ (darker) and 2 σ (lighter) total uncertainty, with both statistical and systematic uncertainty considered. Measurements at around 480 and 2200 meters have larger horizontal error bar due to the device's non-negligible vertical movements in these depths while in the sea. Right: An event display of a muon candidate at depth of 1869 m when the detector was being lowered. The accompanying legend indicates the relative positions of the channels within each slab, with "slab 1" corresponding to the top layer and "slab 4" being the bottom layer beneath the battery. The fact that all channels were over-threshold indicates that a muon passed through all four slabs.

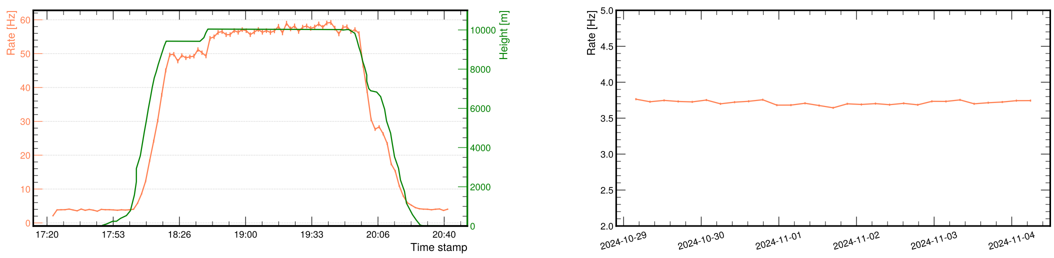

Figure 8: Left: Muon counting rate (orange) during a flight, correlated with altitude (green). Right: Stable muon counting rate over one week of continuous operation.

ability to accurately measure muon flux at various depths in the South China Sea. The initial experimental results align well with our expectations, and we are currently conducting simulations and further analysis to derive more physical quantities related to depth. The portable version of our detector, which exhibited remarkable stability during T-REX 2024, will play a crucial role in future exploration of using plastic scintillator in the deep sea experiment to understand muon properties associated with cosmic rays and extensive air showers. MuonSLab can also provide valuable input to the developments of TRIDENT's simulation and trigger systems. Furthermore, the detector facilitates the use of plastic scintillators for particle identification in the deep sea, offering preliminary experience for future TRIDENT calibration schemes and physics potential exploration.

Acknowledgments

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