Development of a real-time in-situ calibration system for deep-sea neutrino telescopes

Tailin Zhu

on behalf of the TRIDENT Collaboration

Tsung-Dao Lee Institute, Shanghai Jiao Tong University

(t.zhu@sjtu.edu.cn)

TeVPA 2026

2026/09/01

李政道研究所
TSUNG-DAO LEE INSTITUTE

TRIDENT
海 | 铃 | 计 | 划

Calibration Purposes

Event reconstruction uses the timing, charge and spatial distribution of detected photons.
Some calibration inputs enter detector–response model used in event reconstruction.

Calibration Input

Medium: scattering and absorption; Optical background

Geometry: DOM position and orientation; String motion

Sensor response: PMT/SiPM efficiency, timing, waveform

Detector Response

Photon hit time / number

Photon spatial distribution

Photon waveform

Reconstruction

Hypothesis

Likelihood calculation

Physics output

Direction

Energy

Flavour

In the deep sea, these conditions evolve with time → calibration must be in situ and time-dependent.

Calibration Purposes

Event reconstruction uses the timing, charge and spatial distribution of detected photons.
Some calibration inputs enter detector-response model used in event reconstruction.

Calibration Input

Medium: scattering and absorption; Optical background

Geometry: DOM position and orientation; String motion

Sensor response: PMT/SiPM efficiency, timing, waveform

Detector Response

Photon hit time / number

Photon spatial distribution

Photon waveform

Reconstruction

Hypothesis

Likelihood calculation

Physics output

Direction

Energy

Flavour

In the deep sea, these conditions evolve with time → calibration must be in situ and time-dependent.

Calibration Purposes

Event reconstruction uses the timing, charge and spatial distribution of detected photons.
Some calibration inputs enter detector–response model used in event reconstruction.

Calibration Input

Medium: scattering and absorption; Optical background

Geometry: DOM position and orientation; String motion

Sensor response: PMT/SiPM efficiency, timing, waveform

Detector Response

Photon hit time / number

Photon spatial distribution

Photon waveform

Reconstruction

Hypothesis

Likelihood calculation

Physics output

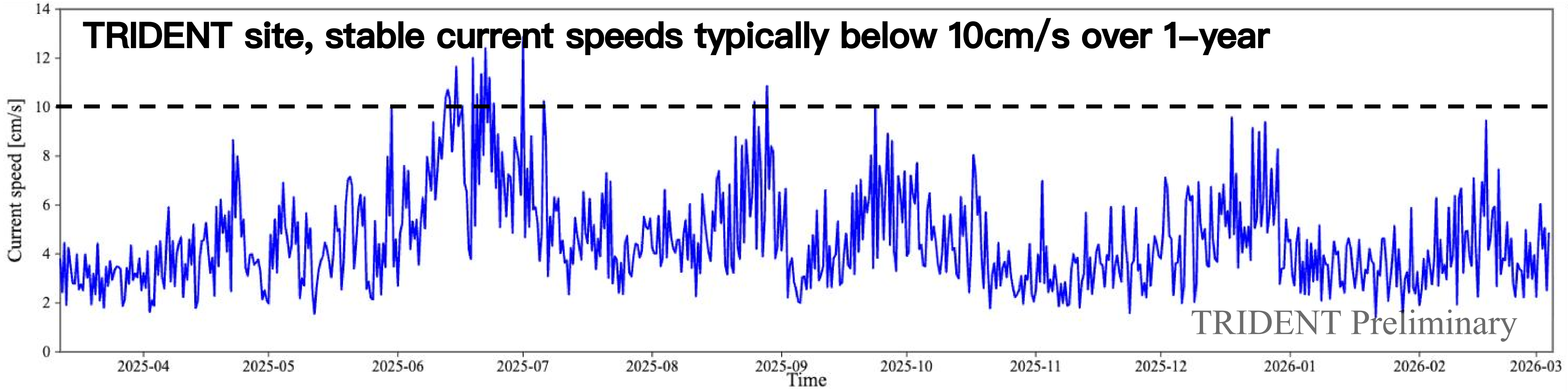
Direction

Energy

Flavour

In the deep sea, these conditions evolve with time → calibration must be in situ and time-dependent.

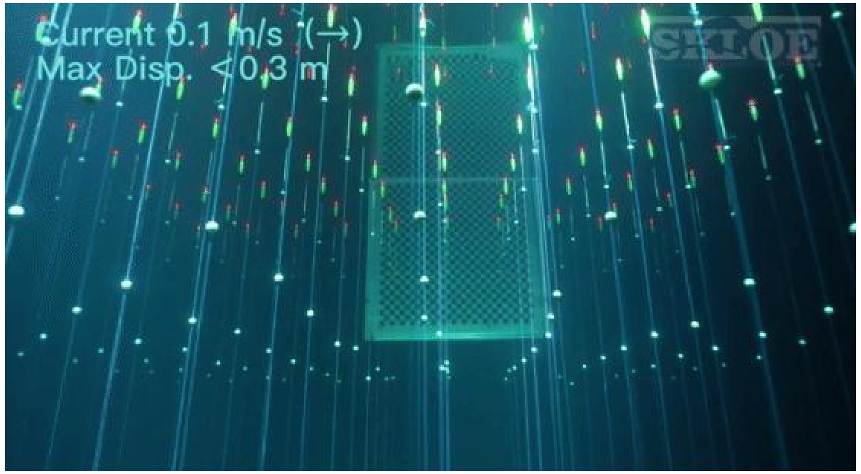
The Need for Real-Time Deep-Sea Calibration



Detector Geometry

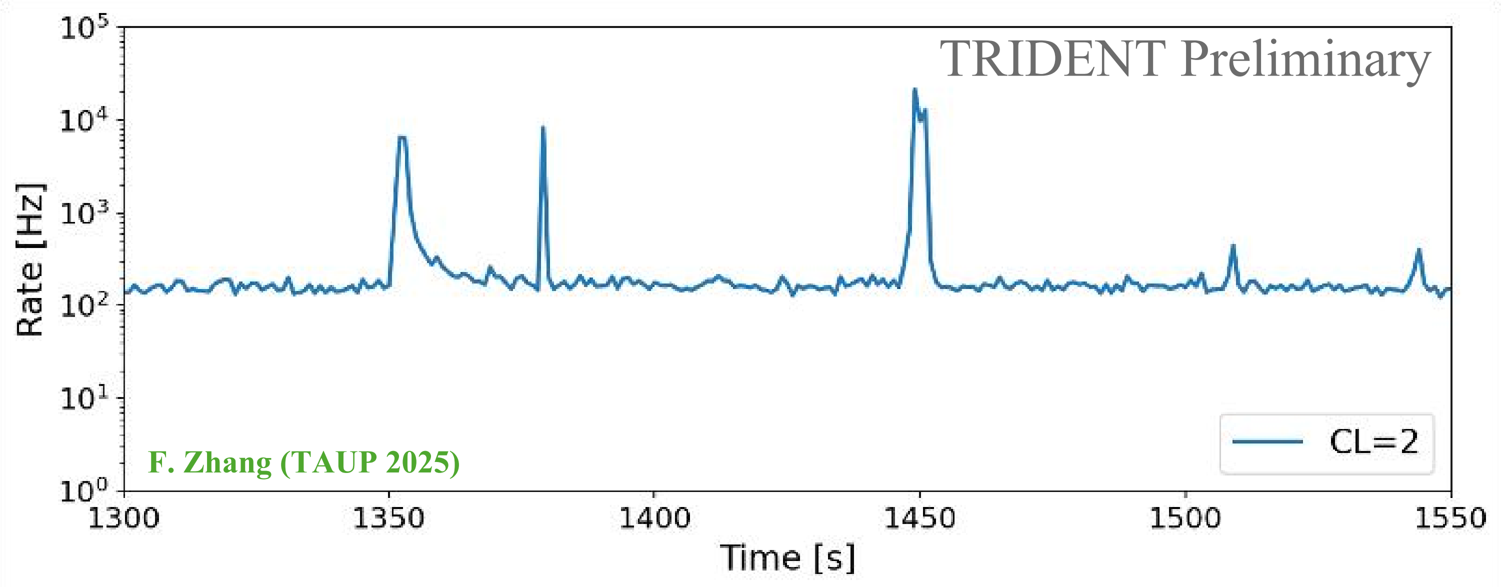
Sea currents may move the strings

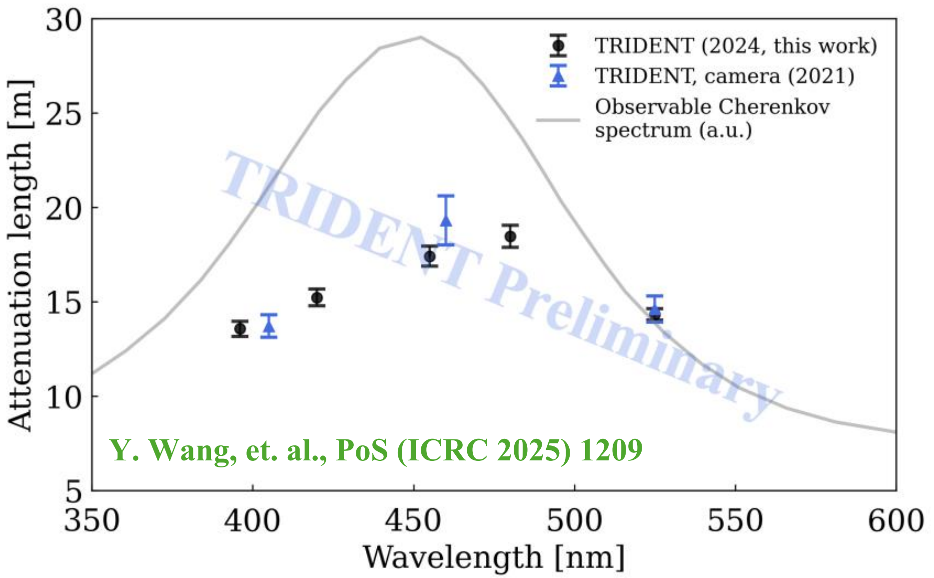
DOM positions measured with acoustic sensors



The Need for Real-Time Deep-Sea Calibration

TRIDENT 海铃计划





Optical Background

^{40}K and bioluminescence affect the observed hit rate and constitute a background

Water Optical Properties

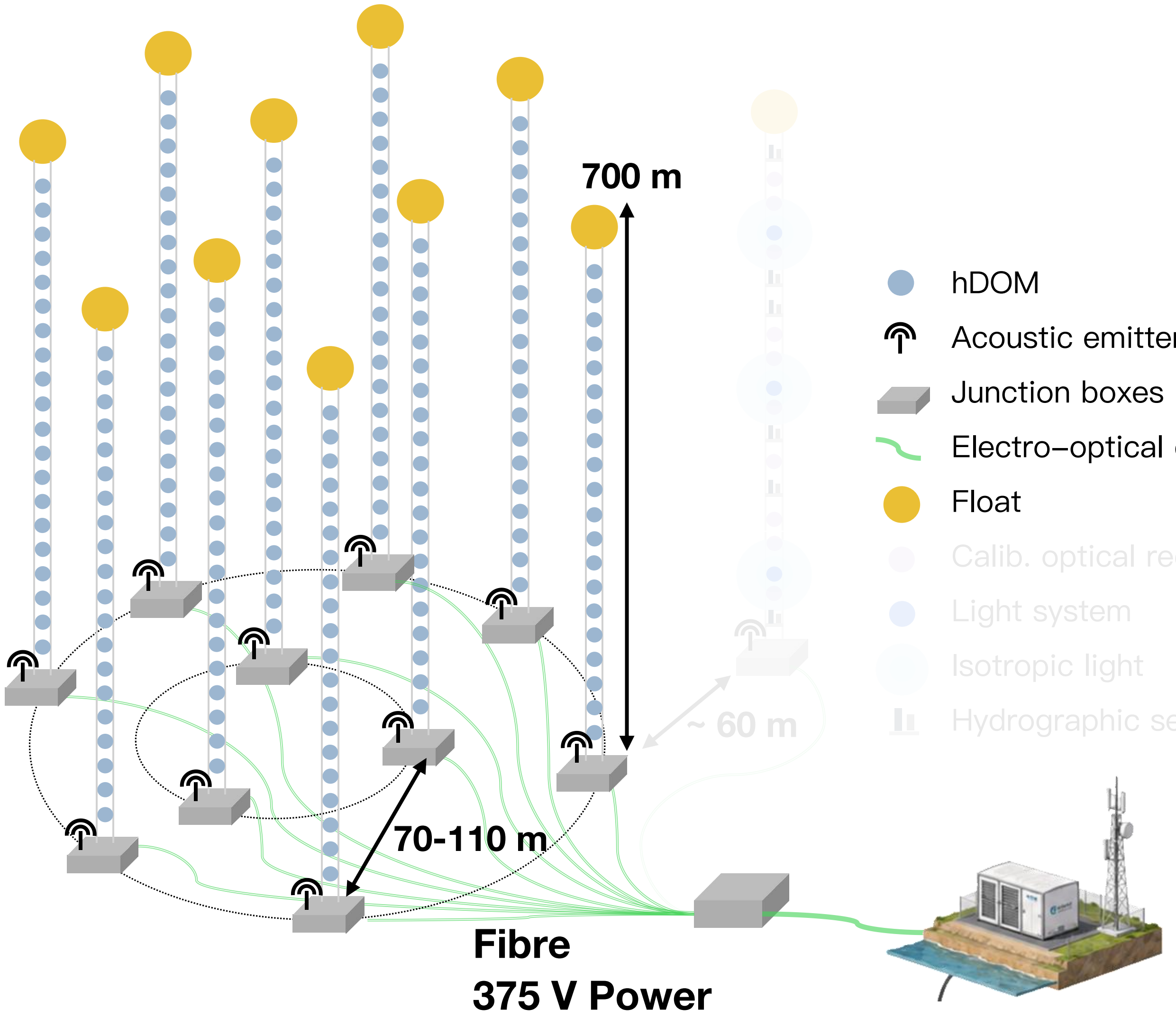
Absorption and scattering affect photon survival and arrival times

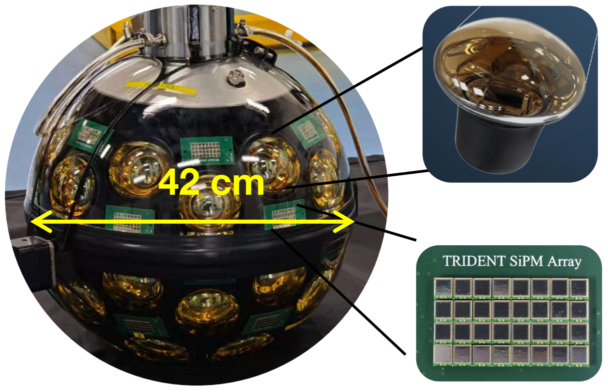
TRIDENT Phase-1

10 optical strings;
200 hybrid–DOMs

A dedicated calibration string

- Real–time data transmitting and power supply
- Sub–ns time sync between calibration string and hDOMs





PMTs:
< 2ns TTS
~30% QE

SiPMs:
< 0.3 ns jitter

Z. Wei, et. al., PoS (ICRC 2023) 1213

W. Li, et. al., NIM-A, 1056 168588 (2023)

W. Tian, et. al., NIM-A, 1076 170489 (2025)

J. Wu, et. al., JINST 20 P07035 (2025)

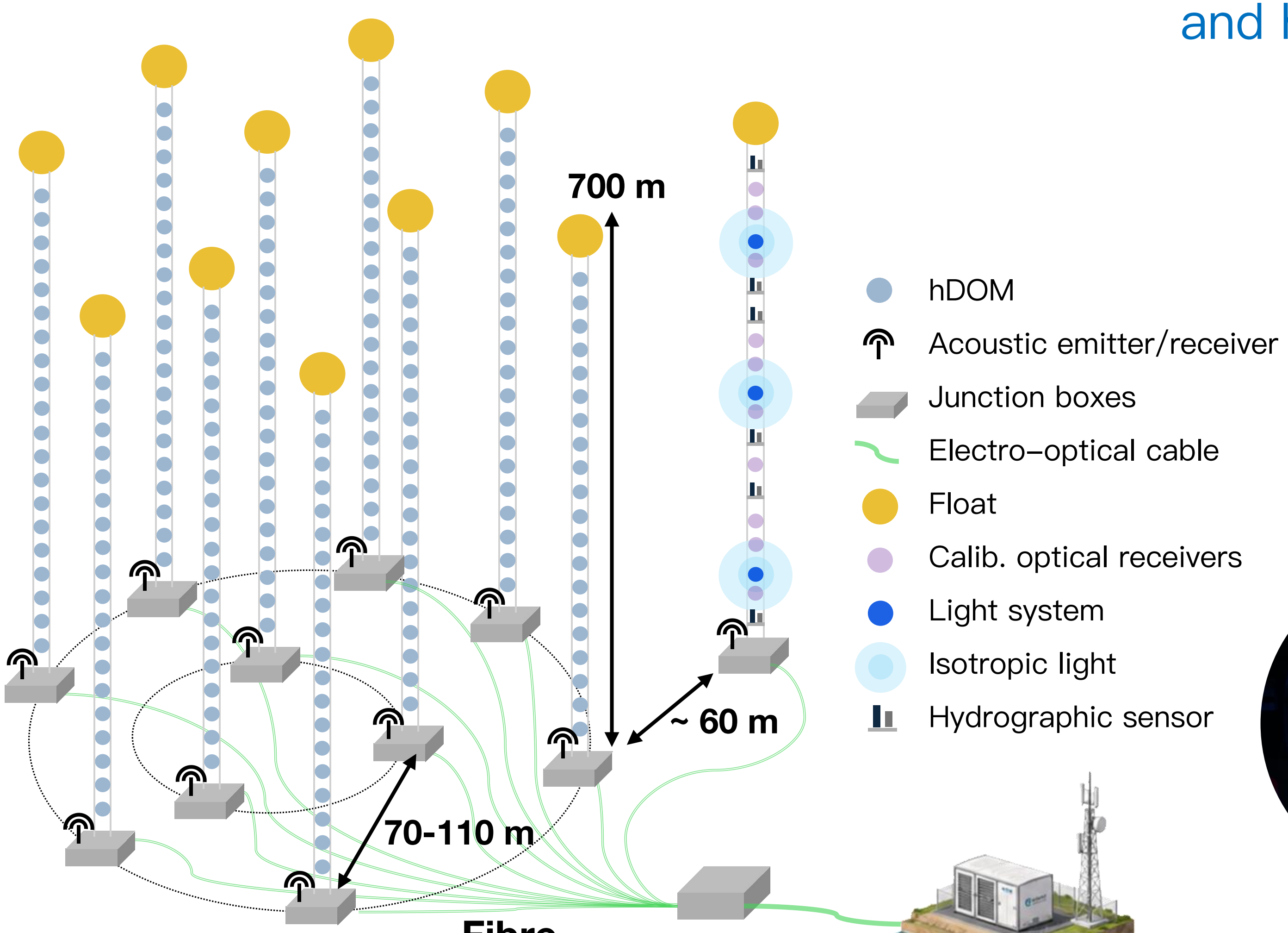
Y. Wang, et. al., PoS (ICRC 2025) 1209

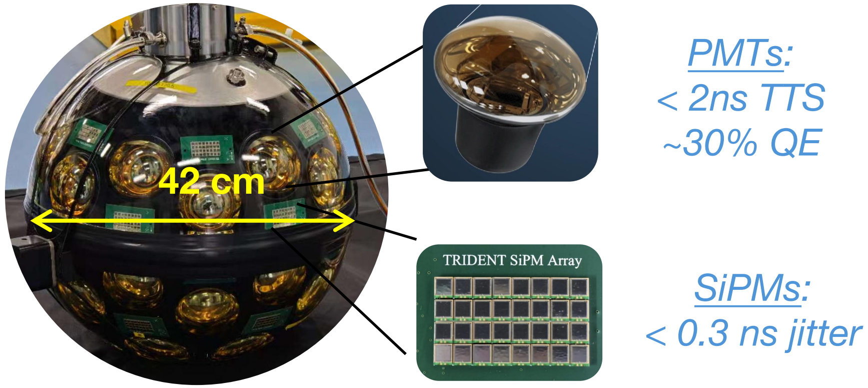
TRIDENT Phase-1

10 optical strings;
200 hybrid–DOMs

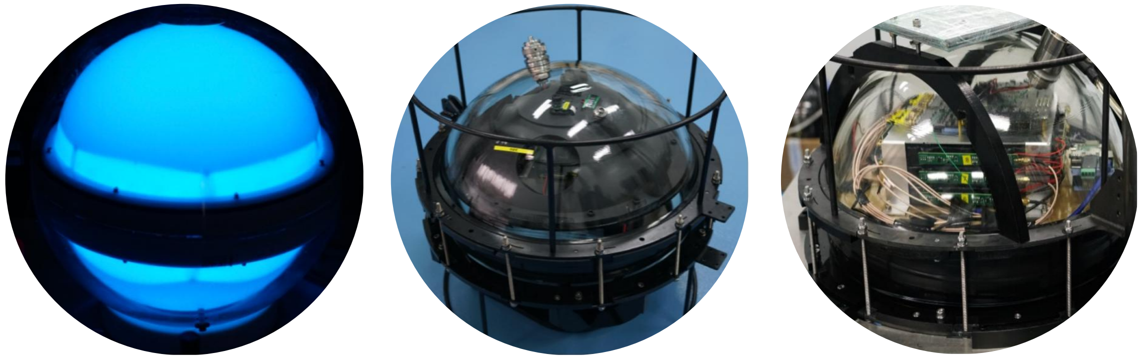
A dedicated
calibration string

- Real–time data transmitting and power supply
- Sub–ns time sync between calibration string and hDOMs





Z. Wei, et. al., PoS (ICRC 2023) 1213



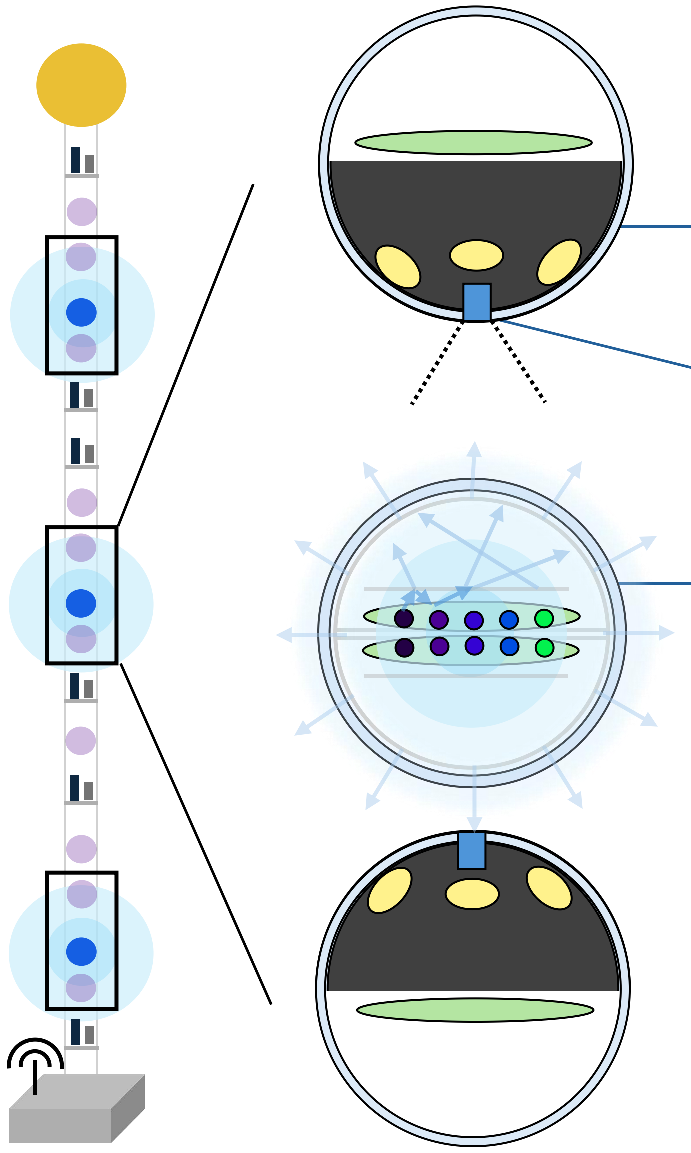
W. Li, et. al., NIM-A, 1056 168588 (2023)

W. Tian, et. al., NIM-A, 1076 170489 (2025)

J. Wu, et. al., JINST 20 P07035 (2025)

Y. Wang, et. al., PoS (ICRC 2025) 1209

Water Optical Calibration



Goal: monitor water optical properties on timescales of seconds at multiple wavelengths.

Light Receiving Module: Camera + PMT

GigE Camera: 5M pixels, 12 bit

25 mm lens: 16° viewing angle

Light Emitting Module: Continuous + pulsed modes

Y. Wang, et. al., PoS (ICRC 2025) 1209
W. Tian, et. al., NIM-A, 1076 170489 (2025)

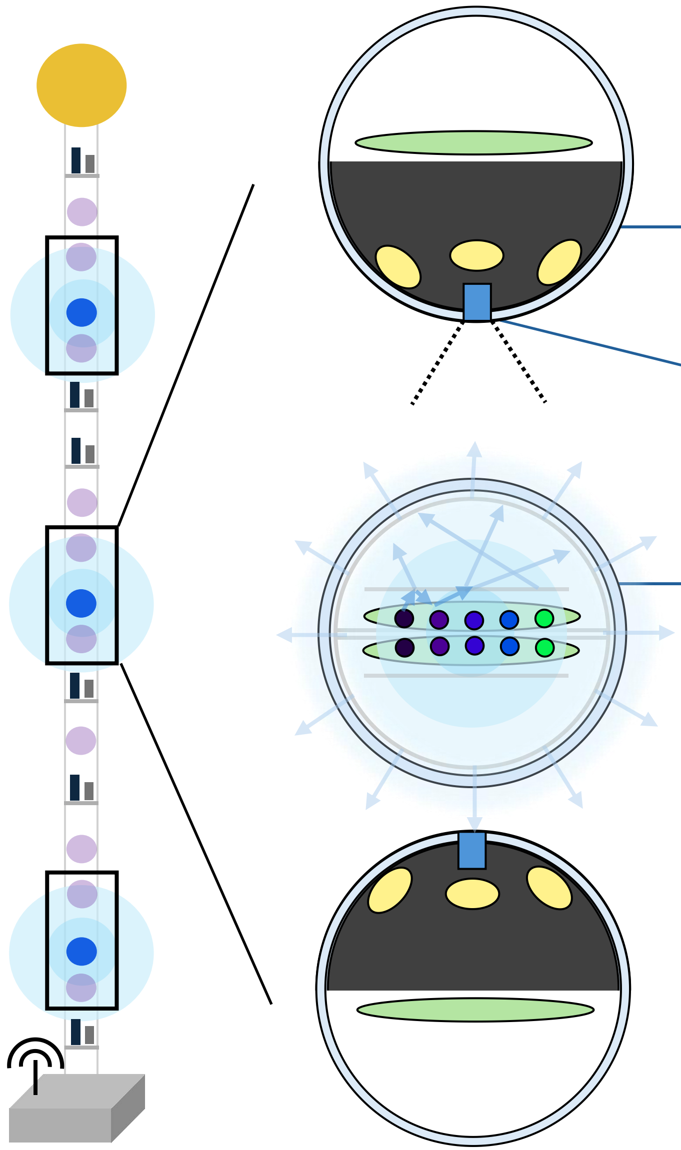
Two receiver distances → attenuation from relative intensity

Camera image halo → sensitivity to scattering

PMT SPE arrival–time distributions → absorption + scattering

Validated at previous site expeditions in 2021 and 2024

Water Optical Calibration



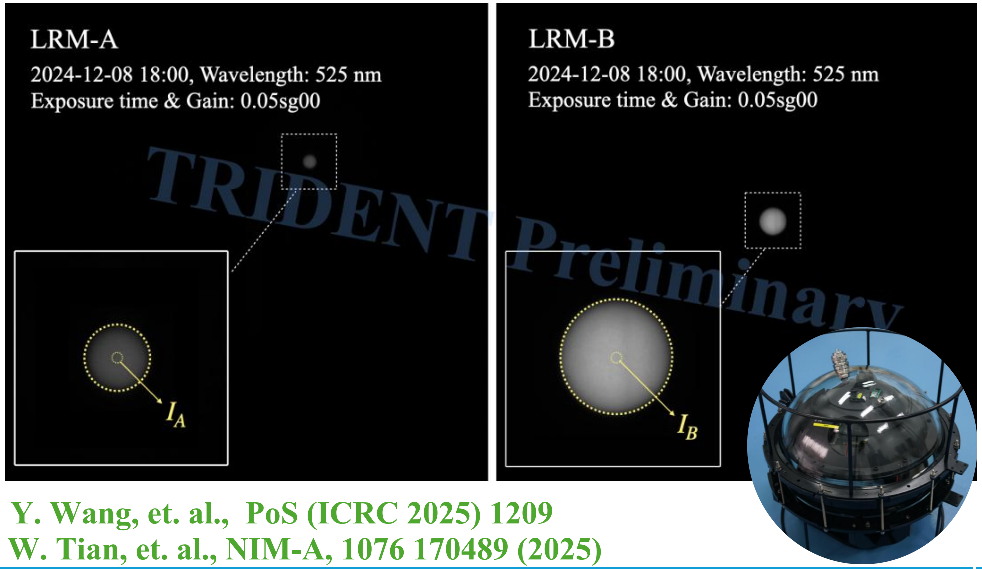
Goal: monitor water optical properties on timescales of seconds at multiple wavelengths.

Light Receiving Module: Camera + PMT

GigE Camera: 5M pixels, 12 bit

25 mm lens: 16° viewing angle

Light Emitting Module: Continuous + pulsed modes



Y. Wang, et. al., PoS (ICRC 2025) 1209
W. Tian, et. al., NIM-A, 1076 170489 (2025)

Two receiver distances → attenuation from relative intensity

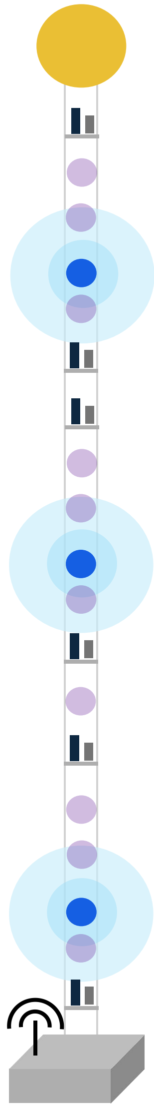
Camera image halo → sensitivity to scattering

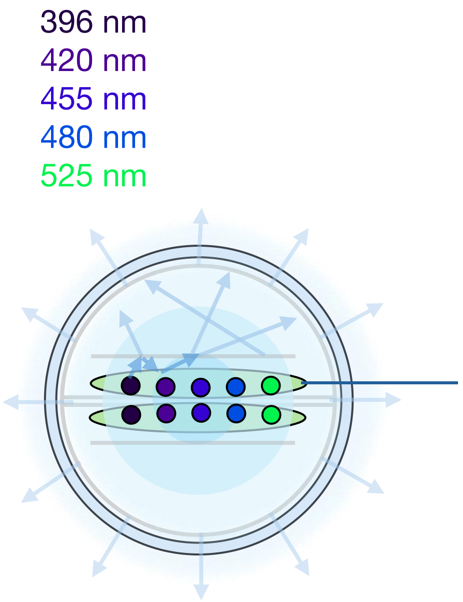
PMT SPE arrival–time distributions → absorption + scattering

Validated at previous site expeditions in 2021 and 2024

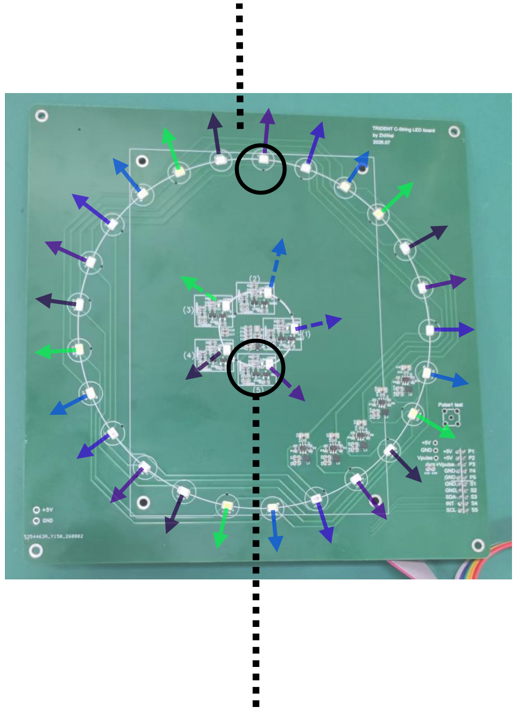
The Light System

One light system, two calibration functions:
water optics + timing response

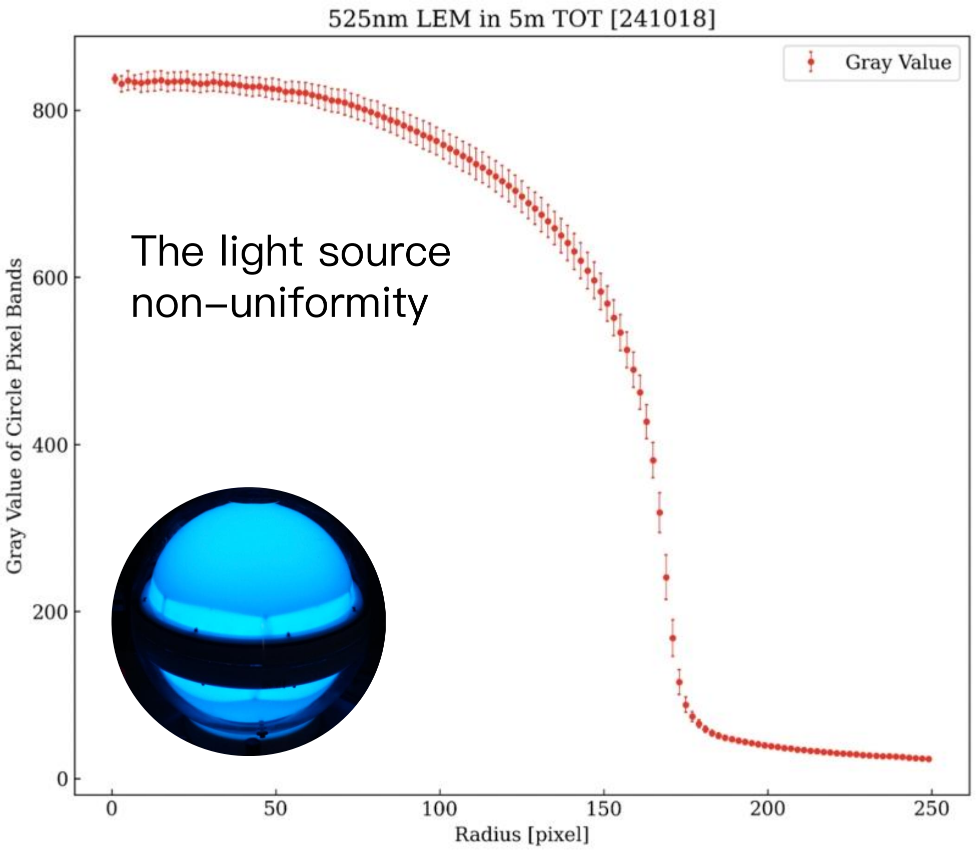




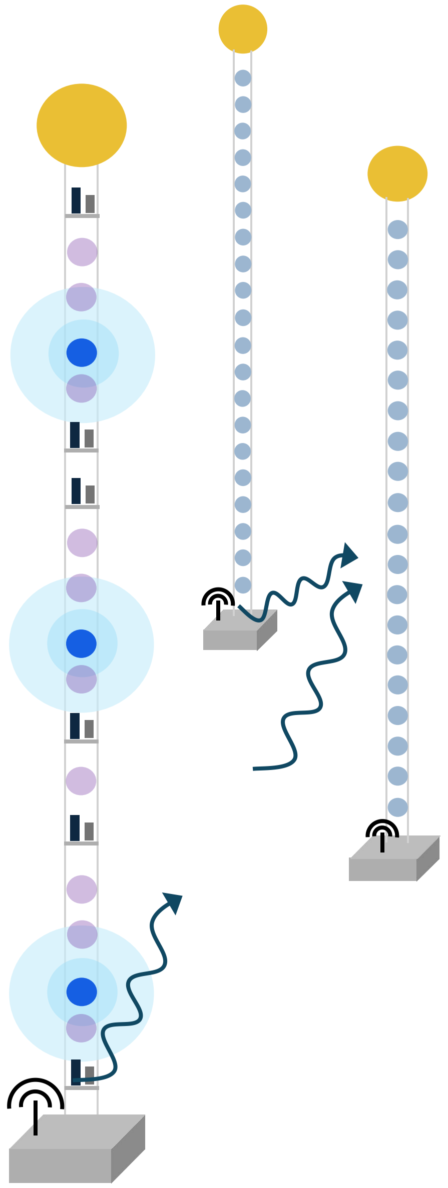
Continuous emitting mode supports camera-based water monitoring



Pulsed LEDs with < 5 ns pulse width; 1-10k
Same pulsed light source for PMT response and inter-DOM timing offsets.



Geometry: Acoustic Positioning



Acoustic receivers integrated in hDOMs

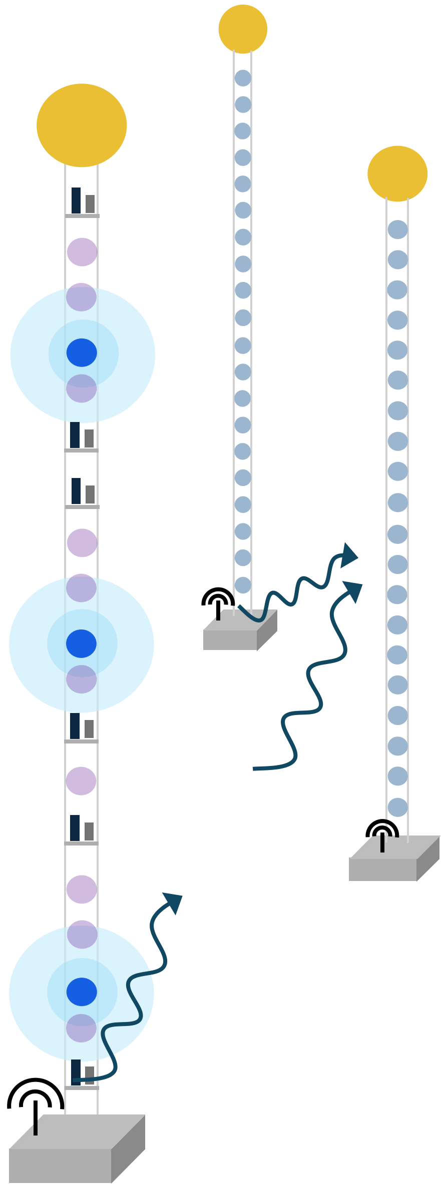
Piezo-acoustic sensors:
sensitive to 10k-70k Hz, -160 dB

Transmitters are deployed at string junction boxes

< 20 cm hDOM positioning precision is targeted to support sub-ns photon timing and ~0.1° track angular resolution at ~100 TeV.

J. Liu, et. al., Ocean Engineering, 347 124038 (2026)

Geometry: Acoustic Positioning

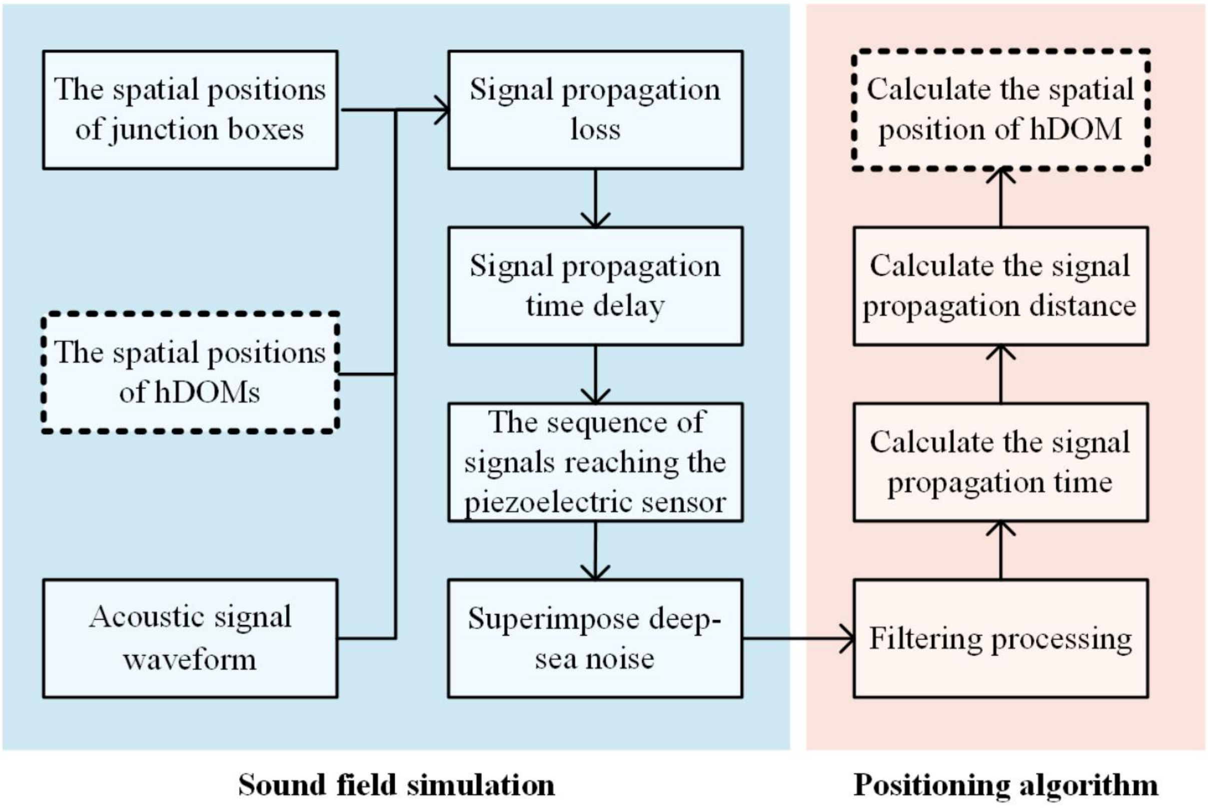


Acoustic receivers integrated in hDOMs

Piezo-acoustic sensors:
sensitive to 10k-70k Hz, -160 dB

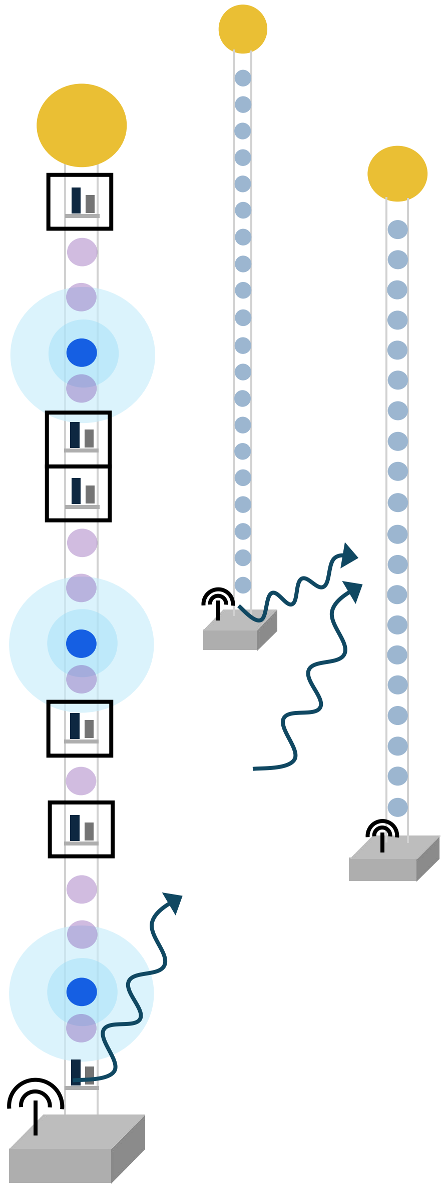
Transmitters are deployed at string junction boxes

< 20 cm hDOM positioning precision is targeted to support sub-ns photon timing and ~0.1° track angular resolution at ~100 TeV.



J. Liu, et. al., Ocean Engineering, 347 124038 (2026)

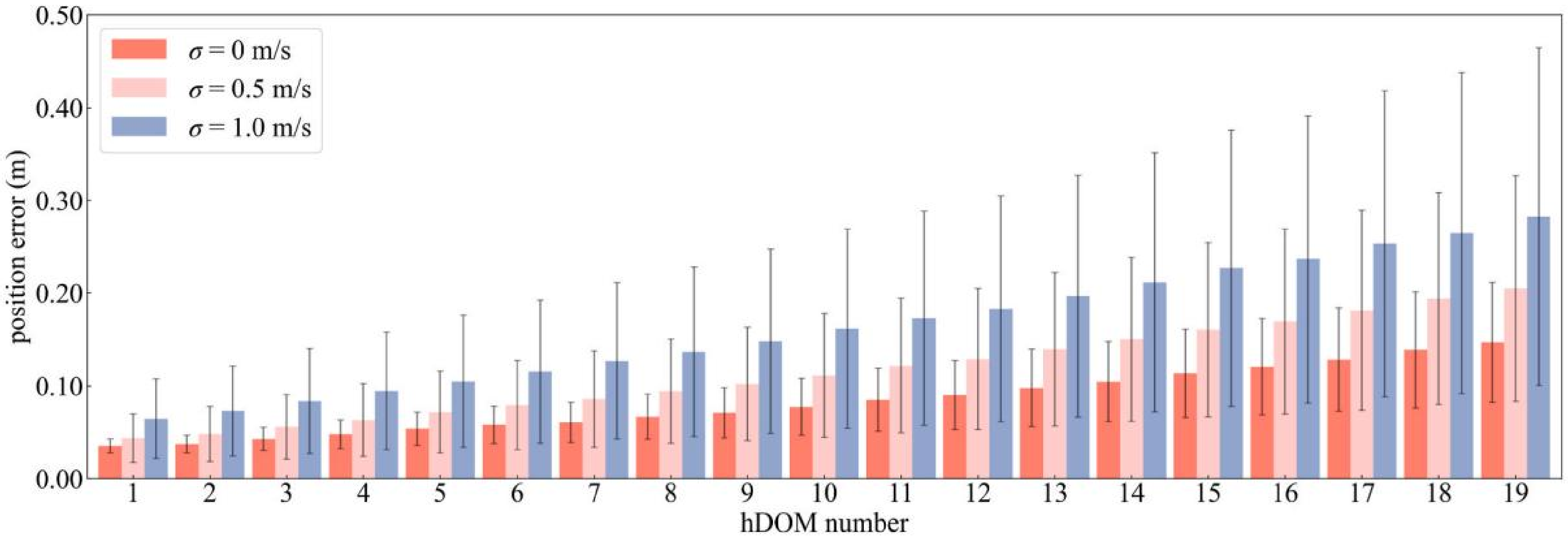
Geometry: Acoustic Positioning



Hydrographic measurements provide environmental inputs to the acoustic positioning model.

- Sound velocity + sea current profile

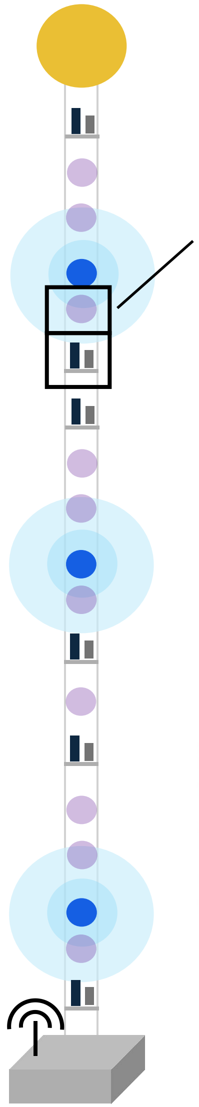
Real-time environmental inputs for acoustic positioning

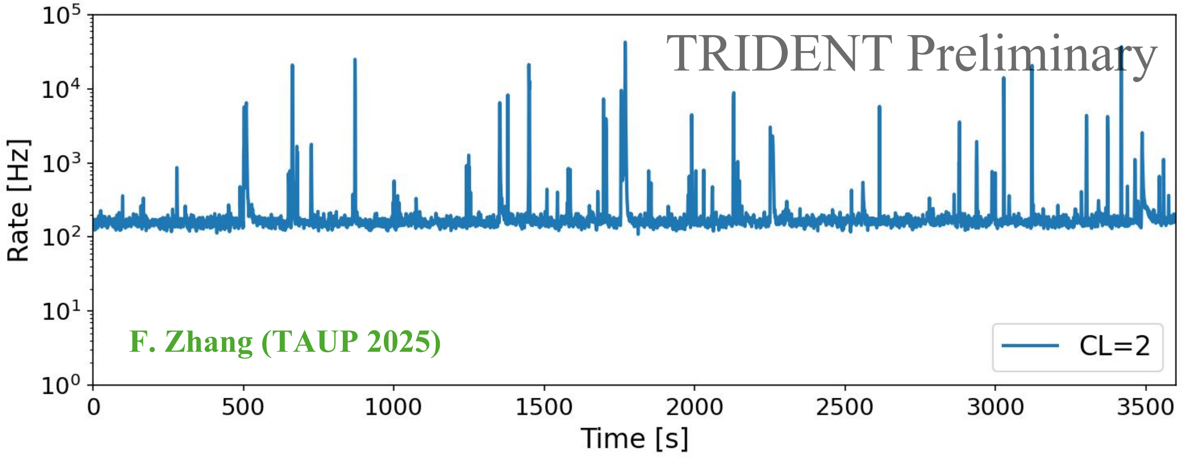


J. Liu, et. al., Ocean Engineering, 347 124038 (2026)

Optical Background: Bioluminescence

Aim: monitor background rate, variability, and environmental correlations





10^3 –10^5 trigger–rate bursts observed on seconds timescales

Camera + PMT: intensity, spatial and spectral information

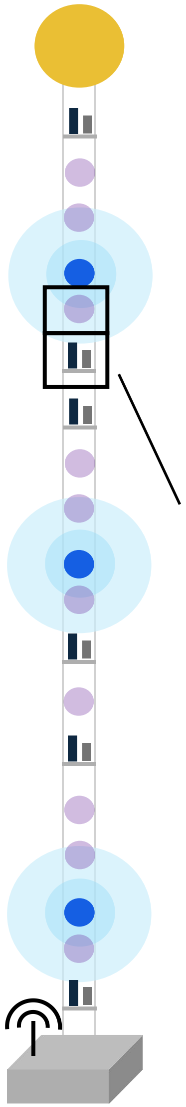
Correlation between bioluminescence and sea currents observed.

Hydrographic data → environmental inputs for background modelling

Optical Background: Bioluminescence

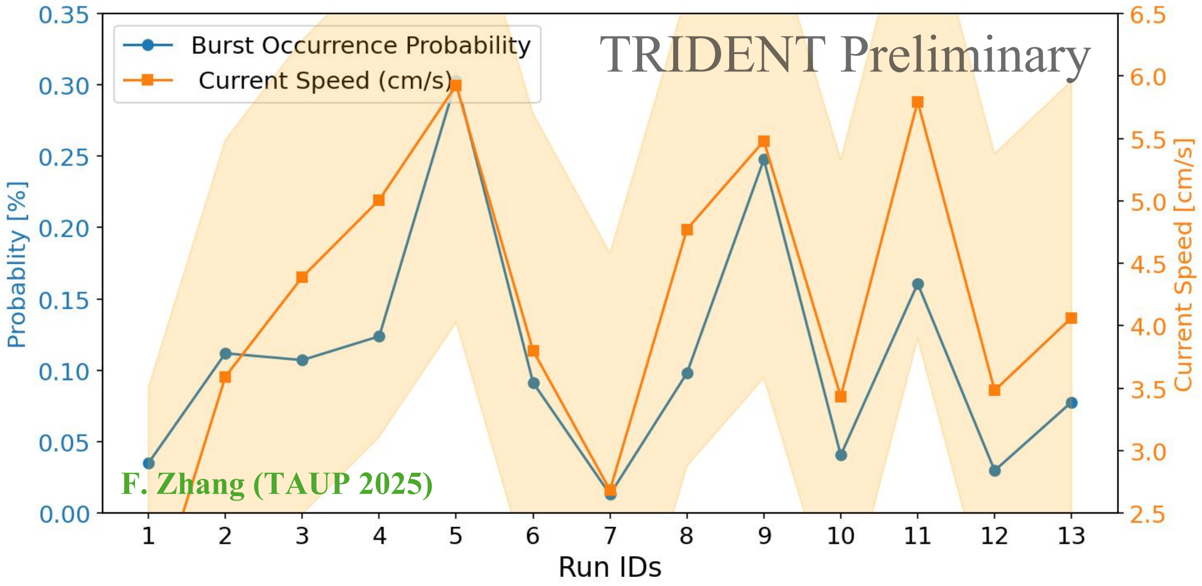
TRIDENT 海铃计划

Aim: monitor background rate, variability, and environmental correlations



10^3 –10^5 trigger–rate bursts observed on seconds timescales

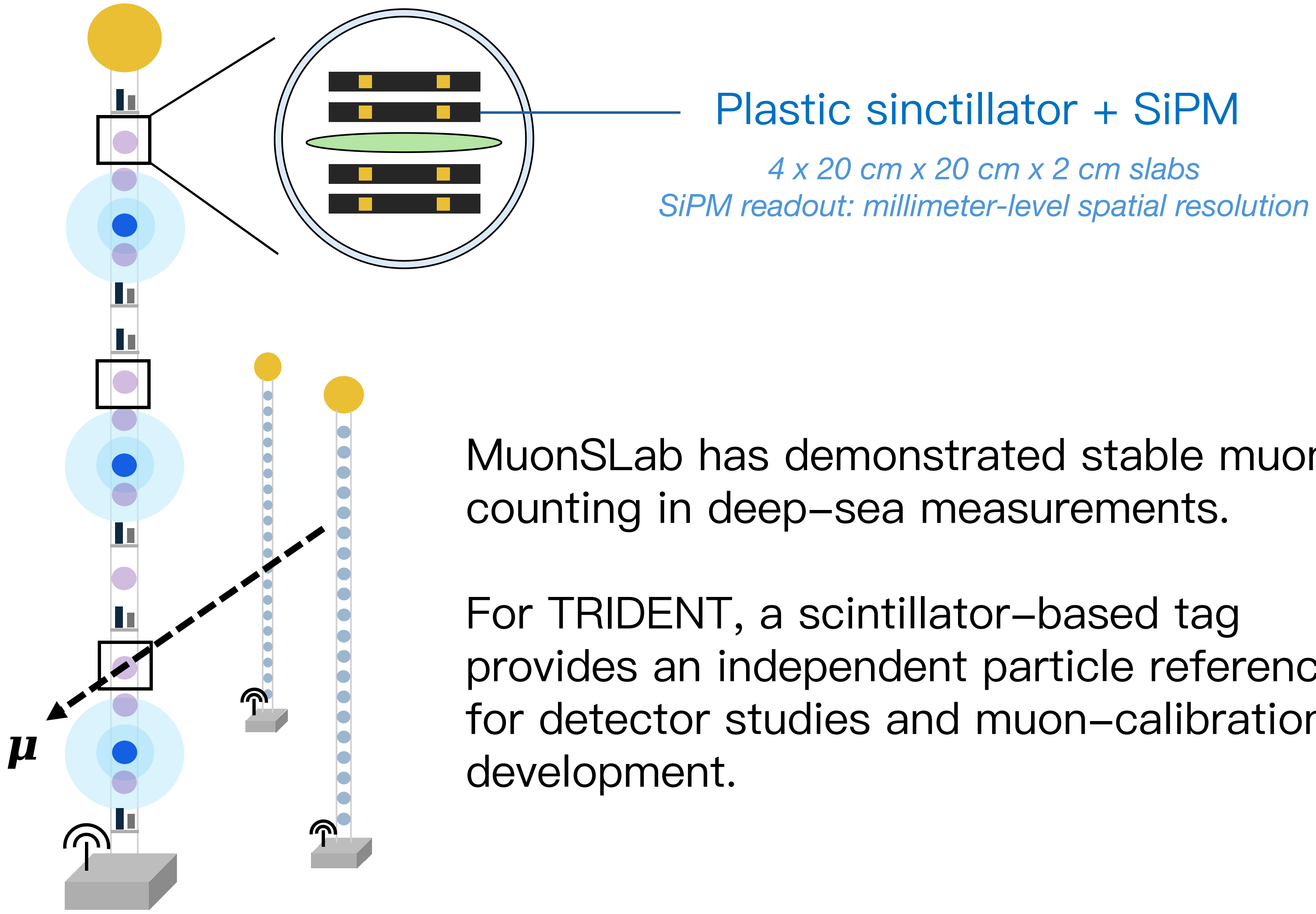
Camera + PMT: intensity, spatial and spectral information

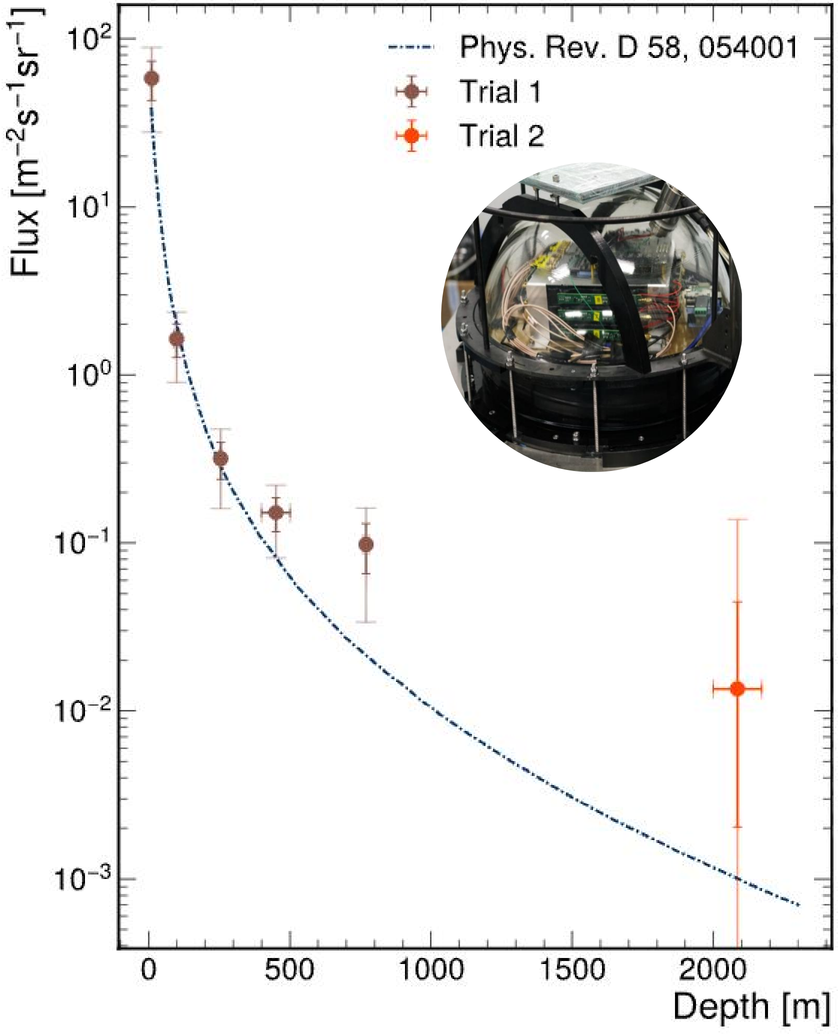


Correlation between bioluminescence and sea currents observed.

Hydrographic data → environmental inputs for background modelling

Independent Muon Tagging

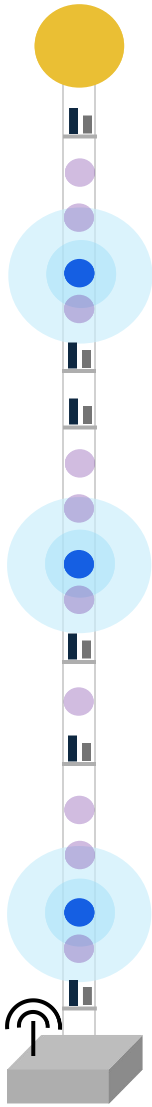




J. Wu, et. al., JINST 20 P07035 (2025)

MuonSLab has demonstrated stable muon counting in deep-sea measurements.

For TRIDENT, a scintillator-based tag provides an independent particle reference for detector studies and muon-calibration development.



Validated in sea trials

Optical calibration strategy

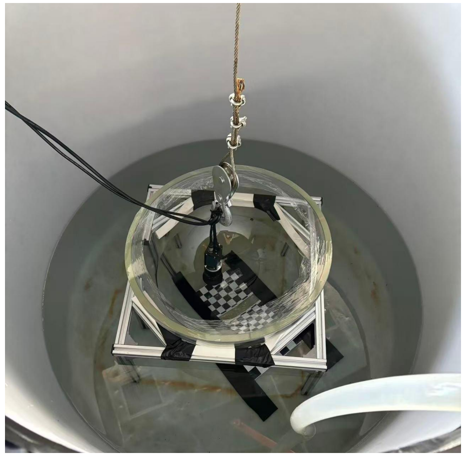
Muon tagging

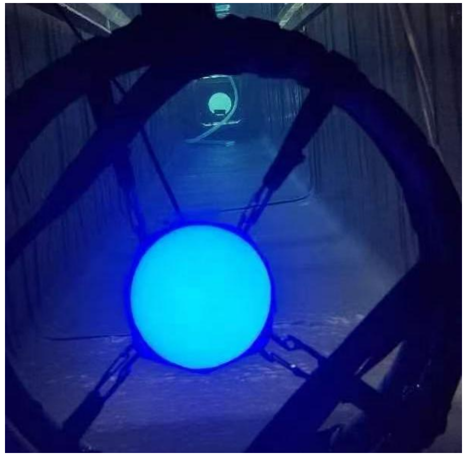
Deepsea conditions characterised

Bioluminescence and environmental correlations

*See **Fuyudi Zhang**'s talk on 2026/09/01*

The First Long-Term In-situ Performance of a Prototype Demonstrator for TRIDENT Neutrino Telescope





Conclusion

- A compact multi–purpose calibration system is under development
- Attenuation–length measurements using cameras and PMTs in 2021 and 2024 sea trials show consistency
- Optical background: camera + PMT + hydrographic information characterise background intensity and variability.
- Timing: pulsed LED + White Rabbit provide precise inter–DOM timing calibration.
- Geometry: precise acoustic positioning required underwater.
- Independent muon tagging: dedicated scintillator–based modules prepared.

Target Phase-1 operation: 2027

Running in the Dark, Calibrating the Way ...

TRIDENT 海 | 铃 | 计 | 划

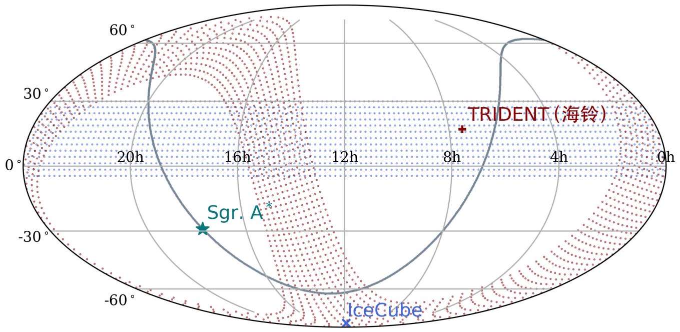
(Pic credit: Yingwei Wang)

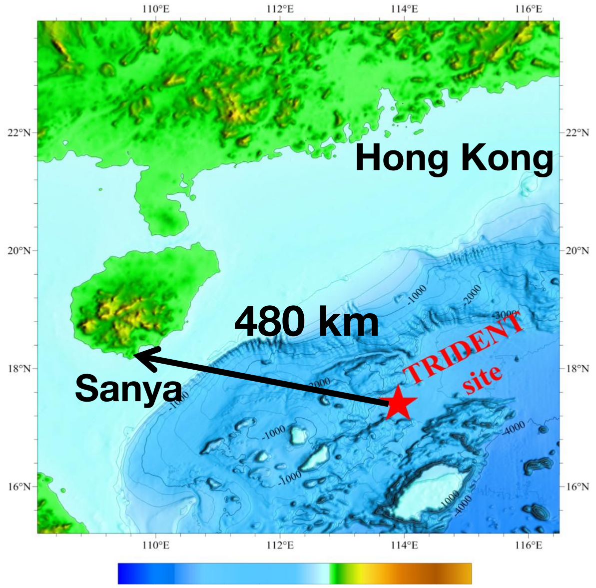
Thank you!

Backup

TRIDENT

- Planned for 8km³ in South China Sea
- 3.5 km deep, flat plane site chosen
- Close to equator for full-sky coverage

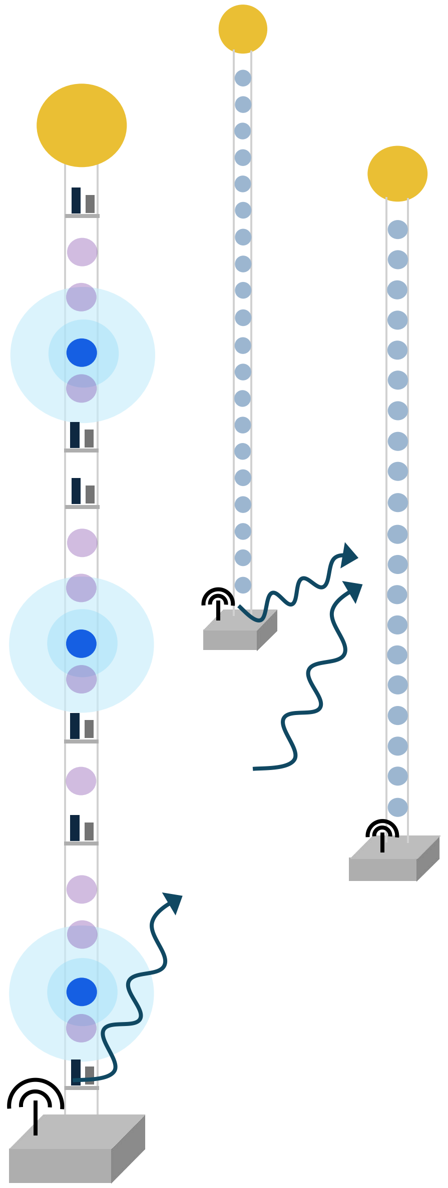




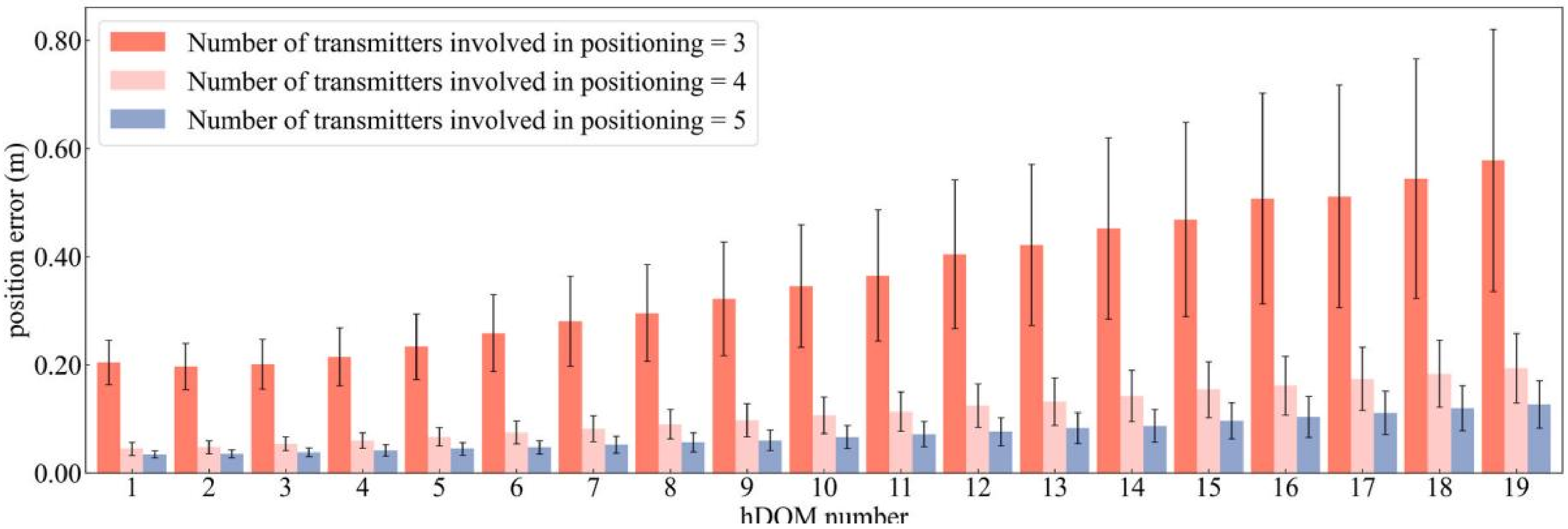
Scientific goals:
- **Point source searches**
- **All-flavour detection @ 100 GeV — EeV**

Detector design:
- Penrose tiling — Irregular 70–110 m string spacing.
- Curved wider pathways for inner string access, to reduce muon corridor events

Acoustic Positioning system



In total 11 transmitters, at least 5 will be used for positioning



J. Liu, et. al., Ocean Engineering, 347 124038 (2026)