PROCEEDINGS OF SCIENCE

# First observational results of Underwater Muon Detection System to Measure Coastal Mixed Layer Depth for Ocean and Climate Studies

**M. Akif Korkmaz*** **and M. Bilge Demirköz**

*Middle East Technical University,*
*Üniversiteler Mahallesi, Dumlupınar Bulvarı No:1 Çankaya, Ankara, TURKEY*

*E-mail:* akif.korkmaz@cern.ch, demirkoz@metu.edu.tr

After atmospheric muons enter the sea, a decreased muon count is observed at the bottom of water. Muon count is inversely proportional to the density of water which can be measured by counting muons at the bottom. Mixed Layer (ML) in Oceans is defined as the less dense upper region of the water column where turbulent mixing occurs. Mixed Layer Depth (MLD) is the depth of this region and shows diurnal, seasonal fluctuations, and spatial variations. MLD can be estimated by combining bottom muon count measurement with the sea surface temperature, salinity, and altimetry data from earth observing satellites. We constructed a scintillator based underwater muon detection system which can measure average water column density by counting surviving muons at the bottom. The detector system deployed in the North-Eastern Mediterranean at METU-IMS Harbour in Mersin/Turkey. Initial observations show consistent muon flux measurements with previous studies. In this work validation of muon detection was made for Mixed Layer Depth measurements. In order to calibrate the MLD estimation via muon count, water density measurements with CTD (Conductivity, Temperature, Depth) will be done simultaneously. In this work we will present our first measurements of atmospheric muon flux together with a simple approach to distinguish muons from other particles. This work is actualization of a previous study "Mixed Layer Depth Measurement in Coastal Waters Utilizing Atmospheric Muons" (10.1175/JTECH-D-24-0044.1) published in Journal of Atmospheric and Oceanic Technology.

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)306

## 1. Introduction

After their creation in the upper atmosphere, Atmospheric Muons reach the sea surface [1]. They exhibit an energy distribution that decreases with their energy [2]. At sea level, the contribution of the muons to the cosmic ray flux of charged particles is highest above energies higher than $1 GeV$ [2]. The sea level muon flux fluctuates 0.1% diurnally and 1% seasonally [3]. There are also Forbush decrease events in muon flux, while there is a coronal mass ejection that can decrease muon flux to 80% of its mean for $3 - 10$ days [4]. Muons reaching sea level continue their journey to depths of water while losing their energy. This results in a decrease in the muon count at the bottom of the water depending mainly on the density of the water column for a fixed depth [5].

In oceans and lakes, due to wind stress, precipitation, and freshwater input, there is a layer of water in the upper region that has an almost constant density and the depth of this layer is called Mixed Layer Depth (MLD) [6]. To study the chemical mixing rate that affects the biology and ecosystem of oceans, observation of variations in the depth of the mixed layer over time is important [7, 8]. As the mixed layer acts as a heat reservoir, the depth of the mixed layer is an indicator of climate change and variations [8]. Therefore, continuous observation of MLD in oceans is essential for atmosphere and climate studies. Current MLD measurement techniques can only provide momentary and localized data, so in this work a continuous measurement technique is proposed, especially for shallow coastal areas [9].

The decreased count of Atmospheric Muons at the bottom can be used to determine the density of the water column employing the Density Equation (1) [5]. In this equation, $\sigma_T$ is the depth-averaged density of the water column and $N_\mu$ is the ratio of surface and bottom muon counts for identical detectors placed at the bottom of the water and on the shore. The constants of $\alpha$ and $\beta$ depend on the total depth of the water column and can be determined by Geant4 simulations. Then the depth of the mixed layer (MLD) can be estimated using the MLD Equation (2) as a function of the total depth $z_T$ [5]. In this equation, $\sigma_t(0)$ and $\sigma_{bot}$ are the surface and bottom density of the water column, respectively.

$$\sigma_T = \alpha N_\mu + \beta \tag{1}$$

$$MLD = z_T \frac{\sigma_{bot} - \sigma_T}{\sigma_{bot} - \sigma_t(0)} \tag{2}$$

## 2. Deployment

To demonstrate this method, an underwater scintillator detector (MuB) and a surface scintillator detector (MuS) were deployed at METU-IMS Harbor (36.565 N 34.256 E) in the Mediterranean Sea together with a Ground Computational unit (GCU), as can be seen in Figure 1. For the underwater scintillator and the PMT unit, a water-tight casing has been made and deployed at depth $4.5m$ in the harbor (Figure 2). After connecting all entire system, an amplitude threshold value of $0.002V$ was chosen to collect the time, the maximum amplitude of the signal amplitude, and the area under the signal curve (Q) for each event. Using the initial data collected, muon event selection cuts were performed.


**Figure 1:** METU-IMS Harbor (36.565 N 34.256 E) and the position of the underwater scintillator (MuB) and the cabin housing the ground scintillator (MuS) and computational unit (GCU) .

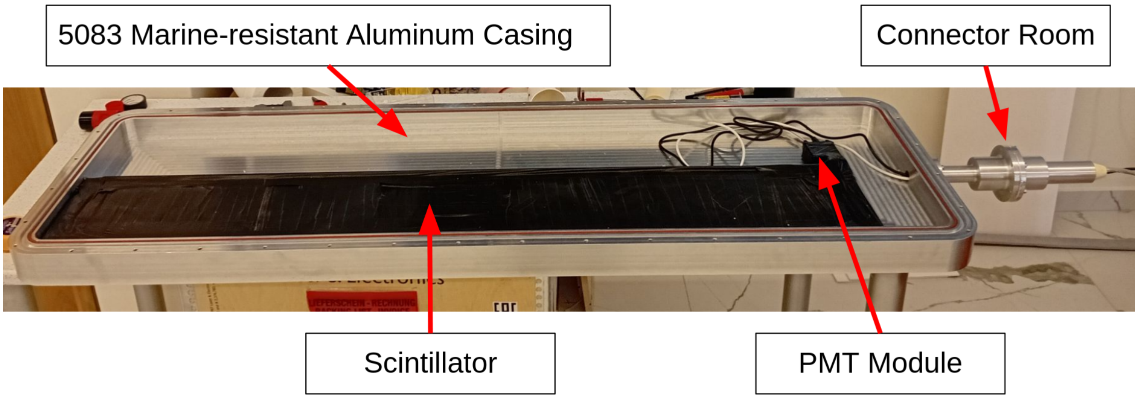


**Figure 2:** The water-tight casing for the underwater scintillator module, the bottom scintillator and the PMT module.

## 3. Results and Discussion

The area under the signal curve (Q) of each event for the surface scintillator (green) and the bottom scintillator (blue) can be seen in Figure 3. Although muon signals from the surface scintillator can be easily identified between $Q = 100$ and $Q = 150$ with a peak in the count, the bottom scintillator showed weaker signals due to power loss inside long cables. To see muon signals from the bottom scintillator, the area (Q) / the maximum signal amplitude was calculated as a representation of the signal length in time, as can be seen in Figure 4.

First, an amplitude cut greater than $0.005V$ was applied to both the data from the bottom and the surface scintillators to eliminate noise. Since most of the background from gammas and electrons cannot reach the bottom scintillator, the remaining events from the bottom scintillator after the first

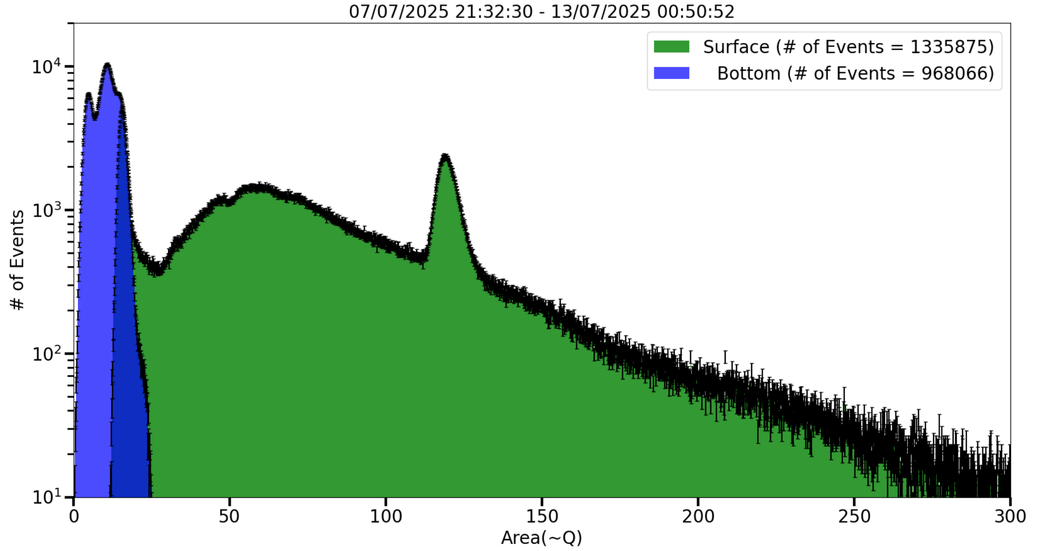


**Figure 3:** The area under the signal curve (Q) distribution for surface (green) and bottom (blue) scintillators.

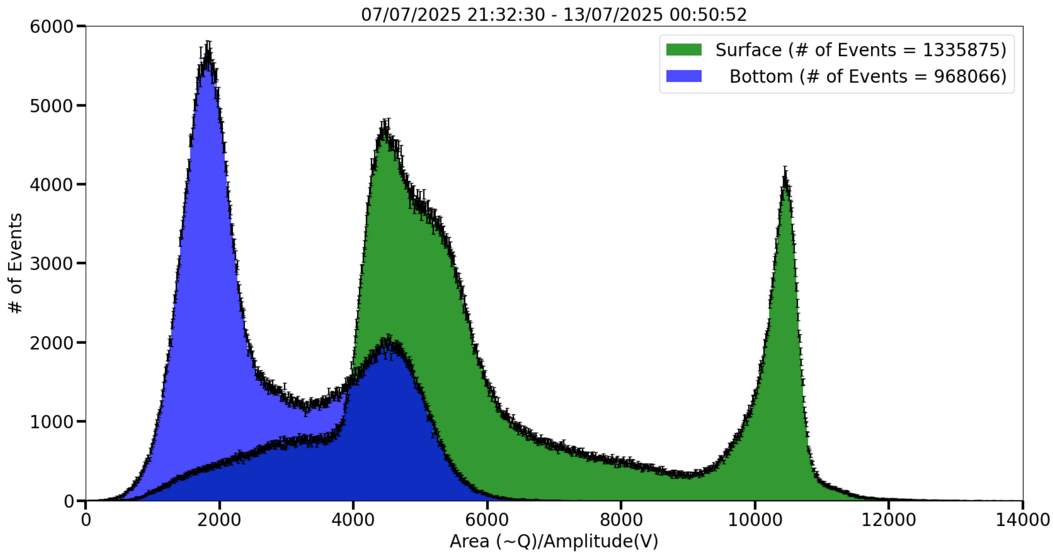


**Figure 4:** The signal length (Area/Amplitude) distribution for surface (green) and bottom (blue) scintillators.

cut are accepted as muon signals, as can be seen in Figure 5. Then a second cut was made on the area under the signal curve to eliminate the background for the surface scintillator. Both cuts and the remaining events can be seen in Figure 6. These events are accepted as muon signals from the surface scintillator.

The results of the cuts on the signal length representation can be seen in Figures 7 and 8 for the surface and bottom scintillators, respectively.

After the selection of events, the ratio of the bottom muon events to the surface muon events was calculated to be $N_\mu = 0.73$. Employing the constants found from Geant4 simulations to the

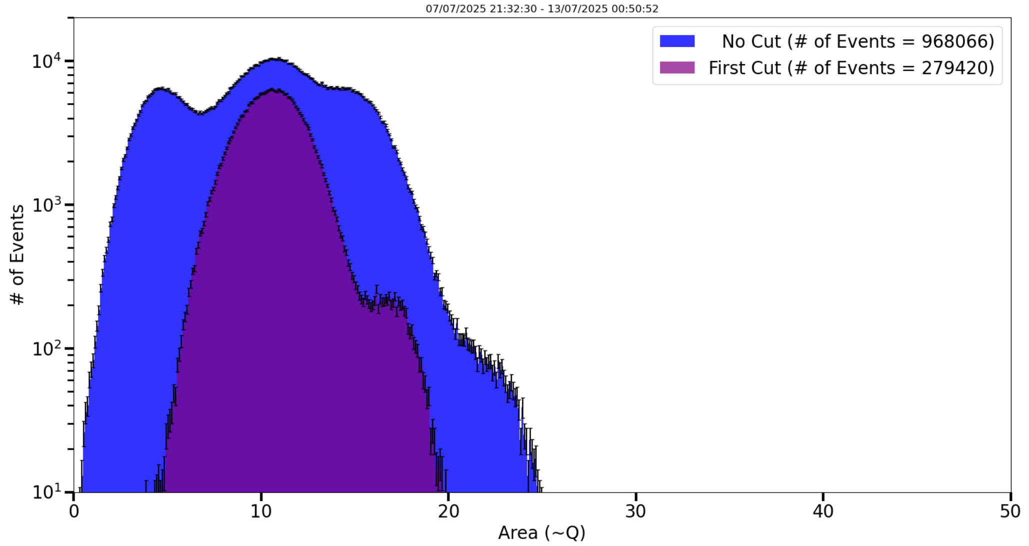


**Figure 5:** The area under the signal curve (Q) distribution for bottom scintillator before (blue) and after (purple) selection cuts.

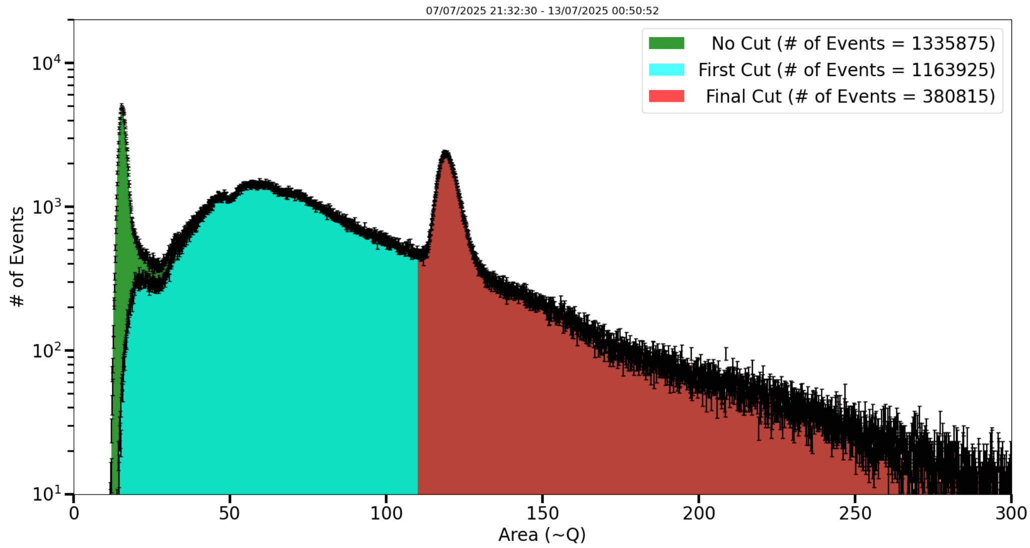


**Figure 6:** The area under the signal curve (Q) distribution for surface scintillator before (green), after first cut (cyan) and second cut (red).

Density Equation (1), Figure 9 was plotted. The ratio found indicates a depth-averaged density of $1020g/cm^3$ for the water column. In Figure 10, this mean density value is inserted into the MLD Equation (2) for a surface density of $1018g/cm^3$ and the Mixed Layer Depth is drawn against the bottom density. Finally, MLD is found to be around $3.5m$ for an expected bottom density between $1027.5g/cm3$ and $1030g/cm^3$ during the experiment.

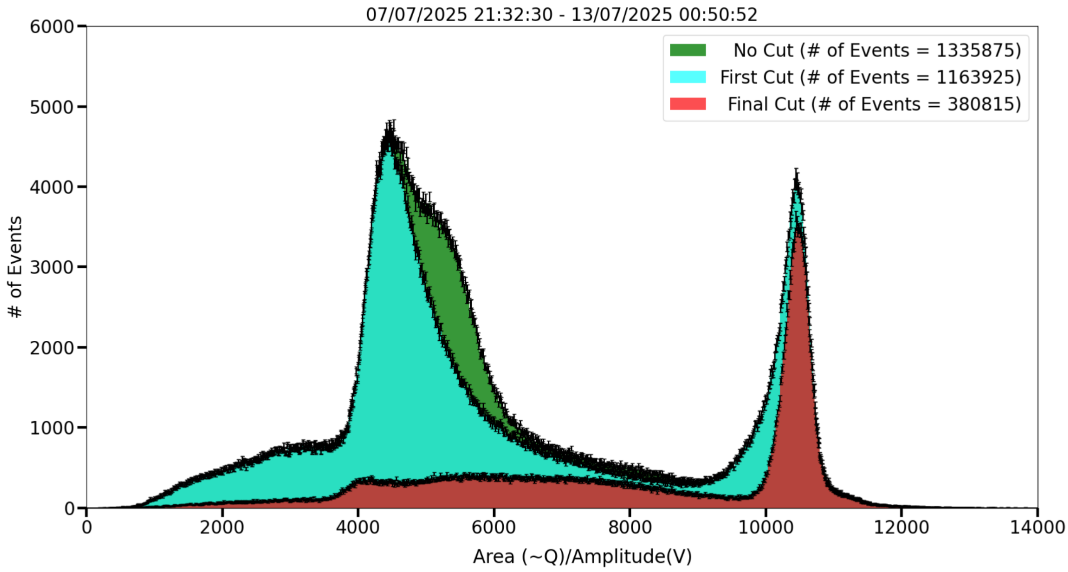


**Figure 7:** The signal length (Area/Amplitude) distribution for surface scintillator before (green), after first cut (cyan) and second cut (red).

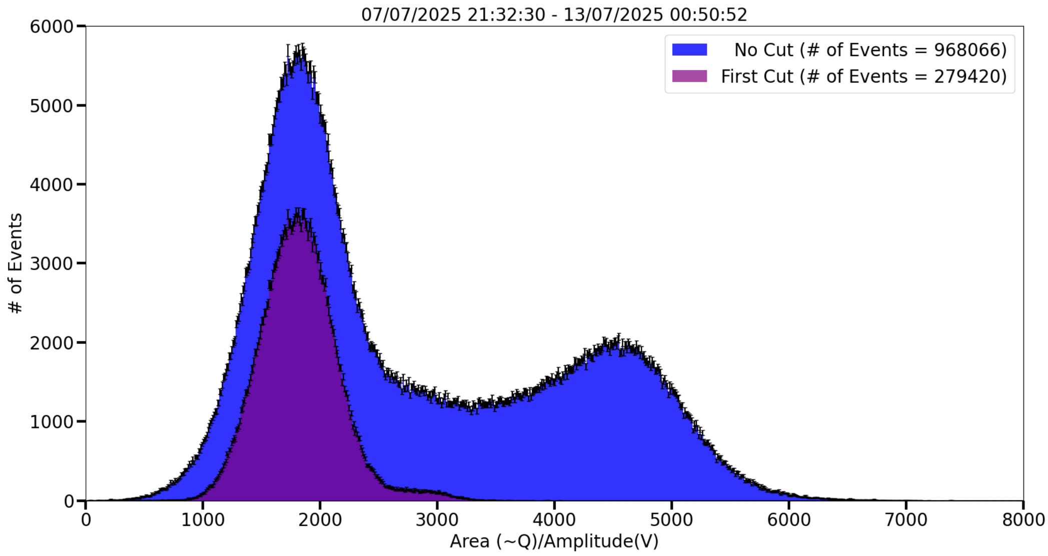


**Figure 8:** The signal length (Area/Amplitude) distribution for bottom scintillator before (blue) and after (purple) selection cuts.

## 4. Conclusion and Prospects

It is shown that muon signals can be distinguished from other particles, such as electrons and gammas, by applying a range selection on the amplitude distribution and then another selection on the signal area distribution. By comparing sea surface muon count and bottom muon count, water column density and Mixed Layer Depth can be calculated using the density and MLD equations.

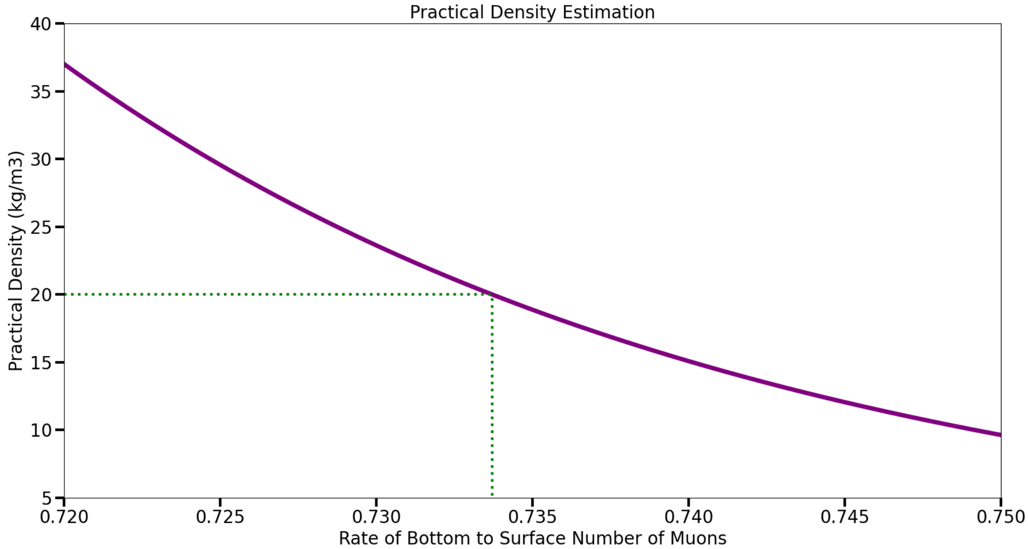


**Figure 9:** Practical density estimation using the Equation (1). Dotted lines shows the experimental results.

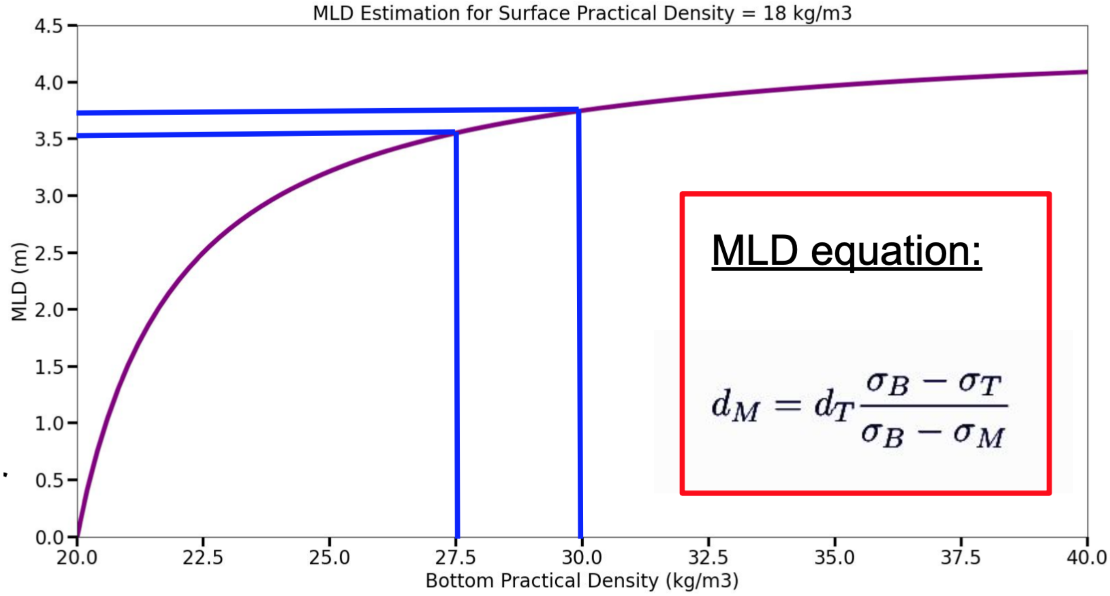


**Figure 10:** Mixed Layer Depth (MLD) estimation using the Equation (2).

The next step of this work will be to collect more data to perform MLD estimations and to validate the method with conventional MLD measurements.

## References

[1] M. Barrantes, J. Valdés-Galicia, O. Musalem, A. Hurtado, M. Anzorena, R. García et al., *Atmospheric corrections of the cosmic ray fluxes detected by the solar neutron telescope at the summit of the sierra negra volcano in mexico*, *Geofísica internacional* **57** (2018) 253.

[2] S. Cecchini and M. Spurio, *Atmospheric muons: experimental aspects*, *Geoscientific Instrumentation, Methods and Data Systems* **1** (2012) 185.

[3] V. Shutenko, I. Astapov, N. Barbashina, A. Dmitrieva, R. Kokoulin, K. Kompaniets et al., *Long-term variations in the muon flux angular distribution*, *Geomagnetism and Aeronomy* **53** (2013) 571.

[4] I. Braun, J. Engler, J.R. Hörandel and J. Milke, *Forbush decreases and solar events seen in the 10–20 gev energy range by the karlsruhe muon telescope*, *Advances in Space Research* **43** (2009) 480.

[5] M.A. Korkmaz and M.B. Demirköz, *Mixed layer depth measurement in coastal waters utilizing atmospheric muons*, *Journal of Atmospheric and Oceanic Technology* **42** (2025) 125.

[6] G.M. Damerell, K.J. Heywood, D. Calvert, A.L. Grant, M.J. Bell and S.E. Belcher, *A comparison of five surface mixed layer models with a year of observations in the north atlantic*, *Progress in Oceanography* **187** (2020) 102316.

[7] R.E. Thomson and W.J. Emery, *Data analysis methods in physical oceanography*, Newnes (2014).

[8] S. Liang and J. Wang, *Advanced remote sensing: terrestrial information extraction and applications*, Academic Press (2019).

[9] S. Xiao, M. Zhang, C. Liu, C. Jiang, X. Wang and F. Yang, *Ctd sensors for ocean investigation including state of art and commercially available*, *Sensors* **23** (2023) 586.