Sintilatör Tabanlı Müon Dedektörüyle Osmaniye Bölgesinde Müon Akı Yoğunluğu Ölçümü ve Atmosferik Basıncın Etkisi

Mahmut GÜDEN[1*], Ahmet POLATOĞLU[2]

[1]Department of Astronomy and Astrophysics, Graduate School of Natural and Applied Sciences, Atatürk University, Erzurum, Türkiye

[2]Department of Astronomy and Space Science, Faculty of Sciences, Atatürk University, Erzurum, Türkiye

[1]https://orcid.org/0009-0007-5170-0428
[2]https://orcid.org/0000-0002-6562-8566
*Corresponding author: gudenmahmut@gmail.com

Araştırma Makalesi

ÖZ

Bu çalışma, Türkiye'nin Osmaniye ili Düziçi ilçesinde, taşınabilir ve düşük maliyetli bir sintilasyon dedektörü ile gerçekleştirilen ilk kozmik ışın müon akısı ölçüm sonuçlarını sunmaktadır. 950400 saniyelik ölçüm süresince kaydedilen 42868 olaydan, istatistiksel filtreleme sonrası 36437'si gerçek müon olarak belirlenmiştir. Ölçüm noktasında ortalama müon akısı 0.0099 ± 0.0001 cm⁻² sr⁻¹ s⁻¹ olarak bulunmuştur (deniz seviyesinden 272 m yükseklikte). Ölçüm verileri atmosferik basınç değişimine göre düzeltilmiş ve barometrik katsayı (β) üstel uyumla hesaplanmıştır. Ayrıca, bölgenin manyetik enlemi (33,7°) ve cutoff/kesme rijiditesi (7,17 GV) belirlenerek yerel kozmik ışın ortamı karakterize edilmiştir. Ayrıca veriler uluslararası nötron monitör verileri ile de karşılaştırılmıştır. Sonuçlar, taşınabilir dedektörlerle güvenilir müon akısı ölçümlerinin mümkün olduğunu ve bu çalışmanın bölge için önemli bir referans niteliği taşıdığını göstermektedir.

Measurement of Muon Flux Density in Osmaniye Region with Scintillator-Based Muon Detector and Effect of Atmospheric Pressure

Research Article

ABSTRACT

This study presents the first experimental measurement of cosmic ray muon flux in Düziçi, Osmaniye, Turkey, using a portable, low-cost scintillation detector with Time-of-Flight (TOF) capability. Over a measurement period of 950400 seconds, the system recorded 42868 events, from which 36437 genuine muons were identified after statistical filtering. The average muon flux at the site was found to be 0.0099 ± 0.0001 cm⁻² sr⁻¹ s⁻¹ at an altitude of 272 meters above sea level. Atmospheric pressure corrections were applied, and the barometric coefficient (β) was determined via exponential fit. The local magnetic latitude (33.7°) and cutoff rigidity (7.17 GV) were also calculated to characterize the site's geomagnetic environment. The data were also compared with international neutron monitor data. The results demonstrate the effectiveness of portable detector systems for reliable muon flux measurements, and establish a baseline for future cosmic ray studies in the region.

1. Introduction

Cosmic rays (CRs) are relativistic particles of mostly extragalactic and solar origin, dominated by protons and light nuclei (≈98%). Upon interaction with the Earth's atmosphere, they generate cascades of secondary particles through hadronic interactions, providing a unique probe of their composition and propagation processes (Dorman, 2004). The study of these cascades is fundamental for understanding both the astrophysical sources of CRs and their modulation by heliospheric and geomagnetic conditions. One of the most important components of secondary cosmic particle showers is the muon particle. Muons, as heavy leptons (~200 × electron mass), constitute the most abundant charged component of secondary cosmic radiation at ground level due to their comparatively long decay length and reduced energy loss in matter (Gaisser et al., 2016). Although their rest-frame mean lifetime is only 2.2 μs, the relativistic dilation effect allows a substantial fraction to penetrate the entire atmospheric column and be observed at sea level. This phenomenon provides a classical experimental verification of special relativity but, more importantly for cosmic-ray physics, establishes muons as the most accessible probe of atmospheric shower development (Zhao et al., 2025). The rate at which muons reach the Earth varies from sea level to high altitudes. As the density of the atmosphere increases, muons interact with more matter, undergo decay and lose their energy. Therefore, muon measurements at different altitudes are critical for understanding the effects of factors such as atmospheric density, magnetic field variations and solar activity on muon flux (Al-Qaaod et al., 2025). Muon monitoring is a fundamental research area in understanding the origin of CRs and their effects on Earth.

A broad range of experiments have been devoted to the detection of atmospheric muons, employing various techniques from scintillator arrays to large-scale water Cherenkov detectors. Time-of-Flight (TOF) measurements with scintillation counters remain one of the standard approaches for resolving particle velocities and directions, as demonstrated in large collaborations such as Main Injector Neutrino Oscillation Search (MINOS) (Michael et al., 2008) and outreach-oriented projects like Cosmic Muon Observer (CosMO) (Franke et al., 2013). Regional-scale observatories, including the Latin American Giant Observatory (LAGO), have further highlighted the potential of distributed detectors for statistical studies of flux variations (Sidelnik and Asorey, 2017). Nevertheless, systematic evaluations of small-scale, portable scintillator systems—particularly in terms of timing resolution, efficiency, and robustness under field conditions—remain relatively scarce in the literature. In particular, issues such as time resolution, efficiency and positional accuracy of small scintillation detectors need further research. There are also gaps in the standardization of methods used in data analysis (e.g. statistical error analysis, event separation) (Denisov et al., 2016). In TOF measurements, the comparability of the results is reduced when the calibration of the timing electronics is not given enough detail. In muon measurement projects, event selection criteria (e.g. coincidence time, threshold values) are not clearly defined, increasing measurement uncertainties. In addition, in experiments with small detectors, the effect of background noise and ambient conditions is not adequately controlled. This limits data

interpretation. In some systems, directional sensitivity was insufficient and TOF data were limited to average velocity estimates.

In this study, we focus on the analysis of muons reaching the atmosphere through CRs using a scintillation detector and TOF method. In particular, the aim is to increase the reliability and accuracy of the data obtained with low-cost and portable detector systems and to reduce uncertainties in time resolution and orientation precision in small-scale experiments. The main problem addressed in the study is the reliable calculation of the local muon flux based on TOF-based muon measurements performed in a rural and relatively low-altitude region, and the physical interpretation of these data through analysis. The measurements were carried out in Düziçi district of Osmaniye province. Using the data obtained from this measurement point with the TOF method, the muon count was analyzed, the muon flux was calculated and the results were compared with similar studies in the literature. In this way, it is aimed to provide new data on the place and potential applications of local muon analysis in the context of global CRs physics. Osmaniye's location near sea level offers a significant advantage for analyzing how muons are distributed in the lower layers of the atmosphere and how their densities vary. While muon measurements at high altitudes are carried out in thinner atmospheric conditions, measurements near sea level take place in a denser atmospheric environment. This difference helps us understand how the muon flux varies with atmospheric processes. Charged particles from the Sun can affect the CRs flux by interacting with the Earth's magnetic field. This effect varies at different latitudes and in different geographical regions. Muon measurements in Osmaniye are an important data source for CRs physics, atmospheric science and astroparticle physics to study the magnetic field properties of the region and the effects of solar activity on this field. No previous experimental muon measurements have been made in Osmaniye province. The fact that this paper is a first for the region makes our study important.

2. Material and Methods

2.1. Experimental Setup and Location

The portable Cosmic Ray Muon Detector system used in the study has a modular hardware architecture consisting of two plastic scintillators, a photomultiplier tube (PMT), a DRS4-based signal readout and timing board, and a computer, as seen in Figure 1. The plastic scintillators, polystyrene-based blocks positioned at a fixed distance from each other, convert the energy of muon particles in the atmosphere into light. This light is converted into primary photoelectrons at the PMT's photocathode, and a multiplier mechanism in the dynode stages increases the number of photoelectrons by a factor of about 10^6 and converts them into a measurable electrical signal. The PMT output is transmitted to the DRS4 board via low impedance coaxial cables. The DRS4 board captures the signal with high fidelity using analog buffering technology with a sampling rate of 5 gigasamples per second and bandwidth up to 1 GHz, while integrated Field Programmable Gate Array (FPGA) hardware handles signal triggering, time

stamping and pre-processing. In the final stage, the processed event data is transferred to the PC via USB 3.0 or Gigabit Ethernet connection, where it is integrated into the raw data set (Polatoğlu et al., 2023).

The system is designed to simultaneously obtain muon flux measurement and particle time-of-flight information. When a muon enters the upper scintillator and produces a short burst of fluorescence and this interaction exceeds the set amplitude threshold, the signal recorded by the PMT is instantaneously triggered in DRS4. In the event that the same particle generates fluorescence above the threshold value in the sub-scintillator, the FPGA verifies the coincidence of the signals over a fixed distance (d) and the time difference (Δt) between the two signals is calculated using the TOF method. The calculated Δt and signal amplitude information is stored in the computer for each muon event. This data structure allows analysis of muon flux density, energy spectrum and direction of incidence. The detector system provides an ideal platform for field studies and educational applications due to its low cost, portability and high time resolution with the nanoscale method. Data about the plastic scintillator, redout system and photomultiplier sensor are presented in Table 1.
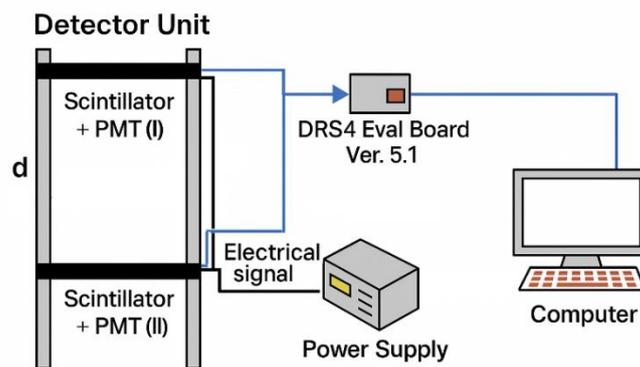

Figure 1. Portable cosmic muon measurement system diagram

Table 1. Equipment and Features of the System (Polatoğlu et al., 2023)

Shalomoe SP101	Made of polystyrene, this device is a plastic scintillator with high vibration power. Size (mm); 50x50x15 Density; 1.02 g.cm-3 Refractive index; 1.58 Operating Temperature; -40 ∘C to 55 ∘C Maximum emission wavelength; 423 nm
Hamamatsu H10721-110 PMT	Size (mm); 50x50x22 Maximum sensitive wavelength; 400nm Time response; 0.57 ns Operating temperature is between 5∘C and 50∘C. Maximum input voltage, current and control voltage are 5.5V, 2.7 mA, 1.1 V respectively.
DRS4 Readout System	For signal generation; FPGA, DAC, ADC chips are available Connection type; USB Data rate; 20MB Maximum voltage input; 2.8 to -0.5 V.

The site where the measurements were carried out is shown on the map in Figure 2 (Directorate General for Mapping/ HGM, https://www.harita.gov.tr/). This location is Pirsultanlı Village, Düziçi District, Osmaniye Province, located in the Mediterranean Region and the east of Çukurova. The exact coordinates of the measurement point are latitude 37.33°N, longitude 36.34°E, and the altitude is 272 meters above sea level.
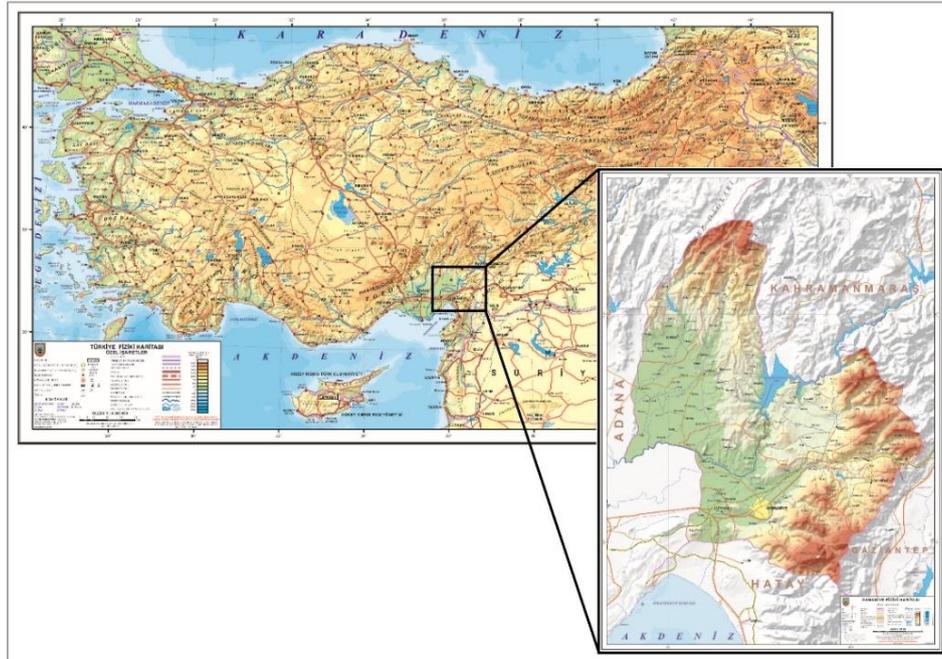

Figure 2. Study area

2.2. Time of Flight (TOF) Method

Various methods have been developed to detect and analyze cosmic ray-muons. One of these methods, the TOF method, is based on determining the velocity of particles by measuring the travel time between two or more detectors (Polatoğlu et al., 2022). The TOF method is critical for the detection and differentiation of particles. This method is widely used especially in the detection of high-energy particles and particle physics experiments. The TOF method basically works by positioning two or more detectors at a certain distance. A timestamp is taken when a muon passes the first detector and a second timestamp is recorded when it reaches the second detector. Using the distance and time difference between the detectors, the speed of the muon is calculated. This information provides important clues about the energies, origins and interactions of muons in the atmosphere. One of the major advantages of the TOF method is that particles can be separated based on their different velocities. In addition, the TOF method is effective in reducing low-energy background noise, thus increasing the accuracy of the measurements. Muon measurements with the TOF method are of great importance for understanding the components of CRs reaching the Earth and investigating the atmospheric effects of these particles. Moreover, the TOF method is frequently used in particle physics experiments thanks to its precise measurements of particle velocities. In particular, the high time resolution of the detectors minimizes

the margin of error in measurements and ensures reliable results. The calculation of muon flux by TOF method is shown in Equation 1 (Rossi, 1964; Grieder, 2001).

$$\Phi = \frac{N \times d^2}{\Delta t \times A^2}$$ (1)

Where N is the number of cosmic muons, d is the distance between the two scintillators, A is the surface area of the scintillator and Δt is the time elapsed during the measurement. The statistical error rate calculation is proportional to the square root of the count value and is presented in Equation 2.

$$\frac{d^2}{A^2 \Delta t} N^{1/2}$$ (2)

The raw dataset contains both real muon signals and spurious counts due to electronic noise or electrons. Therefore, the TOF distribution is first parametrically modeled with a Gaussian function and the mean (μ) and standard deviation (σ) of the resulting distribution are determined. Within the Gaussian distribution, the vast majority of real muon signals fall within the $\mu \pm 2\sigma$ range, while events outside these limits are most likely background noise or electronic errors. Therefore, the $\mu \pm 2\sigma$ cross section contains the true muon counts at about 95% confidence level and minimizes the background effect. The number of events in this interval constitutes N, defined as the net muon count. This cleaned N value is then substituted into Equation 1 to calculate the muon flux. This minimizes the systematic biases caused by electronically-induced and low-energy background counts and makes the flux more reliable.

2.3. Pressure Corrections

The obtained muon flux data were quantitatively evaluated by considering parameters such as detector geometry and measurement time. However, not only these geometric and temporal factors, but also atmospheric conditions play an important role in cosmic ray-induced muons reaching the Earth. In particular, changes in atmospheric pressure have a direct impact on the muon flux and should be taken into account for the accuracy of the measurements. Therefore, the next step is to analyze the effect of atmospheric pressure.

CRs data are significantly affected by atmospheric pressure variations. To remove this effect, the raw count rates (CRraw) are normalized by a correction to the reference pressure (P_0). This is done using the correction equation based on the following exponential relationship (Poirier and Catanach, 2011).

$$N = N_0 \exp\left(\beta \frac{(P - P_0)}{P_0}\right) \rightarrow CR_{corrected} = CR_{raw} \times e^{-B \times (P - P0)}$$ (3)

Where P is the atmospheric pressure at the time of measurement, P_0 is the reference pressure value and β is the Barometric coefficient that determines the sensitivity of the system to atmospheric pressure. Thanks to this transformation, the effect of short-term variations due to pressure is reduced and

physically induced variations in CRs can be analyzed more accurately. In order to determine the effects of atmospheric pressure variations on muon flux, the barometric coefficient (β) was calculated by analyzing the measurement data. The relationship between muon flux and atmospheric pressure is generally expressed as an exponential function $CR_{raw} = N_0 * e^{-\beta*(P-P_0)}$ (Dorman, 2004).

CR$_{raw}$ stands for Raw Cosmic ray count rate, N$_0$ stands for the parameter found from the fit (reference count rate), β stands for Barometric Coefficient, P stands for Instantaneous Pressure, P$_0$ stands for Reference Pressure (1013 hPa at sea level). Edited form of the equation: $\mathrm{Ln}(CR_{raw}) = -\beta * (P - P_0) + Ln(N_0)$

Atmospheric pressure data were provided and the relationship between muon flux and pressure variations was analyzed using regression analysis. For the exponential fit, i.e. to determine the unknown parameters (β) and CR$_{corr.}$ in the equation, the CurveFit Function of the Scipy library in the python software language was used. This function calculates the β values that will provide the best fit between raw CRs data and pressure.

The effect of atmospheric pressure variations on the cosmic ray-induced muon flux has been quantitatively demonstrated. However, not only atmospheric parameters, but also the Earth's magnetic field structure plays a decisive role in cosmic rays reaching the Earth. Accordingly, in order to reveal the geomagnetic properties of the observation location, the magnetic latitude was calculated in the next step. Magnetic latitude information is important as it is one of the main factors that determine the probability of CRs passing through the magnetosphere and entering the atmosphere (Mendonça et al., 2019).

2.4. Magnetic Latitude Calculation

Given the information given, the magnetic latitude can be calculated for a location with a geographic latitude of 37.3351° and a geographic longitude of 36.3419°. The Earth's magnetic pole is located at approximately 80° latitude. The model that determines the relationship between geographic latitude and magnetic pole relies on Equation 4 to calculate magnetic latitude (Smart and Shea, 2005).

$$sin\lambda_m = sin\lambda_g sin\lambda_p + cos\lambda_g cos\lambda_p cos(\triangle \phi) \tag{4}$$

The parameters here are: λ_g =37.3351 °(geographic latitude), λ_p=80 °(magnetic pole latitude), $\triangle \phi$= 36.3419, (difference between geographical longitude and magnetic pole longitude). When the calculation is made using this data: sin(37.3351°)= 0.606, sin(80°)= 0.985, cos(37.3351°) =0.795, cos(80°)= 0.1736, cos (36.3419 °) = 0.829;

$sin\lambda_m = 0.606 \times 0.985 + 0.795 \times 0.1736 \times (-0.309) = 0.597 - 0.043 \approx 0.554$

$\lambda_m = arcsin(0.554) = 33.7°$

The Magnetic Latitude of the observed location was found to be 33.7°.

2.5. Cut-off Rigidity

Cut-off rigidity is a concept that describes the degree to which CRs are deflected or blocked by the Earth's magnetic field. It is the minimum rigidity value that a particle must have in order to pass through the magnetic field (Smart and Shea, 2005). Particles below this rigidity are deflected by the Earth's magnetic field and cannot reach the Earth's surface. The rigidity value at the equator and poles takes different values in different regions due to the variability of the magnetic field and atmospheric permeability. For a more accurate calculation of the measurements and a more accurate inference, the Rigidity value of the location from which the data is taken must be calculated. Equation 5, which called Störmer equation, is used to calculate the cut-off rigidity (Velinov and Mishev, 2008).

$$R_c = 14.9 * cos^4(\lambda_m) \ [GV] \tag{5}$$

The parameters here are R_c= Rigidity, 14.9= constant, λ_m= Magnetic Latitude. Substituted in Equation5 is calculated as, $R_c = 14.9 * Cos\ 33.6^4 = 7.17\ GV$.

Calculations were also made with the Cutoff2050 Geomagentic Calculator program. The results found for 2025-01-01 date and related latitude, longitude and altitude Cutoff rigidity; effective = 7.788 GV, upper = 8.062 GV, lower = 7.666 GV (https://tools.izmiran.ru/cutoff/).

3. Result and Discussions

The Experimental System recorded 42868 CR events, collecting data continuously for a total duration of 950400 s. This raw dataset contains real muon signals as well as spurious triggers caused by electronic noise and other types of particles. To separate the real muon signals, the corresponding TOF distribution was first parametrically modeled with a Gaussian function, and then the mean (μ) and standard deviation (σ) of the distribution were calculated. Since only the events within the $\mu \pm 2\sigma$ range represent true muon counts at approximately 95% confidence level, the 36437 events within this window were defined as the "net muon count" N (Figure 3). The inter-scintillator distance d=12.7 cm and the surface area A=25 cm^2 of each scintillator were fitted to the muon flux formula in Equations 1 and 2. This result indicates an average muon flux density of $0.0099 \mp 0.0001\ cm^{-2}\ s^{-1}sr^{-1}$ at the measurement point. It is important to remember that the flux of cosmic rays varies throughout the year. Every 11 years, like sunspots, cosmic rays reach a maximum and a minimum. As of 2025, the cosmic ray flux is at a minimum, which can be monitored instantly on the Oulu Cosmic Ray station page (https://cosmicrays.oulu.fi/). The flux result of the measurements made in Erzurum center at 1885 m altitude is $0.0235\ cm^{-2}\ s^{-1}sr^{-1}$, while the results of the measurements made at sea level in Antarctica are $0.0164\ cm^{-2}\ s^{-1}sr^{-1}$. These measurements were made in 2022 and coincide with the years when the cosmic ray intensity is higher (Polatoğlu et al., 2023). It is known that the cosmic ray flux increases

as we move towards the poles and as the altitude increases. The obtained flux value of 0.0099 is consistent with other values in the literature.

For the sensitivity and uncertainty analysis, Equation 2 based on Poisson statistics was used. The relative error, calculated based on the square root of the net muon number, is 0.01%. This extremely low margin of error suggests that both the detector hardware (in particular the combination of DRS4 and PMT with high time resolution) and the statistical cleaning method applied ($mean \pm 2\sigma$ filter) significantly improve data quality and measurement reliability.
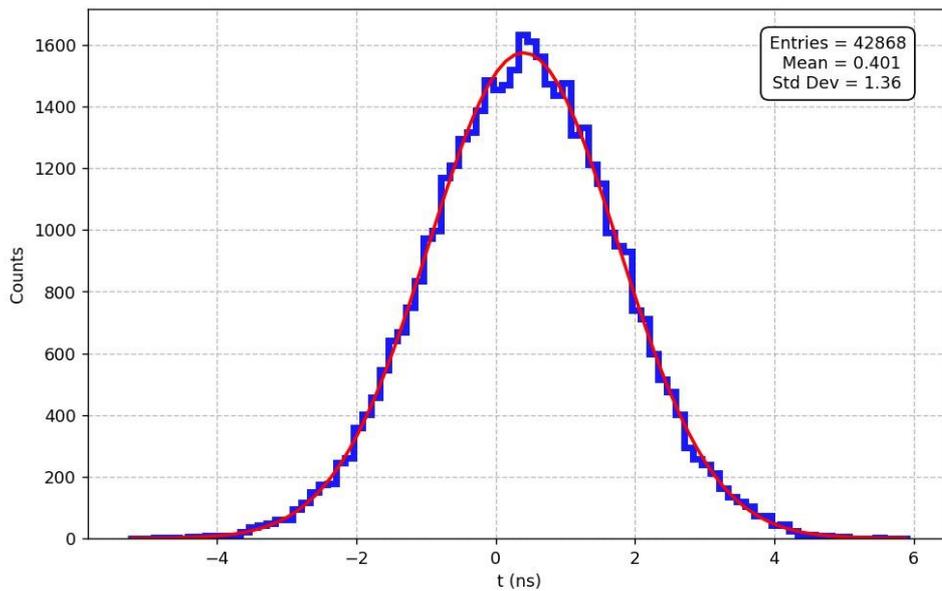
Figure 3. Distribution histogram of cosmic ray-muons according to time of flight

For the barometric correction, we first quantified the effect of pressure variations on the muon count rate and determined the values of the barometric coefficient (β) and the reference count rate (N_0). Atmospheric data were obtained from the open meteo service (Open-Meteo) (https://open-meteo.com). The Open meteo page provides data from ECMWF Reanalysis v5 (ERA5) (https://www.ecmwf.int/). Instantaneous atmospheric pressure data and raw muon rate data were subjected to regression analysis using the Python/SciPy curve_fit function under the exponential model (Equation 3) defined previously. The best fit resulted in $\beta = -0.02089$. These values are the key parameters explaining the suppressive effect of pressure fluctuations on muon flux under our measurement conditions.
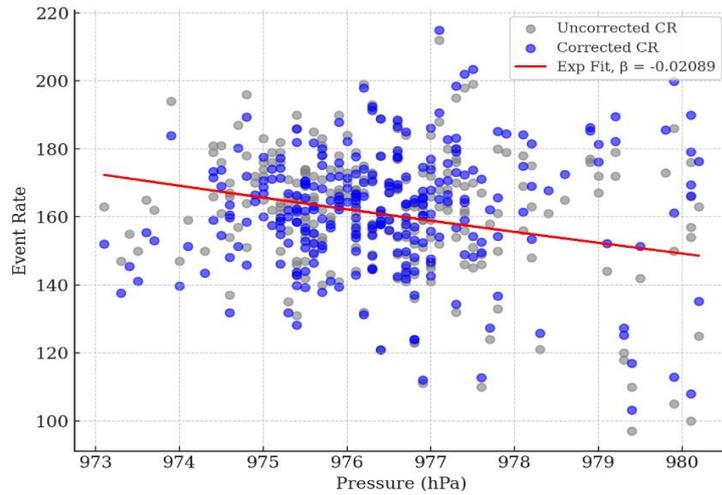
Figure 4. Raw CR and Pressure-Corrected CR Data

The determined barometric coefficient and the reference count rate information were used to process the observed muon count N_{obs} (P) at each time point using the defined correction formula. Figure 4 shows the raw CR data in gray dots, the pressure-corrected count rates in blue dots and the exponential model fit in red. In Figure 5, the deviations compared to the time axis can be observed in detail by plotting the event rate before and after correction. It is clear from these graphs that the measured flux decreases significantly as the pressure increases and that the correction eliminates the systematic trend and stabilizes the data set.

Atmospheric pressure shows a clear influence on the measured muon flux. In our dataset containing 36437 events, the raw flux systematically shifts to lower or higher levels when no correction is applied, resulting in a deviation of approximately 2.48% ($\Delta\%$ = (raw − corr.)/(corr.) × 100). The percentage difference quantifies the atmospheric pressure–induced deviation of the raw flux relative to the corrected reference flux. After applying the pressure correction using the barometric coefficient β obtained from exponential fitting, the flux stabilizes. Since this deviation is significantly larger than the statistical uncertainty (0.01%), the atmospheric effect cannot be ignored. Thus, implementing pressure correction is essential to ensure the accuracy and reliability of muon flux measurements.
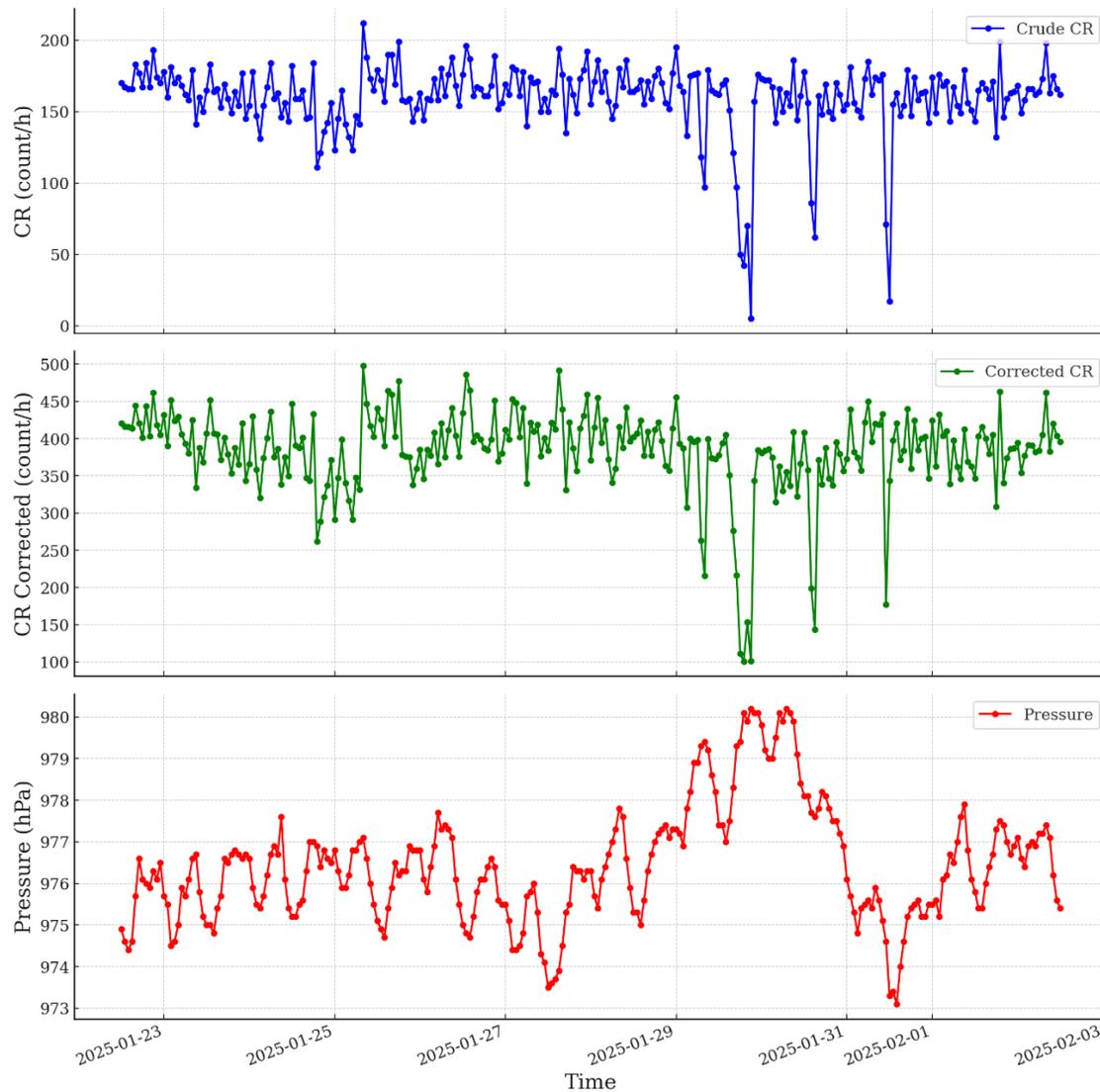
Figure 5. Time variation of cosmic ray count rates obtained by correcting for atmospheric pressure effect

In order to test the reliability and general validity of the results, the results of the post-correction muon detector data are compared in Figure 6 with the results of other reference neutron monitor detectors, such as ATHN and TERA (Neutron Monitor Database/ NMDB, https://www.nmdb.eu/nest/). Despite small deviations due to different location, altitude, geomagnetic rigidity, pressure and temperature conditions, and differences in detector design, the measurement trends of the three instruments partially overlap. The magnetic cutoff value of our measurement point was calculated as 7.17 GV according to Equation 5, indicating that the Osmaniye region has relatively high rigidity and that geomagnetic filtration should be taken into account in muon flux analyses. Furthermore, with the small scintillator surface available, the number of events recorded is relatively small, so the statistical uncertainty obscures small trends. To overcome this situation, we must either reduce the statistical error by significantly extending the data collection time or increase the number of muons recorded by increasing the effective area of our system. Because, given the squared effect of area in the flux calculation,

doubling the scintillator area would quadruple the number of events and increase the sensitivity of our trend analysis and allow us to see pressure-induced variations more clearly.
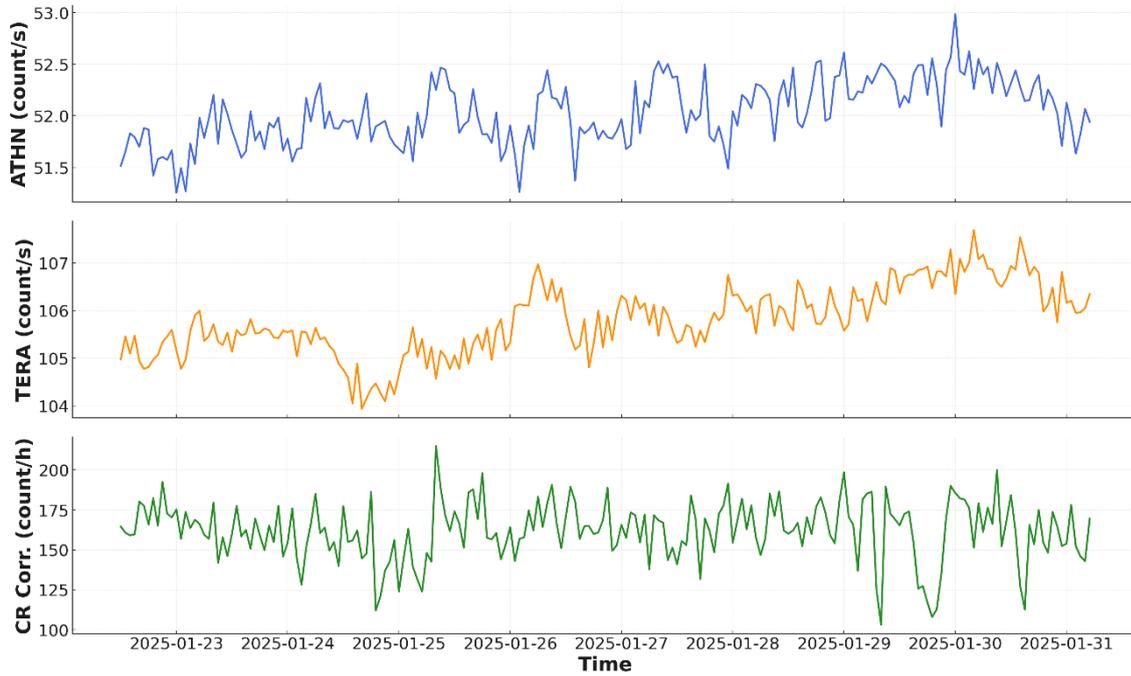

Figure 6. Time series comparison with different detectors

4. Conclusion

As a result of Time-of-Flight (TOF) based field measurements, a total of 36437 muon events recorded over a period of 950400 seconds were analyzed. Using these counts, the average muon flux at the measurement point was calculated as $0.0099 \mp 0.0001\ cm^{-2}\ s^{-1}sr^{-1}$. The statistical filtering and exponential barometric correction procedure ($\beta = -0.02089$) applied to the raw count rates minimized biases due to short-term fluctuations in atmospheric pressure. Thus, the true physical variations of the measured muon flux are more reliably revealed and systematic errors are significantly reduced. Muon flux measurements were conducted with a total of 36437 recorded events, leading to a statistically precise flux determination with an uncertainty on the order of 0.01%. The analysis demonstrates that implementing environmental correction procedures, particularly for atmospheric pressure, is necessary to ensure accuracy and stability in the results. These findings indicate that the applied methodology is reliable for continuous muon monitoring. Future work will extend the observation period and incorporate additional environmental parameters to further improve measurement robustness.

Geomagnetic parameters specific to the region were also calculated considering the conditions of 37.33° N latitude, 36.34° E longitude and 272 meters altitude. In this context, the cutoff rigidity value over the magnetic latitude was found to be 7.17 GV. This value provides important information about the extent to which cosmic rays are filtered by the Earth's magnetic field in the Osmaniye region and is critical for

understanding the regional variations in the muon flux. In addition, the low-cost plastic scintillator and DRS4-based portable system used in the measurement has been shown to produce reliable and precise data thanks to its high time resolution and suitability for field conditions.

This study provides reference data specific to the Osmaniye region with the first local muon flux measurements and demonstrates the practical effectiveness of field portable detectors. The results show that atmospheric and geomagnetic corrections can be successfully applied to field data. In future studies, it is recommended to map the cosmic ray flux on a global scale with simultaneous muon flux measurements at different geographical latitudes and altitudes, and to examine the effects of long-term pressure and temperature changes on the muon flux in more detail. Thus, it will be possible to reach more comprehensive and comparable results in terms of both astroparticle physics and atmospheric sciences.

Statement of Conflict of Interest

The authors declare that there is no conflict of interest between them.

Author's Contributions

The authors declare that they have contributed equally to the article.

References

Al-Qaaod A., Pierrard V., Winant A., Stolzenberg U., Ambrozova I., Sommer M., et al. Correlation patterns of muon flux with vertical atmospheric profiles: insights from Monte Carlo simulations. Journal of Geophysical Research: Space Physics 2025; 130(11): 1–13.

Denisov D., Evdokimov V., Lukić S. Time and position resolution of the scintillator strips for a muon system at future colliders. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 2016; 823(1): 120–125.

Dorman L. Cosmic rays in the earth's atmosphere and underground. New York: Springer; 2004.

Franke R., Holler M., Kaminsky B., Karg T., Prokoph H., Schönwald A., Schwerdt C., Stößl A. CosMO a cosmic muon observer experiment for students. 33rd International Cosmic Ray Conference, 2013, 1-4, Rio De Janeiro.

Gaisser TK., Engel R., Resconi E. Cosmic rays and particle physics. 2nd. ed. Cambridge: Cambridge University Press; 2016.

Grieder PK. Cosmic rays at earth. 1st ed. Amsterdam: Elsevier; 2001.

Mendonça RRS., Wang C., Braga CR., Echer E., Dal Lago A., Costa JER., Munakata K., Li H., Liu Z., Raulin JP., Kuwabara T., Kozai M., Kato C., Rockenbach M., Schuch NJ., Al Jassar HK., Sharma MM., Tokumaru M., Duldig ML., Humble JE., Evenson P., Sabbah I. Analysis of cosmic rays' atmospheric effects and their relationships to cutoff rigidity and zenith angle using global muon detector network data. Journal of Geophysical Research: Space Physics 2019; 124(12): 9791–9813.

Michael DG., Adamson P., Alexopoulos T., Allison WWM., Alner GJ., Anderson K., Andrews M., Arms K., Auty D., Ayres DS., Barrett WL., Barrish BC., Bercovitz J., Blair R., Block C., Boardman RJ., Boehnlein D., et al. The magnetized steel and scintillator calorimeters of the MINOS experiment. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 2008; 596(2): 190–228.

Poirier J., Catanach T. Atmospheric effects on muon flux at project GRAND. Proceedings of the 32nd International Cosmic Ray Conference, 2011, 11–18, Beijing.

Polatoğlu A., Yeşilyaprak C., Kaya M., Niaei MS., Er H. New the design and measurements of the portable cosmic ray muons detector (CRMD) for an observatory. Universal Journal of Physics and Applications 2023; 17(4): 33–42.

Polatoğlu A., Yeşilyaprak C., Niaei MS., Kaya M. Doğu anadolu gözlemevine (DAG) yönelik ilk kozmik ışın dedektörünün kurulması ve test ölçümleri. Turkish Journal of Astronomy and Astrophysics 2022; 3(2): 17–21.

Rossi B. Cosmic rays. New York: McGraw-Hill Book Company; 1964.

Sidelnik I., Asorey H., LAGO Collobration. LAGO: The Latin American giant observatory. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 2017; 876(1): 173–175.

Smart DF., Shea MA. A review of geomagnetic cutoff rigidities for earth-orbiting spacecraft. Advances in Space Research 2005; 36(10): 2012–2020.

Velinov P., Mishev A. Cosmic ray induced ionization in the upper, middle and lower atmosphere simulated with CORSIKA code. 30th International Cosmic Ray Conference, 2008, 749–752, Mexico.

Zhao D., Li P., Li L. Cosmic ray muon navigation for subsurface environments: technologies and challenges. Particles 2025; 8(2): 46.