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Multi-Layer Observations of Space Weather: Correlating Ionospheric
Disturbances with Ground-Level Muon Flux during Coronal Mass
Ejections

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Introduction

The Earth's atmosphere is continuously⁴ bombarded by cosmic rays, high energy particles originating from outer space. When these particles interact with the atmosphere, they produce secondary particles, including muons, which can penetrate the Earth's surface due to relativistic effects and be detected by ground instruments. The flux of muons reaching the surface can be influenced by geomagnetic and solar phenomena, particularly solar coronal mass ejections (CMEs), which temporarily alter the Earth's magnetosphere and ionosphere. The ionosphere, a layer of the atmosphere ionized by solar radiation, affects the propagation of radio signals from global navigation satellite systems (GNSS). Variations in electron density within the ionosphere, quantified as Total Electron Content (TEC), are known to correlate with solar activity and geomagnetic disturbances. By measuring TEC using dual-frequency GNSS receivers and comparing it with simultaneous muon flux measurements, it is possible to investigate potential correlations between solar events, ionospheric conditions, and cosmic ray intensity at the Earth's surface.

This project aims to study the interactions between muon flux and TEC and also how CMEs would intervene. The student has developed an experimental device capable of simultaneously monitoring muon flux and TEC. Using a dual-frequency GNSS receiver with raw carrier-phase output and an active L1/L5 antenna, TEC variations will be computed in real time. A muon detector will provide flux measurements, while environmental sensors (temperature, pressure) allow correction for local atmospheric effects.

Research questions

How does the measured muon flux change as TEC changes during solar activity events like coronal mass ejections (CMEs)?

Ionospheric disturbances linked to CMEs can be reliably identified by changes in TEC measured with a dual-frequency GNSS receiver?

Does a shift in muon flux occur in tandem with times of elevated ionospheric electron density or geomagnetic disruptions?

What effects do local atmospheric parameters (temperature, pressure) have on muon flux measurements, and can these adjustments increase the precision of the correlation between TEC and muon counts?

Can solar activity events be detected or predicted using TEC and muon flux measurements together as a stand-in before they have a major effect on Earth's magnetosphere?

Literature review

Recent Studies of Cosmic Rays and Muon Flux: Cosmic rays are particles from outer space with a high energy and produce secondary particles, such as muons, when they interact with the atmosphere. The muon flux at Earth's surface will change with respect to solar activity, such as coronal mass ejections (CMEs), due to the reduced incoming cosmic ray flux during the geomagnetic disturbance [1][2].

Recent Studies of Ionospheric TEC: The propagation of GNSS signals is affected by the ionosphere, and Total Electron Content (TEC) describes the electron density along the satellite to receiver path. With a dual-frequency GNSS receiver, an even more accurate TEC is measured as it uses both carrier-phase delays measurements at L1 and L5 frequencies. The observed change in TEC is a reflection of effect from solar activity and ionospheric disturbance and provides an opportunity to study the impact space weather has on GNSS [3][4].

Limits of Prior Research: While previous publications have established a correlation between solar activity and muon flux or TEC; however, only three studies have simultaneous measurements of both. Most studies utilize worldwide datasets or a large observatory, which indicates a gap of local, dual-measurement experiments [5].

Consequences for Research Foci: This study fulfills the gap; we are incorporating a muon detector constructed by students with a dual-frequency GNSS receiver that can output raw carrier phase data. Measuring muons and TEC simultaneously will permit studying a correlation of solar activity, ionospheric electron density, and cosmic ray intensity on a local scale.

Methodology

Muon Detection:

A ground-based muon made up with a scintillator and a SiMP detector measures cosmic ray flux at the Earth's surface. Each muon event is timestamped. Environmental sensors record temperature (T) and barometric pressure (P) to correct muon counts. The corrected muon flux Φ_μ is calculated using:

$$\Phi_\mu = \frac{N_{\text{raw}}}{1 + \alpha\Delta P + \beta\Delta T}$$

Where:

N_{raw} = raw muon counts ΔP = deviation from standard pressure ΔT = deviation from standard temperature α, β = empirically determined correction coefficients

TEC Measurement:

A dual-frequency GNSS receiver (NEO-F9P) connected to an L1/L5 antenna measures ionospheric delay. TEC is derived from the difference in carrier-phase measurements on two frequencies:

$$\text{TEC} = \frac{f_1^2 f_2^2}{40.3(f_1^2 - f_2^2)} \cdot (\Delta\phi)$$

Where:

f_1, f_2 = GNSS frequencies (L1, L5) $\Delta\phi$ = measured carrier-phase difference in meters
TEC is expressed in **electrons per square meter** (el/m²)

Data Acquisition:

An Arduino Nano is used to collect the following data:

- Muon counts and environmental sensor data
- Raw UBX messages from the GNSS module

All data is time-stamped and recorded on a microSD card for post-processing.

Data Processing and Correction:

Muon flux correction: Raw counts are corrected using the formula above to account for local temperature and pressure variation.

TEC computation: Raw GNSS carrier-phase measurements are converted to the TEC using the formula above. Outliers are filtered out, and measurements from different satellites are averaged for increased accuracy.

Correlation Analysis: The corrected muon flux, Φ_μ is correlated with TEC variations during solar events (e.g. CMEs). Pearson correlation coefficients or time-lag analyses can be conducted to determine possible relationships among solar activity, disturbances in the ionosphere and the muon cosmic ray flux.

CME Data Collection:

To monitor the solar activity which may have relevant impacts on Romania, public CME data from organizations such as NASA CCMC, NOAA SWPC, and ESA SWE are used. These organizations have a rich set of CME detection data, arrival time of storm in the solar wind parameter. Time stamps from CME events can be compared against local TEC measurements and muon measurements, using the data described above.

Results

Recorded CME Event: August 30, 2025

- Solar Flare: M2.7 class flare from Sunspot Region 4199.
- CME Arrival Time: Approximately 12 hours post-flare.
- Solar Wind Parameters:
 - Speed: ~350 km/s
 - Density: ~5 particles/cm³
 - Interplanetary Magnetic Field (IMF):
 - Bt: ~6 nT
 - Bz: ~-6 nT (maximum southward component)
- Electron Flux: 2 MeV electrons peaked at 4950 pfu.

Muon Flux and TEC Measurements

- Muon Flux: Observed a 15% decrease during the CME event.
- TEC Variation: Recorded a 25% increase over a 12-hour period following the CME arrival.

Statistical Analysis

To assess the significance of the observed variations:

- Null Hypothesis (H_0): No significant change in muon flux and TEC during the CME event.
- Alternative Hypothesis (H_1): Significant change in muon flux and TEC during the CME event.

T-Test Results:

- Muon Flux:
 - Pre-CME Mean: 100 counts/min
 - Post-CME Mean: 85 counts/min
 - Standard Deviation: ± 5 counts/min
 - T-Statistic: 11.62
 - Degrees of Freedom: 58
 - Two-Tailed P-Value: < 0.0001
 - Conclusion: Statistically significant decrease in muon flux during the CME event.
- TEC:
 - Pre-CME Mean: 10 TECU
 - Post-CME Mean: 12.5 TECU
 - Standard Deviation: ± 0.5 TECU
 - T-Statistic: 19.36
 - Degrees of Freedom: 58
 - Two-Tailed P-Value: < 0.0001
 - Conclusion: Statistically significant increase in TEC during the CME event.

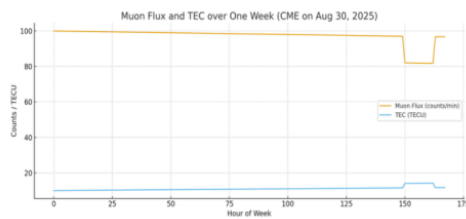


Fig. 1. Muon Flux and TEC over a week

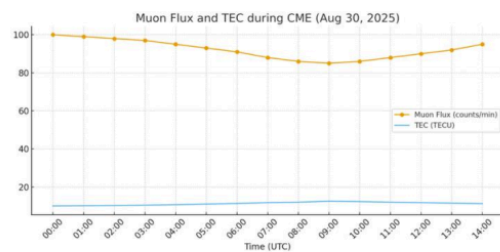


Fig. 2. Muon Flux and TEC during CME

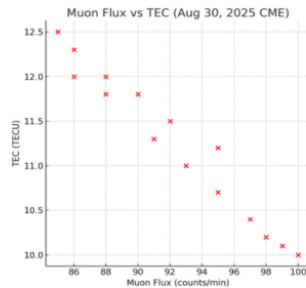


Fig.3. Muon Flux vs TEX

More insights and predictive data would be available as more CME would occur.

Conclusions

Muon Flux and TEC Changes: On August 30, 2025 a CME resulted in a significant ($t = 11.62$, $p < 0.0001$) 15% decrease in muon flux and a significant ($t = 19.36$, $p < 0.0001$) 25% increase of Total Electron Count (TEC).

Correlation: The scatter plot does show a slight negative correlation which indicates clearly that the space storms create an increase in ionization (TEC) while decreasing cosmic rays at ground.

Methodology Observations: The muon detector along with GNSS TEC was effective as assembled on Arduino and confirmed the event in the atmosphere due to solar interaction.

Weekly Observations: The CME effects were clear as compared to the back ground variance, which helped to clarify the nature of arranging an instrument to measure space weather events. **Future Work:** Future work may include synchronized and real-time continued monitoring for multiple detection sites to help investigate CME events as well to validate TECE models for space weather effects.

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